The Physical Characteristics of Mechanical Pipe Organ Actions and how they Affect Musical Performance

Alan G Woolley

A thesis submitted in fulfilment of the requirement for the degree of

Doctor of Philosophy

to

The University of Edinburgh

Abstract

Many organists believe that one of the main advantages of mechanical actions, i.e. those in which there is a direct and uninterrupted mechanical link from the key which the player moves to the pallet valve that admits air to the pipes, is that they allow the player to control the pallet and thus influence the initial sound of the pipe. The need to repeat notes at the rate at which the fingers can comfortably move whilst keeping the required force within an acceptable limit defines a maximum effective mass of the action. The force to start the key moving is a combination of the force exerted by the pallet return spring (approximately constant) and the "pluck" which is the net force due to the pressure difference across the pallet and which has to be overcome before the pallet starts moving but which then reduces as the pressures equalise. Any lack of rigidity in the action will result in the action flexing before the pallet starts opening. When the pluck has been overcome, the pallet will spring partially open. As actions become longer in larger organs, the need to restrict the effective mass means that components have to be made with less material and are thus more flexible. Larger organs also imply more and louder pipes and thus a greater wind requirement, which in turn means more pluck.

This project looks at how the key and pallet actually move compared with what the player believes is happening. Measurements of the movement of the keys and, where possible, the pallets were made using LED and laser distance sensors, with the organists being asked to play in a variety of styles that they believed resulted in the keys moving at significantly different speeds. Sound recordings were made in order to compare the transients.

The results showed that the key movement could be broken down into two distinct parts. The first part is the movement before pluck and thus before the pallet starts opening in which the flexibility of the action was taken up. The relative length of this movement varied very considerably even on short and rigid actions showing elongations when players believed that they were moving the key slowly. The movement after pluck, and thus during which the pallet was opening and admitting air

i

to the pipes, did not vary greatly and in some cases, despite the player very deliberately trying to vary the speed, remained nearly constant. It could be clearly shown that attempts to vary the speed of key movement were, in fact, resulting in distinct rhythmic changes.

The conclusion is that although players vary the time of the complete key movement, any difference occurs mostly in the part of the key movement before the pallet starts opening and thus cannot have any influence on the initial transient.

Declaration

I do hereby declare that this thesis was composed by myself and that the work described within is my own except where explicitly stated otherwise.

Alan Woolley

February 2006

Acknowledgements

Table of contents

List of Illustrations

List of tables

Chapter 1

Introduction

Fig 1 The organ in Bridgewater Hall, Manchester, built by Marcussen of Denmark in 1996 IVP76.

The pipe organ has existed in a recognisable form for several thousand years and its history has been researched and documented, [Williams 1980] [Perrot 1971] and others. Of necessity, the early instruments were entirely mechanical. The large organs of the High Baroque were hand (or foot) blown and all linkages from keys to

pallets and from stop knobs to sliders were also entirely mechanical. As the industrial revolution dawned and mechanical means of supplying larger quantities of air became available and the manufacture of more complex machinery was practical, pneumatic power was applied to the organ in order to reduce the force required to move the keys and also to allow larger and less rigidly laid out organs to be built. In turn, with the advent of electricity, electric power took this change a stage further. Organs became larger, more diverse and, in the opinion of some, less musical.

During the 1920s the Organ Reform Movement (Orgelbewegung) started in North Europe, although its history does not appear to have been well documented, and a return to some of the values of the earlier organs was advocated. Crucial to this became a belief that key action should be mechanical so that the player had a direct link with the pallet. Fig 1 shows a typical recent concert hall organ in the Bridgewater Hall in Manchester built by Marcussen and Son of Denmark in 1996. This organ has four manuals and pedals with 76 speaking stops (IVP76). The key action is mechanical but with a subsidiary electric console which is almost exclusively used[1].

Reference to the list of published works in Chapter 3 indicates that opinions and beliefs vary greatly about the value of mechanical action, particularly in larger organs and this project seeks to shed some light on the question of how much control the organist actually has over the pallet and thus potentially the initial transient of the pipe speech.

Chapter 4 explains some of the physical issues that might affect how much control the player has. It is not exhaustive, but it covers the most important factors.

Chapter 5 describes the development of the equipment used to measure the movements of keys, and where possible, pallets of actual organs whilst they are

---

[1] Private conversation with curator

being played. It is important not to assume that the movement of the key is accurately reflected in the movement of the pallet, but this had to be verified.

Chapter 6 describes a model organ built in the laboratory to develop the equipment described in Chapter 5 and also to help clarify some of the results found whilst taking measurements on site.

The results of the work on site are set out in Chapter 7 with a separate section for each organ visited because the characteristics of each instrument are so different.

The conclusions and suggestions for further work that could be done are presented in Chapter 8.

Chapter 2

Glossary, and workings of the pipe organ

The following table explains the main terms used in this thesis that are specific to the pipe organ. This has been integrated with a description of how the various elements fit together. An adequate history of the organ would occupy too much space and is covered in a number of readily available books [Williams 1980] [Perrot 1971] etc.

Backfall	A lever, pivoted around its middle which reverses the direction of movement of an action (see Fig 2.6)
Balancier	A pneumatic means of assisting tracker actions by opposing pluck by means of a bellows vented to the groove (qv). The area of the top of the bellows is made smaller than the area of the pallet so that there is a residual net pressure against the pallet in order to provide some pluck As soon as the pressures in the groove and windchest start to equalise the effect of the balancier also reduces. The vent from the bellows to the groove is highlighted in red (Fig 2.1).
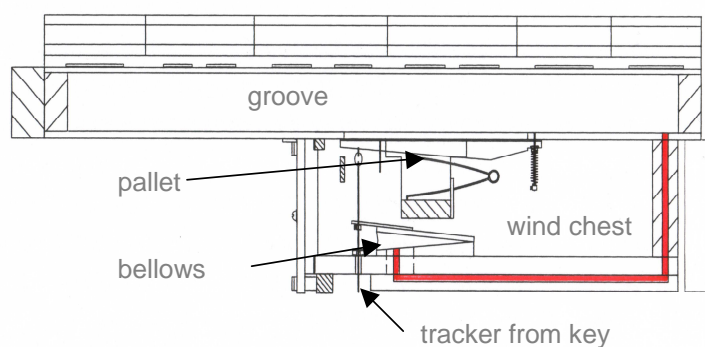
Fig 2.1 Balancier

Barker lever   Also Hamilton lever – Charles Spackman Barker and David
                      Hamilton developed similar devices at about the same time. It
                      was the first form of pneumatic action and introduced a
                      pneumatic motor into the action whilst removing the direct
                      mechanical link.
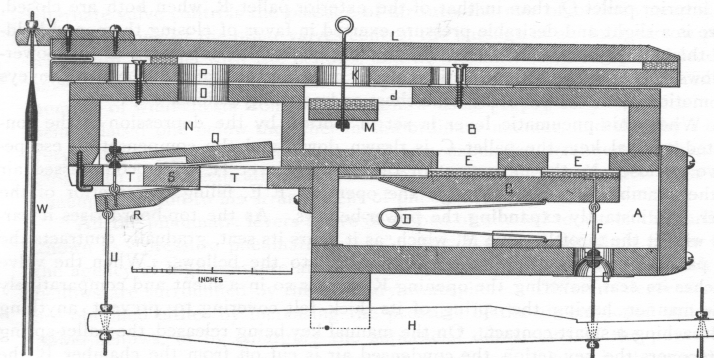
FIG. CLXXXI.

Fig 2.2 Barker lever

The Barker lever is discussed in Chapter 7.9 but Fig 7.9.17 is
repeated here as Fig 2.2 to show the principle of operation
([Audsley 1905] Fig CLXXXI). The tracker from the key is
attached at I at the right of Fig 2.2 and opens pallet G, which
admits air from the pallet box A to the bellows L which rise and
move tracker W which is connected to the pallet in the
windchest. Valves Q and R release the pressure when the key is
released.

Building frame   The basic framework on which the components of the organ are
                      mounted.

Bushing   Material, usually plastic or cloth to reduce the friction between
                      moving surfaces. See for example Fig 4.22.

Choir organ	Generally the third division of a three manual organ in which quiet stops are grouped together. The bottom manual of three and often enclosed.
Chorus	A number of ranks, usually with similar sound characteristics, tuned to the harmonics of the fundamental.
Cipher	The constant sounding of a note due to a fault in the action.
Compass	The musical range covered by a keyboard expressed either as the number of keys or by the pitches of the lowest and highest notes.
Coupler	A means, mechanical or electrical, to allow one division to be played from the keyboard of another.
Division	A part of the organ with distinct characteristics played by a separate keyboard, manual or pedal. The distinction can be tonal or the divisions can be physically separated.
Enclosed	A division in a swell box.
Equivalent Dynamic Mass (EDM)	The Equivalent dynamic mass (EDM) of an object is the mass of a point that would accelerate at the same rate when subjected to the same force. For example, when a force is applied to a key with the finger, the point of contact will accelerate at a rate depending on the inertias of the various components of the action. EDM replaces all these individual components with a single point mass that accelerates at the same rate.
Full organ	A full chorus of stops. It will exclude certain stops that are designed for solo use.
Gearing	A difference in the amount by which different parts of an action move. If the key moves 10 mm and the pallet moves 5 mm, the action is geared down 2:1. Gearing can be done in order to match the required movements of individual components or in order to reduce inertia by reducing the distance moved by parts of the action.
Great organ	The main manual division of an organ generally containing a chorus of principal ranks. It is usually unenclosed. The bottom manual of a two manual organ and the middle manual of three.

Groove	The part of a windchest to which the open pallet admits wind. All the pipes for any note are planted on top of one groove. Individual pipes speak if their slider is open (the stop is "on"). See Fig 4.1.
Hauptwerk	The German equivalent of the English Great organ. The main division.
Key	Can either mean just the part of the key (key head) that is visible to the player at the console or the complete key lever.
Key dip	The amount by which the finger moves vertically downwards when it moves the key. Fig 2.6
Key head	The part of the key visible at the console and thus contacted by the player. Fig 2.6
Key lever	The complete key assembly. Fig 2.6
Manual	A keyboard played by the hands and which controls a specific division of the organ.
Mixture	A stop comprising several ranks of pipes (two to five or more) sounding the upper harmonics of a note. There is no precise definition of the various names given to mixtures e.g. Furniture, but some give some indication of its nature e.g. Cymbel implies a high-pitched mixture. Because of the high pitches, mixtures "break back" to lower pitches through the compass.
Murmur	Individual pipes that give a faint sound due to air leaking into the groove.
Open Diapason	See Principal. The name of the stop on English organs giving the characteristic sound of the organ.
Organ specification, abbreviated	Organ specifications are sometimes abbreviated to indicate the number of manuals (Roman numeral) whether there is a pedal organ and the number of stops. Thus IIIP32 indicates three manuals and pedals and thirty-two speaking stops.
Pallet	The valve opened by the key that admits wind to the pipes.
Pallet box	The part of the windchest containing pressurised air, and from which the pallets control the flow of air to the groove and thus to the pipes. Fig 4.1

Pedal organ   A division of the organ played with the feet. Usually pitched an octave lower than the manuals in English organs, i.e. 16'.

Pipe length   The pitch of an organ pipe is defined by the speaking length (mouth to top) of an open flue pipe two octaves below Middle C (c^1), the normal extent of a manual keyboard in the bass. It is invariably stated in feet. The foundation pitch for manual divisions is 8', making an open pipe actually speaking Middle c^1 approximately 2' long. Pipes speaking an octave above the foundation pitch are designated 4' etc. Stopped pipes, which are approximately half the length of open pipes of the same pitch, are described as if they were open pipes although, particularly in older organs, they may be described as "8' tone" or similar. Mutations are ranks speaking harmonics other than octaves and are usually limited to fifths (2 2/3' etc) and thirds (1 3/5' etc). The dash is frequently omitted.

Pitch notation   There are various notations for musical pitch in common use. That adopted here is that Middle C is c^1 and thus the sequence starting two octaves below Middle C is C c c^1 c^2 c^3 etc. The corresponding lengths of open flue pipes are 8' 4' 2' 1' ½' etc. A manual keyboard of 56 notes starting two octaves below Middle C would have the range C to g^3. A pedal board of 32 notes starting three octaves below Middle C would have the range CC to g.

Pluck   The initial resistance felt at the key due to the pressure difference across the pallet. As soon as the pallet starts opening, the pressures start equalising and the resistance reduces. It is called pluck because it feels similar to a harpsichord touch as the quill plucks the string.

Pressure   Air pressure is measured in inches or mm water gauge (wg) as measured by a simple manometer. 10 mm wg is approximately equal to 1mb. Pressures in mechanical action organs typically range from 45 mm wg to 100 mm wg. Significantly higher pressures are used with electric actions. The upper limit of pressure is due to excessive pluck.

Principal   A group of organ stops, usually open metal flue pipes of medium diameter (2" at c'), giving the characteristic sound of the organ. They appear at different pitches to give a principal chorus. 8' principals are usually called Open Diapason in English organs (Prestant in Germany, Montre in France (particularly if the pipes are in the façade). 4' principals are called Principal or Octave, 2' principals are called Principal or Fifteenth. North European organs often have the divisions based

9

on principals an octave apart – pedal 16', Hauptwerk (Great) 8', Ruckpositiv 4', Brustwerk (loosely Choir) 2'. There would be other stops at 8' on these divisions.

Rank   A set of pipes, one for each key, of similar form and sounding the same. In Fig 2.3, Radley College, (see Appendix 1 for stop list) the ranks of pipes go from left to right. The grooves corresponding to a particular note go from front to back.
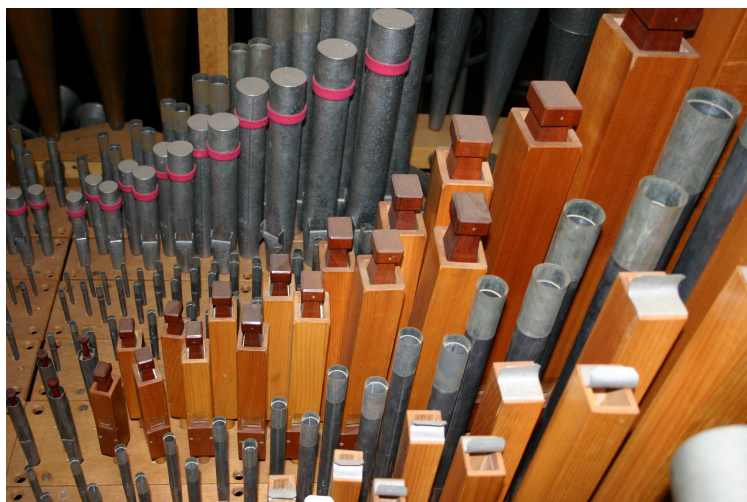
Fig 2.3 Ranks of pipes, Radley College. From bottom to top, Posaune 8 (just visible bottom right), Wald Flute 4, Principal 4, Stopped Diapason 8, Sesquialtera III, Bourdon 16 and Open Diapason 8. Three of the en chamade trumpet pipes can be seen top left between the façade Open Diapason pipes. The Fifteenth 2 and Furniture III are not visible.

Roller   A device for transmitting movement sideways. The trackers are attached to tracker arms attached to each end of the roller. The tracker at the right of the roller in Fig 2.4 pulls down the arm, which rotates the roller. The arm at the left of the photograph pulls down the tracker at its end.

Fig 2.4 A tubular aluminium roller with wooden arms as available from Laukhuff

Roller board   A board on which a number of rollers are mounted. See
                      Fig 4.19.

Rückpositiv   A division on North European organs that is behind the player's
                      back usually on the front of the organ gallery. St Mary's
                      Haddington (Fig 7.6.1) and the Reid Concert Hall (Fig 7.7.2)
                      have Rückpositivs.

Sesquialtera   A Mixture stop containing both fifth and third sounding ranks.

Sticker   A rod that transmits movement in a straight line by pushing. Fig
                      2.6.

Slider   A strip of usually wood drilled with holes that correspond with
                      holes in the top of the groove. Stops are placed on by aligning
                      the holes so that air can flow freely from the groove to the pipe
                      and off by moving the slider so that the passage of air is
                      blocked. Fig 4.1

Sponginess   A movement of the key before reaching the pluck point in
                      which the action acts as a spring due to rollers twisting, levers
                      bending and bushes compressing etc.

Square   Squares change the direction of movement of an action usually
                      through a right angle. In Fig 2.5 the tracker at the bottom left
                      pulls the square arm backwards. The square rotates about its
                      pivot and pulls down on the tracker at top left.
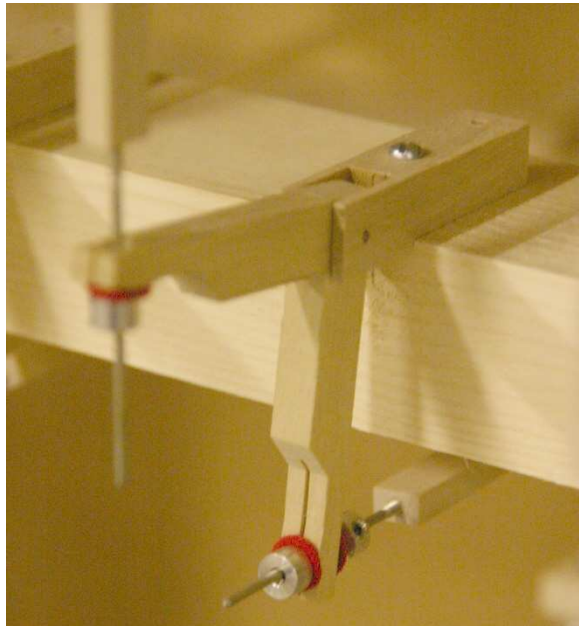
Fig 2.5 A wooden square as supplied by A J & L Taylor

Stop   Alternative name for a rank of pipes or a multiple rank of pipes
                         if they are controlled by the same slider (e.g. mixture). Also
                         used to mean the stop knob used to control a stop. Derived from
                         "stopping" the airflow to the pipes.

Stopped Diapason   A flute pipe formed of stopped wooden or metal pipes.

Swell organ   Generally the second manual division of an English organ. The
                         pipes are enclosed in a soundproof box with moveable shutters
                         controlled by a swell pedal in order to control the volume. The
                         top manual of a two or three manual organ.

Toe   The bottom of the pipe that rests on (is planted on) the
                         windchest.

Touch   In this paper the term touch is used as a general term to describe
                         how the movement of the key feels to the player in terms of
                         inertia, pluck, sponginess, friction etc. It is sometimes used to
                         describe the timing of key movements.

Tracker   A strip of wood or metal that transmits movement in a straight
                         line by pulling. See Fig 2.7

Ventil   A valve, usually in French organs, inside the windchest, that
                         cuts off wind to part of the windchest when more stops are on.
                         There is a separate pallet in both parts of the windchest and thus
                         pluck is reduced when only certain of the stops are on.

Windchest   Overall term for the part of the organ in which wind is
                         distributed to the pipes depending on which stops are drawn and
                         which key is depressed. The main parts are the pallet box,
                         which contains compressed air and the groove on which the
                         pipes are planted. See Fig 4.1.
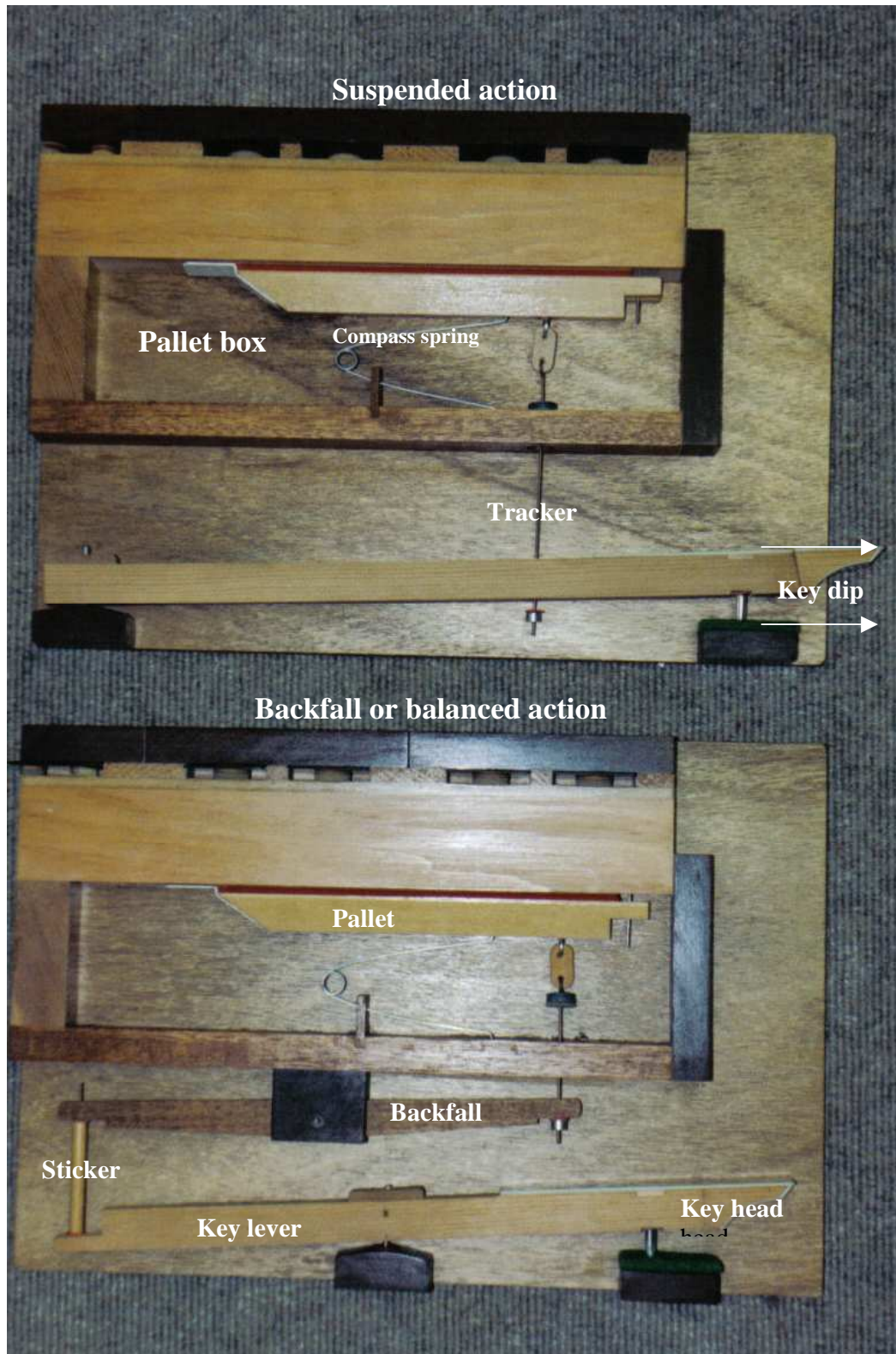
Fig 2.6 Model made by N P Mander Ltd for the University of Reading to illustrate the difference between a suspended (top) and backfall (bottom) action.
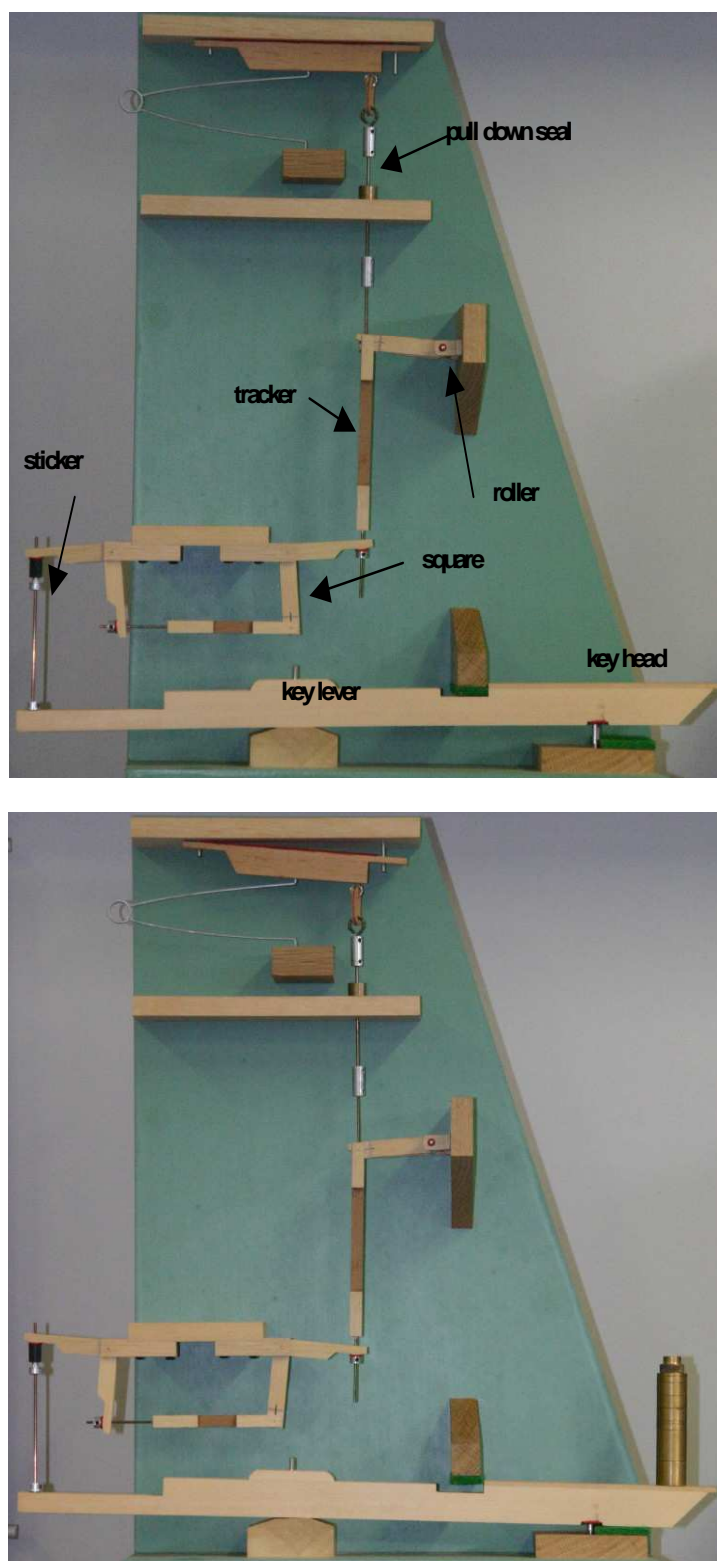
Fig 2.7 Model made by A J & L Taylor Ltd to illustrate their range of mechanical organ action components. The top picture shows the action at rest and the bottom picture shows the key fully depressed.

Chapter 3

Review of published works with critical comments

3.1 Introduction

There are very few objective scientific studies of mechanical actions and most of these are laboratory based rather than involving "real" organs.

Much of the writing is subjective to a greater or lesser extent, which makes it difficult to summarise without introducing further subjective interpretations. Lengthy quotes are printed below in order to give an accurate and unbiased indication of what the authors are saying.

It is sometimes difficult to draw a line at where a discussion about mechanical action should end. Where comments on the use of such devices as Barker levers and balanciers in otherwise mechanical actions add to the overall debate, or indicate the level of understanding of the subject, they have been included.

Terms, such as "touch" are sometimes used without definition, and it is clear that they can mean different things to different people. The glossary in Chapter 2 defines terms in common use in organ building and if there is any ambiguity, how they are used in this paper. It also defines some engineering terms in the context of this paper.

3.2 Critical discussion of published work in chronological order

Dom Bedos (François Bédos de Celles) *L'art du Facteur d'Orgue* **(Paris 1766-78) American translation by Ferguson, Charles** *The Organ-Builder* **(Raleigh NC, The Sunbury Press 1977)**

L'art du Facteur d'Orgue was written between 1766 and 1778. It remains, perhaps, the most comprehensive work on practical organ building in the history of the art. Illustrations from this work have been used in a number of books published right up the current time, as techniques have changed little over the years (for example "The Art of Organ Voicing" by Monette, and "Organ Building and Design" by Anderson). Other commentators have commented on the wisdom of wearing a sword whilst playing (Fig 3.1); this illustration does, however, show the general layout of a large four-manual organ of Dom Bedos's era.

There have been a number of reprints and a number of translations of this book. The American one cited is still available, as is an Italian one.

Dom Bedos describes in great detail the practical construction of a large four-manual organ and calculates the size of pallets and grooves on the basis of the wind requirement of the pipes by totalling the areas of the toe holes.
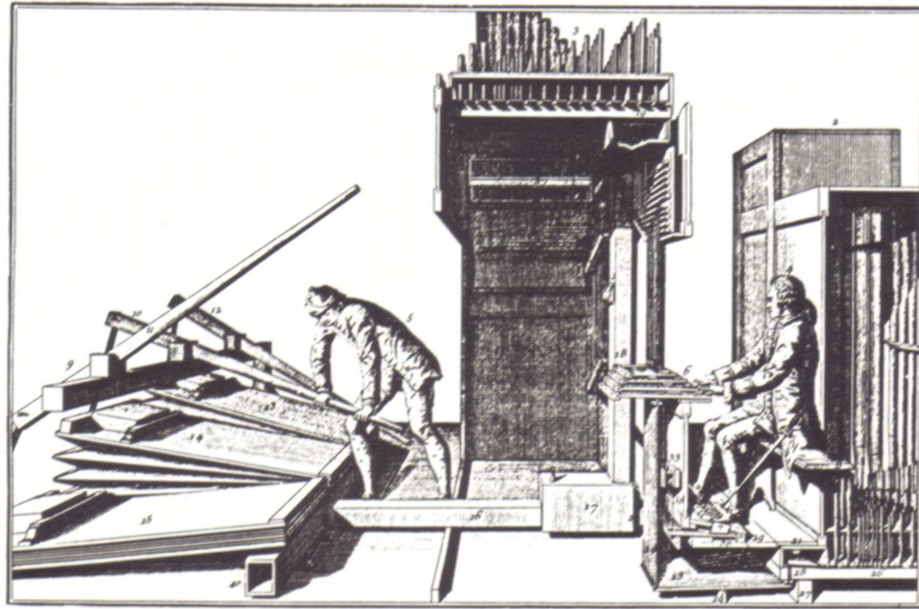
1. A four-manual organ of the eighteenth century.

Fig 3.1 Illustration of a large four manual organ from *L'art du Facteur d'Orgue* by dom Bedos 1766/78

Although he states a maximum pallet size, he does not relate this to pressure. Dom Bedos simply states that if everything gets too big the action will become "hard". He does not explicitly describe pluck, although this is, presumably, what he means by an action being "hard". He cautions against using long rollers in the pedal organ because they twist.

Hopkins, Edward J and Rimbault, Edward F. *The Organ, Its History and Construction* **(London 1877, 3rd Ed. Republished, Bardon Enterprises 2000)**

Between Dom Bedos and Audsley, this was the standard work on organ history and construction. Much like the other two, it gives no details of how dimensions, airflows etc were calculated. It states that the best work used iron rollers but does not state why. It mentions pluck only in terms of the various devices designed to reduce it and gives no indication as to what subjective effect these may have had. It illustrates a form of balancier that has not been identified anywhere else but which would work

perfectly well and has similarities to those used by some current Continental builders).

Audsley, George Ashdown *The Art of Organ Building* (Dodd, Mead & Co 1905 republished by Dover 1965)

Audsley was an ecclesiastical architect who had an interest in organ building and who formed The Art Organ Company with limited success.

Volume two contains a wealth of carefully drawn diagrams of all aspects of organ design up to the time of writing (1905). Despite running to a total of just under 1,400 pages, there is no discussion about calculating dimensions, wind flow etc. Very few of the 400 illustrations are adequately dimensioned. It is nevertheless present in most organ builders' workshops as a record of the principle of operation of some quite obscure actions.

Fig. CLXXVI on page 239 of Volume two illustrates a balancier (again without discussion of its dimensions). This illustration has been repeated in various forms by a number of commentators (as noted throughout this paper), although it cannot be assumed that they all derive from this one. It is shown in Fig 3.2.

FIG. CLXXVI.
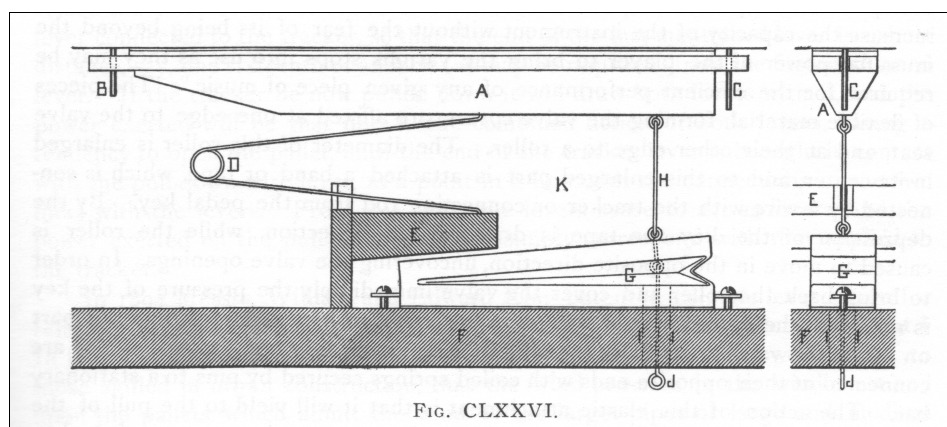
Fig 3.2 Illustration of a balancier by Audsley. The bellows is shown vented to the atmosphere. It should be vented to the groove. It is not clear how this inaccuracy came about.

It has achieved a degree of notoriety in the organ building world because, as drawn, it will not achieve its purpose of relieving the pluck. It will simply apply a constant opposing force to the pallet spring (rather than reducing the force as soon as the pluck is overcome, which is achieved by venting it to the groove and not to the atmosphere). What has apparently never been established is whether this device was ever installed as illustrated, and if it was, what were the thought processes behind it. Audsley's description is peculiarly verbose and obscure even by his standard - he appears to be stating that it will neutralise the pluck and then assist the action against the pallet spring

> Very little beyond the strength of the spring has to be overcome in first drawing the pallet from its seat; and immediately it is open all local pressures cease, so far as it is concerned, while the bellows at that instant comes into active operation, substantially aiding the key action against the increasing strain of the closing spring.

Without dimensions it is difficult to say how it would have operated in practice. Most critics state that once open the pallet will not shut. This is only true if the balancier is of such size that its force is greater than that of the pallet spring.

By venting the motor to the groove and not the atmosphere as illustrated in Fig 2.1, the force applied by the balancier reduces once the pallet starts to open, as the pressure inside the bellows equalises with that inside the chest, and thus it simply reduces pluck

Stainer, John *Complete Organ Method* (New York, Schirmer 1909) p43

> But the object of the player [is] to throw open the pallets in true response to his fingers as regards time, and also to throw them open so thoroughly and rapidly that the wind shall not, as it were, sneak into the pipes and spoil their tone.

He appears to agree with Bethards and Noehren who made similar comments about the tone of pipes when not fully winded. Stainer goes on to say that, in general, it is

safest to adjust the force applied by the fingers to the heaviest manual of any organ because of the risk of missing notes if moving from a lighter one.

Hull, A Eaglefield *Organ Playing: its Technique and Expression* **(London, Augener 1911)**

Hull discusses the variety of attack and release possible with tracker action but implies that the attack means the length of the note and says in a footnote

> Of course, the release itself must be absolutely prompt, but release here refers to the relative length of the sound and the varying amount of separation in the flow of sounds.

Jude, Alexander A "The Barred and Barless Soundboards II" *The Organ* **Vol. 1 No. 4 April 1922 p207**

This is a study of the pressure build up in the pipe foot and thus its effect of the speech of the pipe.

> p207 …except for pure tracker action, where the time of opening is a function of the player's muscular activity.

> p209 Case 2. *Barred slider chest..but with the old all-tracker action.* The only datum difference here is the motion of the pallet. Now, the time generally taken to depress a key is about 1/20 second. This time is largely a function of spring and inertia forces and is almost independent of the *tempo* of the music, legato and staccato. Further, the nature of the "touch" is such that immediately the initial resistance is overcome, the key, as it were, goes down flop, the motion proceeding much more nearly in arithmetical than in the geometric progression of the proceeding case [pneumatic]. We may therefore consider the motion to be..uniform. If the player bangs down the note more quickly he starts the thing going more promptly and the curve begins to rise sooner; conversely, he cannot depress a key and have control of his playing at less than a certain rate a long way remote from that necessary to change the

characteristic. The 1/20 second mentioned above is, therefore, not a salient point of criticism [sic, it is unclear what this means].

Lewis, Walter and Thomas *Modern Organ Building* (London, Reeves 1934 reprinted 1956)

Lewis dismisses mechanical action in a few paragraphs as having no current value.

Bonavia-Hunt, Noel *The Modern British Organ* (London, Weekes, new and revised edition, undated but apparently about 1939) p163

Bonavia-Hunt was a Church of England minister who undertook extensive scientific research predominantly on matters related to pipe speech and voicing.

> Organists regret the loss of intimacy which has never been replaced since the introduction of pneumatic and electric action. The tracker touch can be reproduced in the modern organ but not the "touch on the pallet".

> …the pallet is opened directly by the player's finger….. Whether any advantage is derived ….. is a question that has never been decided. …. I am inclined to believe that there is a modicum of truth in this contention, though it can be pressed too far. Individuality of touch is still possible with electro-pneumatic action, though it seems to be of a different sort.

> For the organ of to-day tracker action is hopelessly inadequate.

There is no discussion of touch characteristics or how to achieve them.

Fig. 14 in Bonavia-Hunt's book is a carefully redrawn version of Audsley's "incorrect" balancier still containing the apparent error. This is surprising given his background.

Challis, John, "The Slider and Pallet Wind Chest" *Organ Institute Quarterly* **Vol. 3 No. 3 Summer 1953 p5**

> If one raises the pressure to 3", the hole at the toe of the pipe will have to be still smaller and there can be no possible communication between pipes.
>
> By that time, the wind resistance against the pallet is so great that the touch of the organ is heavy and impossible to control. The muscular strength necessary to overcome the wind resistance is so great that when one has done it the pallet opens with a jerk.

If the pressure in the chest is increased and the toe hole made smaller, the steady state pressure in the pipe foot will not increase to the same extent and the pressure build up will be slower since it is probable that the toe hole will be the smallest aperture in the system.

Harrison, G Donald. "Slider Chests?" *Organ Institute Quarterly* **Vol. 3 No. 3, Summer 1953 p9**

> To begin with, I have no hesitation whatever in saying that tracker action and slider chests can be excellent in small organs.
>
> It is asserted that direct mechanical action gives the player more intimate personal control of the instrument. This is at least in part psychological and is due to the player's close proximity to the pipes. It is said that the player can influence the attack, i.e., the rapidity with which the tone develops in the pipe, by controlling the velocity of key descent. This is pure illusion. The essence of "tracker touch" is its top resistance, created by wind pressure in the chest. When the finger pressure on the key finally overcomes this resistance and the pallet moves, the key must fall suddenly beyond its breaking point. The only way in which a key could be made to descend more slowly would be to grasp it between the thumb and finger.
>
> A sense of intimate contact and almost unbelievably fine control over the duration of the notes can be effected with a first-class, rapid, electro-pneumatic action when the console is located at an appropriate limited distance from the pipes.

Harrison is stating that the important factors are feedback, both tactile and audible.

Andersen, Poul-Gerhard *Organ Building and Design* (London, George Allen and Unwin 1969) translation by Joanne Curnutt from *Orgelbogen* (Copenhagen 1956)

This book was written by a Danish organ builder, but despite its title says little about organ building, concentrating largely on North European stop lists, and does not enter into any discussion about characteristics of touch and how to achieve them.

> This contact, unconscious though it may be, is present when the organist, through the direct connection, "feels" the pallets [and is lost with Barker levers]

This appears to suggest that it is just the tactile feedback that Andersen is referring to but this is not clear.

Caddy, Roy S, Pollard, Howard F. "An Objective Study of Organ Actions" *Organ Institute Quarterly* Vol. 7 No. 2, Summer 1957 p44

This article shows oscillograms of starting transients of a mechanical action in a model with the key depressed "slowly" and the key depressed "rapidly", and a direct electric action. The speeds of the mechanical action movements are not defined and there is no recording of the key movement. The oscillogram for the "rapid" depression shows a very distinct distortion to the initial transient that was never apparent during the current project. Without knowing the actual conditions of the test it is not possible to form an opinion as to their validity.

He states that Barker levers remove control.

Barnes, William H. *The Contemporary American Organ* **(Miami, Warner 1964) 8th ed**

Barnes was an American organ builder who considered that mechanical action had no relevance to modern building because of its unreliability, the heaviness of touch and its susceptibility to climatic changes. On page 133 he states:

> Today we find a few builders, who are to my mind mentally unbalanced, who urge a return to the tracker action

This represents the dismissive attitude of some organ builders at that time to mechanical action and he appears to be unaware of trends in contemporary European organ building. Ochse (The History of the Organ in the United States) states that the first large new mechanical action organ was imported into the United States in 1957 – in time for the seventh edition of Barnes's book.

Blanton, Joseph E. *The Revival of the Organ Case* **(Albany Texas, Venture Press 1965) p13**

> The organ with an excellent tonal structure but which has one of the available forms of electric key action cannot *sound* as good as it would if it had a well-regulated mechanical key action. With an electrically controlled key action, the organ virtuoso can produce an attack no different from that produced by a child totally ignorant of music. With mechanical key action, he has control over the attack which immeasurably increases the possibilities of phrasing. This is demonstrable.

Blanton emphasises this in a footnote:

> With these differences of attack so easily perceptible, it is surprising that some individuals deny their existence merely because they are insensible to them.

Ellerhorst, Winfred *Handbuch der Orgelkunde* (Buren, Knuf 1965, reprinted 1975 with corrections) in German

This book goes into considerable theoretical detail about basic mechanics, magnetism, acoustics, pipe speech, etc. There is some discussion of inertia but, despite many formulae, there does not appear to be any analysis of a representative action, calculation of sample wind flows or key characteristics. The discussion on keys simply appears to state that the touch weight should be 125 g. This is high for a touch without pluck but low for the initial weight of one with pluck. Ellerhorst may be referring only to electric actions because he suggests an initial 2-3 mm movement of the key before anything happens. Despite the date of the book, Ellerhorst is more interested in technical theory of electric actions but there is significant discussion of the mechanical properties of mechanical actions.

On page 419 he attempts to calculate the net air pressure against a closed pallet. Rather than just using the size of the pallet opening, he appears to be trying to add half the overlap of the pallet over the pallet opening as well. His formula is clearly dimensionally incorrect and the stated result appears to be numerically incorrect. He does nothing with the result anyway.

Ellerhorst has an illustration of a chest containing what appears to be a balancier vented to the atmosphere (Fig 221 p392). The purpose of the illustration is to show a means of attaching the front board of the chest. He states that the bellows serve the same purpose as a "Pulpeten" i.e. a leather seal around the pull-down wire. It would indeed seal the opening, but it is a complex way of doing it and, whilst he does not give any dimensions, the size implied by the diagram indicates that it is far too large for that purpose alone, and assuming that it is as wide as the pallet opening, too large simply to relieve pluck which it would not do anyway as it would have to be vented to the groove (see the discussion relating to Audsley on page 18). It may however be

worth noting that most, if not all, current forms of balancier of this general type provide no seal whatever, as the pallet pull-down passes outside the bellows, presumably for ease of construction.

Klotz, Hans. *The Organ Handbook* (St Louis, Concordia Publishing House 1969) Translated by Krapf, Gerhard from *Das Buch von der Orgel* (Kassel, Barenreiter) 7th ed 1965 p40

The primary advantage of tracker action is its absolute precision. The speech of the pipe responds instantly and sensitively to the player's attack. The advantage will be gratefully acknowledged by the organist who knows from experience with electro-pneumatic or direct electric consoles, how the rhythmic movement of polyphonic textures becomes paralysed by the imprecision of electric action. How different with tracker action organs!

But tracker action is vastly superior to electric action not only with regard to articulation but also with regard to touch. In this respect, electric action effects absolutely nothing; the initial excitation of the speech is totally unaffected by the touch. Yet, it is precisely this inception of the tone which is essential for the character of the speech. The tracker action – and even the Barker lever – by contrast faithfully transmit the touch to the speech of the pipe. Oscillograms of relevant tests furnish indubitable proof. The possibility of influencing initial excitation is essential, if music rather than impersonal sound is to be produced. Naturally, no player can consciously cultivate every single tone by his touch, but he does convey, both consciously and subconsciously, a detailed personal expression to the structural elements of the total sound spectrum, which – by contrast to the tracker action – is obscured by electric action.

In depressing a key of a tracker-action keyboard, a definite point of resistance must be overcome. The organist can feel the sudden overcoming of resistance at the instant the pallet is engaged. Through his finger his mind perceives exactly the disposition of the initial excitation, thereby gaining a felicitous sense of security in the playing of complex polyphonic textures. A further convenience is the circumstance that far less effort is required to hold down the key than to depress it; that also contributes to clean rhythmic playing.

There is no discussion of playing weights or how to achieve them and there is no reference to the source of the oscillograms.

The illustration of a balancier in the German edition (not present in the American one) is unclear. The illustration of the open pallet shows the motor inflated to the same extent as that for the closed pallet. This assumes that the motor would return to its open state once the pressure was equalised. It is more likely that it would collapse at least partially under its own weight and, in any case, illustrating it this way fails to convey the means of operation clearly.

This and other discussions of the imprecision of electric actions may have been (but there is no evidence that they were) clouded by the fact that early multiplexed keyboards allegedly had a sampling rate too low to keep up with fast music and introduced significant and variable delays.

Norman, John and Herbert *The Organ Today* (London, Barrie and Rockliff 1966) p28

John Norman is an electronic engineer by training and who worked for Hill, Norman and Beard for many years before leaving to join IBM. He continued to work as an organ consultant.

> It need not be matter for surprise, that in the last fifteen years, the wheel of fashion, or appreciation, has turned full cycle, and many sensitive players are re-discovering artistic values and interpretive aids, in a well-designed and perfectly made tracker action. The sense of a crisp direct finger control over the precise moment of speech of the pipe is enjoyed, together with actual control of the intonation or speech attack, although this is a subject of much controversy.

> [All the commas are in the original text.] This sense of direct control, leads to claims by sensitive players, that they can control, not only the timing, but also the rate of opening of the pipe-valve, and hence the degree of 'attack' in the pipe speech. Those who reject this claim, contend that the effect is solely subjective, sensed only

by the player, and is inaudible to the listeners. They support this view with data from highly organized experiments with seemingly convincing conclusions. Nevertheless, sensitive musicians with wide experience of antique or modern tracker-actioned instruments, are equally convinced that there is this inherent musical advantage.

Probably the explanation lies in one aspect, neglected or overlooked in the opposing arguments and experiments, and that is, the style and voicing technique applied to the pipes used in the tests. Pipes voiced in the best manner, on medium wind-pressures, in the style common in the last hundred years, have firm and relatively 'slow' speech, which is comparatively insensitive to small wind-pressure differences and attack qualities, and thus are irresponsive to variation by slow or rapid opening of the key valve.

On the other hand, those experienced in voicing pipes on classical low wind-pressures in the range of 1½ in. wg. to 2¼ in. wg. using the antique lip-regulation and open-tip method, know how sensitive such pipework is to quite small pressure variations arising from the qualities of the windchests used. Considerable power and quality change is possible with ±⅛ in. wg. pressure. With that type of pipe speech, there is no doubt that some control of intonation is possible by sensitive keyboard touch.

During a private discussion John Norman stated that experiments at IBM had shown that "key click" on computer keyboards increased the accuracy of typing even though they had no relation to what was actually happening. The new computer on which this thesis is being typed has a less pronounced "key click" than its predecessor and the rate of keying errors is noticeably higher.

Pollard, H F "Time Delay Effects in the Operation of a Pipe Organ" *Acustica* **Vol. 20 No. 4 1968 p189**

This paper is intended to show how various forms of action affect the time taken from touching the key to sound being produced.

Two of the categories of action are "old mechanical" and "new mechanical". No further information, such as size in terms of number of stops or length of action, is given. If all tests were carried out in Australia then "old" may have a different

meaning from that which is generally understood regarding European organs i.e. late nineteenth century rather than seventeenth century.

Old mechanical organs were subjected to "slow", "fast" and "mean" touches. These are not defined. It is not clear whether these represented normal playing or "laboratory" tests.

New organs were only subjected to "slow" and "fast" touches. One outlying high initial delay (time from first key movement to sound 1 dB above background) was excluded because it "very high" and comparative figures from the two types of organs were rounded in such a way as reduce the difference them.

He assumes that the motion through a mechanical action is determined by the velocity of a mechanical impulse through wood. This assumes complete rigidity, which this thesis shows is never achieved.

He quotes Lindhardt [Lindhart 1962] *inter alia*

> The key starts moving down, in the case of mechanical action the pallet starts to open

It is shown in Chapter 6.2 of this current study that this is not the case.

Sumner, William Leslie. *The Organ* (London. Macdonald 4th ed 1973) p332

> Towards the end of the eighteenth century and in the first half of the nineteenth, organs grew out of all proportions to the necessities of a musical instrument, and towards the end of this period high-pressure stops were introduced on a considerable scale. Thus, the fingers and feet of the organists of these instruments were sorely tried and the need for some assistance was seen. But it must be said at the outset that nothing has yet been discovered which gives the organist more control of the pipework of his instrument and allows a greater variety of subtle touches than a well-made tracker action in a small or moderate-sized, low pressure organ

Sumner quotes Dr John Camidge of York Minster writing in 1833 to Charles Spackman Barker, who had sought his support for his pneumatic lever:

> "… Mr Hill, of the late firm of Elliott and Hill, has erected our organ, and, I assure, the playing is no sinecure; it is most laborious work to go through a grand or last voluntary with the whole power of the instrument. Such a difficult touch as that of York Cathedral is doubtless sufficient to paralyse the efforts of most men, I assure you. I, with all the energy I rally about me, am sometimes inclined to make a full stop from actual fatigue in a very short time after the commencement of a full piece."

Norman, John "The Design of Organ soundboard Pallet Valves" *JIMIT* Spring 1977 p44

This paper covers the calculation of the airflow through the pallet opening and, more interestingly, calculates that pluck is minimised when the action is geared to make the pallet opening width equal to 4/3 of the pallet drop.

Soderlund, Sandra *Organ Technique an Historical Approach* (Chapel Hill, Hinshaw Music 1980)

> The only way to achieve expressive nuances on the organ is by manipulating the duration of the notes themselves and of the spaces between them

Soderland quotes extensively from early works and there is no mention of anything other than the length of notes.

Collins, Peter. "A Question of Touch" *JBIOS* Vol. 6 p 36

Peter Collins was one of the leaders in the return to the classical style of organ building, as exemplified by Greyfriars Kirk, Edinburgh, and advocates a scientific approach to organ building.

Collins's paper discusses action masses and air pressures but then goes on to compare a Victorian mechanical action with a modern equivalent – a very valuable exercise that needs to be done properly. Instead of calculating the EDM of the various components, he calculates their actual mass. The two are only approximately equal for trackers and stickers that move approximately in a straight line. All rotating components have an EDM significantly less than their actual mass. Collins's calculation is only of value in determining the strength of the building frame and the floor loading.

Wills, Arthur *Organ* Yehudi Menuhin Music Guides (London, Macdonald 1984) p19

> In any discussion about the respective merits of different types of organ action the words 'light', 'sensitive' and 'responsive' are usually bandied about, often being used without adequate definition. What needs to be made clear from the outset is that tracker actions, rather than the simple on-off electric switch type of mechanism, offer the player the possibility of being able to control the speed of attack of the sound. Without varied attack and release characteristics, notes have a monotonous uniformity which can be likened to human speech without consonants. But some tracker actions are so heavy, sluggish or spongy, and therefore unresponsive, that playing of any kind is impeded, and sensitive playing rendered quite out of the question. Then, certainly, a good electric action seems preferable for any music….
>
> [Barker levers] did not allow physical control of the speed of opening and closing of the pallet

Wills goes on to compare the organ with the piano and harpsichord and concludes that a tracker action falls somewhere in the middle.

Hoffman, Ludwig "Mechanical Action" *ISO Information* No. 26, June 1986 Translation by Keith Reginald Foster

This paper explains in some detail the calculation of pallet opening sizes and how pluck can be minimised. There are, however a number of problems.

Hoffman graphs key force against movement for a number of pluck to pallet spring ratios and states that, empirically, they should be about equal and between 120 and 160 grams in total. The graphs are based on no stops being on. On page 31 he states:

> Of course other measurements could be undertaken, by which different registrations could be characterised. There is an additional force that could gauged by such a measurement – the dynamic force of the wind, or the fluid pressure generated by the moving air. This is of course a highly variable factor and will not be considered any further at this time.

Woolley (*Actions and Reactions* Journal of the Institute of Musical Instrument Technology, September 2002) makes the point that the majority of organ performances take place with one or more stops on, and to base these calculations on the only case that does not happen in practice requires justification. It is possible that air leaking past the pallet increases the pressure in the groove but not to the extent that the pipes murmur. This might reduce the measured pluck with no stops on.

> Excursions into the esoteric realms of fluidics are seldom worth a practicing organ builder's time. (page 14)

One of the graphs does, however, show the effect of the "tutti". This correctly shows that the effect of the airflow is felt over a greater key movement, but it also shows that the peak force required to start the key moving increases. This requires explanation (of which there is none) because this force should simply be pluck (a function of the difference in air pressure across the closed pallet) and the force exerted by the pallet spring (see comments about Donahue, page 35, who describes the same phenomenon).

Hoffman recommends that a safety factor of one third be added to the total area of the toe holes in order to allow for inefficiencies. This requires more investigation and quantification (discussion with builders revealed that they add a safety factor of

between one fifth and one half) as it may indicate a fundamental inefficiency in the standard bar and slider wind chest. Any excess size is directly reflected in the pluck.

He states that a long, thin pallet (opening 43.63 cm x 1.1 cm, these numbers being derived as the result his method of calculation) is undesirable because of the risk of it becoming misaligned. Unless he is suggesting that the pallet will warp, it is not clear why, as the pallet can (indeed must) be made wider than the slot and is closely guided so that it cannot move sideways. (The German text uses the word *verwirft,* which the Collins German Dictionary defines as (*verwirren*) *"to become tangled, up, snarled up or confused in relation to thread etc"*).

He states that the pallet opening width should never be less than twice the pallet drop (even though it will reduce the pluck to airflow ratio) because "the wind streams overlap, imparting mutually disruptive forces". They will overlap (Chapter 4.2.2), but he does not elaborate on how this will manifest itself. John Norman (formerly of Hill, Norman and Beard) in a private discussion with the author stated that he regularly used "narrow" pallets and that they appeared to smooth the airflow rather than disrupt it although this had never been formally studied.

Forsyth-Grant, Maurice *Twenty-One Years of Organ-Building* (Oxford, Positif Press 1987)

Forsyth-Grant was an electrical engineer who went into organ building as a second career.

> Of course I am not an organ-builder by profession (any of the establishment will tell
> you that).

On the one hand he was responsible for some clearly "neo classical" style organs (such as New College Oxford, 1969, etc) but he was also quite prepared to build an extension organ (in which ranks are extended in compass so that they can sound at a number of pitches by using a separate electric valve under each pipe) if that was the

best option in particular circumstances. He was an advocate of chipboard as a stable constructional material along with composite sliders and aluminium pallets etc, which was very much against the trend prevailing at the time of using only traditional materials and methods.

Perhaps surprisingly, he goes into very little detail about his key actions although clearly prefers mechanical. He incorrectly states that the form of balancier illustrated in Audsley would cause the key to remain down, but used the correct version widely.

A leaflet clarifying Grant, Degens and Bradbeer's move to share the premises of Alfred Davies and Son in Northampton states (British Organ Archive, undated but about 1970):

> Our policy to design and build the modern Classical Organ with slider chests, low pressure pipe work voiced in the open foot principle[1], together with correctly designed casework, will be rigidly maintained. Wherever practical we will recommend only the use of full mechanical action to Manuals and Pedals.

He clearly considers mechanical action to be a desirable element of a pipe organ, but not an essential one.

Ogasapian, John K. *Church Organs – A Guide to Selection and Purchase* OHS & AGO 1990 p108

> The bottom line is that, aside from artistic considerations (and many if not most organists and builders tend to prefer trackers for artistic reasons), tracker action represents the wisest economy and should be chosen whenever and wherever it is possible to do so, especially for a small pipe organ.

---

[1] I.e. the airflow through the pipe is controlled by changing the cross section of the flue rather than changing the size of the toe hole.

Baker, David *The Organ* (Princes Risborough, Shire 1991 reprinted 1993) p10

> Tracker action allows the player to be in close contact with the instrument and the pipes. A much more sensitive touch can be used with such an action and a good player can articulate the sound of the pipes by the way in which he or she depresses the key

Donahue, Thomas *The Modern Classical Organ* (North Carolina, McFarland 1991) p71

> The organist can control the speed at which the pallet opens and closes

> The entire effect is subtle but definite. The organist's ability to control this for musical purposes is probably limited

> A mechanical key action should have little slack or "play", so that any downward movement of the key is matched by a similar movement of the pallet. …the organist's fingers are responsible for the position of the pallet at all times.

He goes into considerable detail about the advantages of mechanical action and the ability of the player to control the movement of the pallet. He is of the opinion that it is possible to control the pallet beyond the plucking point, but appears to assume that any action is completely rigid.

He quotes some figures for pluck measured on the organ at Souvigny in France built by Clicquot in 1982 that show that for some keys it is higher with the Plein Jeu rather than just a Bourdon 8' [Legros 1976]. Since pluck is a function solely of the pressure in the wind-chest on one side of the pallet and atmospheric pressure on the other, there might be an increase in pluck between no stops on and a single stop on due to leakage past the pallet not being vented through the pipe but is unlikely that this would of sufficient magnitude to have any effect when more than one stop was on. Donahue suggests that the increase might be due to the changes in wind pressure that occur when air is in motion.

Apart from a total resistance of 140-160 grams (which he gets from Hoffman q.v.), he does not quantify any of the characteristics.

Bellochio, Mathew-Michael. *Long Run Concerns* (The American Guild of Organ Builders Convention, Portland, Oregon 1992 video recording)

This lecture (also *Beginnings and Endings* by the same author) describes how good engineering practice can minimise inertia whilst maximising rigidity.

Bellochio measured that seven "typical" commercially available felt washers nominally 3 mm thick will compress by 4.24 mm as measured at the key when a force equivalent to a weight of 180 g is required to open the pallet. This is in addition to any other flexibility. He states that most of these washers can simply be omitted so long as the action is under tension and thus not prone to rattling. Washers can be used on the "return" side of a component in order to reduce movement. (Fig 3.3 shows standard felt washers on the roller arms at Tonbridge School and thicker washers on the return side).
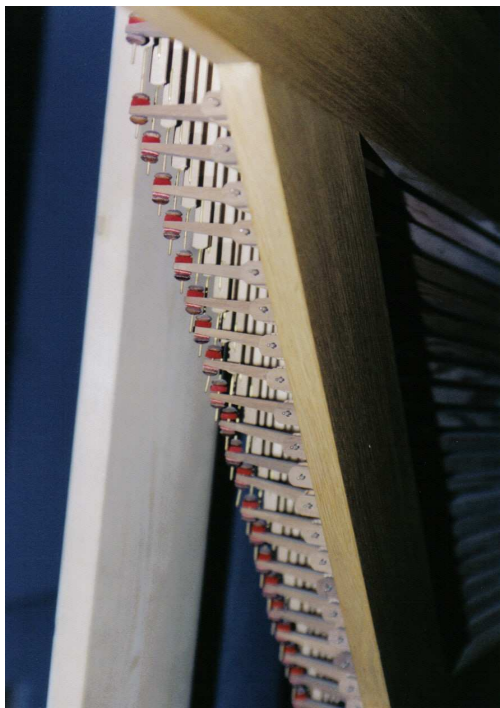
Fig 3.3 Tonbridge School Chapel. Felt washers on roller arms.

He concludes that aluminium squares are better than wooden ones by measuring the net weight exerted at the end of a horizontal arm. There is no direct relation between this and inertia of the component as installed, although there may be a close correlation in the case of standard squares. The metal squares use needle bearings and the wooden ones have undefined bearings. High friction will cause a significant error in measuring the weight exerted at the end of one arm. This experiment was repeated in a modified form for this project and the results are presented on page 94.

There is no discussion about how touch might be related to sound.

Hurford, Peter. *Making Music on the Organ* (Oxford, OUP 1995) p15

> The only completely satisfactory form of action is one in which the movement of the player's fingers is accurately reflected in miniscule detail at the pallet; and the only means by which this may be achieved is through a purely mechanical linking of finger and tonal source - as with any other musical instrument.

Nevertheless, Hurford's discussion on touch considers solely differences in tempo and does not mention variation in the speed of key movement.

The drawings of actions and pipes are among the clearest of any so far found.

Fisher, Roger. "The New Marcussen Organ in the Bridgewater Hall, Manchester" *Organists' Review* no. 326 May 1997 p93

> The touch of the uncoupled manuals is splendid and I am sure that it was wise to use pneumatic balancers on an organ of this size.

> When full organ is in use, only the Great and Pedal are actually being worked mechanically, and the other three-fifths of the organ are, at that stage being worked electro-magnetically. Although some of the subtlety of mechanical action must inevitably be sacrificed when manuals are coupled, the mechanical action of

whichever manual is being played at the time has a satisfying feel and this gives the
player confidence

Hollick, Douglas. "'Great Dane': Manchester's new Marcussen" *Choir and Organ* **vol. 5 no. 2 March/April 1997**

The touch is firm, but not unduly heavy, and quite deep, but one has to remember the
size of the organ, and the length of some of the action runs; the response to the finger
is commendably light…"

Bicknell, Stephen. "Raising the Tone" *Choir and Organ* **vol. 5 no 2 March/April 1997**

Bicknell was a designer on some of the large mechanical action organs built by
Mander for whom he worked for a considerable time.

He questions whether mechanical action should be used indiscriminately particularly
where assisters are required and suggests that it is the timing rather than modification
of the transient that is important in an "otherwise dangerously inexpressive instrument".

He is of the opinion that it is not possible to make an electric keyboard with a contact
point sufficiently near the top to replicate a mechanical action.

Now, unlike the skill of controlling chiff, articulation is a game anyone can play

Moreover, as a listener I find it quite easy to hear the articulation in an otherwise quite
average performance, provided the action is mechanical. Barker lever or charge
pneumatic preserve some of the detail. On exhaust pneumatic, electro-pneumatic and
direct electric much of it is lost.

He goes on to say about organ builders' approaches to building large mechanical
actions:

> What actually happens is that organ-builders all avoid the issue furiously: they either build true copies (where the problem doesn't arise - 'yes, we really *are* going to make the action as heavy as in Bach's day') or they cheat.

By "cheat" he means that they include pneumatic or electric devices to "make life easier".

Williams, Peter and Owen, Barbara *The Organ* The New Grove Music Instrument Series (London, Macmillan 1997)

There is no discussion on the merits of particular actions, characteristics or how to achieve them despite this book often being the cited as the definitive guide to all aspects of the organ.

Thistlethwaite, Nicholas.   *The Making of the Victorian Organ* (Cambridge University Press 1999)

Although not really considering actions in any significant way, the author includes some illustrations of advances made during the period he is writing about. He includes an illustration of a balancier (which he attributes to Barker), which is a variation on the Audsley "incorrect" style.

Noehren, Robert. *An Organist's Reader* (Michigan, Harmonie Park Press 1999) p161

Noehren was at various times an organ builder and Professor of Music and chairman of the Organ Department at the University of Michigan at Ann Arbor from 1949 to 1960, continuing as University organist until 1976. He started his organ building career building mechanical actions but later turned against them. This makes this lengthy quote of particular interest.

It is not easy for the layman or even a professional organist to understand the construction of either electric actions or mechanical actions as organ builders do. An organ action, in elementary terms, simply opens and closes a pallet or a valve. Both organist and organ builder believe that the pallet of a slider-chest controlled by mechanical action can be opened at varying speeds, but it is not well understood how such varying speeds of the key action can be used in the subtle art of making music, nor is it well understood that the pallet must be opened rather quickly by a fast action of the finger or it will fail to open. The organist, even one with skill, when playing an organ with mechanical action, may be unaware of what happens when he depresses the key within the rhythmical motions of a musical phrase, either in an allegro or an adagio. Even in an adagio, when he is playing very slowly, it is not easy to perceive that his finger action must be nearly as quick as it is in an allegro movement or the keys will not be depressed. Even in terms of slow motion or simply moving slowly from one note to another, the finger action must be relatively quick to overcome the resistance of wind pressure against the pallet. The wind pressure in the chest determines the value of the resistance.

On a large wind-chest, the resistance from the wind pressure is even greater than on a smaller wind-chest and a still quicker and firmer action of the finger is required. In his subconscious, the organist who is familiar with playing a tracker organ harbors an experience which warns him that unless he uses quick enough movement the pallet will not open. He has instinctively learned to adjust the speed of his finger action to the resistance of the organ action. Even in the playing of an adagio, when his rhythm reflects a sense of quiet motion, he may be deceived, for he may believe that he is affecting the speech of the pipes when it is rather the rhythm in playing rubato or the delaying of a note here or there that is giving him such an impression. It is possible he confuses the speed of his finger action with the rhythmic motion of the phrase, and is unaware that his finger action is only just slightly slower than the finger action he uses in an allegro movement. It is never slow enough to alter the affect of the articulation of a pipe appreciably. If his finger action was any slower, it would not be able to open the pallet at all. The expressive energy he brings to the movement in rubato will indeed affect what he is doing rhythmically and cause him to believe that he is playing a more sensitive action. The proximity of the keyboards and trackers to the pipework, relatively close to the action at the wind-chest, contributes to a more immediate response than an organ where the keyboards are located some distance from the pipework, typical of electric action. This helps to influence his belief that mechanical action is more sensitive than electric action. Regardless of the type of action, a

keyboard only a few feet from the pipework is obviously more responsive than one controlled by electric action some distance from the pipework…..

In sum, many organists have only a vague notion of their finger action at the keyboard of any organ, and the organ builder has just as vague an idea in musical terms of how his instrument is played. Both organist and builder come to the organ with different kinds of knowledge and are rarely able to discuss their problems except in very general terms. [He suggests that pianists have a better idea.]

An organist who has become critical and sensitive about his use of his touch will observe more closely the problems of organ action organ to organ, and will gradually seek for a kind of action, whether it be mechanical or electrical, which is responsive and light enough, even with all manuals coupled, to play at any tempo with sensitive rhythmic control. It is also necessary to have a key action in which repetition is fast and precise. In the construction of mechanical action, in an attempt to lighten the action, the organ builder can only go so far before there is too much inertia and the key will not return fast enough. The action of a large tracker organ controlling a wind-chest with 10, 12, or 15 registers, when large pallets and more wind are involved, generally speaking, is too heavy and not light enough to permit anything less than a very fast finger action in order to depress a key. It is quite evident that an organist playing an organ with a heavy action has little control to engage in effective rhythmic nuance.

Here is a very clear opinion that the player cannot significantly vary the way that he moves the keys given by an organ builder, performer and teacher. This may have come about through close observation and personal experience, but it lacks objective evidence to support it. This is an example of where opinions can be readily tested by experiment. Noehren's position at the University of Michigan might have led to such an exercise being carried out.

Part of this book had previously been published in "The Diapason" [Noehren 1993].

Curley, Carlo *In the Pipeline* (London, Harper-Collins 1998) p179

Mechanical action, far from being displaced by electric action, has staged a remarkable comeback since World War II. This kind of key action certainly has its

devotees, and in recent years has been elevated to cult status in some quarters. Its adherents claim that the mechanical linkage between the keys and the valves offers a subtle control over pipe speech. For me, this is science fiction. At best, if you are playing slowly on a single stop on a very sensitive mechanical action (such as a small continuo instrument) such intimate control may perhaps be possible. But is it desirable? Not to me. Pipes are voiced for the onset of wind as it is provided normally. Any variation in its supply or release simply exaggerates all kinds of non-musical sounds within the pipe speech, detracting from beauty rather than creating it. The differences are utterly unlike those that the pianist can effect through the control of his instrument. Furthermore, the idea that the player can exercise such subtle control while playing at any reasonable tempo is simply unrealistic. Clearly, to some organists, a good tracker organ can be most gratifying to play, much like a fine harpsichord. But, in the final analysis, there is no difference for the audience to hear and I trust that they prefer to pay for things which they *can* hear!

Robert Noehren was not only an organ-builder, but was Professor of Music and chairman of the Organ Department at the University of Michigan at Ann Arbor from 1949 to 1960, continuing as university organist until 1976. In this position he helped to educate a generation of young organists. He puts the case most eloquently: [see quote from Noehren on page 40]

[Curly continues] There is an additional difficulty in controlling the 'speed of descent' and it's the organ's equivalent of the 'pluck' in a harpsichord – once the seal around the pallet has been broken, the resistance to the player's finger drops markedly and the key 'plops' down. So exercising control in this motion is akin to attempting to break a piece of glass in slow motion. In real music and with manuals coupled, it is more like trying to break several pieces of glass at the same time.

Instead of opening up new horizons, tracker action for me imposes a number of distressing limitations. I need a prompt attack and release, as one gets on a Steinway or Bechstein piano. And most tracker/mechanical actions simply cannot offer this. They all seem to suffer from an uneasy compromise. To achieve acceptable return speed, strong springing is indicated. But that makes the action heavier to play. However light (or otherwise) the builders contrive to make the forces needed to move the keys when playing slowly, tracker actions can be hopeless for really fast (e.g. toccata) playing simply because there is such a mass of inert wood- or metal-work flailing around [etc].

Curley makes the specific point that pipes are voiced for one specific rate of attack and that varying this is detrimental to the tone.

Jones, Kenneth "Manual Coupling in Larger Organs" *Organists' Review*, **November 1999 no 336 p322**

Cathedral of the Madelaine, Salt Lake City (IV/P 60, 1989). This organ has pneumatically operated sub pallets that are larger than the mechanically operated pallets. The wind supply to the pneumatic motors is controlled by a ventil connected to the stop action. The pneumatic pallet is only brought into effect when a certain number or combination of stops is drawn and the additional wind supply is required.

St Peter's Church, Eaton Square, London (IV/P 65, 1993).

> Here the Great, Swell and Solo departments have secondary pallets for their bottom 32 notes, operated electrically and fired by optical switches at the pull-downs of the primary pallets. The firing point occurs when the primary pallet is about 2mm open. It is important that the switches are precise and without hysteresis, as upon release of the key the pallet must close completely before the first pallet approaches closure, thus handing over control to the first pallet for closure and snap bedding of that pallet, which is the one responding to the player's finger.
>
> ……the first pallet should be small (relative to the size of the soundboard/department) but only as small as necessary to permit purely mechanical coupling. It would be possible to make the first pallets very small, but this would make the touch, the feel, unreal for a large organ. And over-light mechanical actions are difficult for the player to control.
>
> …….The key-action at St Peter's, Eaton Square, uses electric power *in a manner which is altogether and fundamentally different from organs with mechanical key-action and electric coupling.* At Eaton Square, at all times, and in all coupling conditions, the attack and decay of the wind supply to all the pipes is directly under the control of the player's fingers, and without compromise.

Ritchie, George and Stauffer, George *Organ Technique* (Oxford OUP 2000) p5

> 'Allow' the finger to depress the key. The downward motion should be as rapidly as
> possible.

> The chief advantage of tracker action is that the player has direct control over the
> opening and closing of the [pallet].

If the downward motion should always be as rapidly as possible, it is not clear what
advantage the direct control of the pallet gives.

**Marsden Thomas, Anne. *A Practical Guide to Playing the Organ* (London,
Cramer 2001)**

Marsden is Director of the St Giles International Organ School

> [Mechanical] is the most sensitive and reliable action. The pipe responds promptly,
> and you feel in control of the pipe's speech.

> Musical expression at the organ is controlled by three means: silences of variable
> length are inserted between the notes (touch), notes are played slightly ahead of, on,
> or slightly after the beat (rhythm), stops are changed and expression pedals are
> adjusted (registration).

> Control of the attack is essential for musical playing on the organ. By detaching notes
> to reveal the attack, or attaching the notes (legato) to mask the attack, you can create
> entirely different effects on the organ. You can also control the impact of the attack:
> the more you detach the notes, the more audible the following attack seems.

Marsden is clearly stating that the only control that the player has is by varying the
rhythm and not by varying the transient.

Klais, Phillip. Institute of British Organbuilding meeting, Symphony Hall, Birmingham June 2001

At a meeting of the IBO to mark the opening of his new organ in Symphony Hall, Birmingham, Phillip Klais stated his reasons for building large mechanical action organs (after joking that, contrary to rumour, this was not the first time that the mechanical console had been used):

- The layout constraints imposed by a mechanical action force the designer to plan the organ carefully and lay it out in such a way that the action runs are as short as possible and the chests are planted simply.

- It prevents the temptation to use extended ranks, borrowing, split and remote chests, and other "undesirable" things possible with electric actions.

- The logical layout makes the tuner's job easier.

Mr Klais also stated these reasons to the author during a private conversation. He does not mention musical advantages.

van Oortmerssen, Jacques *Organ Technique* (Göteborg, Göteborg Organ Art Centre 2002)

van Oortmerssen is Professor of Organ at the Amsterdam Conservatoire.

Although van Oortmerssen talks about "sensitive actions" and the need either to release chords simultaneously or in a controlled staggered way, he does not discuss the control of the transient.

Moyes, Andrew. "Tracker or Electric" Letter in *Organists' Review* November 2002 no 346 p373

> When the rather convoluted tracker runs for Southwell Minster organ were being designed, I needed to know the distribution of inertia in a typical mechanical action.
>
> As a yardstick, calculating the moments of inertia for a medium-sized modern tracker organ with trackers 3 metres long and good playing characteristics gave:

Key	60%
Trackers	12%
Pallet	8%
Squares and backfalls	7%
Roller & arms	5%
Other	8%

These are not moments of inertia (which only apply to rotating components anyway) but, presumably, relative proportions of effective dynamic mass.

Moyes says that the effective mass of the key at the point of attachment of the tracker is 86 g. The critical factor is the effective mass at the point of finger contact and without knowing where on the key lever the tracker is attached, this information is not useful. The relation between the effective mass of the key and the pallet suggests that the mass of the pallet relative to the key is quite low. The relation between the actual mass and the effective mass of both components is essentially the same, as they move in similar manners. This means that the actual masses should be in the same proportion. Peter Collins [Collins 1982] suggests a ratio of 1.6:1 rather than the 7.5:1 shown above but this will vary considerably between instruments.

We are also told that the trackers are three metres long and have a mass of 15 grams (which is close to the figure calculated in this thesis). This would suggest an EDM of 75 grams according to the above ratios rather than the stated 86 grams but this could be accounted for by the difference in position on the key lever of the finger contact point and the tracker attachment point.

Taking the effective key mass to be 86 grams implies a total action inertia of 143.3 grams, which is approaching the limit (150g) for achieving a repetition rate of eight notes per second with a playing weight of 80 grams. This seems high for a "medium sized" organ which might be expected to be comfortably less than the maximum.

Speerstra, Joel (Ed) *The North German Organ Research Project at Göteborg University* **(Göteborg, Göteborg Organ Art Centre 2003)**

This project set out to reconstruct a North German organ based on the organ built by Arp Schnitger in Lübeck Dom (1699) and St Jacobi. Hamburg (1693). Extensive research was done on historical pipe making methods but apart from measuring key movement and force, the opportunity was not taken to study how organists actually played despite the availability of expertise and equipment in the University.

Grassin, Didier. "Trackers – material evidence" *Organ Building* **(Bury St Edmonds, Institute of British Organ Building vol 3 2003) p72-75**

This paper discusses the physical properties of a number of materials used for trackers. It looks at mass, stretching, thermal expansion and gravitational deflection of horizontal trackers.

Angster J, Pitsch S, Miklós A. "The Influence of Different types of Wind Chests on the Sound Formation of Flue Organ Pipes" *CFA/DAGA'04 (French Acoustical Society/German Acoustical Society)* **(Strasbourg March 2004)**

This paper describes the difference in harmonic formation between a slider chest and a cone chest but does not state how the key of the slider chest was moved or consider how it may vary.

Fischetti, Mark "Working Knowledge – Pipe Organs" *Scientific American*, **July 2004**

This article is one of a series explaining the workings of everyday objects suggested by readers. Fischetti states that:

> As listeners sought a greater variety of sounds from ever larger churches and municipal halls, however, greater wind pressure was needed, and players had to press even harder on a key to open a pallet against that pressure. Designers eventually turned to new-fangled electricity to solve the problem.

> Today organs with each of these types of "actions" (mechanical and electric) are still made. "There are differences of sound", says Stanley Scheer, vice president of Casavant Frères … "There is a kind of refinement in sound quality to certain designs, a kind of excitement to others".

We are not told whether these differences can occur within different types of action or between them.

Pykett, Colin "The Physics of Organ Actions" *Pykett.org.uk* **(accessed 24th October 2005)**

Dr Colin Pykett is a physicist and his article covers the calculation of pluck and action masses and no other work in the public domain covering this material came to light during this review. It does, however, contain some errors and some statements that appear to need further explanation.

> Consider a conventional long, thin pallet hinged at one end. The ratio of windway to pluck is given by Q=2d/wp approximately, where d is the distance the pallet descends; w is the width of the aperture it covers; and p is wind pressure. An efficient valve clearly must have as a high a value of Q as possible…

> Note the curious fact that the length of the aperture does not arise here, therefore Q is dominated by aperture width rather than length. It follows that, in the limit where a

pallet aperture is infinitely thin (w tends to zero), pluck vanishes but the windway remains.

Q=2d/wp only applies to a pallet drop where d is less than w/2, i.e. the pallet drop is less than half the width of the pallet opening - not what would generally be considered a "thin" pallet. In fact pluck will remain constant and the windway will be maximised.

…a modern roller assembly made of aluminium tubing 8 mm diameter with a 6 mm bore, a length of 1 metre and having roller arms 50mm long has an EDM (Equivalent Dynamic Mass) of about 0.15 gm. This compares with its actual mass of about 32 gm.

On page 89 it is shown that such a roller (without the arms) will have a mass of 59.4 g and an inertia of 0.297 g. Pykett appears to have made his calculations using a bore of 7 mm. His comments about the difference between the actual mass and the rotational inertia are very valid.

..the masses of stickers, provided they are short and lightweight, can likewise be ignored.

This is true, but stickers are of relatively large cross section because they have to resist buckling. If they are anything other than short they cannot be ignored. Note the diameter of the sticker in Fig 2.6.

The equivalent dynamic mass (EDM) of a backfall action is dominated by the total tracker masses. The masses of all other components contribute less to the EDM even if their masses are greater than those of the trackers. Rollers are almost always negligible in terms of their effect on action inertia.

On page 65 it is calculated that a one-metre length of typical modern wood tracker, 8 mm by 1.3 mm, has a mass and thus inertia of 4.16 g. The maximum EDM of an action to achieve a playing weight of 80 gm and a repetition rate of eight times per second is shown on page 64 to be 150 gm. It is not clear how this is dominated by the tracker mass. The discussion of rollers in this thesis suggests that they are not

"almost always negligible". This statement is presumably based, in any case, on Pykett's incorrect calculation on the lightest commonly used rollers.

> <u>Maximum allowable tracker length</u> [in a suspended action]. For a repetition rate of 8 notes/sec the maximum allowable tracker mass is 228 gm.

Even allowing for Pykett's suggested gearing ratio of 7:10, this is equivalent to an EDM at the key head of 159.6 g before any other components are taken into account (against the target maximum of 150 g).

Pykett does not make more than passing mention of looseness and does not consider flexibility at all.

Bethards, Jack M. "A Brief for the Symphonic Organ" *The Diapason* **(Des Plaines, Illinois, Scranton Gillette) vol. 96 no. 9 September 2005 p22**

Bethards is President and Tonal Director of Schoenstein & Co Organ Builders of San Francisco.

> The most important reason for absolute uniformity of chest response under all conditions is the fact that pipes do not have the flexibility to adjust for variations in attack, wind supply, and release as do other musical instruments.

> This leaves the valve as the only means of control and that control is limited even on the best mechanical action. I submit that this element of control is actually a negative because variations in valve action, being different from the ones experienced by the voicer, will be more likely to degrade pipe speech than to enhance it.

Here is an organ builder clearly stating reasons why changing the transient is undesirable.

Bohn, David. Wisconsin Alliance for Composers – www.wiscomposers.org, *On the Nature of the Beast that does not Breathe – A composer's-Eye View of Writing for the Organ* **Newsletter date unclear**

> This type of action is the oldest, and many organists consider it best in that it gives them the illusion of precise control over what is occurring. The prime weakness of a mechanical action is that it gets harder to control (particularly….when couplers are engaged) on a larger instrument

Clarke, Arthur C. *2010 Odyssey Two* **(London, Voyager 1997) p246**

> "Thank you, Hal. On the button"

> Now that was another phrase that was badly dated; for at least a generation, touch pads had almost entirely replaced buttons. But not for all applications; in critical cases, it was best to have a device that moved perceptibly with a nice, satisfying click.

3.3 Discussion

The above quotes give an idea of the breadth of opinions about the merits of mechanical actions over the past 230 years. As far back as 1778 Dom Bedos describes the action as becoming "hard" if the air requirement is too great. He is presumably referring to pluck. He also describes flexibility in the pedal action if the rollers are too long.

In 1909, Stainer expresses the view that that the air should not be allowed to "sneak" into the pipe and spoil its tone. This view is also expressed by Curly (1998) and Bethards (2005), who both point out that pipes are voiced for a constant airflow.

Jude (1922) and Harrison (1953) both describe the key "flopping down" as pluck is overcome and thus removing any control of the pallet.

None of these authors, however, back up their opinion with any objective evidence and no authors describe how any control of the pallet could be used in a musical context.

Chapter 4

Mechanical Characteristics of Organ Action Components

4.1 Introduction

This chapter discusses the principal mechanical characteristics of pipe organ action components that affect the touch (which can be simplistically defined as "what the player feels when he moves a key"). It covers the most commonly used action components, many of which are commercially available from a number of different manufacturers and is intended to give a comprehensive but not exhaustive discussion of the factors involved.

Many action components (typically key levers, squares, roller arms, pallets) are made out of wood, the most even grained of which is not perfectly uniform and, in practice, an allowance must be made for this.

4.2 Pluck

The one characteristic that defines the nature of the touch of a mechanical pipe organ action is pluck (being analogous with the feel of the plectrum plucking the string of a harpsichord. It is also called "top resistance".). Pluck is caused by the pressure difference across the closed pallet. Fig 4.1 reproduces an illustration by Audsley of a cross section of a bar (groove) and slider wind chest[1]. The groove or bar is the channel on which all the pipes for one note are planted. The sliders (S) are movable strips usually of wood that determine which ranks of pipes receive air from the groove by lining up holes in the slider with corresponding ones on the top of the groove. The pallet box (ABDH) contains pressurised air whereas the groove (bar) contains air at atmospheric pressure. The net force of the pressurised air has to be overcome in order for the pallet to start opening. As soon as the pallet starts opening, the pressures on either side of the pallet start to equalise and the additional force reduces very quickly. The feeling has been likened to pushing a finger through a thin layer of ice.
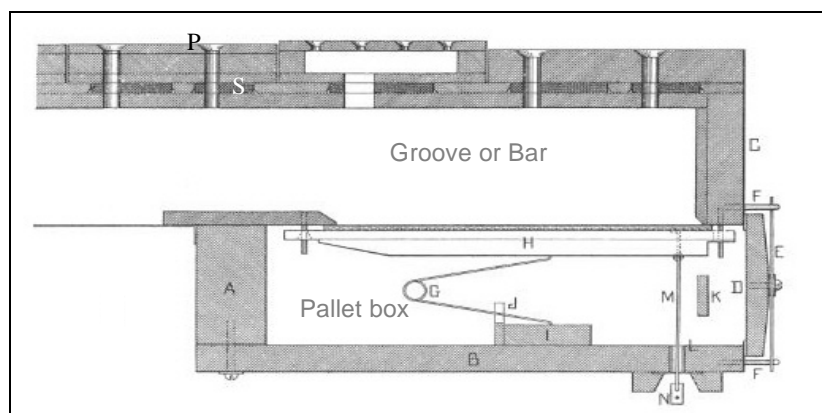
Fig 4.1 Cross section of a bar (groove) and slider windchest adapted from Audsley Fig CLIX. The significant parts are: N connected to the tracker from the key and pulling open pallet H via tracker M, compass spring G providing the closing force on the pallet, pallet box containing pressurised air, groove connecting all pipes played with one key, slider S shown open so that the pipe, planted in tapered hole P, will speak when the pallet is opened.

---

[1][Audsley 1905], page 215 – Audsley calls it a "slider and pallet wind-chest"

The bar and slider wind chest has remained in its current form for so long because it is simple and because the force against the pallet due to air pressure in the pallet box helps seal the closed pallet against leaks round its edges into the groove that might cause pipes to murmur.

4.2.1 Calculation of Pluck

Pluck is the force measured at the pallet pull down that exerts an equal and opposite torque on the pallet as the force exerted by the net air pressure in the pallet box. A cross section of a typical pallet is shown in Fig 4.2. For ease of calculation the pallet opening is illustrated as being central between the hinge and the pallet pull down. This would not generally be the case and appropriate adjustments to the calculations must be made. In particular, in a suspended action the pallet pull down may be some way further back to allow for the gearing down of the action at the key. (See Fig 4.13a) Other variations will be dictated by the geometry of the action. The length of the pallet opening is l_o and the width w. The distance between the hinge and the pull down is l_p. Let the pressure in the pallet box be p.

The force, F_p, against the pallet due to the air pressure is given by:

$$F_p = pA = pwl_o \tag{1}$$

where p is the pressure in the pallet box

       A is the area of the pallet opening

       w is the width of the pallet opening

       l_o is the length of the pallet opening
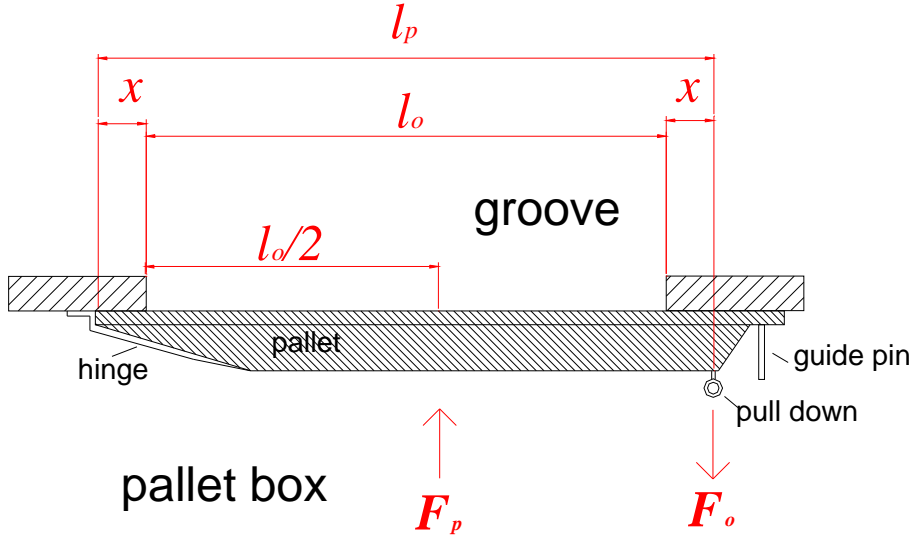
Fig 4.2 Cross section of a typical pallet. The pallet opening has length l and the net force due to the air pressure difference between the pallet box (high pressure) and the groove (low pressure) is F_p acting on the bottom of the pallet at the centre point of the pallet opening. The tracker from the key is attached to the pallet pull down and applies a force F_o. In this illustration, the section of pallet between the pull down and the hinged end is centred under the pallet opening, where x is the distance between the pull down and the hinged end from the respective ends of the pallet opening. The force F_p thus acts at the mid point between the pull down and the hinge.

The force F_p acts through the centre of the pallet opening at distance $l_o/2$ from the hinge end of the pallet opening. This point is $l_p/2$ from the hinge. F_p exerts a torque, τ, on the pallet where

$$\tau = F_p \frac{l_p}{2} = \frac{pwl_p^2}{2} \tag{2}$$

To overcome this torque at $l_p/2$ requires an equal torque at distance l_p from the hinge end. Thus

$$\tau = F_o l_p = F_p \frac{l_p}{2} \text{ , therefore}$$

$$F_o = \frac{F_p}{2} \tag{3}$$

where F_o is the force to open the pallet as measured at the pallet pull down.

4.2.2 Airflow through pallet opening

The method used by organ builders to calculate the airflow through an open pallet has been described by Hoffman[2] and Norman[3]. This method takes no account of fluid dynamics and is over simplistic. Fig 4.3 illustrates an open pallet where l is the length of the pallet opening, w is the width of the pallet opening and d is the vertical distance by which the pallet opens.
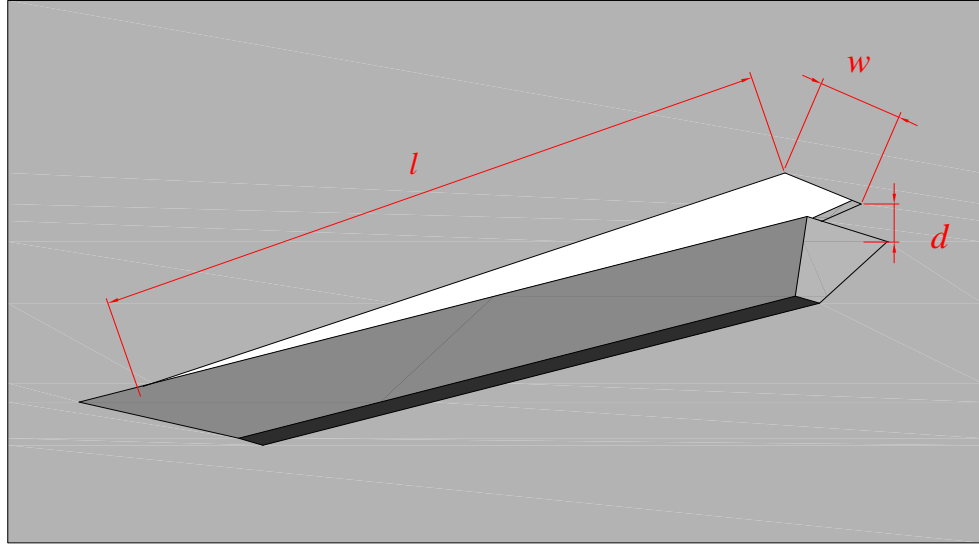
Fig 4.3. Diagram of an open pallet. *l* and *w* are the length and width of the pallet opening and *d* is the pallet drop, i.e. the vertical distance through which the pallet opens measured at the front of the pallet opening.

Fig 4.4 is reproduced from Hoffman's paper.

---

[2] [Hoffman 1986]
[3] [Norman 1977]
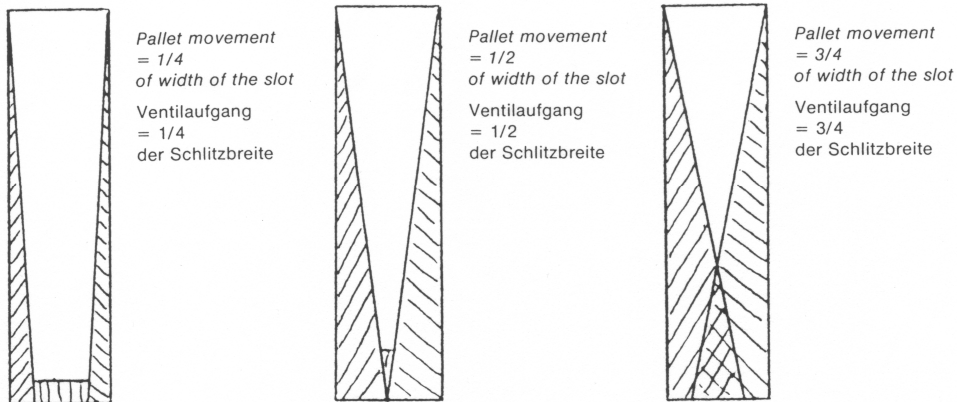
Fig. 8
The drawing shows a pallet-fall equal to 1 / 4, 1 / 2, and 3 / 4 of width of the slot
Graphik über das Verhältnis zwischen Ventilschlitzfläche und Durchlassfläche bei verschiedenem Ventilaufgang

Fig 4.4. Illustration by Hoffman to represent the airflow through the pallet opening with varying degrees of pallet drop *d* measured vertically

The shaded triangles represent the triangles formed by the open pallet and the top of the pallet box when viewed from the side (area *wdl*/2), the hinge being at the top of the illustration. In the first case, along with a small area at the open end, these two triangles represent the limiting area through which air can flow. The area between the two triangles at the open end due to airflow round the end of the pallet is unlikely to become significant because pallets generally open at least to half the width of the opening.

When the pallet drop becomes greater than half the width of the pallet opening (third illustration in Fig 4.3, the triangles overlap i.e. the amount of air that can pass above the pallet cannot pass through the pallet opening, the width of which now becomes the limiting factor at the open end of the pallet.

Fig 4.5 is a diagram of a pallet opening viewed from above where *l* is the length of the pallet opening, *w* is the width of the pallet opening and *d* is the vertical distance by which the pallet opens. Assuming laminar flow, the triangles *ld* represent the area formed by the open pallet and thus the area of airflow over the top of the pallet. The

red triangle represents the area where the area of airflow over the top of the pallet is greater than can pass through the pallet opening.
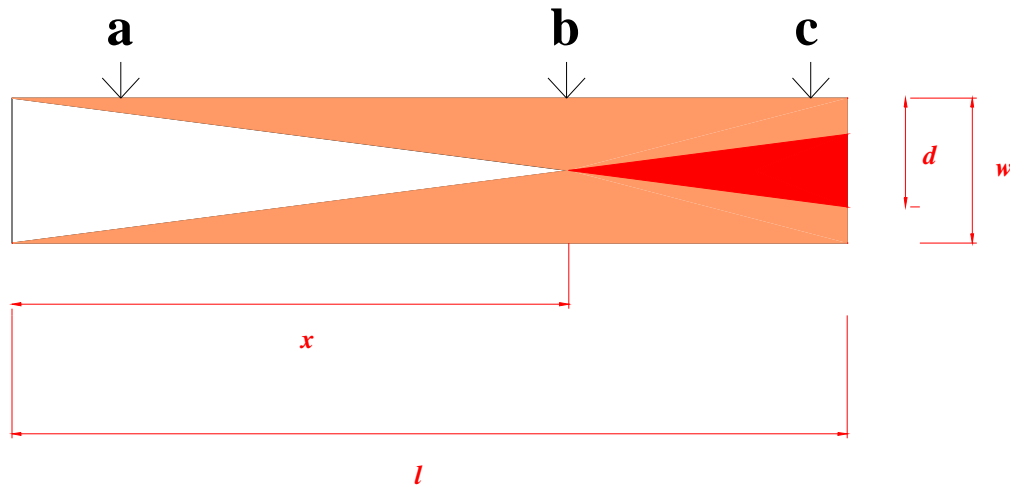
Fig 4.5 Diagram showing a pallet opening from above showing the airflow over the pallet and through the opening assuming that the pallet drop *d* is greater than half the width of the pallet opening *w*

Fig 4.6 shows a cross section of the pallet and pallet opening at the points **a**, **b** and **c**. At point **a** the airflow over the top of the pallet (shaded pink) is less than can pass through the pallet opening. At point **b** the airflow over the pallet is equal to the airflow through the pallet opening and at point **c** the airflow over the pallet cannot all pass through the pallet opening. The overlap is highlighted in red. The laminar flow could be improved by rounding the edges of the pallet opening.
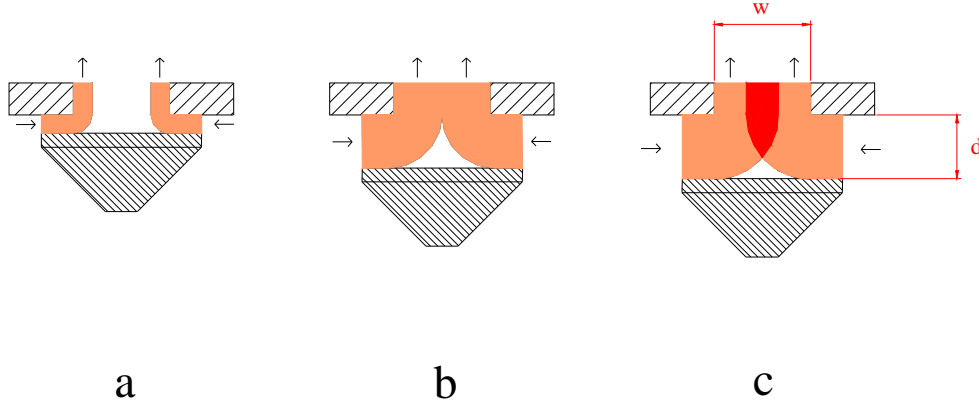
Fig 4.6 Diagram showing the cross section of the pallet and pallet opening viewed from the front at the three points a, b and c indicated in Fig 4.5. *d* is the pallet drop and *w* is the pallet opening width. The arrows indicate the direction of airflow. The pink shading represents air that can flow over the top of the pallet and through the pallet opening. The red shading represents the part of the pallet opening through which the air flowing over the pallet cannot all flow.

If the length of the pallet opening is l cm then, in the first case in Fig 4.4, above, (pallet drop less than half the pallet opening width), the area of airflow is equal to the area of the two shaded triangles, i.e. *dl* (ignoring any airflow round the open front of the pallet).

Where the pallet drop is greater than half the pallet opening width, as in the third diagram, the area of the wind way is most easily calculated by subtracting the unshaded area in Fig 4.5 from the total area of the pallet opening. If the height of the unshaded triangle is x, then, from similar triangles,

$$\frac{d}{l} = \frac{0.5w}{x}$$

$$x = \frac{wl}{2d} \qquad\qquad (4)$$

The area, A_t, of the unshaded triangle is

$$A_t = 2\frac{x}{2}\frac{w}{2} = \frac{xw}{2} \tag{5}$$

substituting for x from equation 4.

$$A_t = \frac{wl}{2d}\frac{w}{2} = \frac{w^2l}{4d} \tag{6}$$

The area of airflow, A, becomes

$$A = wl - A_t = wl - \frac{w^2l}{4d}$$

$$A = wl\left(1 - \frac{w}{4d}\right) \tag{7}$$

This is the formula derived by Norman[4] by a different process.

Hoffman [1986] does not justify his statement that the pallet drop d must not exceed half the pallet opening width w otherwise "mutually disruptive forces" will occur. Norman[5] has stated that narrow pallet openings appear to smooth the airflow, but this is an empirical view. Bishop and Son[6] use long, thin pallets because of the favourable airflow to pluck ratio and have found no problem.

If the gearing is increased to increase the pallet opening in order to increase the airflow, the pluck as measured at the key increases. Norman showed that the minimum pluck for a given area of airflow occurs when the pallet opening width equals 4/3 of the pallet drop.

---

[4] [Norman 1977] p44
[5] Discussion with author
[6] Discussion with author

4.2.3 Reducing pluck

As organs become larger with more and/or louder pipes per note, three factors relating to the pallet and pallet opening become critical:

airflow

pluck

Equivalent Dynamic Mass (EDM)

If all the pipes are to be fully winded then the airflow is a function of the total of the air requirements of the individual pipes. Since pluck is fixed for a particular pallet opening area and wind pressure it is necessary to try to maximise the airflow to pluck ratio. From the discussion above, it can be seen that as the pallet opens further the airflow increases but pluck (as measured at the pallet pull down) remains the same. If the pallet moves further in order to increase the airflow and the key movement remains the same, the pluck as measured at the key head will increase in the same ratio (as will the EDM of the pallet).

Pluck may be reduced by inserting triangular pieces into the pallet opening at the hinge end to match the areas through which no air flows. If this is done by narrowing the outside edges of the opening, as some organ builders do, the airflow is likely to be reduced by having to pass through a narrow channel with a rough leather surface on at least one side (unless the face of the pallet is also narrowed). Their use, in principle, means that airflow is optimised irrespective of the shape of the pallet opening. Hoffman goes through the calculation of pluck against airflow for tapering pallet openings.

If the pallet is hinged along its long side and not at the end (i.e. is "very wide") the predominant airflow is through the end of the opening and a pallet opening of 1cm would require a pallet drop of 1cm in order to give unrestricted airflow through the

entire pallet opening. This would only be practical if there is sufficient width in the pallet box for the hinges. "Sideways" hinged pallets have been used and an example photographed in Johannes Klais Orgelbau's workshop in Bonn during 1999 is shown in Fig 4.7. This organ was under restoration. The problem with such an arrangement would be sealing the tracker attached to the pallet pull down as it passed through the bottom of the pallet box, as it would move a significant distance sideways. It was not possible to determine how this was achieved in the example photographed, but it could be achieved without excessive movement of the tracker as it enters the windchest by having a final flexible coupling inside the pallet box at the expense of having part of the mechanism relatively inaccessible.

Fig 4.7 Pallet hinged along its long side.

4.3 Maximum Allowable Action Mass

The maximum allowable EDM (equivalent dynamic mass) or inertia of an action is determined by the required repetition rate, the maximum allowable force applied by the finger and the distance of finger movement.

These values are to some extent subjective, but a repetition rate of eight notes per second should be considered the minimum, being equal to demi-semi-quavers at 1 crotchet per second and represents a reasonably fast trill. It can easily be exceeded in a small organ. The action, therefore, has to move from one extreme to the other in 62.5 ms.

The player can, to some extent, vary the time of key depression, but the key return time is determined by the pallet spring. This force exerted by the spring will, in fact vary, but over the relatively short distance involved it is assumed for the purpose of this discussion to be constant. The maximum allowable force has been found empirically to be 80 g force (as stated by Hoffman[7]) and a key head movement of 1 cm is adopted as a convenient round number, (although it should be noted that measurements taken during this study suggest that it is frequently slightly less).

The key head, i.e. the point of contact with the finger, is taken as the point of movement for the complete action and the Equivalent Dynamic Mass (EDM) of the action is defined as the equivalent point mass located at the point of contact of the finger and key head that would give the same acceleration under the same force as the complete action. From Newton's laws of motion, with acceleration from rest

$$d = \tfrac{1}{2}at^2$$

where d is the distance travelled by the point of contact of the finger and key head

a is the acceleration of the key head

t is the time of motion of the key head

and since

$$F = Ma$$

---

[7] [Hoffman 1986]

where F is the force applied to the key head to return it to its rest position by the

pallet spring.

M is the Equivalent Dynamic Mass (EDM) of the action

then

$$M = \frac{t^2 F}{2d}$$ (12)

Since release time $t = 62.5$ ms, $F =$ weight of 80 g and $d = 1$ cm

$$M = \frac{0.0625^2 \times 80 \times 981}{2 \times 1}$$

$$M = 153.3 \ g$$

Thus the total Equivalent Dynamic Mass (EDM) of the action is 153.3 grams in order to achieve a repetition rate of eight notes per second with a force required to keep the key depressed equal to a weight of 80 grams and with a key dip of 1 cm. 150 grams is a convenient round figure to adopt as the target maximum EDM for this action.

4.4 Trackers

Trackers are the components of an action that transmit motion by pulling in a straight line (Fig 2.7). The two critical factors for trackers are mass and stretching.

4.4.1 Tracker mass

Modern trackers are frequently made out of pine or similar wood. Their mass is calculated by multiplying their volume by their density. Pine has a density of approximately 0.4 g/cc. A standard manual tracker with a cross section of 8 mm by

1.3 mm will have a mass of 0.8 cm x 0.13 cm x 100 cm x 0.4 g/cc = 4.16 grams per metre length. Fig 4.8 shows wooden trackers in the organ at Bridgewater Hall, Manchester.
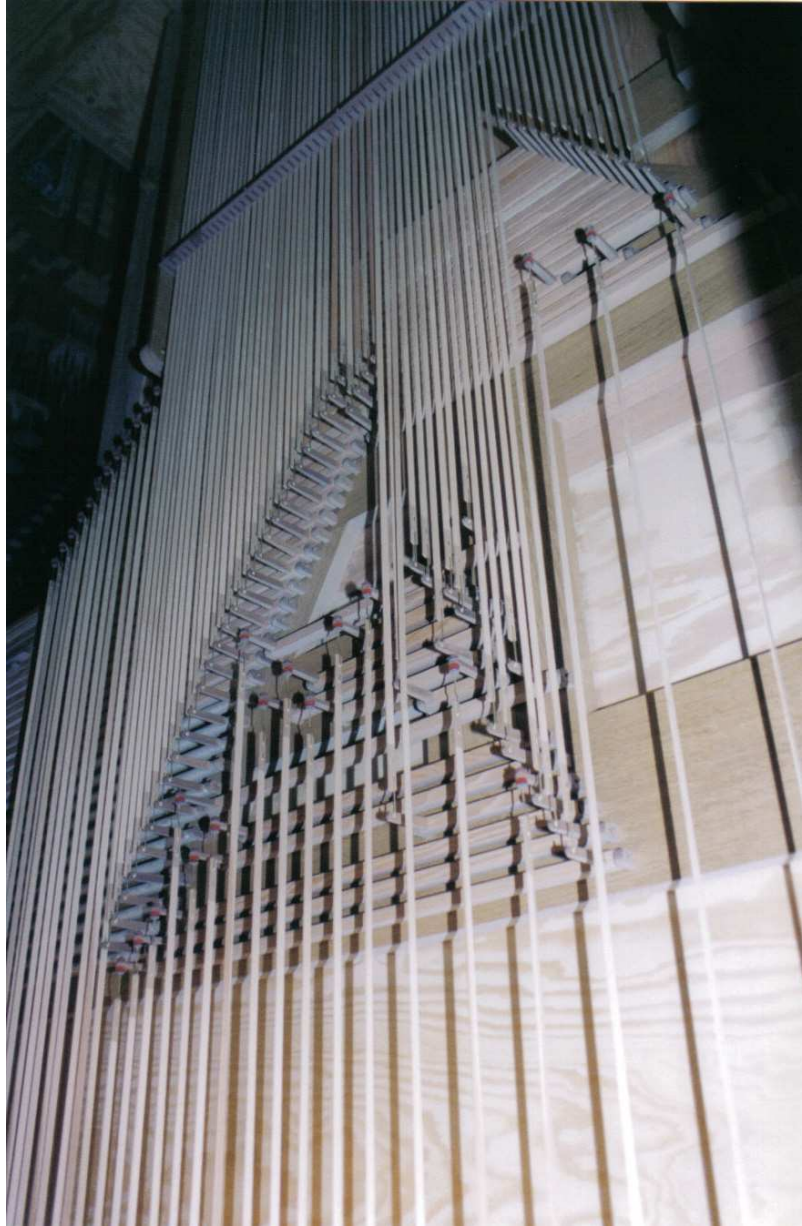
Fig 4.8 Wooden trackers and rollers. Bridgewater Hall, Manchester

Phosphor bronze has a density of 9 g/cc and wire of 1.65 mm diameter will have a mass of πx0.0825²x100x9 = 19.24 g per metre. Wooden trackers are usually

terminated with phosphor bronze wire (Fig 2.5) and it should be noted that 5 cm of phosphor bronze wire at each end of a 0.8 cm by 1.3 cm pine tracker is equal to 46 cm of tracker.

Aluminium has a density of 2.7 g/cc and wire of 1.65 mm diameter will have a mass of 5.77 grams per metre. Fig 4.9 shows aluminium trackers at New College Oxford.
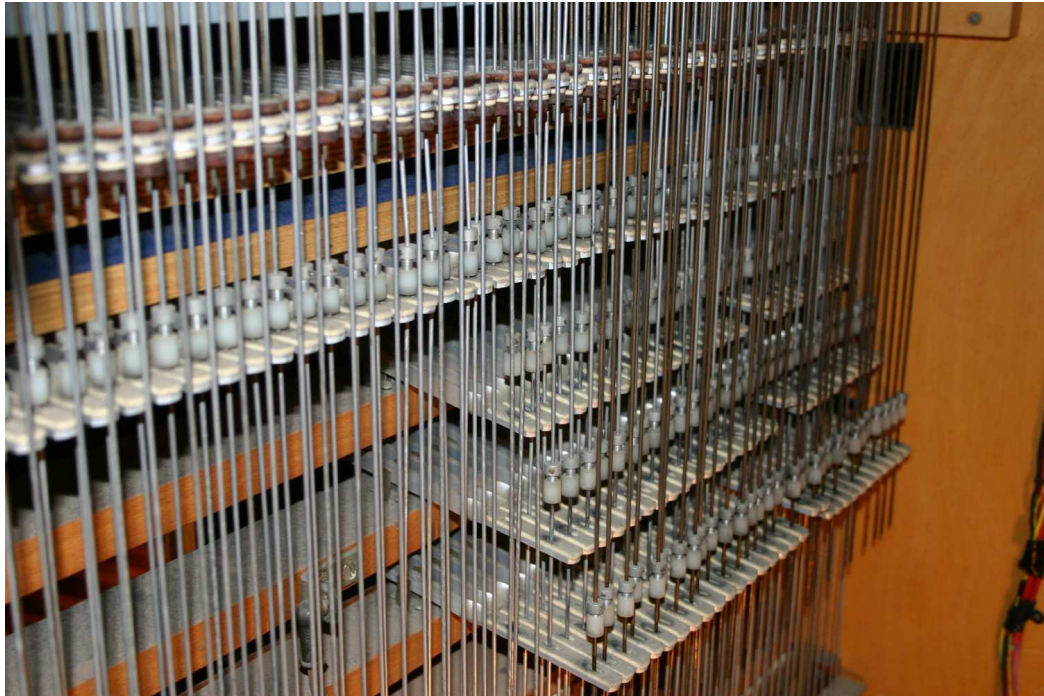
Fig 4.9 Aluminium trackers at the back of the console. New College Oxford. The additional trackers to the right are for the pedal couplers.

4.4.2 Stretching

The amount a material stretches (within its elastic limit) is determined by its Young's modulus and the applied force per unit of area.

$$E = \frac{stress}{strain} \tag{13}$$

where E is Young's modulus

stress is force per unit area

strain is extension per unit length

Rearranging:

$$strain = \frac{stress}{E}$$

For wood, E is approximately 10 GN/m²

Assume a force equal to a weight of 200 g, i.e. 1.96 N

Then   strain = $(0.2 \times 9.81/(0.008 \times 0.0013))/10^{10}$

strain = 1.89×10^{-5}

Thus a one-metre length will stretch by 0.0189 mm

Five metres will stretch by 0.094 mm etc. If the tracker is attached 7/10 of the distance from the pivot to the key head, the force will be increased in inverse proportion, i.e. by 10/7, and the amount of stretching will therefore increase to 0.134 mm, and this in turn is increased in proportion to the leverage of the key lever, i.e. 10/7 again, giving movement at the key head of 0.192 mm, i.e. just under a fifth of a millimetre.

This degree of stretch will be increased further if the trackers are longer or the gearing is greater and adds to the overall flexibility of the action.

Phosphor bronze has a Young's modulus of 100 GN/m² and so for wire 1.65 mm diameter (standard "action wire")

strain = $(0.2 \times 9.81/\pi 0.000825²)/10^{11}$

strain = 9.18×10^{-6}

Thus a one metre length will stretch by 0.00918 mm i.e. approximately one half the amount of a pine tracker but with a mass 4.6 times greater.

Aluminium has a Young's modulus of about 70 GN/m² and one metre of 1.65 mm diameter wire will stretch 0.013 mm.

Thin rods are susceptible to buckling under compression loads however, and, if the moving action is allowed to continue unchecked, when the tracker comes to rest when the key hits the key bed, that part of the action that the tracker has started moving will continue to move causing the tracker to buckle. This may affect the repetition rate of the action or may allow components to become dislodged even if the bearings have no slack. (This assumes that the tracker stops dead.)

For a rod pinned at both ends (a tracker with normal attachments) the minimum force required to start buckling is given by[8,9]:

$$W = \frac{\pi^2 EJ}{L^2} \tag{14}$$

Where W is the force to start buckling

E is Young's modulus

J is the second moment of area of the section

L is the length of the rod

This is the minimum force because, if there is no sideways displacement, the rod will simply compress. Thus, for a wooden tracker with an oblong section,

$$J = \frac{BH^3}{12} \tag{15}$$

---

[8] [Gieck and Gieck 1997] page P22
[9] [Matthews 2004] page 83

Where B is the width of the section

     H is the thickness of the section

For a one metre length of pine tracker 8 mm x 1.3 mm

$$W = (\pi^2 \times 10^{10} \times (0.008 \times 0.0013^3)/12)/1$$

$$W = 0.145 \text{ N}$$

This is equivalent to a weight of 14.7 grams. Since the buckle load is inversely proportional to the length squared (equation 14), a two metre long tracker will buckle under a load of 3.68 grams and can readily be shown to buckle under its own weight simply by trying to hold it vertically from its base, and it will thus not prevent the pallet from continuing to move.

Over-runs are readily prevented, however, by placing stops at the end of travel of any components likely to do so and it is unnecessary to pursue the mathematics further. Action overruns are a problem in actual organs where stops have not been incorporated.

4.5 Stickers

Stickers move under compression in a straight line (Fig 2.6). In this case buckling is the significant factor, along with mass.

From equation 14, above, $W = \dfrac{\pi^2 EJ}{L^2}$

Where W is the minimum force required for buckling

     E is Young's modulus

J is the second moment of area of the section of the sticker

L is the length of the sticker

Assume that the load is 200 g, i.e. a force of 1.96 N, and that there is no safety margin.

For a circular section,

$$J = \frac{\pi \times r^4}{2}$$

Therefore

$$W = \frac{\pi^2 E \pi r^4}{2L^2} = \frac{\pi^3 E r^4}{2L^2}$$

$$L = \sqrt{\frac{\pi^3 E r^4}{2W}} \tag{16}$$

For phosphor bronze wire with a diameter of 2 mm and E = 10^{11} N/m²

$$L = \sqrt{\frac{31.00 \times 10^{11} \times 0.001^4}{2 \times 1.96}}$$

$$L = 0.889 \text{ m}$$

If the action is geared down by 70% and a safety factor of 100% is introduced, then this length will reduce by a factor of $\frac{10}{7} \times 4$ to

$$L = 0.156 \text{ m}$$

Thus, a phosphor bronze sticker 2 mm diameter and 0.156 metres long will have a mass of 4.41 g, a similar mass to a wooden tracker one metre long, in order to ensure that it is unlikely to bend.

Similarly, for a wooden sticker 3.5 mm in diameter and E = 10^{10},

$$L = \sqrt{\frac{31.00 \times 10^{10} \times 0.00175^4}{2 \times 1.96}}$$

$L = 0.861$ m, or approximately the same as phosphor bronze 2 mm diameter.

The mass of a wooden sticker 0.156 m long would be 1.20 grams and is thus to be preferred as a material for stickers.

The above should, nevertheless, indicate why long stickers are to be avoided where mass is critical. Note the diameter of the sticker in the model action by N P Mander Ltd for Reading University (Fig 2.6).

4.6 Key levers, pallets, backfalls, squares etc.

4.6.1 EDM of rotating components

These are all essentially rods pivoted about an axis perpendicular to their length. Fig 2.6 shows the model made by N P Mander Ltd for the University of Reading to illustrate the difference between a backfall action and a suspended action.

Initially assume that a key lever is a rod with no width or height and that it is freely pivoted at one end. The EDM of the rotating rod will be calculated by equating the kinetic energy required to move its point of contact with that of a point mass moving the same distance.

The kinetic energy of rotation is given by:

$$KE = \tfrac{1}{2} I \omega^2 \qquad\qquad (17)$$

where I is the moment of inertia of the key lever

       ω is the angular velocity

The kinetic energy of a mass moving in a straight line is given by:

$$KE = \tfrac{1}{2} m_2 v^2 \tag{18}$$

Where m_2 is the mass of the object

       v is its velocity

Equating the two:

$$\tfrac{1}{2} I \omega^2 = \tfrac{1}{2} m_2 v^2 \tag{19}$$

For a narrow rod rotating about its end

$$I = \tfrac{1}{3} m_1 l^2 \tag{20}$$

Where m_1 is the mass of the rod

       l is the length of the rod

Thus

$$\tfrac{1}{2} \times \tfrac{1}{3} m_1 l^2 \omega^2 = \tfrac{1}{2} m_2 v^2 \tag{21}$$

At length l from the pivot,

$$v = l\omega \tag{22}$$

Substituting this into the formula gives

$$\tfrac{1}{2} \times \tfrac{1}{3} m_1 l^2 \omega^2 = \tfrac{1}{2} m_2 l^2 \omega^2 \qquad\qquad (23)$$

Simplifying gives

$$m_2 = \tfrac{1}{3} m_1 \qquad\qquad (24)$$

Thus the effective mass is one third of the actual mass.

However, this makes a number of assumptions. Key levers are not uniform narrow rods – they have width and thickness and have variations in their cross sections at the key head and along their length to accommodate the pivots and the tracker mounting. The width of the lever is irrelevant but the height of the key will have a small effect on the effective mass.

For a rectangular plate, equation x becomes

$$I = \tfrac{1}{3} m_1 \left(l^2 + h^2 \right) \qquad\qquad (25)$$

Where h is the height of the key lever

If the lever is 50 cm long and 2.5 cm high

Then

$$l^2 = 2500 \,\text{cm}^2$$

and

$$\left(l^2 + h^2 \right) = 2506.25 \ \text{cm}^2$$

This difference of 0.25% can be disregarded for practical purposes but must be borne in mind for exceptional cases.

A typical natural key lever will widen at the playing end to fit round the accidentals and will also have a covering of a material possibly with a greater density than the rest of the lever. It may also be cut away at various points – any undercutting at the head will offset the extra mass from the key covering or widening. A number of sample key levers are illustrated and it must be emphasised that each case must be taken on its own merits. A large mass at the end of a slender lever will have a significant effect on the inertia.

These additions and cutaways can be included in the calculation by using the parallel axis rule. This states that

$$I_1 = I_0 + Mh^2 \tag{26}$$

where I_1 is the Moment of Inertia of the part of the object about the required axis

I_0 is the Moment of Inertia of the part of the object about one of its own axes parallel to the required one.

M is the mass of the part of the object

h is the distance between the two axes.

Fig 4.10 Swell keys partially removed in order to gain access to Great tracker connections, Radley College, Oxfordshire. Variations in the cross section of the key lever along its length are apparent.

Because of their relatively large cross section to minimise bending, key levers have a relatively high mass per unit length and long key levers should be avoided where total inertia is critical. In particular, the use of "long" key levers in suspended actions should be carefully considered: the effect of varying the cross section is discussed below.

The effective mass is only approximately one third of the actual mass for objects rotating about their end or their centre (in which case, assuming the same overall length, the lower moment of inertia is balanced by the additional distance travelled – the key lever rotates through double the angle).

If the key lever is balanced at a point two thirds of its length from the key head (Fig 4.12) then, if the total length is l, the total moment of inertia is equal to the moments of inertia of the two parts of the lever on either side of the pivot.

$$I = \frac{1}{3}\frac{m}{3}\left(\frac{l}{3}\right)^2 + \frac{1}{3}\frac{2m}{3}\left(\frac{2l}{3}\right)^2 \tag{27}$$

this simplifies to:

$$I = \frac{ml^2}{9} \tag{28}$$

If this is equated to the kinetic energy at a distance $\frac{2l}{3}$ from the pivot, then

$$\tfrac{1}{2} \times \tfrac{1}{9} m_1 l^2 \omega^2 = \tfrac{1}{2} m_2 \left(\tfrac{2}{3} l^2\right)\omega^2 \tag{29}$$

This simplifies to:

$$m_2 = \tfrac{1}{4} m_1 \tag{30}$$

That is, the effective inertia at the end of the lever is one quarter the mass of the actual lever. The movement of the far end of the lever is half that of the key head.

This is the minimum value for the effective mass as a proportion of the actual mass and the relationships are shown in Fig 4.11.

Graph to show how equivalent dynamic mass (EDM) varies with pivot position
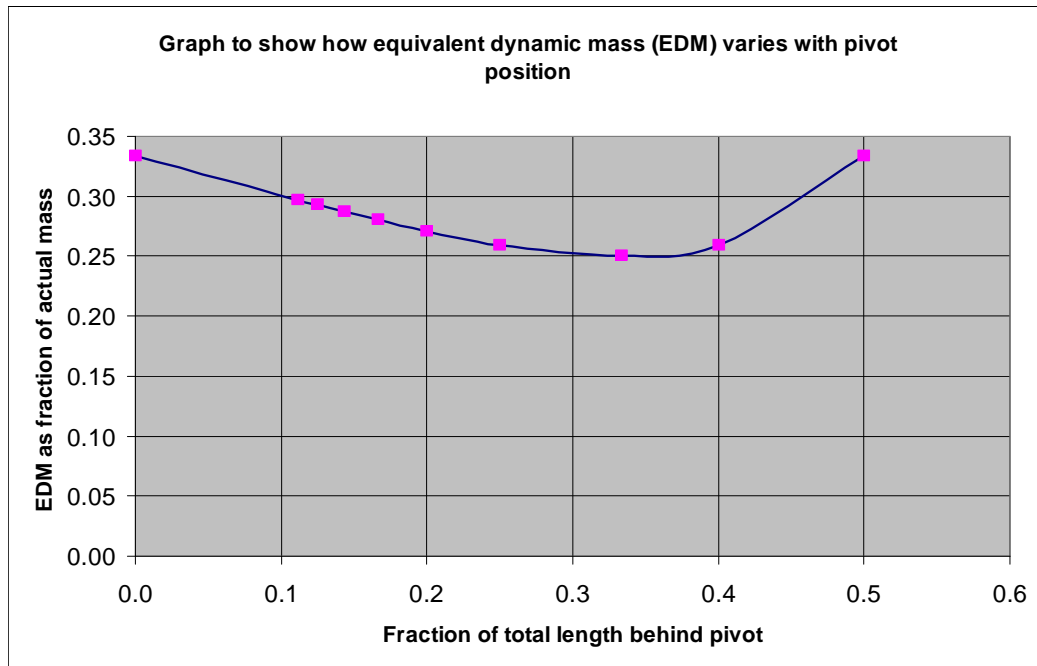
Fig 4.11 Graph showing how Equivalent Dynamic Mass varies with the position of the pivot point on a rod.

Fig 4.12 illustrates a rod pivoted such that one third of its length is behind the pivot. The point at which the force is applied will accelerate at four times the rate that a point mass equal to that of the rod would under the same force.
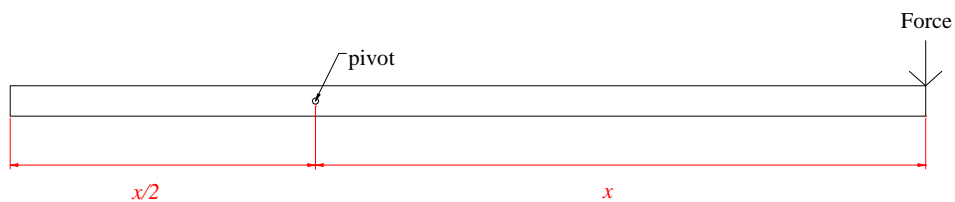
Fig 4.12 Diagram to illustrate the effect shown in Fig 4.11. The point of application of the force will accelerate at four times the rate that a point mass equal to the mass of the rod would.

The masses of components can be reduced by reducing the amount of material in them as shown in examples of pallets by two organ builders. Fig 4.13a shows pallets by Peter Collins with routed slots and Fig 4.13b shows tapered pallets by Bishop & Son.
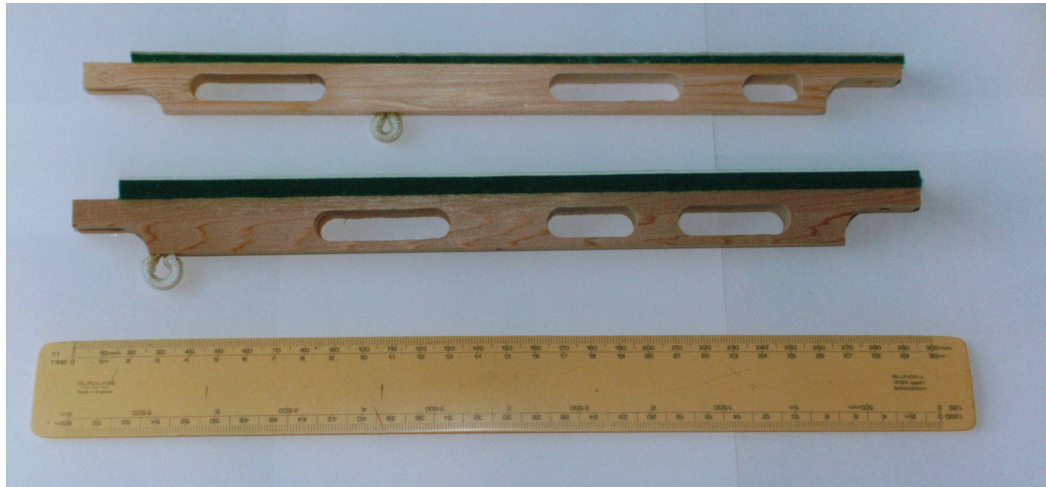
Fig 4.13a Pallets by P D Collins with routed slots in order to reduce inertia. The top pallet has its pull-down further towards the hinge (right) in order to allow for the gearing of a suspended action.
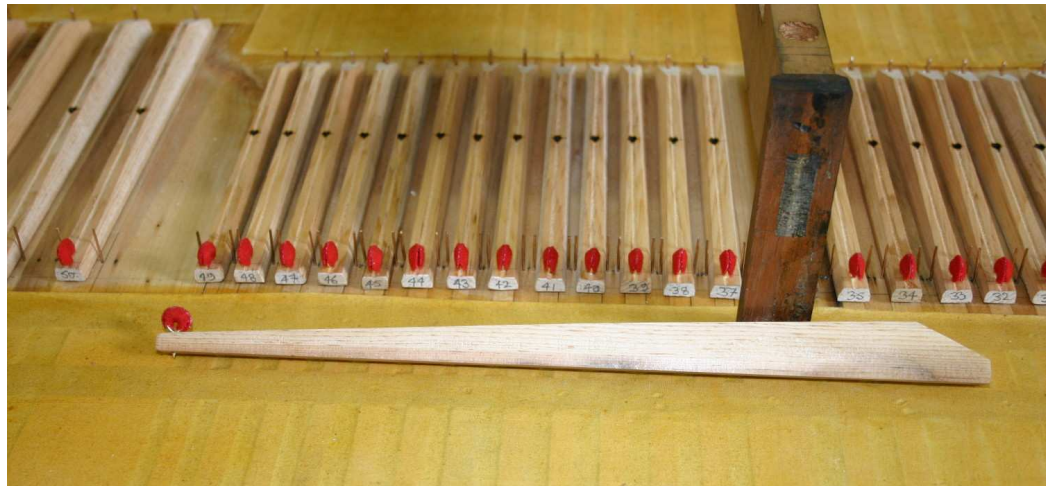
Fig 4.13b Pallets by Bishop and Son, tapering in order to reduce inertia. They are hinged at the thicker end.

4.6.2 Bending of roller arms, square arms and key levers etc

Fig 4.14 Roller arms New College Oxford. The tracker ends are plastic.

The deflection at the position of load of a simple beam is given by:

$$d = \frac{Wl^3}{3EJ} \tag{31}$$

where

       W is the applied load

       l is the length of the beam

       E is Young's Modulus

       J is the second moment of area of the section

For a rectangular section $J = \frac{BH^3}{12}$

Where

B is the breadth of the lever

H is the depth of the lever

For a circular section $J = \dfrac{\pi r^4}{4}$

These formulae relating to simple beams pivoted at one end relate to components such as roller arms and square arms.
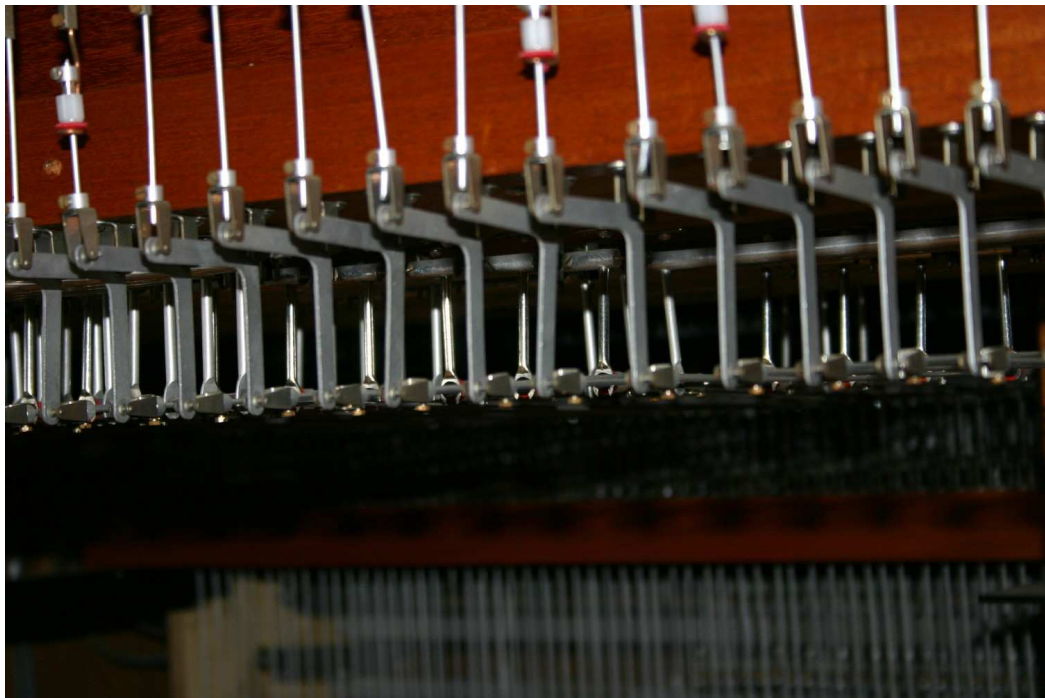
Fig 4.15 Metal Squares, Radley College
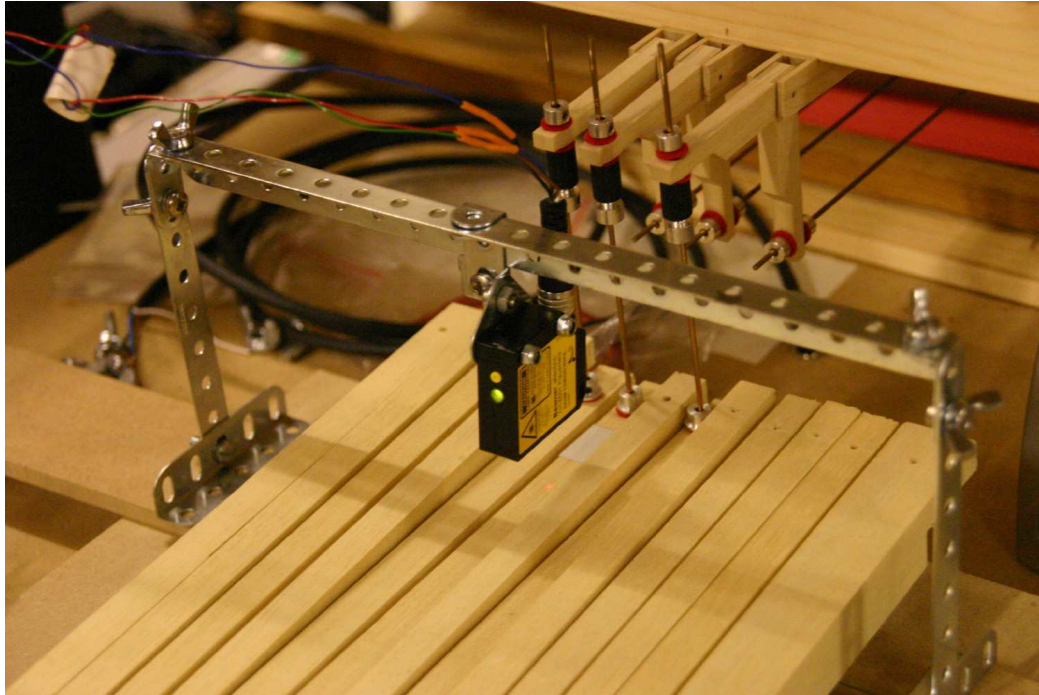
Fig 4.16 Wooden squares with phenolic bushings in the model organ, University of Edinburgh.

Key levers, whether suspended or balanced, are supported at the back and part way along, with a force applied at the key head. A suspended key lever with the tracker attached half way along will bend exactly the same amount as the same lever balanced in the middle and pivoted at the back.

For a suspended key lever, the deflection at the end of the key head is given by[10]:

$$d = \frac{Wc^2}{3EJ}(c+l) \tag{32}$$

where

W is the load at the end of the key lever

E is the Modulus of Elasticity

J is the Second Moment of Area

---

[10] www.Engineersedge.com

c is the distance from the key end to the tracker

l is the distance from the tracker to the pivot

The actual movement of the key takes the form shown in Fig 4.17. It should be noted that the key arcs upwards from the tracker to the pivot.
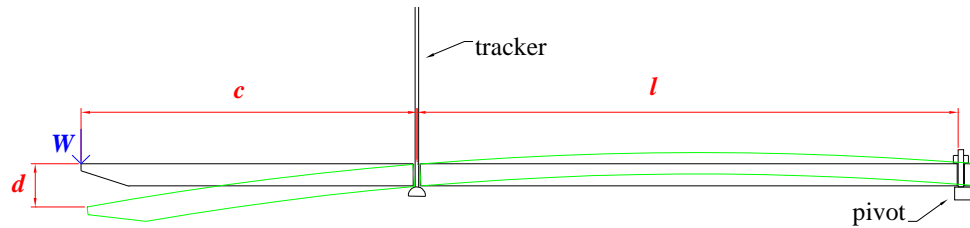
Fig 4.17 Diagram showing how a key lever bends. The rest position of the lever is outlined in black. When a force W is applied to the key end the key lever bends in the form shown by the green outline until the tracker starts moving. l is the distance from the pivot to the tracker, c is the distance from the tracker to the key head, d is the distance by which the key head deflects.

Assuming that the key lever is a uniform oblong cross section, $J = \dfrac{BH^3}{12}$

Where B is the width

H is the height

For wood, E is approximately 10 GN/m².

Assuming a key lever of uniform cross section 1 cm wide by 2 cm high and 1 m long with the tracker attached 0.4 m from the key head i.e. $B = 0.01$ m, $H = 0.02$ m, $c = 0.4$ m and $l = 0.6$ m, if a force W equal to a weight of 200 g applied at the end of the key is necessary to start the tracker moving, the key head will move by a distance $d = 1.57$ mm due to the key lever bending before the tracker starts moving.

4.7 Rollers

4.7.1 Introduction

In a large mechanical action pipe organ, the action from the key to the pallet under the pipes can be long and complicated. The windchests are invariably wider than the keyboard and the pipes are rarely arranged chromatically. The movement of the key has, therefore, to be transmitted sideways.

This is traditionally achieved using a roller. This is a rod or tube, most commonly of steel, aluminium or wood, pivoted about its axis and with an arm at both ends to which the rest of the action is attached. Wooden rollers are frequently of oblong cross section with the long sides curved. This is supposedly to allow for clearance between adjacent rollers because wooden rollers are of greater cross-sectional area. All three materials are in current use and available from the main organ component suppliers in various cross sections.
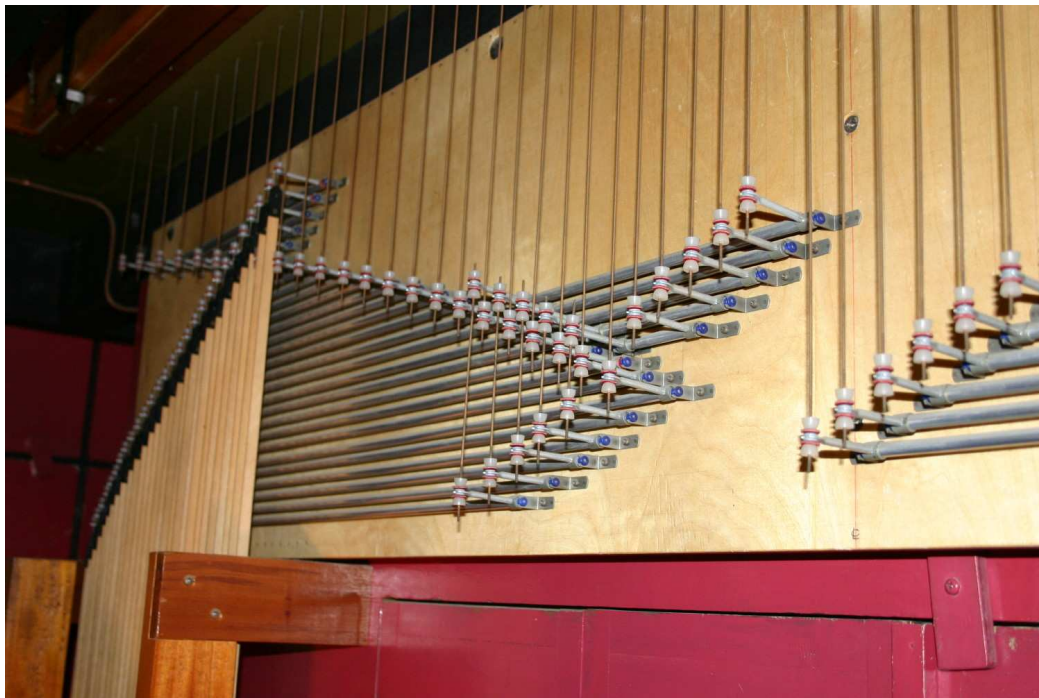
Fig 4.18 Roller board with aluminium rollers, New College Oxford

Audsley states, "in old work (rollers) were invariably made of wood; but in modern organ building they are usually made of iron".[11] He states the advantages as being "they occupy much less space, they do not warp or twist, they have no tendency to spring in action, they are not affected by damp or drought, and they have a much neater appearance". He expresses the view that aluminium arms would be much better than iron ones, but does not consider whether aluminium would be a better material for the rollers themselves. There are no calculations or specific justifications for these statements.
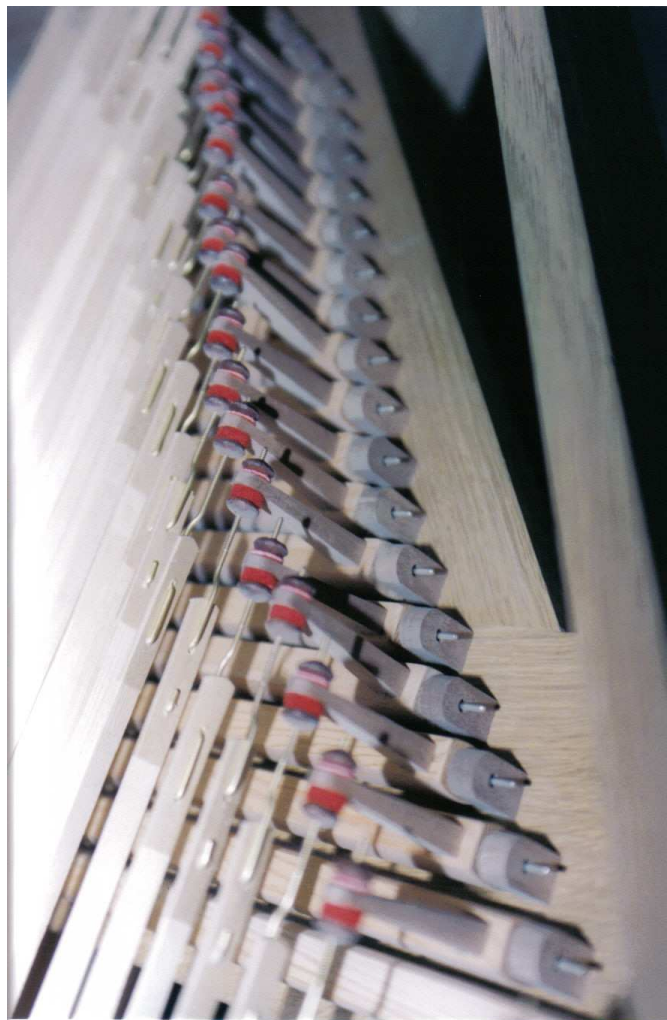
Fig 4.19 Wooden rollers and arms. Bridgewater Hall, Manchester

[11][Audsley 1905] page 178

The three primary factors in choosing a material for rollers are:

EDM

Resistance to twisting under load. Any twisting of the roller will result in the action feeling "spongy" i.e. the key will move without the pallet moving. When the stored energy is finally released when the force on the pallet is sufficient to overcome the pluck, the pallet will spring open in order to catch up with the key.

Friction – this is discussed briefly in section 4.8

4.7.2 EDM (Inertia) of rollers

The EDM of a roller can be calculated by equating its rotational inertia with that of the equivalent mass at the end of the roller arm on the basis that the energy put into the two systems is the same.

The kinetic energy of rotation of a tubular object is given by:

$$KE = \tfrac{1}{2}I\omega^2 \tag{33}$$

Where I is the moment of inertia of the roller

ω is the angular velocity

The kinetic energy of a mass moving in a straight line is given by:

$$KE = \tfrac{1}{2}m_2v^2 \tag{34}$$

Where m_2 is the mass of the object

v is its velocity

Equating the two:

$$\tfrac{1}{2} I \omega^2 = \tfrac{1}{2} m_2 v^2 \tag{35}$$

For a tube pivoted on its axis:

$$I = \tfrac{1}{2} m_1 \left(r_1^2 + r_2^2 \right) \tag{36}$$

Where m_1 is the mass of the roller

$\qquad$ r_1 is the outside radius of the tube

$\qquad$ r_2 is the inside radius of the tube

In the case of a solid rod, r_2 becomes zero.

Equation (35) can be rewritten:

$$\tfrac{1}{2} \cdot \tfrac{1}{2} m_1 \left(r_1^2 + r_2^2 \right) \omega^2 = \tfrac{1}{2} m_2 v^2 \tag{37}$$

At a distance, x, from the axis

$$v = x\omega \tag{38}$$

and equation (37) becomes:

$$\tfrac{1}{2} \cdot \tfrac{1}{2} m_1 \left(r_1^2 + r_2^2 \right) \omega^2 = \tfrac{1}{2} m_2 \left(x\omega \right)^2 \tag{39}$$

In order to calculate m_2, equation (39) can be simplified and rearranged:

$$m_2 = \frac{m_1 \tfrac{1}{2} \left(r_1^2 + r_2^2 \right)}{x} \tag{40}$$

x is the length from the centre of the roller to the position on the arm where it is attached to the tracker.

In order to calculate typical values, it is necessary to calculate the mass of various configurations of rollers.

The densities of the three common materials are:

Steel   9.0 g/cm³

Aluminium   2.7 g/cm³

Oak   ~0.7 g/cm³

A circular tube will have a mass of:

$$m_1 = \pi(r_1{}^2 - r_2{}^2)ld$$

where r_1 is the outer radius of the rod

r_2 is the inner radius of the tube

l is the length of the rod

d is the density of the rod

For a solid rod, r_2 is zero

Therefore for an aluminium rod 10 mm diameter and one metre long:

$$m_1 = \pi \times \left(0.005^2\right) \times 1 \times \left(2.7 \times 10^3\right)$$

$$= 0.212 \text{ kg}$$

$$= 212 \text{ g}$$

Assuming that the roller arms have a typical length of 5 cm (x in equation (19), substituting in equation (19)

$$m_2 = \frac{0.5 \times 0.212 \times 0.005^2}{0.05^2}$$

$$= 0.00106 \text{ kg}$$

$$= 1.06 \text{ g}$$

This is for a one-metre length, and can be multiplied by the actual length to give the inertia for a particular roller.

The results for other diameters and materials are tabulated below, in Table 4.1.

Mass and EDM per metre for various forms of roller			
Material	Cross section	Mass	EDM
	mmø (out x in)	g	g
Aluminium rod	10	212	1.06
Aluminium tube	10x6	138	0.923
Aluminium tube	8x6	59.4	0.297
Steel rod	8	396	1.27
Steel rod	7.4	338	0.948
Steel tube	8x6	174	0.866
Wood	20	220	4.40
Wood	24	322	9.35

Table 4.1 Mass and EDM for various configurations of roller

A wooden roller of 20 mm diameter has approximately the same mass as an aluminium rod of 10 mm diameter but its inertia is four times as great because there is more mass further from the axis. Similarly, the inertia of a 10x6 aluminium tube is 87% of that of a solid 10 mm rod, but the mass is reduced to 65%. Because the inertia is a function of the square of the distance from the axis, denser materials have a lower rotational inertia for a given mass.

4.7.3 Twisting

The second important factor is the amount by which rollers twist when a force is applied to one end by the tracker attached to the key. There will be a resistance at the other end due, amongst other things, to the pluck (the net force on the pallet due to the higher pressure air inside the windchest, which reduces when the pallet starts to open and the pressures start to equalise) and the force exerted by the pallet spring.

The angle of twist is given by:

$$\theta = \frac{\tau L}{JG}$$

(41)

where　θ is the angle of twist

　　　　τ is the applied torque

　　　　L is the length of the roller

　　　　J is the second moment of area of the roller

　　　　G is the rigidity or shear modulus of the material

Assume that the pluck is 120 g (quite high, but the choice of material only becomes critical when approaching the limit), the pallet spring exerts a force of 80 g and that the roller arms are 5 cm long. The torque being applied to the roller at the point at which pluck is overcome is:

$$\tau = 0.2 \times 9.81 \times 0.05$$

(42)

$$= 0.0982 \ Nm$$

The polar second moment of area of a tube about its axis is given by:

$$J = \tfrac{1}{2}\pi\left(r_1^{\,4} - r_2^{\,4}\right) \tag{43}$$

where r_1 is the outside radius

r_2 is the inside radius

The modulus of rigidities, G, of the various materials are:

Steel   80 GPa

Aluminium   25 GPa

Oak   0.7 GPa

For the same solid aluminium rod 10 mm diameter and one metre long, substituting in equation (21):

$$\theta = \frac{0.0982 \times 1}{25 \times 10^{9} \times 0.5\pi \times 0.005^{4}}$$

$$= 4.00 \times 10^{-3} \text{ radians}$$

At the end of a 5 cm long roller arm this is equivalent to a movement of 0.20 mm before the pallet starts opening. Again, a two metre long roller would introduce a movement of 0.40 mm, a five metre roller would twist 1.00 mm, etc.

Table 4.2 tabulates the movement at the end of a 5 cm roller arm with the inertia figures from Table 4.1 and also adds some extra configurations that have the same degree of twist as a solid 10 mm diameter aluminium rod. All tubes are assumed to have a bore of 6 mm, as this is a commercial standard. A greater bore would be advantageous so long as the material does not deform. The inertia is multiplied by the twist in the last column and it should be noted well that the degree of twist is directly inversely proportional to the inertia. In other words for a given material, any

configuration of tube exhibiting a particular degree of rigidity will also exhibit the same inertia. The actual mass of the roller will vary significantly.

It should also be noted that the most efficient material, based solely on these criteria and by a small margin, is steel tube.

Mass, EDM and twist per metre for various forms of roller					
Material	Cross section	Mass	EDM	Twist (50mm arm)	Inertia x twist
	mmø	g	g	mm	g.mm
Al rod	10	212	1.06	0.200	0.212
Al tube	10x6	138	0.923	0.230	0.212
Al tube	8x6	59.4	0.297	0.713	0.212
Al tube	10.3095x6	149	1.06	0.200	0.212
Steel rod	8	396	1.27	0.151	0.193
Steel rod	7.48	338	0.965	0.200	0.193
Steel tube	8x6	174	0.866	0.223	0.193
Steel tube	8.15x6	188	0.965	0.200	0.193
Wood	20	220	4.40	0.447	1.962
Wood	24.44	328	9.81	0.200	1.962

Table 4.2 Comparison of mass, EDM and twist per unit length for various configurations of roller.

The various configurations with the same rigidity as 10 mm diameter aluminium rod are summarised in Table 4.3.

Mass, EDM per metre for various forms of roller for constant twist					
Material	Cross section	Mass	EDM	Twist (50mm arm)	EDM x twist
	mmø	g	g	mm	g.mm
Al rod	10	212	1.06	0.200	0.212
Al tube	10.3095x6	149	1.06	0.200	0.212
Steel rod	7.48	338	0.965	0.200	0.193
Steel tube	8.15x6	188	0.965	0.200	0.193
Wood	24.44	328	9.81	0.200	1.962

Table 4.3 Configurations of roller exhibiting the same degree of twisting under the same load.

From this it can be seen that wood has little to recommend it. It has roughly the same mass as a steel rod and, assuming the same bearing, will have the same friction, but has ten times the inertia and three and a quarter times the diameter. A steel tube of the same rigidity has one third of the diameter and has 0.57 of the mass of wood and will thus have 0.57 of the friction. Don Bedos[12] illustrates wooden roller boards with alternate roller arms of different lengths so that the rollers can overlap because of the space that they occupy.

The twisting of rollers is further complicated if they sag in the middle due to gravity. Long rollers are either supported in the middle or split into two separate sections otherwise they twist more than unsupported ones. The Laukhuff[13] catalogue states that tubular aluminium rollers of 10 mm outside and 6 mm inside diameter should not exceed 110 cm unsupported.

4.8 Friction

The remaining critical factor in all components is the effect of friction on the bearing surfaces.

Static friction is the resistance to starting an object sliding over another object and kinetic friction is the resistance to it continuing moving once it has started. The latter is always less than the former.

Bushed bearings will be considered later because their effects are difficult to calculate.

Assuming that the roller bearing is a smooth pin running in a smooth hole larger than the pin, the static friction measured at the bearing is equal to the weight of the roller

---

[12] [Don Bedos 1766]
[13] [Laukhuff 2000]

multiplied by the static coefficient of friction. The frictional force is independent of the area of the bearing surface (another important factor to bear in mind). Since the roller and arm are a simple lever, the force applied to the end of the roller arm in order to overcome static friction is inversely proportional to the distance from the axis of the end of the roller arm to the distance from the axis of the bearing surface since the torques (force times distance) must be equal and opposite.

Two sample commercial bearing pins are 1.65 mm and 3.00 mm in diameter (0.825 mm and 1.50 mm radius respectively). Assuming a 5 cm roller arm, the force required to overcome friction is reduced by a factor of 60.6 (50/0.825) in the first case and a factor of 33.3 (50/1.50) in the second. The larger diameter pin increases friction in the action due to the roller bearings by 75% (but reduces the risk of damage due to the fragility of the pin).

The material that the pins rotate in is critical to the amount of friction, and varies greatly. The coefficient of static friction between steel and steel is around 0.74, reducing to around 0.2 if lubricated. Between steel and Teflon it is 0.04. Ball bearings have a coefficient of rolling friction of around 0.002 because the metal surfaces do not slide against each other (this is why railways are so efficient). The coefficient of kinetic friction of steel on steel reduces to around 0.57. There will thus be a greater force required to start the roller turning than to keep it moving (by about 30%) which will be in addition to the pluck caused by the pallet opening (but may not occur simultaneously with it). The kinetic friction will provide a constant opposition to the movement of the key. When the key is released, the frictional forces will work in the opposite direction and thus still oppose the motion. This is why the pressure on the key has to be reduced significantly before the key will start moving upwards.

Assuming that phenolic bushings have a similar coefficient of friction to Teflon [Willcock and Booser 1957], then the additional friction due to the extra mass of steel tube rollers over aluminium ones is around 0.026 gram against a reduction in inertia of 0.095 gram – a net advantage of about 0.07 gram for a one metre length.

The friction due to cloth bushings is very difficult to calculate because of the fibrous nature of the material and because, in the case of a circular bush, the fibres apply a force to the pin. Empirical tests on cloth bushings suggest that the friction is relatively high. Some new cloth bushed squares will not move under their own weight. It is not clear what effect on friction and looseness will occur over time. Further work remains to be done on friction.

A simple test using two squares, identical apart from one having a cloth bushing and one having a phenolic bushing (Fig 4.20), showed that the end of one of the horizontal arms of a phenolic bushed square exerted a static weight of 1.2 g and the additional force required to start it moving vertically was unmeasurable (i.e. less than 0.1 g) whereas the cloth bushed one exerted no static weight and required a force of 3.0 g to start it moving vertically. The difference of 1.8 g is due to friction and is directly translated into action "weight". A metal square with needle bearings (Fig 4.22) exerted a static force of 0.6 g and required a force of 1.3 g to start it moving. This is significant particularly when several such bearings are present. This experiment did not allow a differentiation between static and dynamic friction. The cloth bushing is likely to compress over time and thus reduce friction but this may be at the expense of allowing excess slackness. An arm from a wooden square is shown resting on a digital balance in Fig 4.23. The square is moved downwards in order to measure the additional force required to overcome friction.

Fig 4.20 Wooden squares. The one on the left has a cloth bushing and the one on the right a phenolic bushing.
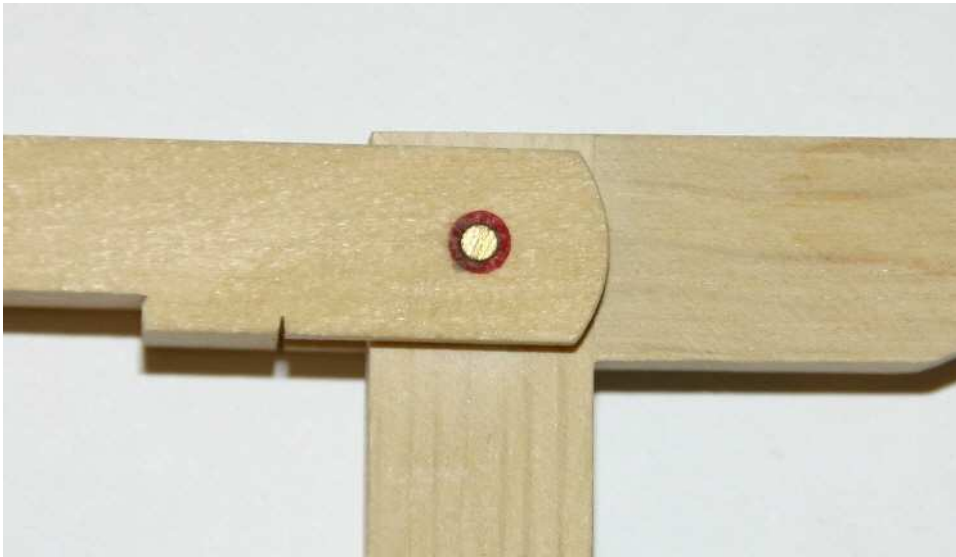
Fig 4.21 Close up of the cloth bushed pivot of the wooden square shown in Fig 4.20

Fig 4.22 Aluminium square (Laukhuff) with needle bearing.

Fig 4.23 Measuring the force required to start a square arm moving.

The lowest friction would be obtained by using ball bearings but they require very precise alignment. The small angle through which rollers and squares move might allow a more innovative form of pivot with surfaces not moving against each other.

4.9 Movements not accounted for elsewhere

It has so far been assumed that the motion of trackers and other similar components move in a straight line. Fig 4.24 shows the movement of a square, the black outline is the rest position and the blue outline is the position that gives a tracker attached to it a vertical displacement of 10 mm. It can be seen that the tracker will also moves sideways by approximately 0.6 mm. This adds 6% to the EDM of the tracker, which is unlikely to be significant but should not be forgotten. In practise, as shown in Fig 2.7, the horizontal movement is minimised by suitable geometry of the components.
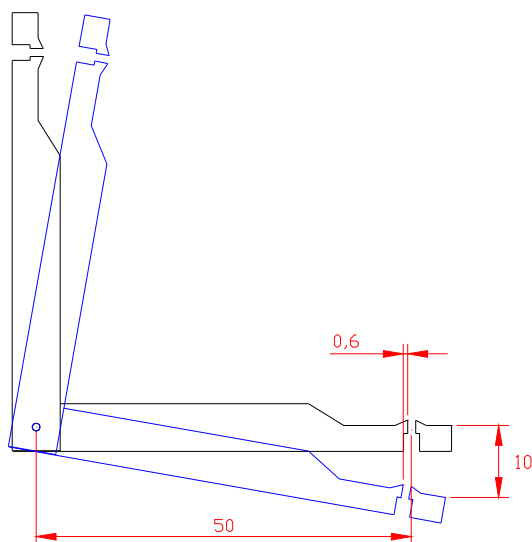
Fig 4.24 Diagram of the movement of a square showing that there is also a sideways movement of the attached tracker

Pallet pull down seals (Fig 6.1.10, the brass cylinder at the base of the tracker inside the pallet box) move sideways if the tracker attached to the pallet moves sideways as the pallet hinges downward. A tracker attached 20 cm from the hinge of a pallet will move 0.25 mm sideways if the pallet drops is 1 cm. The cloth-bushed brass seals used in the model organ have a mass of 8.5 g and if the key drop is also 1 cm, their movement will therefore contribute an EDM of about 0.21 g to the action, although this movement, as in the model organ described in Chapter 6, may be absorbed by flexibility in the linkages.

Chapter 5

Experimental Apparatus

5.1 Introduction

As a project of this sort had not been undertaken before, it was necessary to develop a reliable, accurate and portable means of acquiring data from actual organs on site. Much of the development work was done on the laboratory model described in Chapter 6, but experience of taking measurements in the confines of cramped organs led to considerable refinement.

5.2 Choice of distance sensor

In order to measure the movement of the various components, it was necessary to find measuring devices with the following characteristics:

- Small enough to be positioned over keyboards and within pallet boxes without impeding the movement of the player, the movement of the component being measured or other components.

- No risk of damage to the organ.

- An operating range of not less than 10mm, as this was the maximum movement expected to be encountered. Since measurements were generally taken from key levers and pallets, it was usually possible to position the sensor so that it operated within this range.

- Response time of around 0.001 second. The time of travel of a key and pallet post-pluck was around 20 to 30 ms and this response time was necessary in order to provide a reasonable resolution of these movements.

- Repeatable response. It would not be practical to calibrate the sensors on-site and it was essential that measurements could be compared without adjustment.

- No hysteresis. Measurements of the return of the key and pallet were required.

- Linear output. Because of the large quantity of data collected it would have been impractical to correct all the data points and it was therefore necessary that the output be sufficiently close to linear over the range being used as to provide an acceptable degree of accuracy without correction. It also meant that distance sensors merely had to be operating within their range and did not have to be positioned with great accuracy which would have been difficult inside some of the spaces available.

- Output independent of supply voltage. Whilst accurate power supplies were built for all the measuring devices, for maximum reliability devices tolerant of a range of voltages were to be preferred.

- Not affected by reflectivity of surface being measured. The components encountered would be made out of a variety of materials in various conditions and not necessarily smooth. Attaching reflective strips to keys was not a great problem but it would have been difficult and unreliable to do so to the bottom of pallets.

- Simple interface using existing data acquisition hardware and minimal additional electronics in order to reduce cost and take advantage of existing knowledge.

- Cheap. The devices themselves must be cheap as the budget for further purchase was small.

5.3 Options available for distance sensors

The technologies that appeared to be available for distance sensors were:

Ultrasonic
Mechanical
LED based
Laser

Ultrasonic sensors, similar to the devices that surveyors use to measure room sizes, were large and had poor response times and poor resolution.

Mechanical devices, which typically involved an extending wire wrapped round a drum, were large and had poor repetition rates. They would have been very difficult to install and would have needed rigid attachment to the object being measured.

At the time of starting the project there were no laser sensors that had the required range and were sufficiently small. They were, in any case, expensive.

5.3.1 LED/Phototransistor sensors

The first devices looked at were some LED/phototransistor sensors that had already been used in the Department by Dr Maarten van Walstijn. This is the OPB704, which is an industry standard sensor primarily intended as an optical switch rather than for distance measurement, however, its output does vary over a limited range. A review of devices available on the market did not suggest that there was anything more suitable. It comprises an infrared LED and a phototransistor matched in spectral sensitivity and mounted at an angle to each other in a plastic housing such that their axes meet 5 mm in front of the face of the case. It is illustrated in Fig 5.1 and the data sheet is reproduced in Appendix 6. Initial tests showed that its output was repeatable and that its response time was well within the range required. The OPB704 only required two resistors to give a voltage output to the data acquisition (daq) box. Their useful operating distance was however too narrow at approximately 4 to 8 mm. They cost about £7 each and so some could be sacrificed in order to see if their operating range could be varied.

The obvious way to increase the useful operating range was by using a lens over the face of the sensor. Tests with a circular glass lens showed that a lens of +2 dioptres would extend the operating range to that required. A search for a readily available lens of the required focal length and size resulted in tests with viewfinder elements from disposable cameras. Some of these were very close to the size of the end of the sensor and of a suitable focal length. However, tests showed that they were opaque to infrared light and therefore of no use. No other suitable options were found.

Disassembling an OPB704 showed that it contained a discrete LED and photodiode mounted in such a way that indicated that it might be possible to decrease the angle between them and thus increase the focus distance and thus the useful operating range.
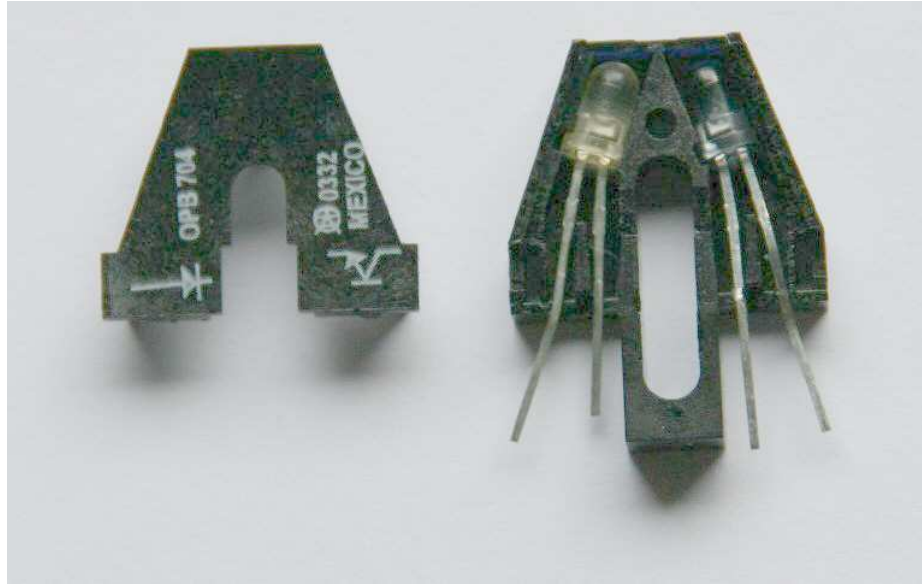
Fig 5.1 OPB704 LED distance sensor with its cover removed.

After some trials, it was found that carefully cutting down the centre of the device from the mounting end to the operating end with a band saw, stopping just short of the face, meant that the back part could be squeezed together and stuck with epoxy resin whilst maintaining the light baffle between the LED and phototransistor. An example of the various stages is shown in Fig 5.2. This method was, however, not very precise and no two resulting devices had exactly the same response characteristics. There was no practical way of making them exactly the same and so individual calibration curves were made for each device using a digital calliper and bench digital voltmeter.
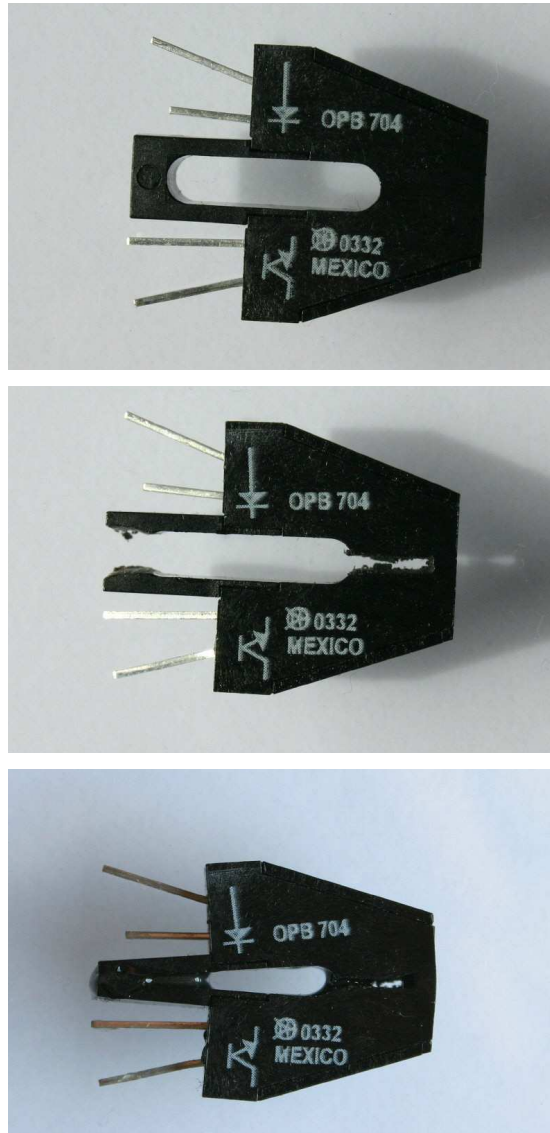
Fig 5.2 The three stages in extending the operating range of an OPB704

The device was very sensitive to the reflectiveness of the surface being measured and a range of commercially available reflective surfaces was investigated. These tended to be either too directional to align accurately or not reflective enough to operate within the required range. Reflective tape sold for attaching to cars and bicycles showed the most promise, but reflections from the smooth surface swamped the phototransistor. After some experimentation it was found that sticking a layer of matt "magic" tape on the surface did not significantly reduce the effect of the reflective beads but eliminated the surface reflections. Tests showed that the resulting

reflective strip was consistent across several batches and was therefore adopted as the standard reflective surface. For use on actual instruments, this combination was further stuck to low tack masking tape in order to ensure that it could be removed easily without any risk of leaving a mark on any of the surfaces likely to be encountered. There also had to be no risk of the reflective strips doing any damage if they did fall between the keys.

The electronics simply comprised two variable resistors for each sensor and a box containing eight channels was assembled. Two-channel 3.5mm jack connectors were adopted as the standard means of connecting the sensors to the box because of cost considerations and the ease with which they could be extended. Two core screened audio cable was used for the connection (RS Components ref 337-224). RCA connectors were used to connect with the data acquisition (Daq) box using ready-made audio cables because they were cheap and worked satisfactorily. RCA to BNC adapters were used on the Daq box.

The operating voltage range is quoted as 4.5 to 16 V and 10 volts was adopted as the standard in order that the output remained within the 10 V maximum input capacity of the Wavebook. The output is voltage dependent and initially the voltage source was supplied by a bench power supply (HQ Power PS1503SB) that had been calibrated against a digital multimeter (Racal Dana 4008). The bench supply was consistently accurate to within the final digit of its display (0.01 V). This arrangement was used for the first few site visits but the power supply was too bulky for easy transportation and a stabilised power supply was constructed to convert the output of a standard plug top unstabilised 18 volt power supply into stabilised outputs of 5, 10 and 15 volts to suit the various devices being used. This used standard LM317T voltage stabiliser ICs in the basic configuration shown in the data sheet. Resistors with 0.1% tolerance were used to ensure accuracy and stability. The output from this became unacceptably noisy when using the LED sensors later in the project and the bench power supply was reverted to.

One problem found with these sensors is that they are susceptible to interference from mains lights and other, not always obvious, sources. Although a problem in dark buildings, it was necessary to switch off all adjacent mains lights if at all possible.

The calibration curve of a typical sensor is shown in Fig 5.3.

LED Sensor 7
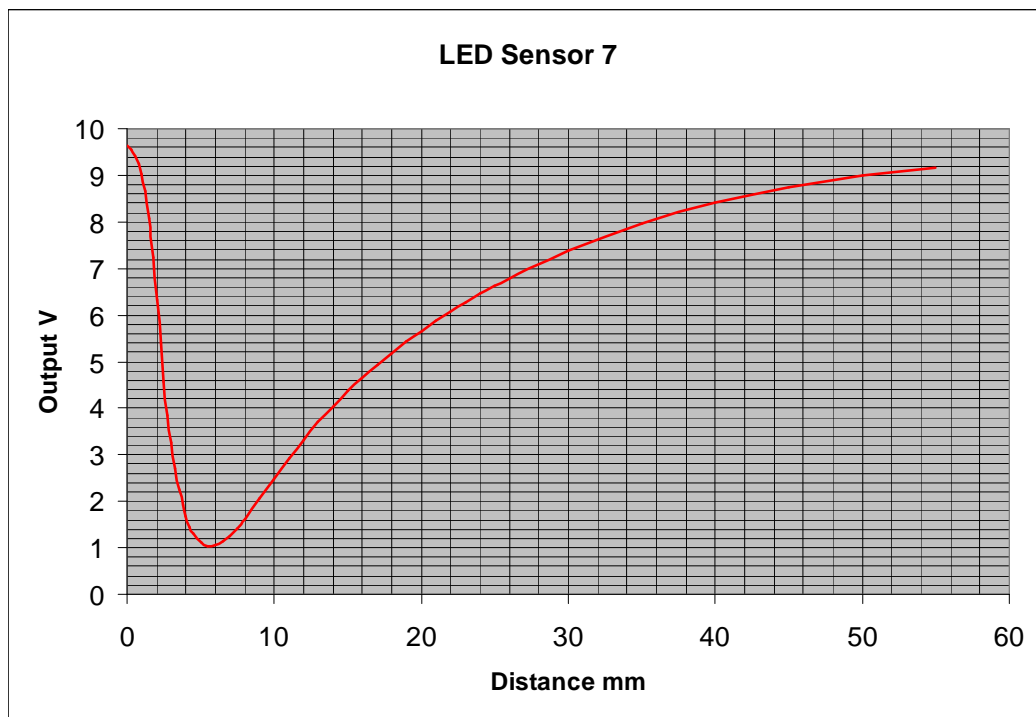
Fig 5.3 Calibration curve for a typical OPB 704 LED distance sensor.

A typical key head movement is 8 – 9 mm and with the sensor mounted towards the back of the key head with a movement of around 6 mm the output is sufficiently close to a straight line to produce acceptable comparative distance measurements without any correction. Making such corrections would have been impractical because of the number of data points collected.

Fig 5.4 shows the part of the curve covering a distance of 8 to 18 mm and the majority of measurements were kept within this range.
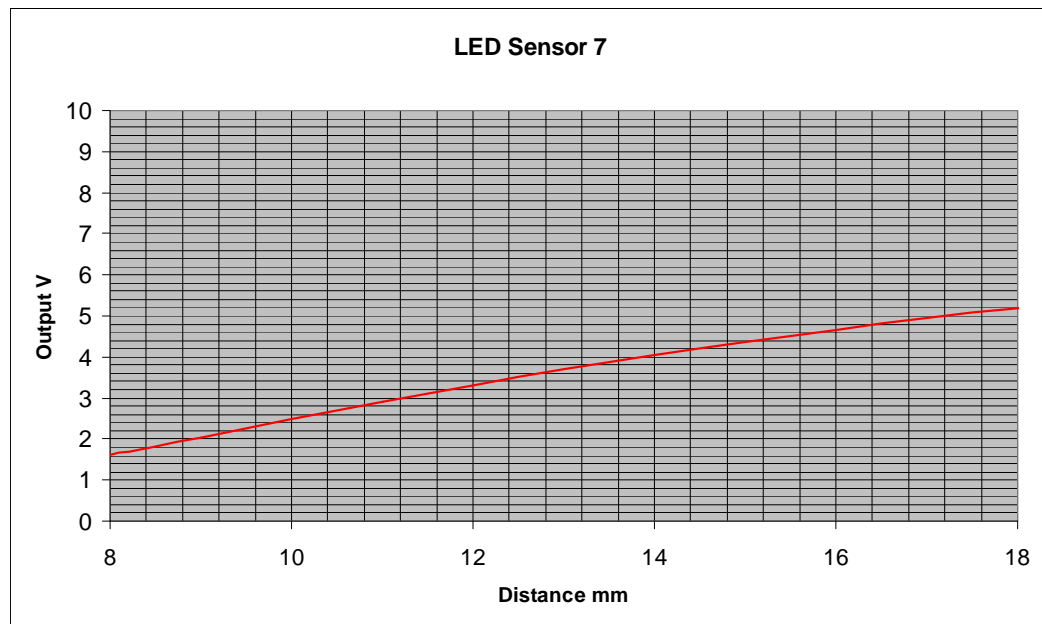
Fig 5.4 Calibration curve of an OPB 704 distance sensor over the range 8 to 18 mm.

The error over a measuring range of 6 mm is approximately ±0.05 mm

5.3.2 Mounting of sensors

At an early stage it was decided that Meccano would be used to mount the sensors because of the wide range of sections readily available and its reasonable degree of rigidity. Various configurations were tried. Initially attempts were made to make the sensors fully adjustable so that they could be individually adjusted so that their output fell in the most linear part of their range. After considering a number of different mountings, including gimbals, one attempt using universal joints fabricated from model car suspension components and modified Meccano strips showed promise and is illustrated in Fig 5.5.
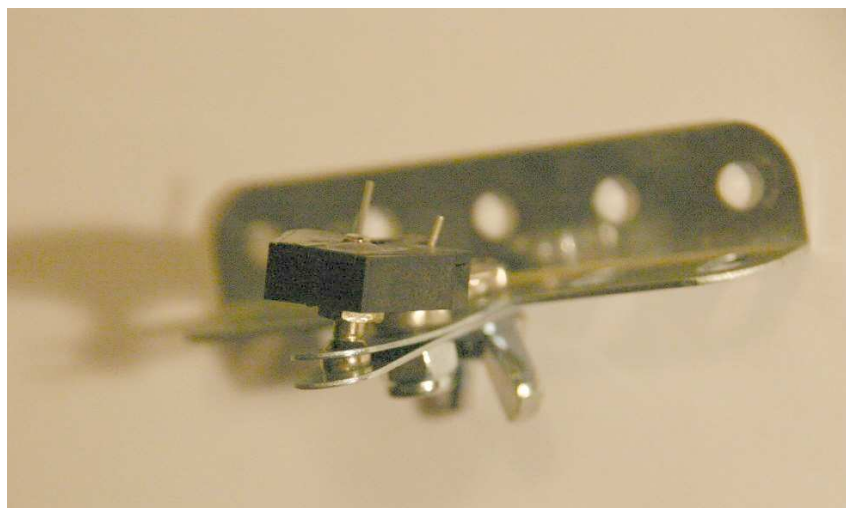
Fig 5.5 Early attempt at making adjustable mounting of sensor using ball joint from a model
car suspension and a modified Meccano strip.

They were, however, too bulky to position over adjacent keys and impeded the
player too much. They were also too difficult to set up on site because of flexibility
in the long strip over the keys and movement due to the player knocking them whilst
playing. It was, therefore, decided that it was preferable to accept the higher error
due to the different characteristics of the sensors so long as they were operating close
to their most linear range, and to use a much simpler but more rigid mounting.
Height adjustment was made by one of two means depending on the space available
on site. Simple mountings utilising the elongated holes in standard Meccano
components were used space as was at a premium. A further set of mountings was
also used where space was available and these are shown in Fig 5.6. Nylon bushed
nuts were used so that the legs could be adjusted without tools but would also remain
in place when set.
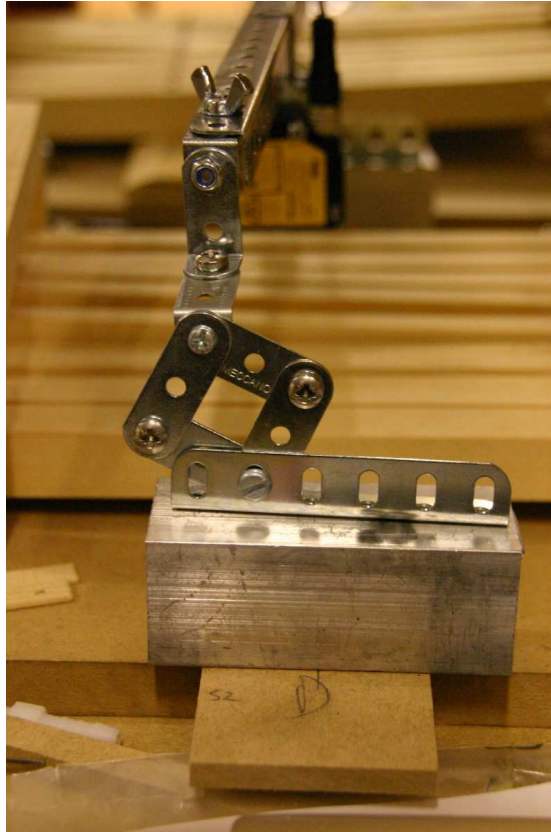
Fig 5.6 Pantograph adjustment for sensor mounting strip.

The first modified sensors were bolted to their mountings through what remained of the original mounting slot. This may have changed the angle between the LED and phototransistor and, in any case, after a while the whole assembly had a tendency to disintegrate. In the final version, a flat face of the plastic housing was epoxied to the metal strip as can be seen in several of the illustrations. This had the advantages of simplicity and rigidity.

Initially the sensor assemblies were simply bolted to a long strip in the correct positions for a particular set of keys on one keyboard. It quickly became apparent that it would be necessary at least to be able to slide the sensors along the strip to align them with any (natural) keys on any keyboard. The final arrangement is illustrated in Fig 5.7 and has proved to minimise (but not eliminate) the risk of the player knocking them during playing whilst being able to accommodate most keyboards. Some organ builders such as Willis make a point of building ornate key

cheeks that make mounting the sensor frame difficult. Music desks frequently overhang the top manual making measurement on those manuals difficult or impossible. A typical installation is shown in Fig 5.7 with the sensor array over the Great keys of the 1857 J W Walker at St Mary's Church, Ipswich. This particular installation allows some access to the accidentals. Particularly where the key cheeks of a higher manual protrude to a greater extent, the sensors have to be placed further forwards and thus impede the player to a greater extent. Attempts to make the sensor mountings completely rigid where also negated by the flexibility of some keyboards – adjacent keys visibly moved when keys were depressed.

Fig 5.7 LED sensors positioned over the Great manual at St Margaret's Church, Ipswich. Reflective strips are attached to the keys in order to give a consistent output.

The LED sensors were only used inside the experimental windchest for early measurements. At that time they were mounted on a simple bracket purpose made for the distance involved.

5.3.3 Laser sensors

Although laser sensors were available from the start of the project, they were either too big or did not have a suitable operating range. Their price of several hundred pounds meant that, unless they met the requirements closely, there was no justification for seeking funds to buy them.

During the course of the project a new range of sensors was introduced by Baumer Electric AG. One of these, the OADM 1216430/S35A, met the requirements closely and the University purchased two of these devices one of which is illustrated in Fig 5.8.

Fig 5.8 OADM 1216430/S35A laser distance sensor by Baumer Electric AG.

The essential characteristics of this device are a range of 10 mm between limits of 16 mm and 26 mm, linear output, relatively small size and straightforward power requirement (voltage independent) and signal connections. The output is 4mA to 20mA, which needed to be converted to the voltage input of the Iotech Wavebook. The author is grateful to the electronics technicians for their advice on modifying the standard published op amp circuits to suit. The circuit is shown in Fig 5.9. Resistors with 0.1% tolerance were used and a value of 402Ω gave a nominal output of 1.608V

to 8.040V , comfortably within the 0-10V range of the Wavebook and also allowing some positioning tolerance on most keys and pallets.
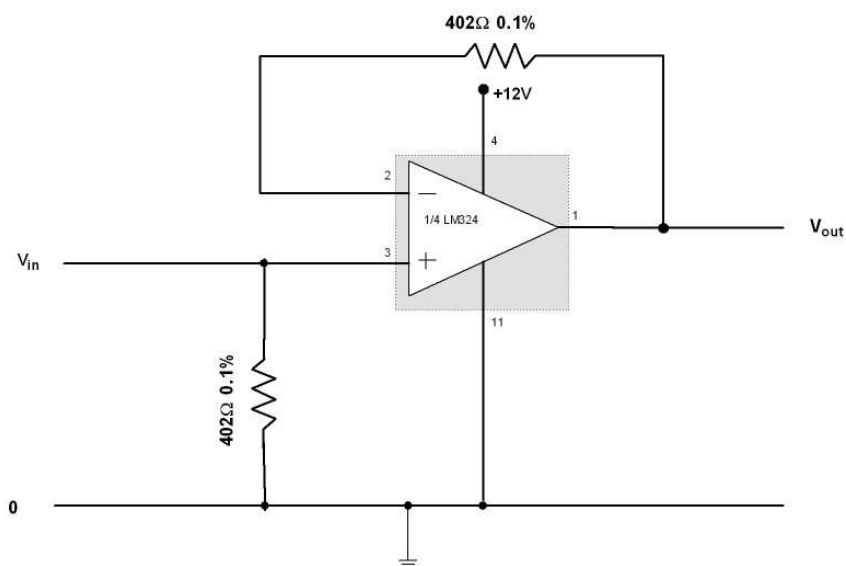

Fig 5.9 Circuit diagram of the current to voltage converter used to condition the output of the laser sensor.

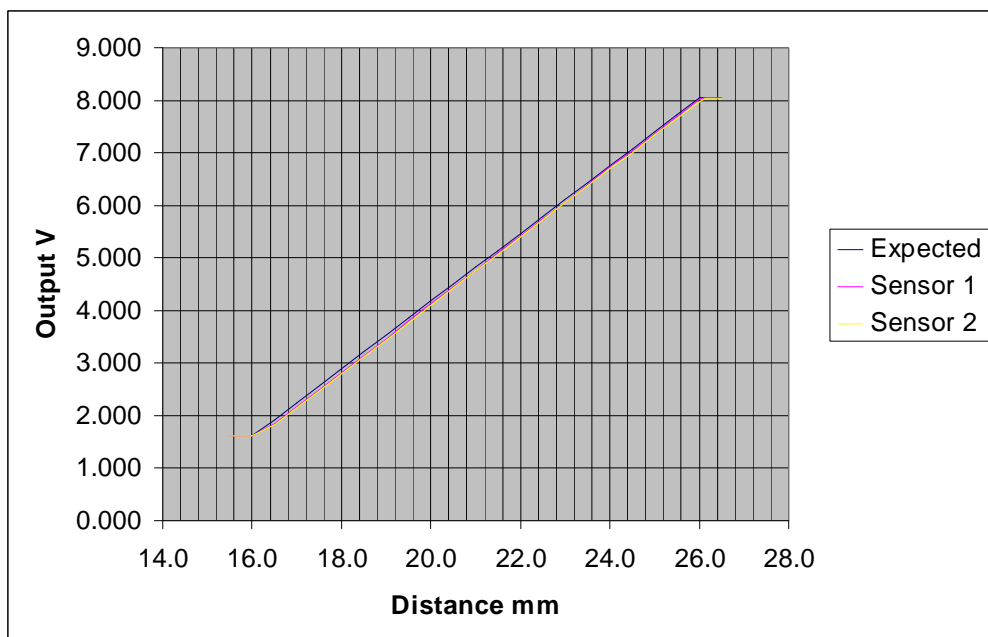The actual calibration curves are shown in Fig 5.10.

Fig 5.10 Calibration curves of the two laser sensors.

The operating voltage was set at 15V because this was the maximum voltage of the pressure sensor used at the same time and thus avoided the need for two power supplies.

The operating range of 16 mm to 26 mm is close to the minimum range that can be used since a key head will typically move through about 8 mm and a pallet end by slightly less. Since the sensor was mounted at the back of the key head, the movement was less and the sensor could generally be mounted in such as way as to remain in range at all times. Only one organ investigated, Epping Upland, presented a problem because the key dip at the front of the key was around 13mm. Careful choice of keys and positioning the sensors as far back as possible meant that the sensors could be kept in range except during key bounce.

The minimum distance from the element being measured proved not to be a great problem – it did prevent measurement on some upper manuals with overhanging music desks. The main problem encountered was that unless the overrun of the pallet was checked, the pallet could easily go out of range. This was not a problem from the point of view of measuring the critical movement of the pallet but in some cases the overrun could be of sufficient magnitude as to hit the sensor and thus dislodge it with the risk that it might then cause damage. This implies an overrun of over 16mm against a working movement of typically around 8mm. This is a serious defect from an organ-building point of view because it increases the risk of connections coming apart, and the time taken for the pallet to return to its design open position means that repetition of notes may be affected. The model organ did not at first incorporate pallet stops (on the grounds of simplicity) but they had to be installed subsequently because of the pallets in the flexible action run hitting the sensors.

For the first tests the cables supplied with the sensors were used but these were too stiff to be safely used within the windchest. The sensors tended to move and it could be very difficult to prevent pallet springs from contacting and thus moving the cable. The cables were in any case too thick to route round the edge of the front board without extensive air leaks although this was more a problem due to the sound of the

air leaking than one of losing air pressure. By replacing the cables with individual thin wires, both of these problems were solved and the front boards could generally be screwed back in place without significant leaks, permanent deformation to the seals or risk of movement. Simple twisted connections were used on the extension cables to the Daq box. This was partly for simplicity of connection on site and also so that the connections came apart readily if the cable became snagged in any way so that the risk of damage due to pulling on the cable was minimised – working so close to delicate mechanisms in such confined spaces was a constant concern. Although every effort was made to route cables to prevent it happening, even a relatively thin cable could do serious damage to a small pipe if pulled tight.

5.4 Software

The software used for the manipulation of data were:

WaveView 7.14.16 (Iotech Inc), the most recent version of this software, was used to record the data from the Iotech Wavebook. The data was collected in ASCII and Wav formats.

Microsoft Excel 2000 was used to process the ASCII data and to produce all of the graphs. Its simplicity of use compensated for any shortcomings in the presentation of the graphs.

Cool Edit Pro 1.2a (Syntrillium Software Corporation) was used to process the Wav files.

Sigview32 1.9.1.0 was used to produce the 3D spectral analysis visualisations from the Wav files.

The two programs used to process the sound recordings use fast fourier transforms (ffts). Ffts have some limitations and there is a compromise between time resolution and frequency resolution. Ffts are calculated over a user-defined number of data

points. The frequency resolution equals the sample rate divided by the fft points. The time to fill the time buffer equals the fft points divided by the sample rate. At relatively low sample rates as used here this can introduce significant distortion particularly as the buffer initially fills up. At a sample rate of 10 kHz, an fft over 512 points will be averaging over just under 1/20 second which is the order of time that is being studied. The maximum frequency recorded is, in any case, equal to half the sample rate.

Chapter 6

Model organ

6.1 Building of model organ

6.1.1 Introduction

In order to carry out controlled experiments and to make further investigation of phenomena encountered on site, a model organ was built in a laboratory at the University of Edinburgh. A general view is shown in Fig 6.1.

6.1.2 Design concept

The intention was that it would allow for the modelling of as wide a variety of conditions as possible with the attendant risk that it would model none of them well. It is a bar and slider chest comprising twelve grooves and five sliders. The pallet openings are individually variable by replacing individual boards, as are the boards with the pallet pull down openings.
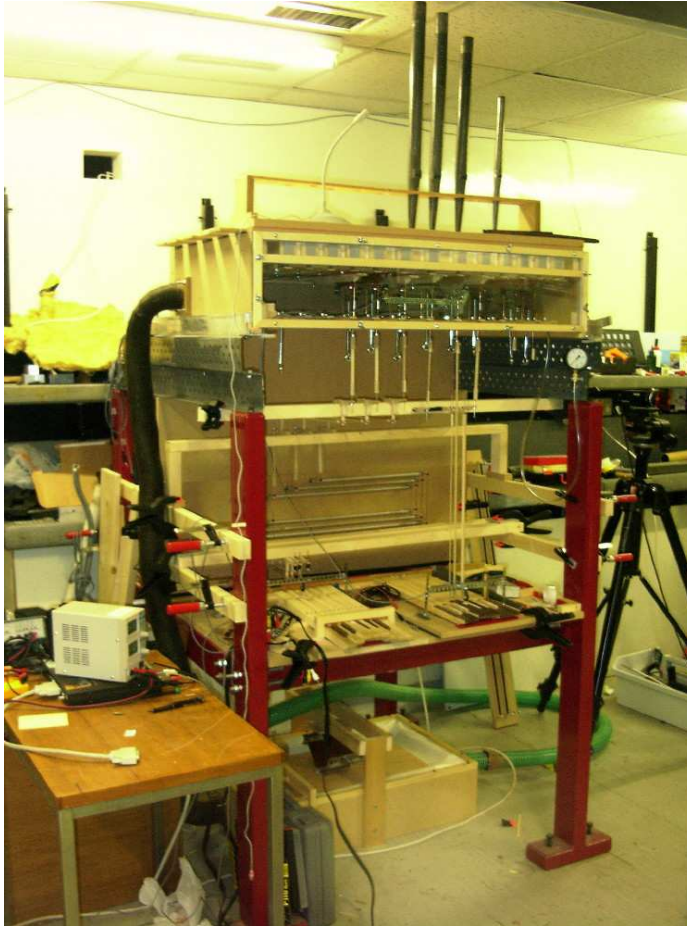
Fig 6.1 The model organ built in the laboratory

The building frame was made from some of the steel supports from a redundant wave tank that fortuitously became available. Their rigidity and size were entirely suitable for the new purpose and the dimensions of the wind chest were determined by the size of the frame. The height of the mounting for the windchest was increased using u-channel steel with angle steel used to rest the windchest itself on. This allowed a working space of 77.5 cm between the key bed and the bottom of the windchest.

18 mm thick MDF (medium density fibreboard) was chosen as the basic material for construction because it is cheap, relatively easy to work, is sufficiently strong and stable for the size involved and its susceptibility to water damage was not a problem in the laboratory. The front of the chest was made from 8 mm thick polystyrene sheet

to allow visual observation of the pallet movements. It has proved to be extremely durable and static (and therefore dust) free. The front is sealed by strips of dense rubber foam stuck round the edge. This has proved very effective but may not be sufficiently durable for a real instrument. The front is attached to the chest using wing nuts and is shown in Fig 6.2

Fig 6.2 Method of mounting front of windchest to model organ

Commercially available slider seals[1] were used. These comprise two parts and are glued around the fixed holes in the boards on either side of the slide. The bottom part comprises an airtight foam ring and a layer of low friction material and the upper part

[1] [Lauhuff 2000]

comprises just a ring of low friction material. Fig 6.3 shows the seals in place with the top board removed and inverted to show the seals. The sliders themselves were made from 6mm MDF, which has the advantage of having a smooth surface to bear against the slider seals.

Fig 6.3 The top of the windchest from the model organ under construction showing the slider seals

There is always some air leakage past pallets and this was traditionally led away from the pipe holes by gouging diagonal channels in the sliders and bottom board. It was frequently still necessary to provide bleed holes in the groove to prevent the pipes from murmuring when a stop was drawn but no note sounding. Laukhuff[2] give a choice of two different types of bleed arrangement in their commercially available windchests. It is probable that bleed holes have been used in order to avoid addressing the underlying problem on many occasions. The bleed holes in the Great

---

[2] [Laukhuff 2000]

chest at New College, Oxford are shown in Fig 6.4. They are drilled into the bottom of the grooves, which extend in front of the windchest, the removable fronts of which can be seen at the bottom of the picture.

Fig 6.4 Bleedholes in the bottom of the windchest, New College, Oxford

Since the aim is simply to prevent audible murmurs, it is probable that the pressure in the groove is still greater than atmospheric and thus there is a constant flow of air to the pipes when the stop is on. This may affect the pipe speech and may well vary from pipe to pipe, but has not been investigated. No bleed holes were incorporated into the model organ, and it was necessary to have a second slider (without pipes) open in order to prevent murmurs. This arrangement was satisfactory since not all stops had pipes in place. It also allowed the open pipe hole to be used for the tubing to the pressure sensor.

From the outset it was considered essential that it was possible to model the widest possible range of variables in the windchest. This included different pallet openings

and pallet sizes. It was arbitrarily decided to vary the groove width through the compass with two grooves of each width in a mirror image around the two widest ones in the centre. These had widths of 12 mm, 14 mm, 16 mm, 20 mm, 32 mm and 38 mm. The grooves had a constant length of 56 cm and height of 4 cm.

In order to allow for as much flexibility as possible, it was decided at an early stage to make the pallet openings on individually replaceable boards. These were initially sealed directly against the blocks separating the grooves, with the edges covered with thin leather, but these proved to leak too much and a further 6 mm MDF board with a routed hole the width of the groove and longer than any expected pallet opening was firmly glued to the bottom of the groove.

A completed replaceable pallet board assembly is shown in Fig 6.5. For ease of replacement, spring mounted pallets were used Fig 6.6. The pallets used are a selection of commercially available[3] pallets and ones made by the author to a similar design. The shape and standard of finish of pallets varies considerably and is unlikely to be a significant factor. Compare the rough finish and simple design of the front of the pallets in Fig 7.8.5 from St Stephens Centre, Edinburgh by Willis in 1880 with the modern pallets in Fig 4.13a. (Peter Collins) and Fig 4.13b (Bishop and Son). A single front guide pin running in a slot in the middle of the front of the pallet was arbitrarily selected – Fig 7.8.5 shows guide pins either side of the pallet. The guide slot of the commercial pallets is bushed with red cloth (organ literature frequently states the colour of the bushing) and those made for the model are not. It was considered satisfactory for the pallet leather to close directly against the MDF board, as this is very smooth. In real organs where the pallet would otherwise close against a planed wooden surface, a facing of a smooth material is used, for example buckram.
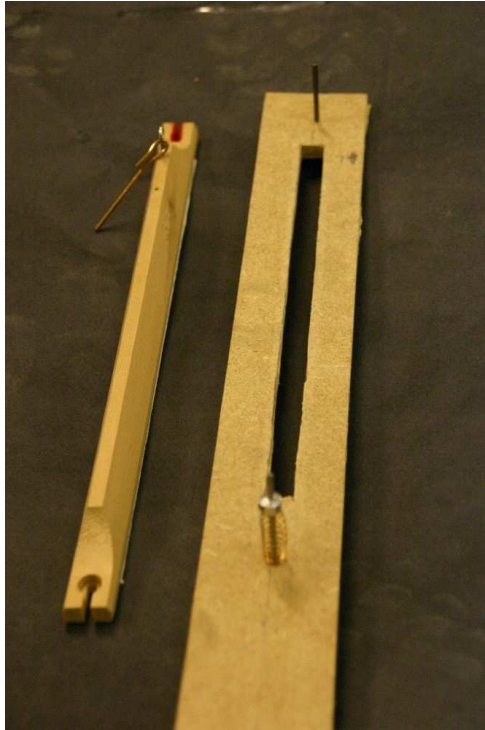
---

[3] Aug. Laukhuff

Fig 6.5 Board with pallet opening cut into it with a pallet laid alongside. The back of the assembly is at the front of the photograph.

Fig 6.6 Detail of pallet hinge. The spring holds the pallet in place and allows easy removal.

The pallet springs are Laukhuff compass springs with 10 cm arms and made out of 1.5 mm diameter wire. The design of compass springs varies in detail but, whether bought in or fabricated (they are readily made on a jig), they do not differ greatly (Fig 6.8). They are commercially available in a variety of sizes and materials and are adjusted by bending to change the angle between the arms.

Fig 6.7 shows John Bailey of Bishop and Son adjusting a spring from the Great organ at Radley College to a mark made using the spring from a carefully regulated note as a template in order to equalise the spring force throughout the compass.

Fig 6.7 A compass spring being adjusted to a mark to indicate the correct tension for the spring. Radley College, Oxfordshire, Great organ

Because it was expected to have to vary the spring tension relatively frequently, the tension of the springs in the model organ was made externally adjustable by locating the bottom of the spring in a shallow hole drilled in the end of a screw eye which was screwed through a hole in the replaceable board in the bottom of the windchest. The spring was prevented from rotating by two pieces of wire let into the same board. This arrangement can be seen in Fig 6.8. A similar arrangement for prevent the springs from rotating over time is used anyway, often by locating the springs in a slot in a strip of wood.
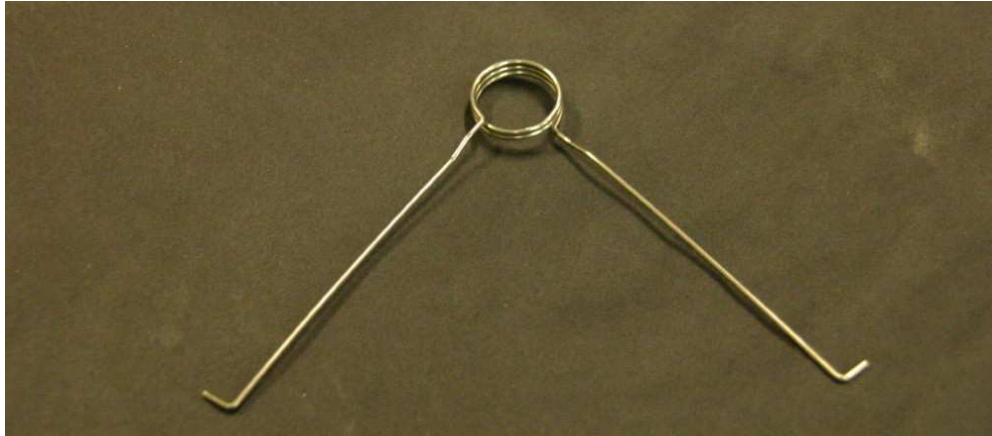
Fig 6.8 A commercially available compass spring (Laukhuff) as used in the model organ. The
arms are 10 cm long and the wire 1.5 mm diameter.

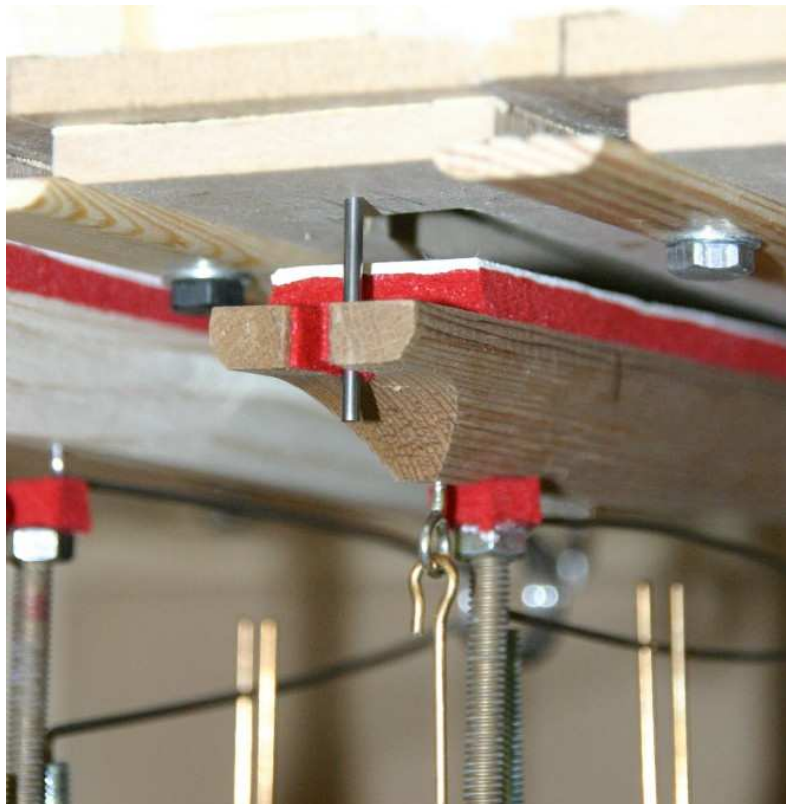An open pallet showing the pallet opening is shown in Fig 6.9.

Fig 6.9 An open pallet from the model organ. The pallet is by Laukuff and the guide slot is
bushed with cloth. It is sealed against the pallet opening by a strip of leather over a layer of
felt. The pallet stops on the end of the threaded rods (for ease of adjustment) can be seen.

Pallet stops were excluded from the initial design for simplicity and to allow maximum visibility of the action. The extreme overrun that this allowed in the "flexible action" meant that they subsequently had to be installed, because the pallets were hitting the sensors. These were also made to be adjustable and can be seen in Fig 6.9.

The pallets were attached to the pallet pull downs with a simple eye screwed into the pallet and a loop in the end of the pull down (Fig 6.9). Other methods are used, including wrapping cloth around the wire in the above arrangement, and using leather punchings as can be seen in Fig 6.10, which is a photograph of part of the model provided by A J & L Taylor Ltd.

Fig 6.10 An alternative means of attaching the tracker to the pallet pull down.

The author has never established the supposed advantage of these methods – any noise would be inaudible outside the chest and some of these methods will introduce flexibility.

There are a number of problems created by the need to pass the pallet pull down through the bottom of the windchest. If the pull down moved in a straight line, it would have to be precisely aligned to pass through a small (to prevent excessive air loss) hole in the bottom of the windchest. This can be achieved by attaching a thin metal strip over a larger hole as illustrated by Audsley (Fig 4.1). However, because the pull down is attached to the pallet at one end and, probably, a square or roller arm at the other, both of which move through arcs, the pull down actually moves sideways – although the theoretical movement in the model organ appears to be accommodated by flexibility in the linkages. To allow for this movement, however, various methods including leather pouches (pulpeten) have been used. Another common method, and that adopted for the model, is to make the hole in the bottom board considerably oversized and run the pull down through a bushed brass (or lead) cylinder, which slides across the top of the bottom board. These are commercially available[4] and can be seen in Figs 6.3 and 6.7.

Fig 6.11 shows the tracker passing through the bottom of the windchest.

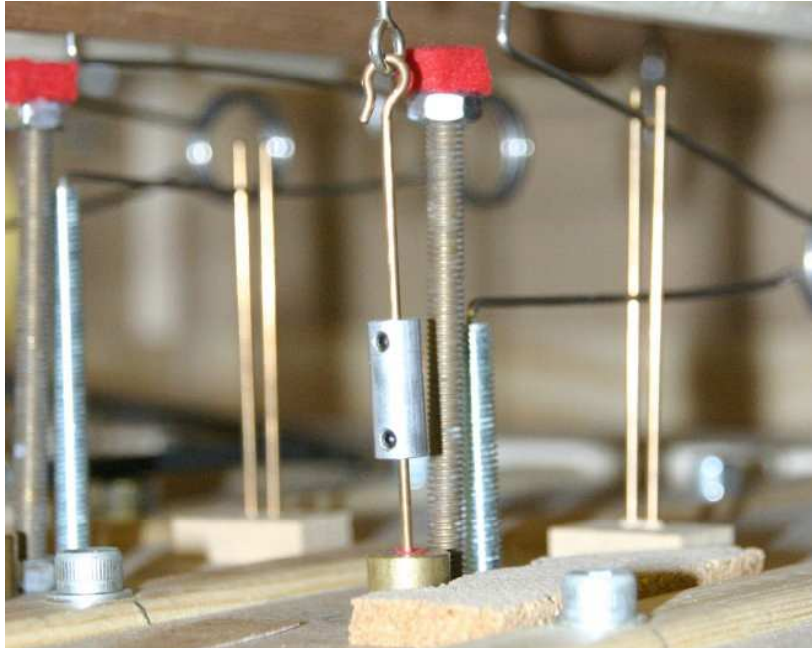[4] The pull down seals in the model were supplied by A J & L Taylor

Fig 6.11 The tracker passing through the bottom board of the pallet box

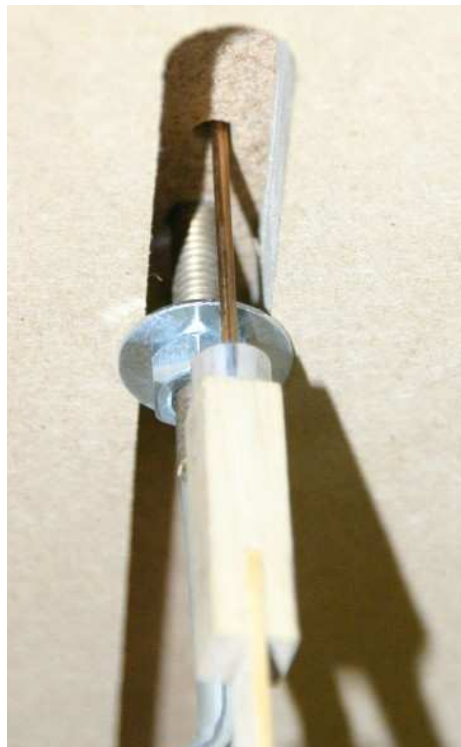Fig 6.12 shows the tracker coming out of the underneath of the Pallet box.

Fig 6.12 The tracker emerging from the bottom of the windchest with the mounting for the
pallet stop behind it.

The pallet openings used are 20 cm by 2 cm, which with a wind pressure of 75 mm wg (7.5 mb) gives a pluck at the front of the opening of 150 g. It was not felt necessary to take full advantage of the possibilities offered by the model because of the quality of the results obtained from real organs.

6.1.3   Rigid action

Two different action runs were incorporated into the model – a very rigid one and a flexible one, each with three notes.

The rigid action is suspended i.e. the 49 cm long key lever is pivoted at the back and the key is literally suspended from the tracker, which is attached 16 cm from the front. The key is pivoted 1 cm from its back and the gearing at the key lever is thus 0.67:1. The key levers are pine, the natural heads are covered with rosewood and the sharps are made of ash (Fig 6.13).

Fig 6.13 The keys of the suspended action.

The middle key (f^1) is attached directly to the pallet by the tracker and incorporates no bushing (apart from in the pull down seals) and no felt washers. The pallets are leathered but not felted and it is possible that a different type of leather would have provided a better seal. The leather used was supplied as being suitable for facing pallets, but David Page of Forth Pipe Organs[5] did not consider it so. The smooth surface of the leather was glued to the pallet top, as is normal practice – Fig 6.14. Note the flattening of the leather where it contacts the bottom board and also the amount of dirt on the leather after two years of very limited use.

Fig 6.14 Pallet from the rigid action. The leather is flattened where it closes round the pallet opening.

It is not clear why the leather is glued on the smooth side and opinions differ about the circumstances in which there might be advantages is attaching the leather by its rough surface – one opinion is that at high pressures (>100 mm wg, 10 mB) the air leaks through the grain of the leather[6]. The other two keys required short rollers to align them with their pallets (Fig 6.15). No pallet stops were incorporated into this action because the overrun was not excessive.

---

[5] private discussion
[6] private discussion with Dr David Wylde, Henry Willis and Sons

Fig 6.15 Roller from the rigid action. Phenolic bushings to the pivots and no felt washers.

6.1.4 Flexible action

The flexible action replicates a typical larger organ action in which there is significant movement before pluck is overcome. This was achieved by incorporating one metre of aluminium tube roller, outside diameter 8 mm and inside diameter 6 mm and by using cloth bushes and washers in every junction.

The rollers were divided into two in order to fit them into the building frame. The greater rigidity of shorter rollers is offset by the compression under load of the extra felt washers. The general arrangement of the action from the back of the keys can be seen in Fig 6.16. The two sections of each roller are joined by a tracker, which is off the picture to the right.

Fig 6.16 The keyboards and rollers of the flexible action from the model organ.

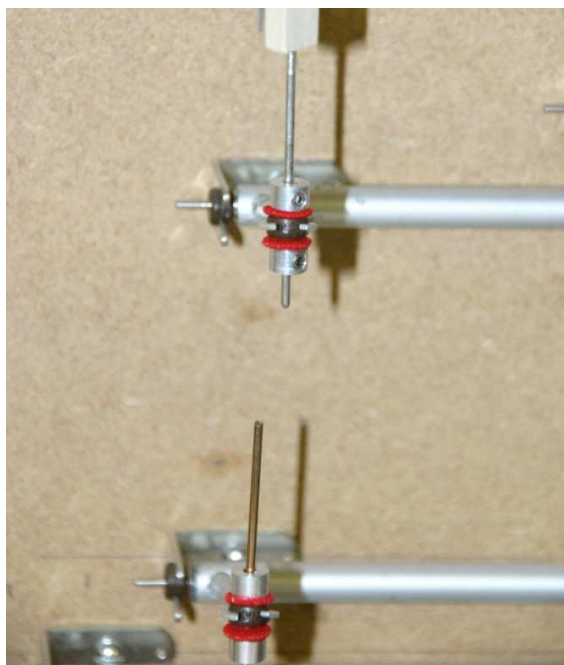The roller arms are shown in more detail in Fig 6.17.

Fig 6.17 Metal roller arms from the flexible action.

Fig 6.18 shows the arrangement of washers on the square arms. The squares were supplied by A J & L Taylor Ltd and have 50 mm arms. The square arm moves either side of horizontal in order to minimise sideways movement of the tracker.
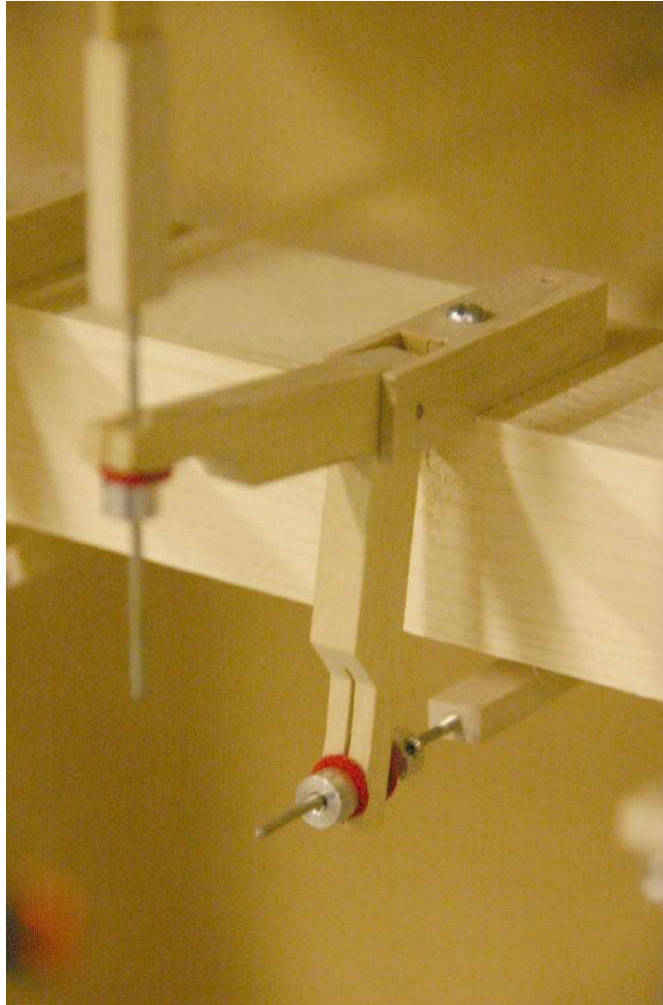

Fig 6.18 Wooden square from the flexible action.

The keys of this action are 45.5 cm long pivoted 20 cm from the back and with the sticker attached 1.5 cm from the back. This gives a gearing of 0.76:1. The keys are shown in Fig 6.19.

Fig 6.19 Balanced keys from the flexible action.

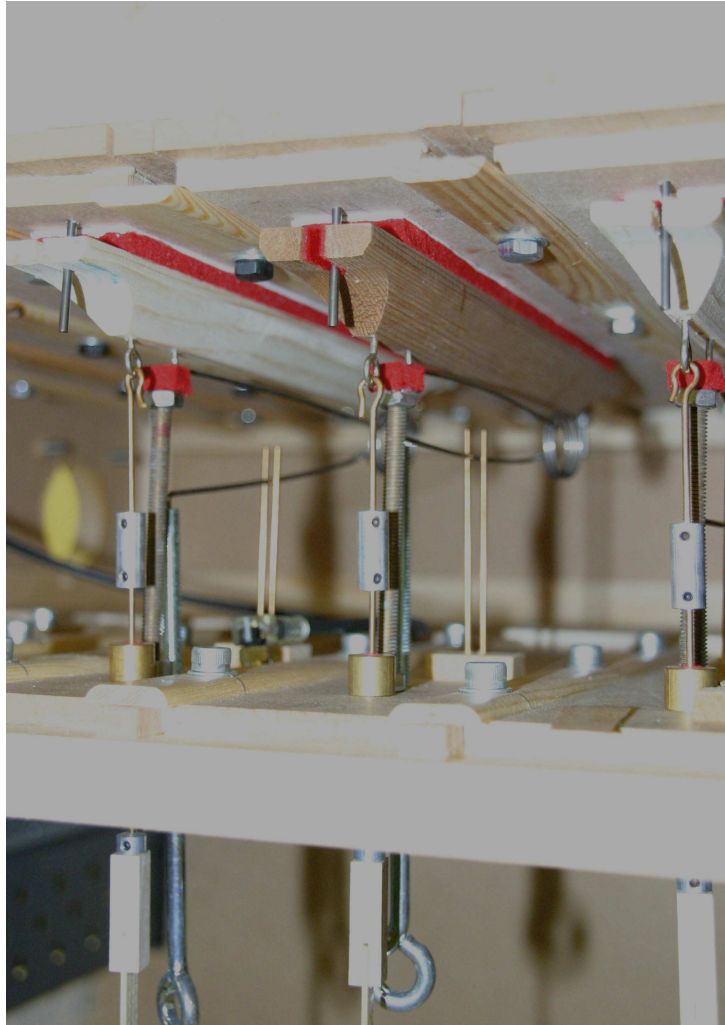The windchest end of the flexible action is shown in Fig 6.20.

Fig 6.20 The windchest end of the flexible action.

Empirical tests show that there is an initial movement of approximately 3.5 mm out of a total key drop of 9 mm. Fig 6.21 shows one of the keys on the flexible action just before going through the pluck point.
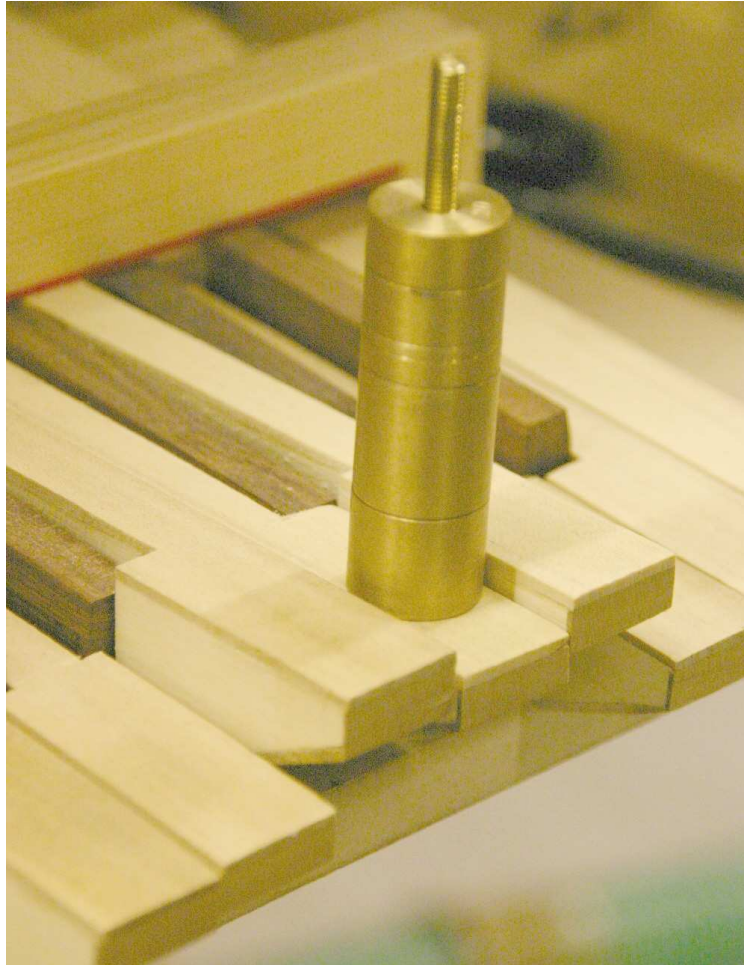
Fig 6.21 Flexible action key showing the point just before pluck.

6.1.5 Blower and regulator

The blower of the model organ was obtained from an old pipe organ and has no markings to indicate its origin. The regulator was built for the model and incorporates an inverted schwimmer pantograph[7] to apply pressure to the floating plate. The pressure can be adjusted by varying the tension of the springs. The complete regulator is illustrated in Fig 6.22 and the pantograph in Fig 6.23.
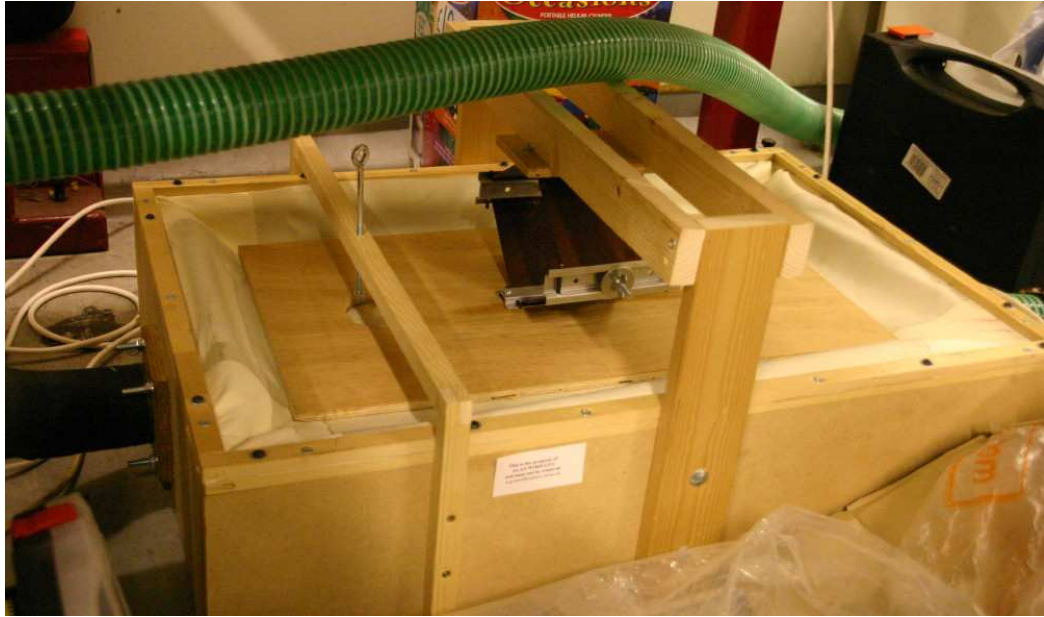
---

[7] Aug Laukhuff

Fig 6.22 Pressure regulator from model organ. When the plate rises against the spring tension from the pantograph to a preset level, the valve on the top of the plate is opened by the end of the threaded rod. The plate rises and falls depending on the wind requirement of the organ, and the excess is vented through the valve.
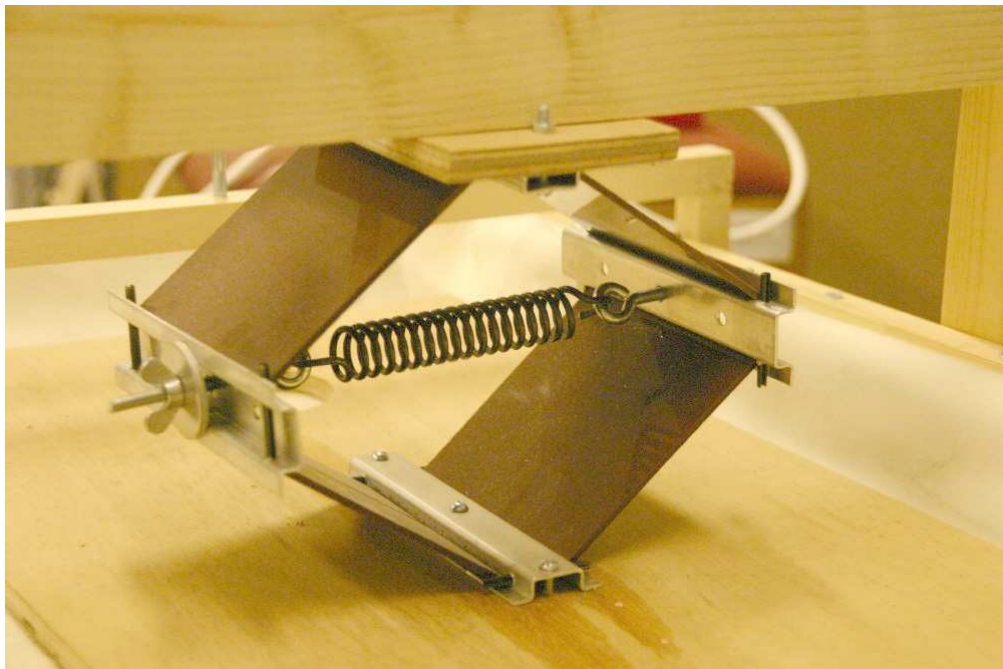

Fig 6.23 Pantograph assembly exerting force on regulator plate.

6.2 Results from Model Organ

The model organ was used to develop the equipment used for making measurements on actual organs and for clarifying issues found during these measurements. Since the objective of the project was to determine what organists did during normal playing, it was not appropriate to use the results from playing isolated notes in the laboratory when other results were available. This did, however, mean that the full potential of the model was not used and leaves considerable scope for further work. Early results showed that players would move an isolated key more slowly than they would when attempting to play a note slowly during normal playing and the results from the laboratory model must be treated with caution. However, a number of recordings are reproduced here in order to clarify effects observed during site work. Fig 6.24 illustrates many of these effects and also includes a measurement of the pressure in the groove. The key movement was "slow". The pipe is an f^1 principal pipe obtained from an organ builder and not revoiced for this exercise. This pipe was used for these measurements because of its prompt speech. 1 mb = 10 mm wg.
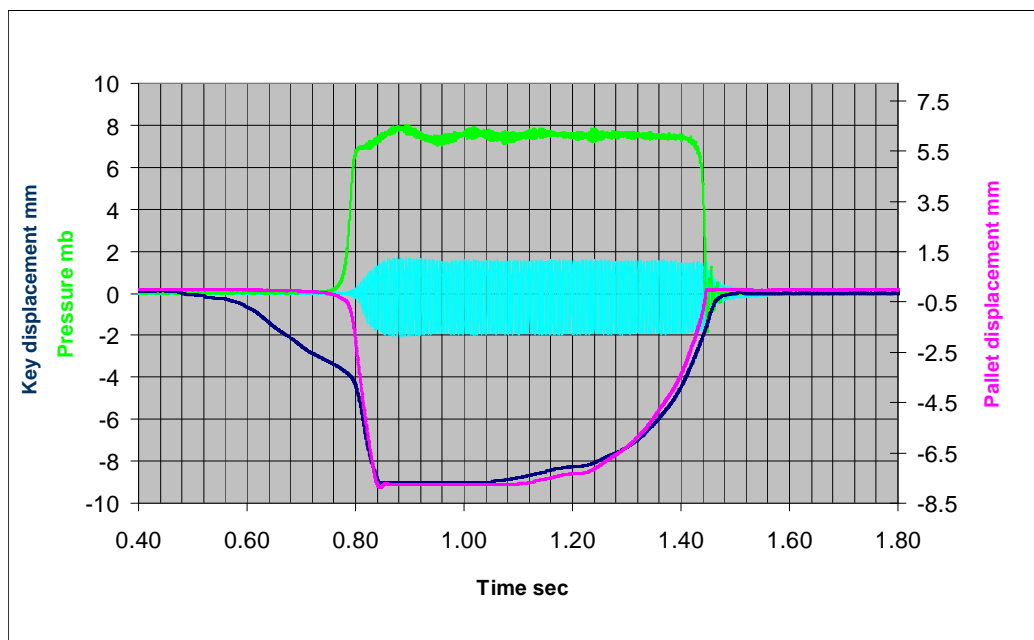

Fig 6.24 Complete recording of a "slow" key movement on the flexible action of the model organ. The blue curve is the sound envelope.

This graph should be compared with Fig 6.34 to show the effect of a slower speaking pipe. The characteristic shape of the key movement due to flexibility in the action can be seen. The key movement slows down between about 0.60 sec and 0.75 sec as the resistance felt at the key head increases due to the action behaving like a spring until the pallet starts opening. The pallet first starts moving at about 0.74 sec at the same time as the air pressure starts rising. The sound envelope starts developing at about 0.78 sec. the key speed increases from about 0.795 sec as pluck is completely overcome. The pallet catches up with the key movement just after 0.80 sec and follows it closely for the rest of its travel. The pressure starts to increase in the groove at about 0.75 sec i.e. there is some leakage before the pluck point.

The most important features of Fig 6.24 are:

- o The key moves a significant distance before the pallet starts to open

- o The key slows down due to the increasing resistance as the action flexes (rollers twisting, washers compressing, levers bending etc.)

- o When sufficient energy is stored in the flexed action (in this case after about 3.4mm key travel), pluck is overcome and the pallet springs open and catches up with the rest of the action

- o As the resistance due to pluck is overcome the key increases in speed of movement as it is not possible to reduce the force being applied by the finger in the time available

- o The air pressure in the groove starts to rise at the same time as the pallet starts to open

- o The air pressure reaches a peak early in the pallet movement (after about 2 mm pallet travel)

o   The pallet starts to open at about 3.3 mm key travel and the pressure in the groove reaches a maximum at about 4.5 mm key travel out a total of 9 mm. This is the only part of the key movement that could affect the transient.

o   There is a delay before the pipe starts to speak

o   The key is on the key bed and the pallet is fully open before the pipe has reached stable speech

o   There is a delay before the pallet starts to close when the key is released (probably due to friction)

o   Later in the release movement the pallet starts to close in advance of the key movement (due to air pressure)

o   The pallet is firmly seated before the key has returned to its rest position (in this case the key has 1.6mm to go)

o   The sound envelope does not start to diminish until the point at which the pallet closes.

The low frequency variation in the pressure is a characteristic of rotary blowers and the high frequency pressure variation is due to the sound wave being transmitted to the groove.[8] The former is often cited as a problem with rotary blowers and the latter is often cited as an advantage of bar and slider windchests – there is coupling through the groove between the pipes of one note, although no evidence came to light that this has been properly studied.

The critical part of the key depression is shown in Fig 6.25.
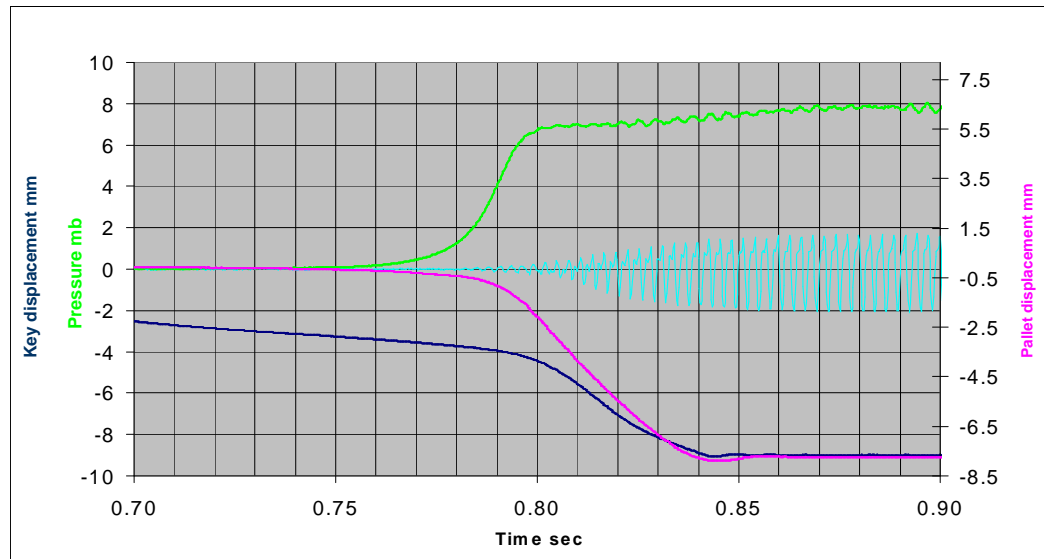
---

[8] Discussion with Prof. Andras Miklós

Fig 6.25 Key depression from the "slow" movement shown in Fig 6.24. The blue curve is the sound envelope.

This diagram very clearly shows that the pressure in the groove goes from zero to maximum over a small part of the key movement – between about 3.3 mm and 4.5 mm travel. Any movement outside this range cannot affect the pipe speech. The low frequency variation in wind pressure may influence the transient but that is a function of the wind system and not the key action.

The slow key release shows that the key initially leads the pallet (Fig 6.24). This is possibly due to friction. After about 1 mm travel by the pallet, it starts leading the key. This is probably due to the effect of the airflow past the pallet. The pallet finally closes significantly ahead of the key reaching its rest position, and can be seen to be accelerating over the last part of its travel whilst the key is decelerating. This "snap" closing due to the net force of the air pressure against the pallet aids its sealing against the pallet opening. It also means that the final part of the pallet movement is outside the player's control. Despite the very slow key release, there is no diminution in the sound amplitude until the pallet is firmly seated.
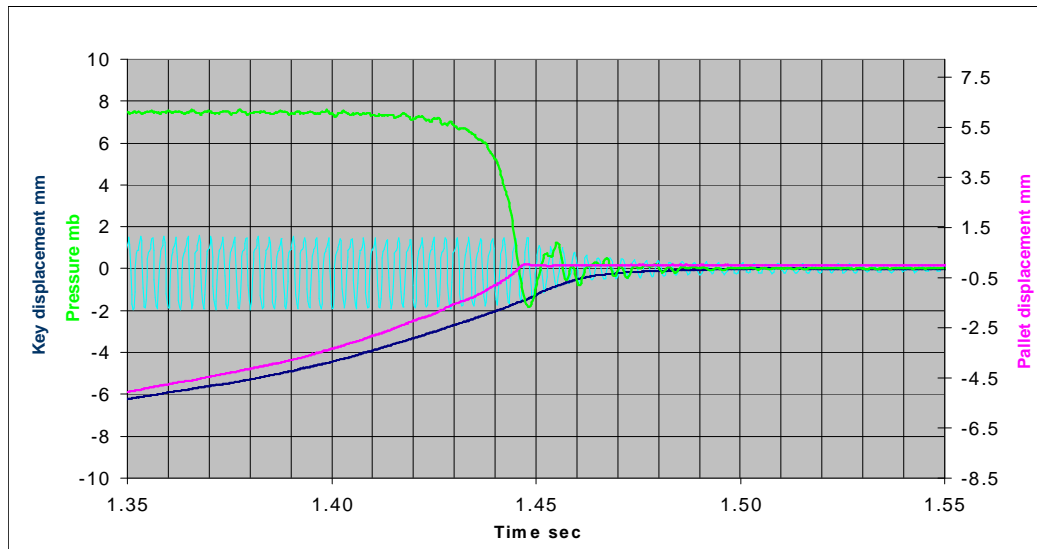
Fig 6.26 Key release from the sequence shown in Fig 6.2.1. The blue line is the sound envelope.

Fig 6.27 shows an even slower key release that shows the acceleration of the pallet just before it closes and also some diminution of the sound amplitude in this region. Such a slow closure of the pallet is unlikely to occur in normal playing.
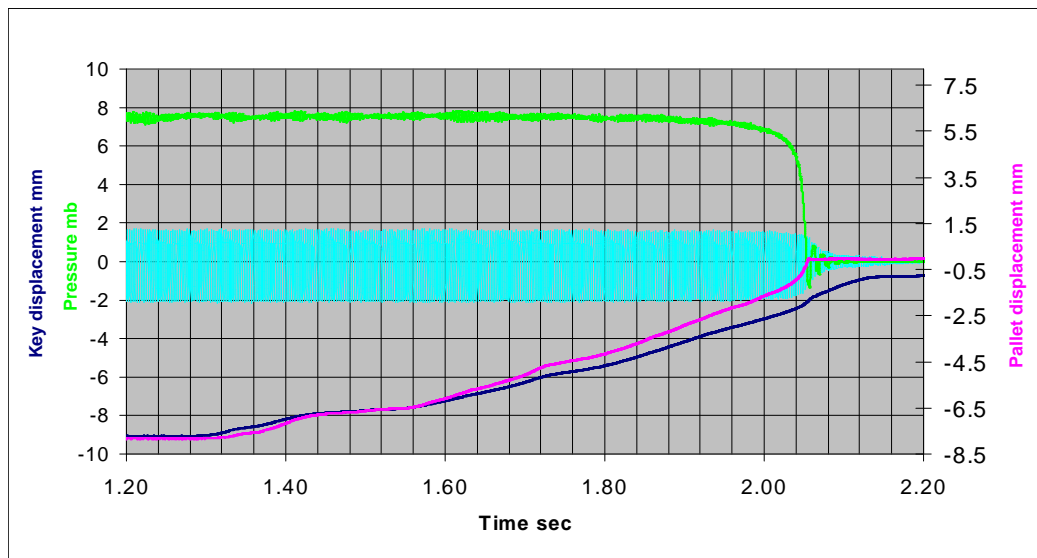

Fig 6.27 Very slow key release on flexible action of the model organ. The blue line is the sound envelope.
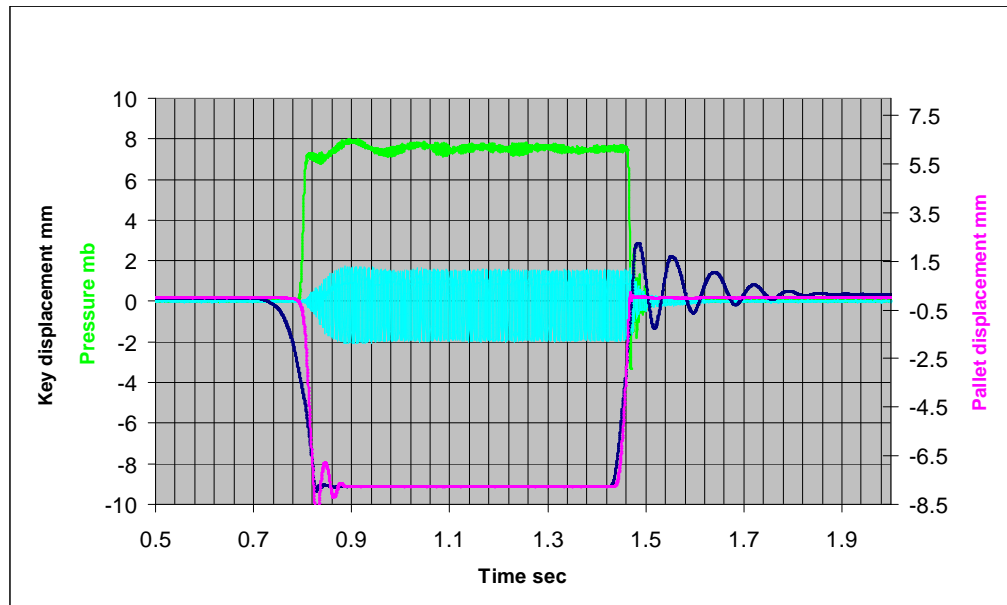
Fig 6.28 shows a "fast" key movement.

Fig 6.28 Complete recording of a "fast" key movement on the flexible action of the model organ. The blue line is the sound envelope.
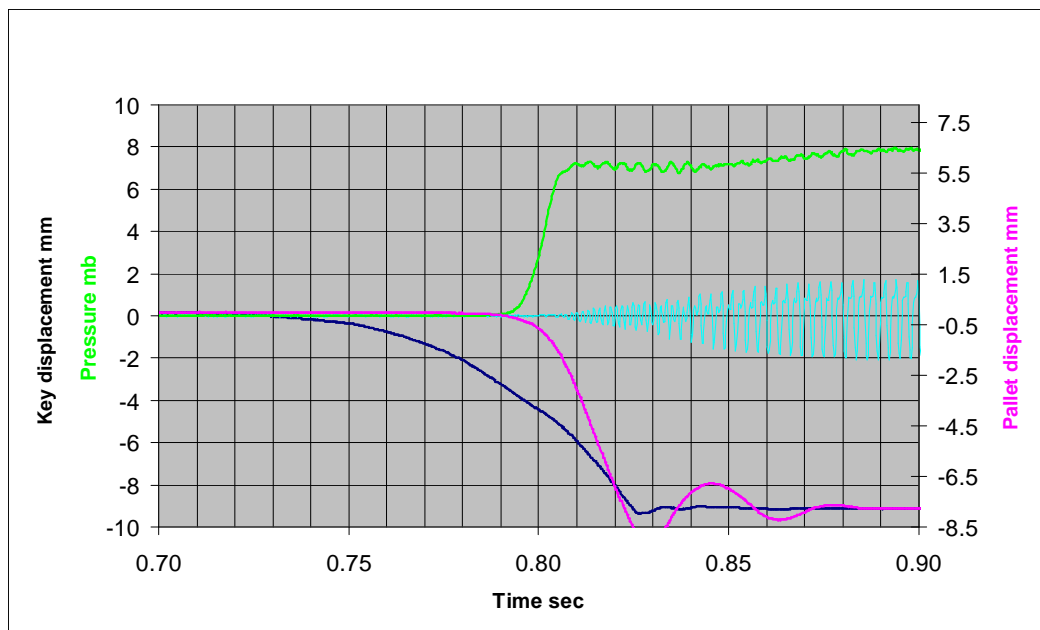
The key depression is shown in Fig 6.29.

Fig 6.29 Key depression from Fig 6.28. The blue line is the sound envelope.

143

A slight change in gradient of the key movement curve can be seen at the 4 mm point corresponding with the more prominent change visible in Fig 6.25.

The key release is shown in Fig 6.30 and shows the same characteristics as Fig 6.26.
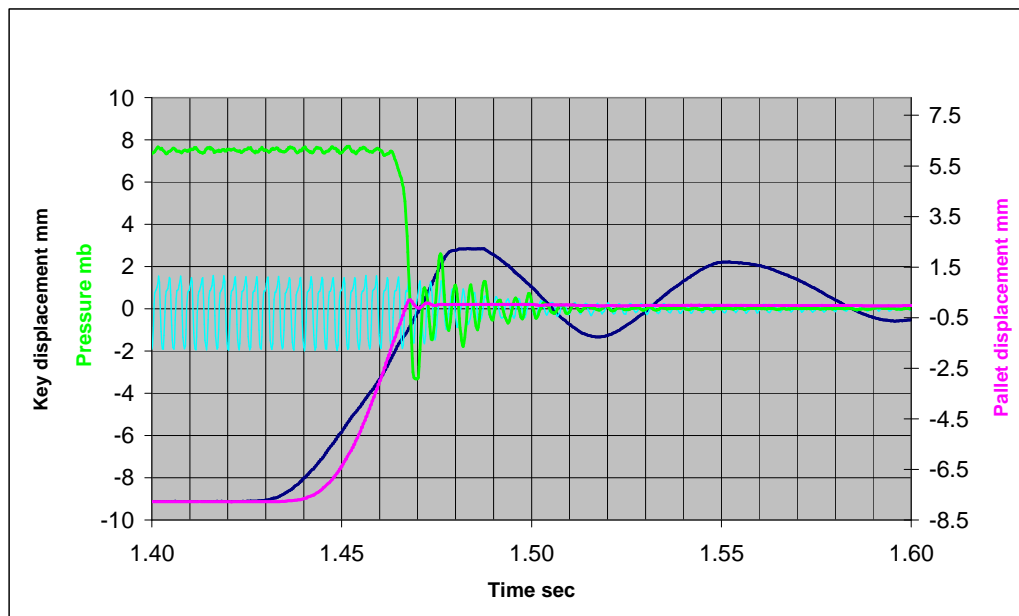
Fig 6.30 Key release from Fig 6.28. The blue line is the sound envelope.

The two sound envelopes from the slow key release in Fig 6.27 and the fast key release in Fig 6.30 are superimposed in Fig 6.31 in order to show that the diminution of the sound amplitude does not follow the key or pallet movement.
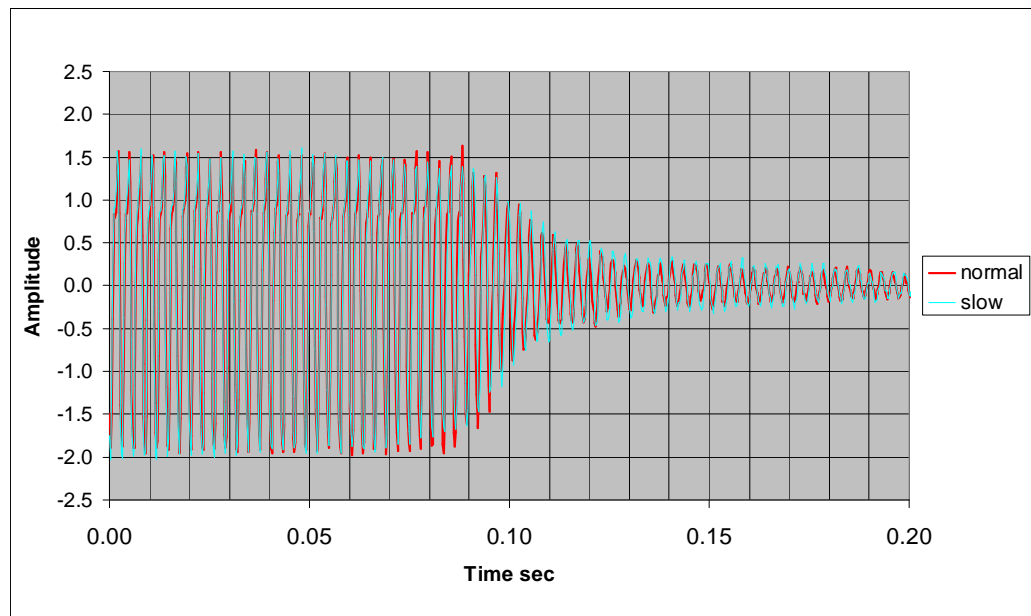
Fig 6.31 The final transients from the "fast" (Fig 6.27) and "slow" (Fig 6.30) pallet closures superimposed to show the lack of difference compared with the difference in pallet movement.

The rigid action of the model was then used to compare a "slow" followed by a "fast" key movement. The complete recording is shown in Fig 6.32.
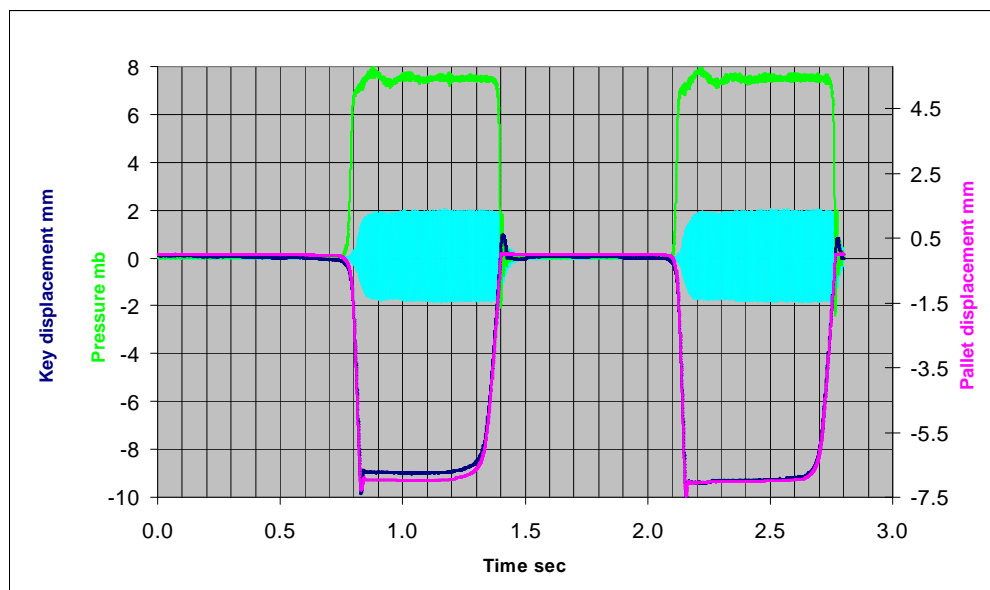

Fig 6.32 Complete recording of "slow" followed by "fast" key movement on the rigid action of the model organ. The blue line is the sound envelope.

The only obvious difference is that the second "fast" movement resulted in the key being pushed further into its bed. Fig 6.33 shows the four curves from the two key depressions shown in Fig 6.32 on the same graph separated horizontally to highlight the similarities.
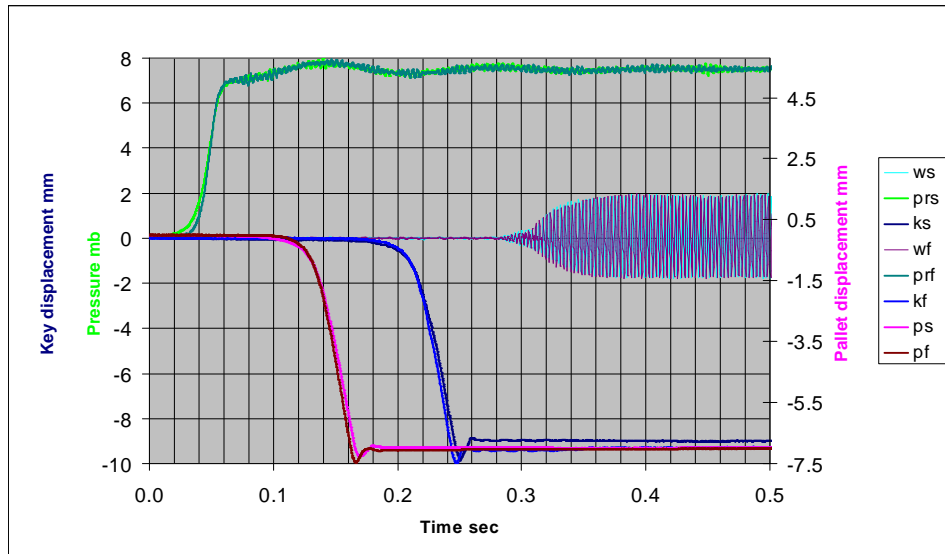
Fig 6.33 The key (k), pallet (p), pressure (pr) and sound envelope (w) measurements from Fig 6.32 grouped together to show the similarity between the "fast" and "slow" movements.

Fig 6.2.34 shows the measurements of a complete "fast" sequence using a different pipe from a different rank (narrower principal, c^2) on the rigid action. This pipe consistently did not start speaking until after a significant delay of approximately 40 ms after the pallet started opening.

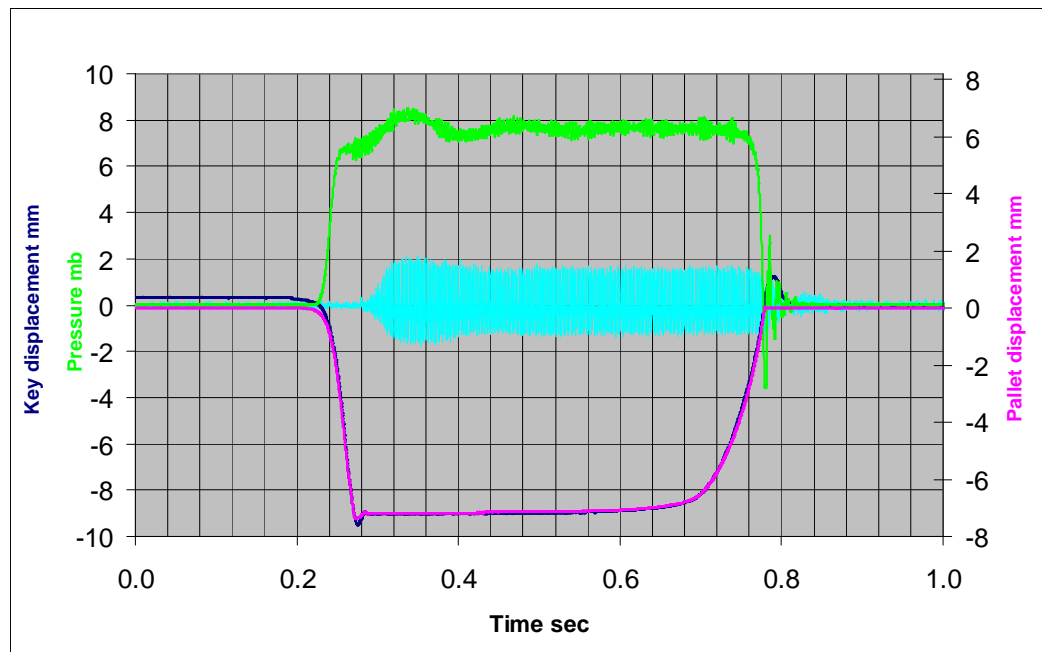Fig 6.34 Complete recording of a key movement on the rigid action of the model organ using
a slow speaking pipe. The blue line is the sound envelope.

The effect of how differently voiced pipes might have affected the results was not
pursued because the purpose of this exercise was to identify differences due to
different key movements.

Chapter 7

Fieldwork

7.1 Introduction

The fundamental element of this project is that it was intended to study real organists playing real music on real organs. The ideal would have been to place sensors on the key levers inside the organ case so that they would not be apparent to the player and to leave them in place with as many players as possible playing the instrument.

The opportunity to do this did not however present itself and, in any case, few of the actions examined could accommodate sensors on the backs of the keys. It was therefore necessary to take measurements with the sensors over the key heads. This immediately created two problems. Firstly the player was always aware of their presence and secondly they physically impeded the accidentals to a greater or lesser extent. The apparent ability of individual players to work round the sensors influenced the music and exercises that they were asked to play. This was inevitably a subjective decision. Some players found it very difficult to avoid touching the sensors even though they were placed as far back on the keys as was possible. Apart from the problems caused by the sensors moving during a set of measurements there was a risk of injury to the player.

It became obvious early in the site visits that asking players to repeat an exercise in the same way many times did not result in a consistent set of samples. The player appeared to start thinking too hard about what they were trying to do so that their playing did not represent their natural way of playing the particular exercise. A discussion with the project's supervisor, an international concert organist, added support to this view. Whilst accepting that the best results would be obtained by players repeating exercises many times, it was decided that more representative results would be obtained by asking players to play a number of different exercises and looking for common threads in the results.

The organs and organists used for measurements were largely random depending on where it was possible to spend some time. It was also determined by the generous donation of time by organ builders.

Players were asked to play notes in isolation in the style that they thought that they played during pieces of music. They were then asked to play either a piece of music of their choice that they felt comfortable with or a theme provided by the researcher. It was not appropriate to ask the organists to play the same piece of music because it would not necessarily indicate how they naturally play.

7.2 Reid Concert Hall, University of Edinburgh

7.2.1   Introduction

The organ in the Reid Concert Hall of the University of Edinburgh was built by Jürgen Ahrend of Leer in North Germany in the 18th century German style. The specification is shown in Appendix 1.

This organ has a very "light" action with no bushing and with relatively little pluck (50 g plus 50 g at Middle c^1 on the Hauptwerk). The console and façade of this organ are shown in Figs 7.2.1 and 7.2.2 respectively.

Fig 7.2.1 The console of the organ by Jürgen Ahrend in the Reid Concert Hall of the University of Edinburgh

Fig 7.2.2 The façade of the organ by Jürgen Ahrend in the Reid Concert Hall of the
University of Edinburgh

For the purpose of these exercises, the organ was played by Dr John Kitchen, University Organist and Edinburgh City Organist, who is intimately familiar with the instrument.

7.2.2   Improvised theme

The first session took place on the 6th December 2004 and used the LED sensors. It was not possible to gain access to the inside of the chests in order to record the pallet movements. In the first exercise, Dr Kitchen played an improvised sequence of notes "legato, moving the keys as slowly as possible". This theme is shown in Fig 7.2.3.

Fig 7.2.3 Improvised theme used by Dr Kitchen for this exercise.

Fig 7.2.4 Manual keyboards of the organ by Jürgen Ahrend in the Reid Concert Hall of the University of Edinburgh

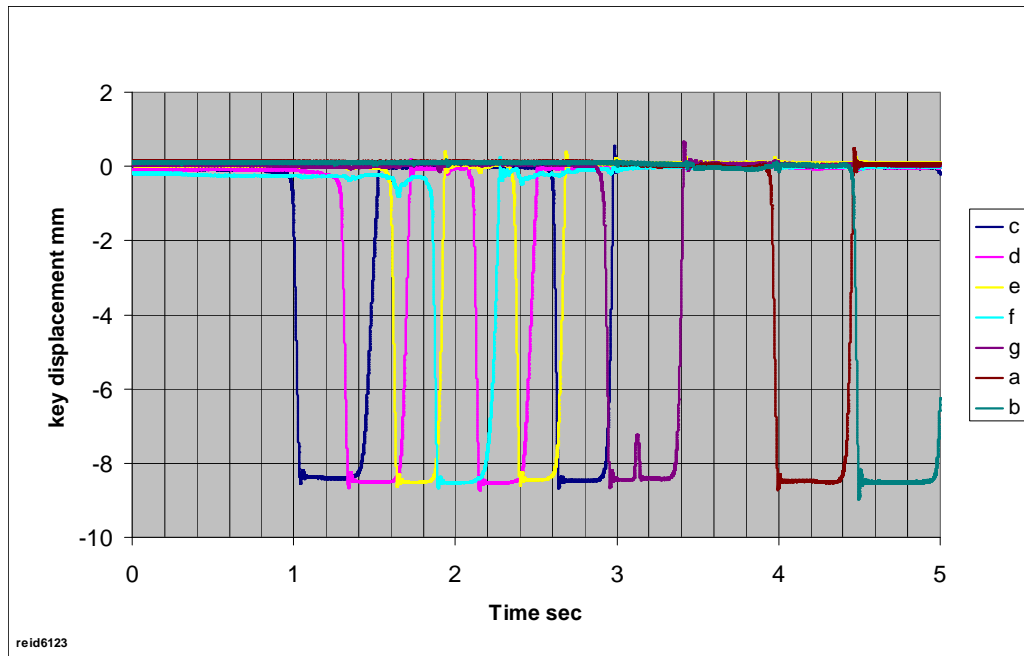Fig 7.2.5 shows the complete key movements of the theme in Fig 7.2.3.

Fig 7.2.5 Graph showing all key movements in a legato performance of the theme improvised and played by Dr John Kitchen and shown in Fig 7.2.3. Ahrend organ Reid Concert Hall University of Edinburgh
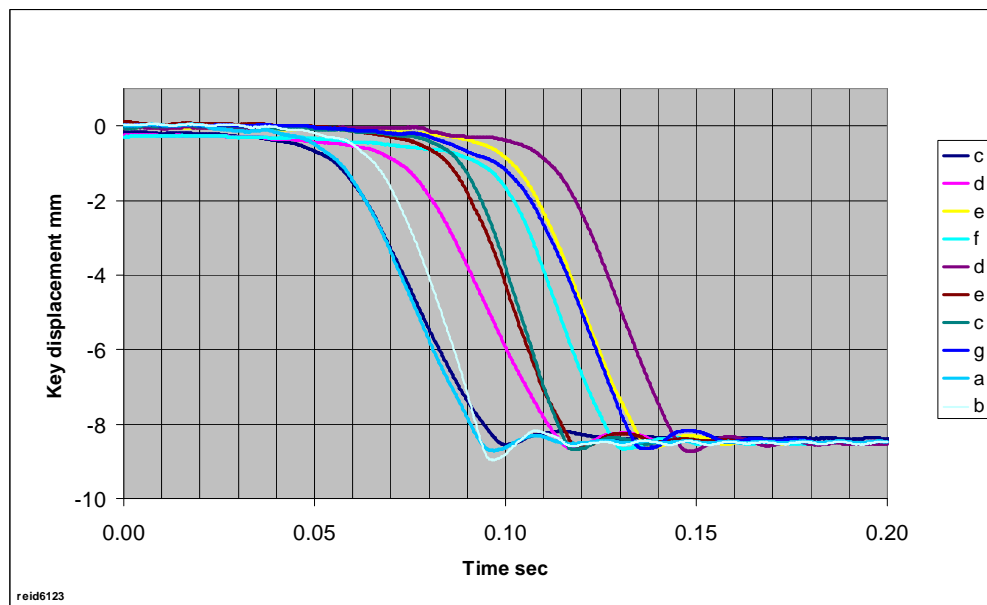

Fig 7.2.6 Graph showing the key depressions from the sequence depicted in Fig 7.2.5.

Fig 7.2.6 shows the key depressions from the movements shown in Fig 7.2.5. The legend to the right of the graph shows the correct sequence as written in Fig 7.2.3 but the curves are placed on the graph in random order.

Dr Kitchen was then asked to play the theme moving the keys significantly more quickly but changing nothing else. The complete recording of the sequence is shown in Fig 7.2.7.
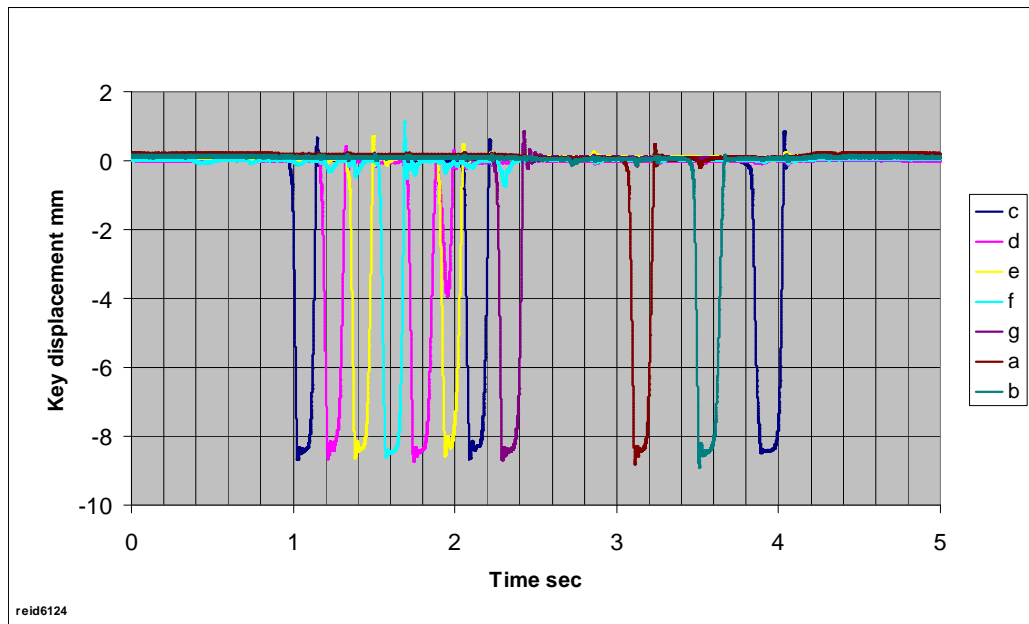

Fig 7.2.7 Graph showing all key movements of the theme improvised and played by Dr John Kitchen and shown in Fig 7.2.3 with faster key movements relative to Fig 7.2.5. Ahrend organ Reid Concert Hall University of Edinburgh

The total playing time measured to the start of the key release of the b^2 reduced from 4.00 s to 2.62 s i.e. by 34.5%.

Fig 7.2.8 shows the key depressions of the movements shown in Fig 7.2.7
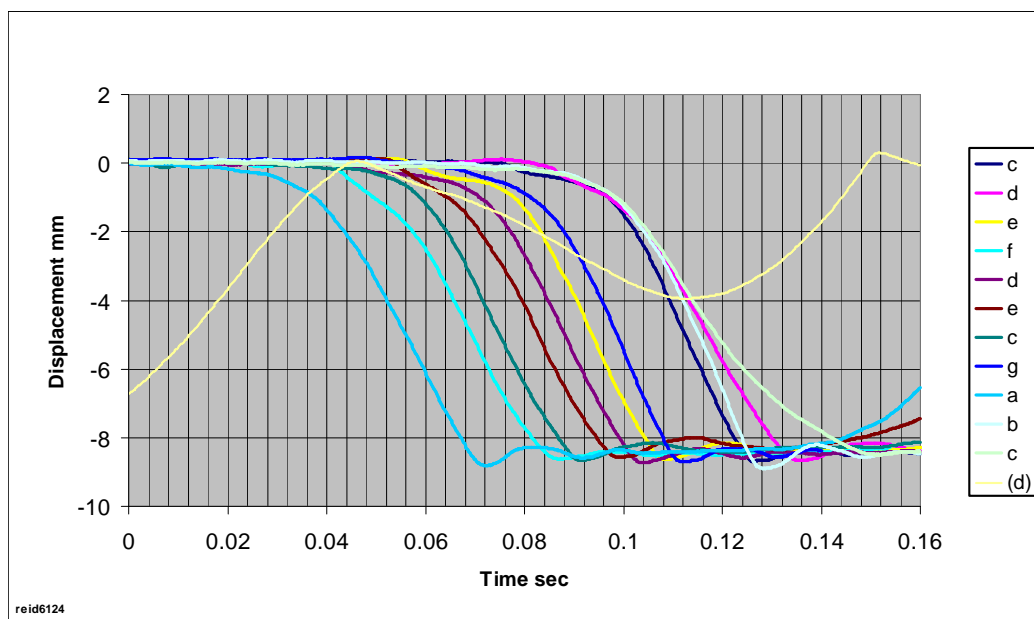
155

Fig 7.2.8 Graph showing the key depressions from the sequence depicted in Fig 7.2.7. The bracketed d indicates a note that was accidentally moved along with the adjacent one.

The bracketed d was due to the player inadvertently moving this key at the same time as the second e^1. It can therefore be disregarded, but it does not appear to have had any obvious effect on the intended note. This can clearly be seen in Fig 7.2.7.

When asked how much quicker he thought that he was moving the keys, Dr Kitchen, after some consideration, said that he felt that he was moving them five times as quickly. This is clearly not the case for the movement after pluck has been overcome. It is difficult to determine when the key first starts moving because of noise from the sensors and the small initial movement of the keys.

Several of the curves clearly demonstrate the key moving before overcoming pluck, most noticeably the final one, which represents the second d^1 of the sequence and the curve representing f^1. These curves indicate that there is approximately 0.35mm movement of the d key and 0.62mm movement of the f^1 key before the pallet starts to open. These movements can only be estimated in the absence of pallet movement measurements but are based on other actions (including the model) where both

156

movements were measured. The differences between keys will arise because of differences in the action runs between notes, differences in the way the individual notes are regulated and even, possibly, systematic differences in the way the player moves different keys. The times of key travel and lengths of notes are shown in Table 7.1

Note in sequence	Post-pluck movement time			Total length of note		
	Slow ms	Fast ms	% reduction	Slow ms	Fast ms	% reduction
c^1	48.4	38.4	20.7	2322	624	73.1
d^1	47.6	39.4	17.2	1962	587	70.1
e^1	43.2	34.6	19.9	1521	589	61.3
f^1	40.2	37.0	8.0	1924	642	66.6
d^1	45.2	35.6	21.2	1750	693	60.4
e^1	40.8	33.6	17.6	1436	578	59.7
c^1	38.8	38.0	2.1	1575	650	58.7
g^1	43.2	33.0	23.6	2322	682	70.6
a^2	39.6	35.4	10.6	2578	632	75.5
b^2	35.6	35.2	1.1		753	
c^2		58.2			856	
average	42.3	38.0	14.2			69.6

Table 7.1 Comparison of the post-pluck key travel times and the overall lengths of the notes between the two performances of the improvised theme. The "slow" columns represent the theme played "legato with the keys moved as slowly as possible" and the "fast" columns represent the theme played with the key movement five times faster and nothing else changed.

7.2.3 Accented note

The second exercise was designed to identify what the player did when he "accentuated" a note. He believed that he was hitting the note harder in order to achieve this.

Fig 7.2.9 shows the sequence played "normally". Dr Kitchen was playing the Two Part Invention no.1 in C by J S Bach.
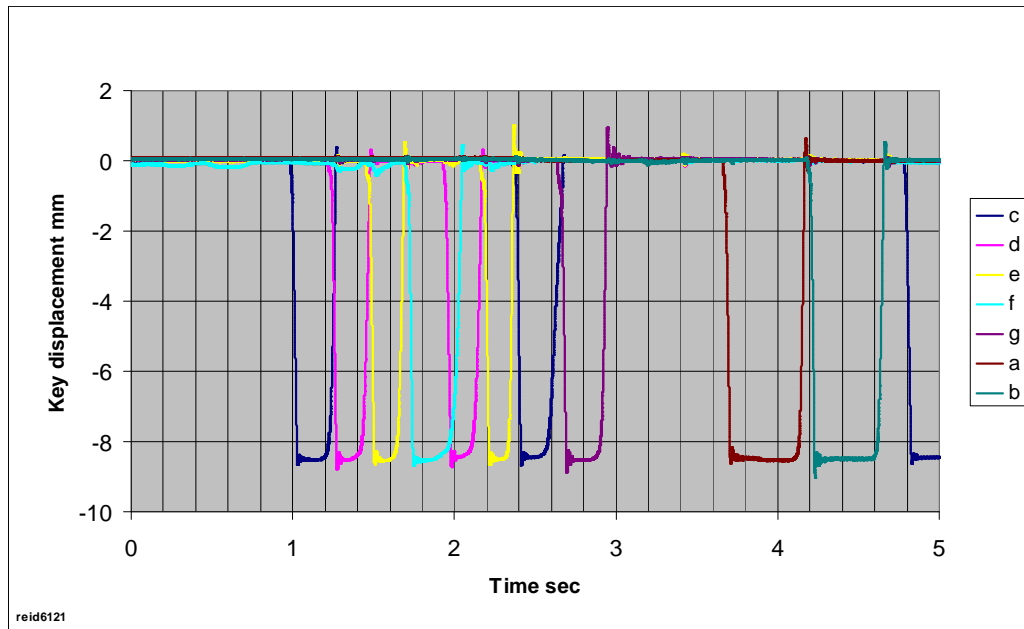

Fig 7.2.9 Graph showing key movements during a performance of the Two Part Invention no.1 in C by J S Bach by Dr John Kitchen on the Ahrend organ in Reid Concert Hall of the University of Edinburgh

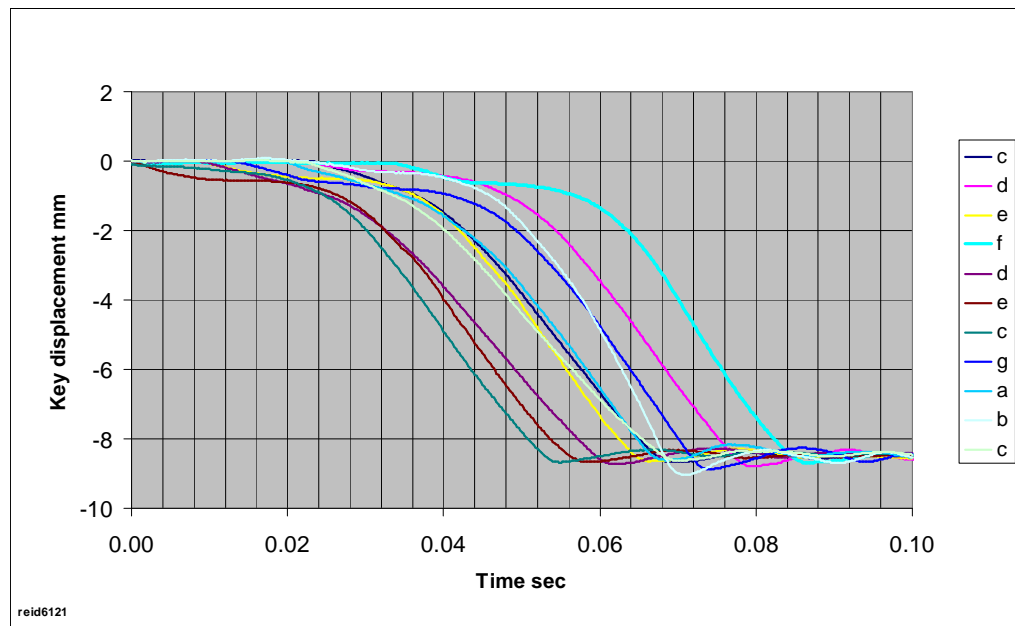Fig 7.2.10 shows the key depressions of the movements shown in Fig 7.2.9.

Fig 7.2.10 Key depressions from the sequence shown in Fig 7.2.9

The initial movement of the keys up to the point at which pluck is overcome can very clearly be seen in some of these curves. The fourth note, f^1, which will subsequently be accented, is at the right hand end of the sequence and has a very distinct initial movement. The time of pre-pluck movement is approximately 23.4ms and the critical post-pluck time is approximately 27.2ms (the approximation arising because of the difficulty in assessing exactly when the pallet starts opening).

Fig 7.2.11 shows the same sequence but with the fourth note, f^1, accented by being "hit hard".

The times of the rest of the notes have not been tabulated but it can be seen that the slopes are similar.
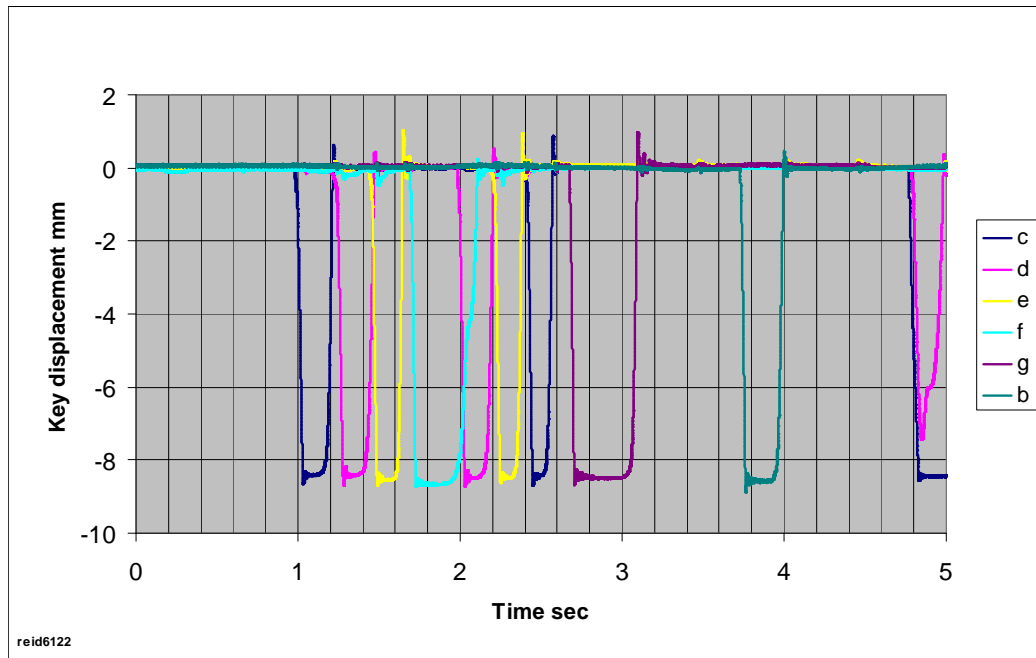
Fig 7.2.11 Graph showing key movements during a performance of the Two Part Invention no.1 in C by J S Bach by Dr John Kitchen on the Ahrend organ in Reid Concert Hall of the University of Edinburgh. The fourth note, f^1, has been accented by being "hit harder".

From this it can immediately be observed that the right hand movement shows the d^1 key being inadvertently moved along with c^1 and that the fourth note, the one being accented, has a brief pause in front of it and has been lengthened.

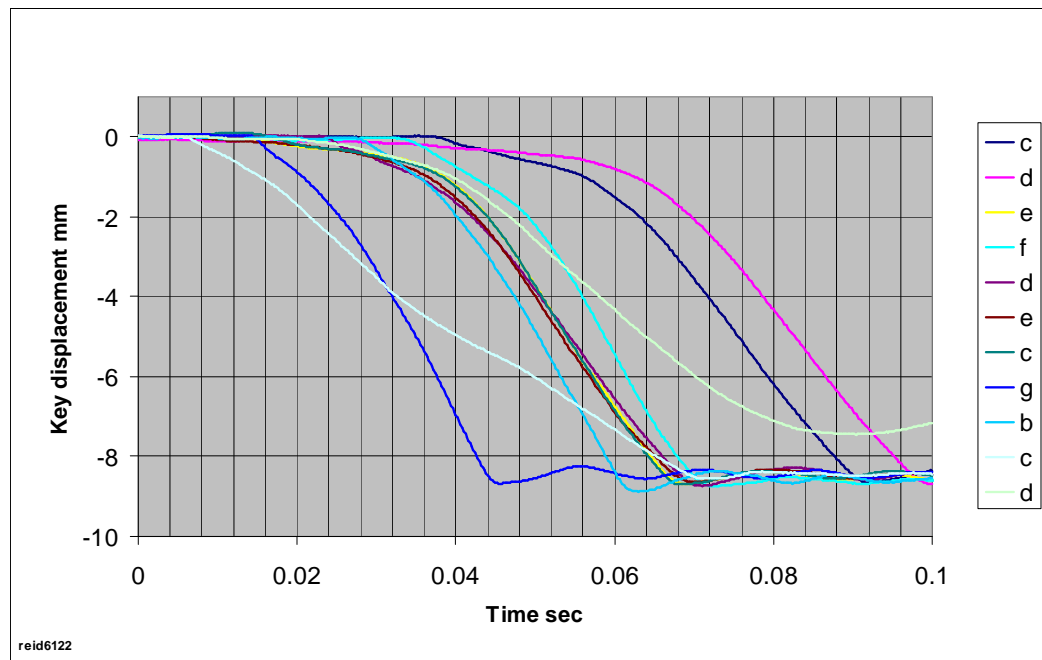Fig 7.2.12 shows the key depressions of the sequence depicted in Fig 7.2.11.

160

Fig 7.2.12 Key depressions from the sequence shown in Fig 7.2.9. The fourth note, f^1, has been accented by being "hit harder".

From this it can be seen that the pre pluck movements for most of the key movements are very much less distinct. In the case of the "accented" note there is a change in gradient, but it occurs at a higher point and the initial movement is a relatively straight line. Taking the same point in the key movement as the estimated pluck point (1.25 mm travel), the pre pluck time has reduced to 8.8 ms (from 23.4) and the critical movement has increased from 27.2 ms to 28.2 ms. This difference is probably within the error of estimating the pluck point. Subsequent notes show a marked change in pre pluck shape – it is shorter.

The two movements of the f^1 key are shown in Fig 7.2.13. The points of initial pallet opening have been placed roughly on top of each other and it can very clearly be seen that the curves after this time do not differ significantly.
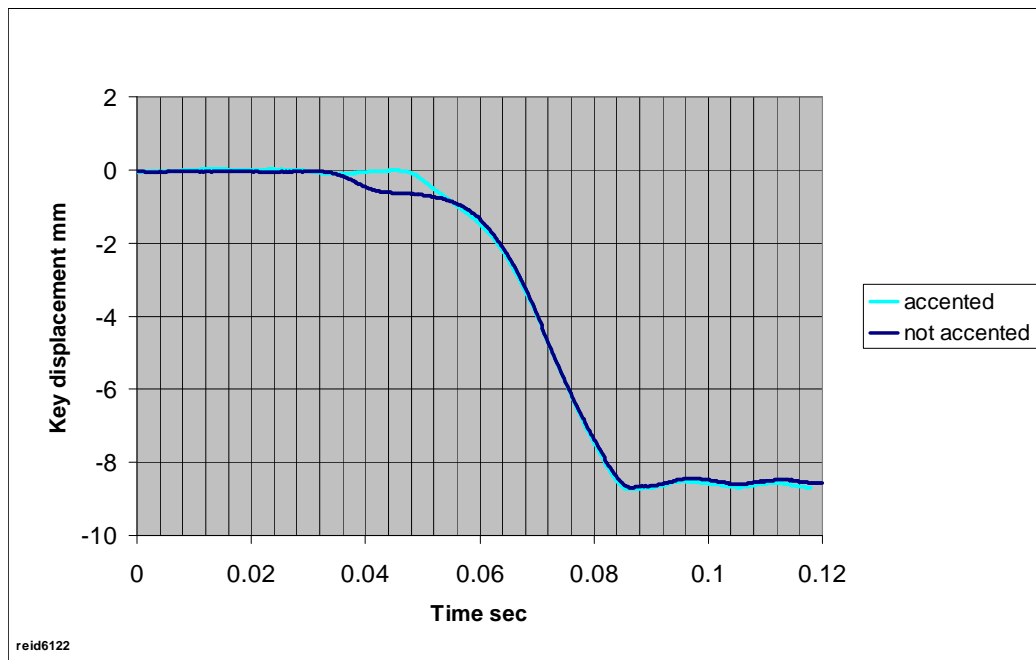
Fig 7.2.13 Graph comparing the same notes from two performances of the same sequence but with one accented by being "hit harder"

The key releases for the non-accented sequence are shown in Fig 7.2.14.
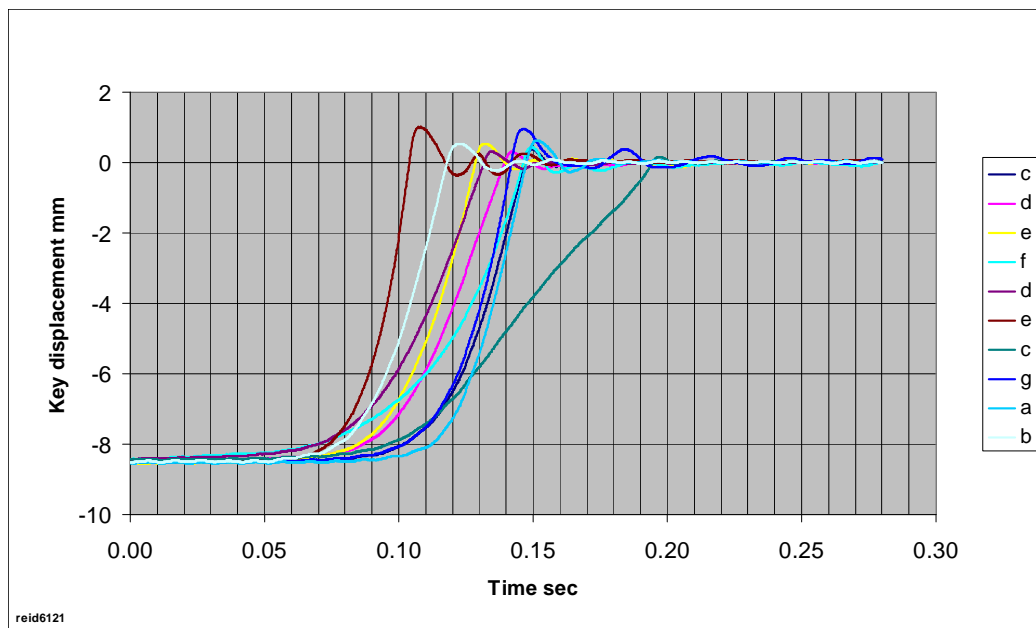

Fig 7.2.14 Graph showing the key releases from the unaccented sequence shown in Fig 7.2.9

There is some variation, but with one exception, they are fairly closely grouped and the variation is unlikely to be significant. The one obvious exception is likely to be random and could be due to such factors as the player changing hand position.

The key releases for the accented sequence are shown in Fig 7.2.15.
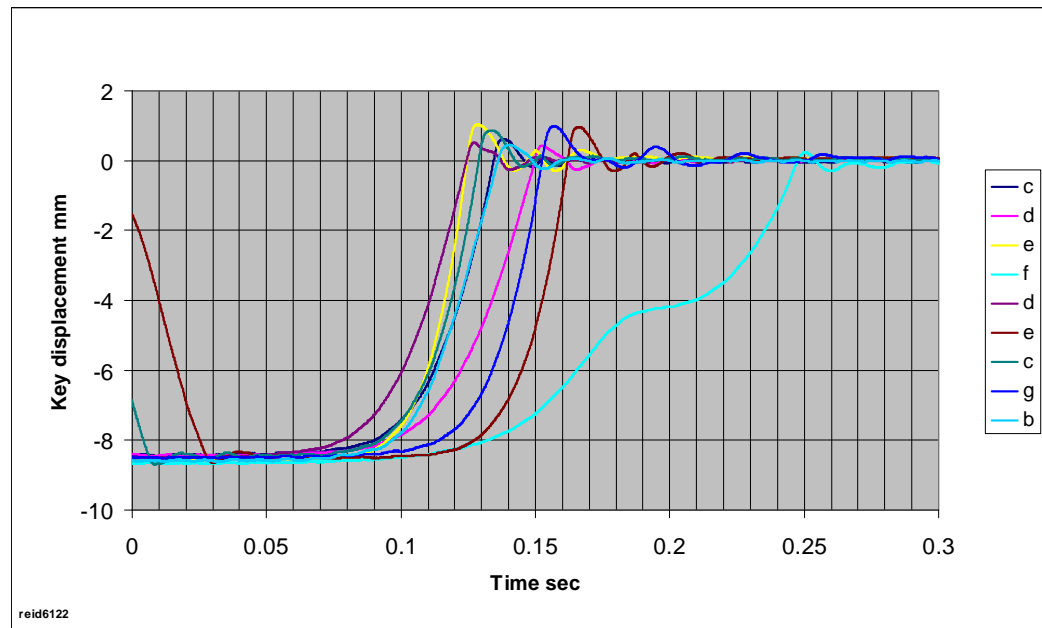

Fig 7.2.15 Graph showing the key releases from the accented sequence shown in Fig 7.2.11

With the exception of the accented note itself, the releases are very similar. The accented note has a significantly elongated release with a check in the middle. There is no obvious reason for this and tests reported elsewhere in this thesis indicate that it will not affect the sound.

These results clearly indicate that Dr Kitchen has a very clear perception of the musical effect that he is trying to achieve but that this is not reflected in the way that he moves the keys. His changes in playing style may be necessary for him to produce a musical performance, but they do not actually produce an audible effect.

7.3 Rose Hill Methodist Chapel, Oxford

7.3.1 Introduction

Rose Hill is a southern suburb of Oxford. The Methodist Chapel contains a one manual and pedal organ with six stops (one divided) on the manual and one on the pedal. The builder is unknown, but John Bailey, its tuner, suspects Hill around 1845. The current disposition is one manual and pedal and eight stops which are listed in Appendix 1.

This organ was brought to the author's attention by Dr John Singleton who responded to the article published in the IBO Newsletter (Appendix 7). Dr Singleton is a physicist who was working in New Mexico at the time but who retained interests with his former employers, the University of Oxford. He had previously been organist of the chapel for ten years. Dr Singleton agreed to a measurement session at Rose Hill on the 6th October 2004 whilst on a visit to the UK in order to try to establish whether he was making the variation in key movement that he thought that he was.

7.3.2 Increasing speed of key movement

The LED sensors were used for all measurements as a power supply problem meant that the laser sensors could not be used. The sensors were positioned above the naturals of the octave above Middle c^1. The sensors were rigidly attached to the frame at this stage, but were sufficiently well centred to give satisfactory results on some of the notes. Results from the sensors too near the limits of the range have been disregarded.

In total thirteen sets of readings were taken and some representative ones are reproduced below.

The first graph, Fig 7.3.1, shows the player playing a sequence of notes whilst trying to move the key at increasing speed.
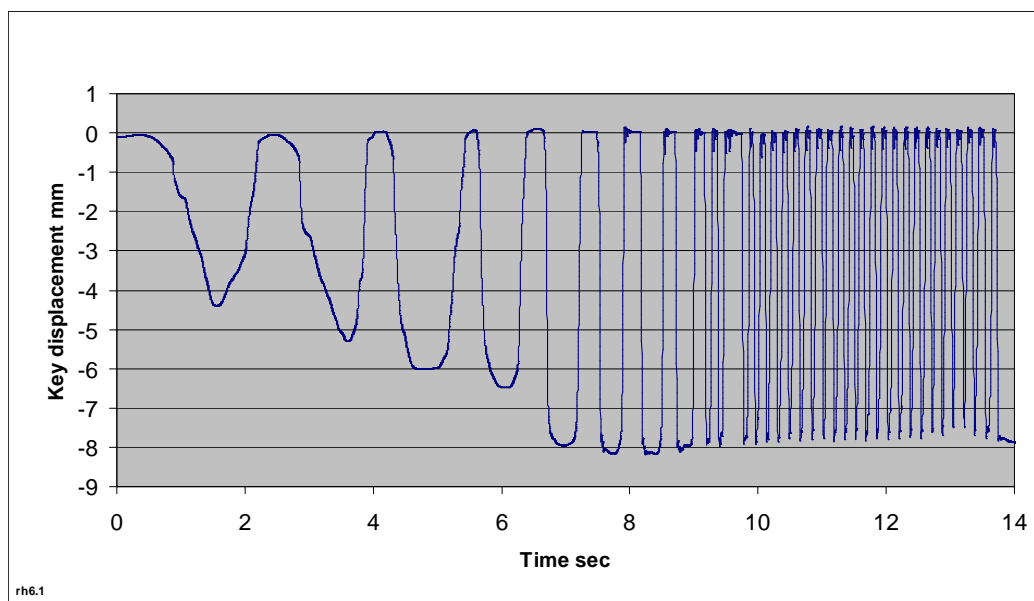

Fig 7.3.1 Graph showing key movement against time as the player tries to move the key increasing quickly. Stopped diapason c^1, Rose Hill Methodist Chapel. 0 displacement is the rest position of the key and downward movements are indicated by a negative displacement.

The sampling rate for this sequence was 1000 Hz. The first few movements are very slow – taking approximately 1 second for the depression and not reaching the key bed. From number 5, the key appears to reach the limit of its travel although some variation is apparent due to compression of the felt key bed itself.

From number 11 onwards, the keystrokes, both in terms of note length and speed of movement, become more or less constant despite the player's attempt to increase the speed.

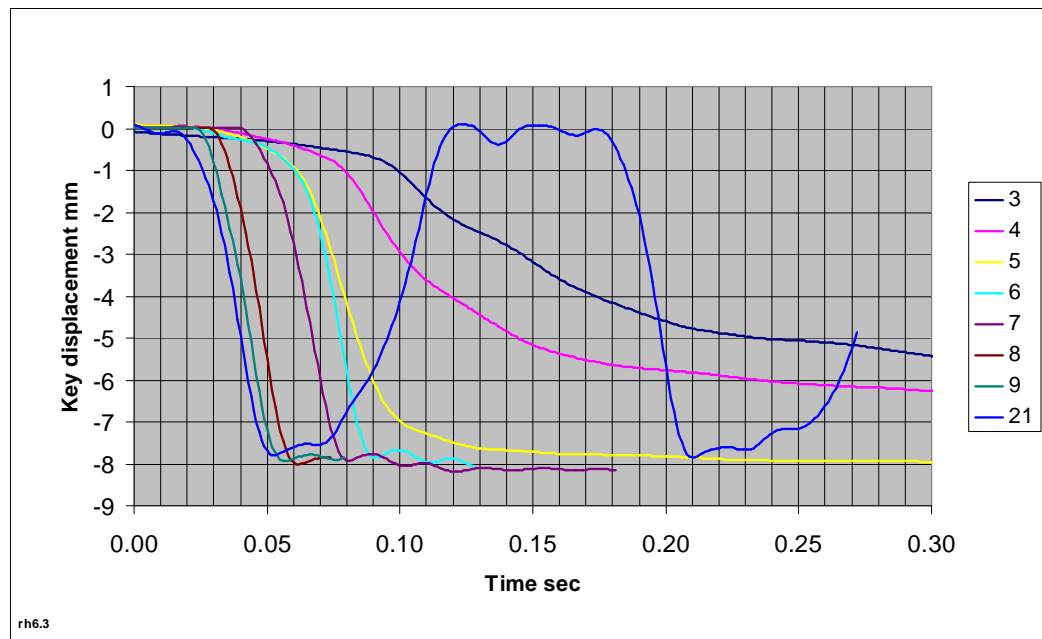Fig 7.3.2 shows selected representative key depressions from those recorded in Fig 7.3.1.

Fig 7.3.2 Selected representative key movements from Fig 7.3.1. The curve numbers correspond with the number of the curve in the previous graph where the first key movement on the left in number 1. The horizontal displacement is arbitrary. Rose Hill Methodist Chapel Middle c[1].

The first two key movements have been disregarded as being unrepresentative of normal playing although this is a subjective judgement. The horizontal displacement is simply for ease of interpretation and has no significance. Only one representative curve is shown after the ninth movement because by this stage the movement had achieved a considerable degree of consistency. The first four curves (numbers 3,4,5 & 6) show a distinctly shallower start up to between 0.8 mm and 1 mm. This is due to the small amount of flexibility in the action being taken up until pluck is overcome. This is not apparent in later movements, which suggests that the player is doing something fundamentally different. Movements 8 and 9 both took 30 ms and movement 21 took 34 ms (i.e. longer) from rest to full travel.

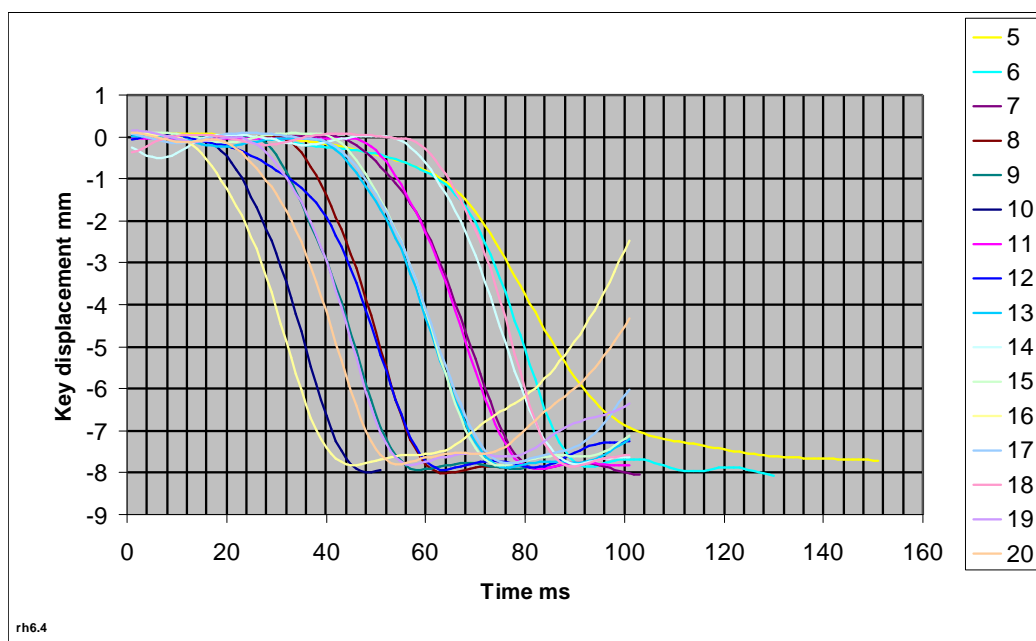Fig 7.3.3 shows all movements from number five to number twenty.

Fig 7.3.3 Graph showing the key movement against time for all movements from number five to number twenty as depicted in Fig 7.3.1. Rose Hill Methodist Chapel Middle c[1].

After the first two movements all curves are remarkably similar. The obvious exception, in the pre-pluck movement, is number twelve (dark blue). There is no obvious explanation for this. This is the second key movement after a short break in the sequence in which the player apparently prepared himself for the faster key movements to come. This was an early indication, not fully recognised at the time, that even if players could vary the initial notes of a sequence to some extent, this was not necessarily so when they were in the middle of a piece.

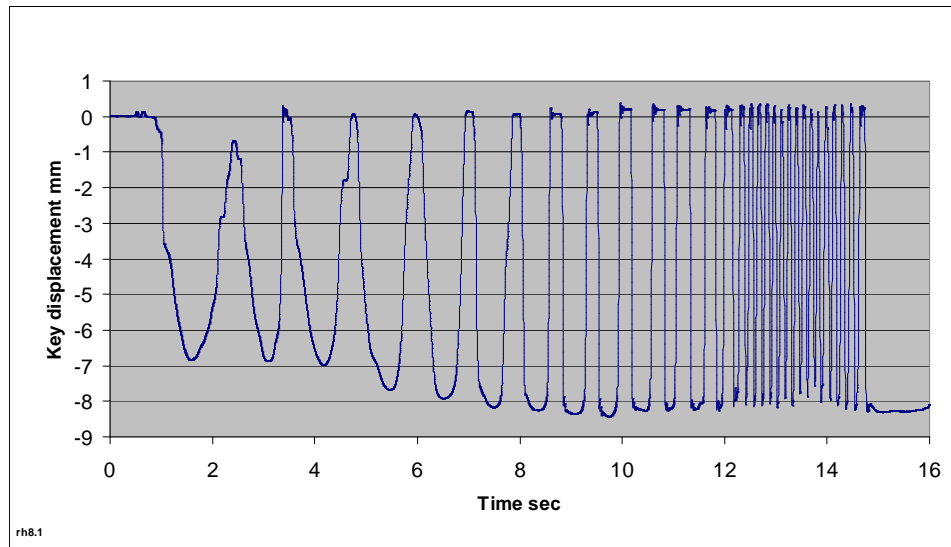Fig 7.3.4 shows the same exercise but on full organ less the Dulciana.

Fig 7.3.4 Graph showing key movement against time as the player tries to move the key increasing quickly. Full organ less Dulciana, c^1, Rose Hill. 0 displacement is the rest position of the key and downward movements are indicated by a negative displacement.

Again, the first movements have been disregarded in the following chart, Fig 7.3.5, which shows representative movements. For clarity, these have been restricted to five, the others following the same pattern as previously.
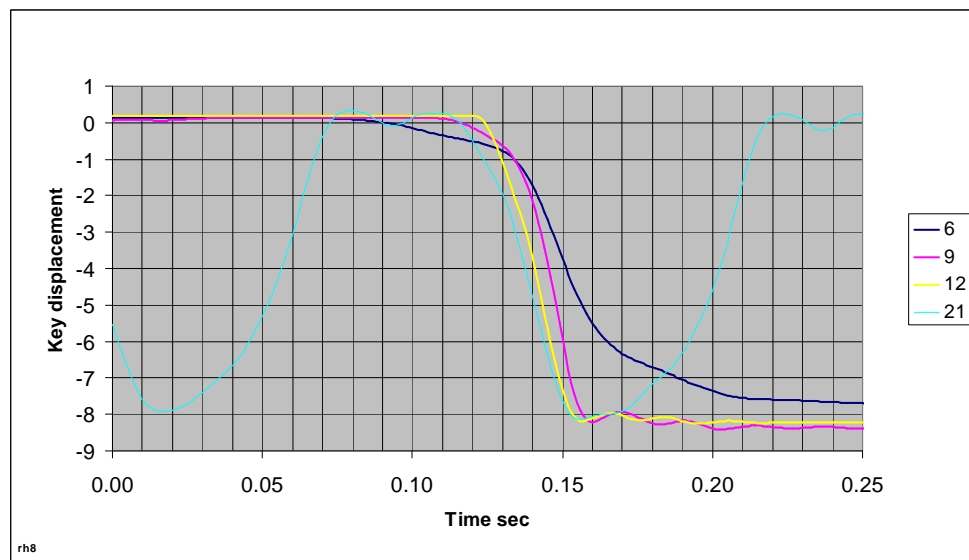

Fig 7.3.5 Selected representative key movements from Fig 7.3.4. The curve numbers correspond with the number of the curve in the previous graph where the first key movement on the left in number 1. The horizontal displacement is arbitrary. Rose Hill Middle c^1.

Again, it can clearly be seen that after the first few movements the profile of the key movement becomes fairly constant. The total time for movement number 12 is 31ms and number 21 is 40ms. Again, the "faster" movements are slightly slower than the early ones although neither shows the pre-pluck effect of numbers six and nine. This again suggests that the player is doing something fundamentally different – possibly playing from the wrist rather than the finger, the inertia of the whole hand not being affected by the varying resistance of the action as is the finger alone.

Fig 7.3.6 shows the velocity of the movements shown in Fig 7.3.5. These have been calculated assuming a linear output from the sensor. The expected average value would be about 0.26 ms^{-1} given a key dip of 8 mm and a time of travel of 30 ms.
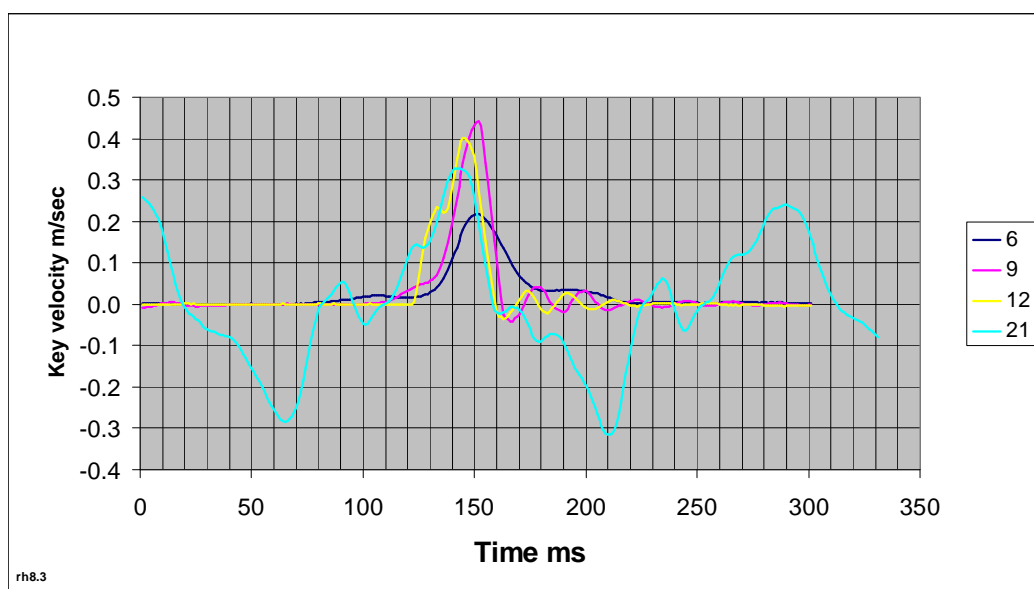

Fig 7.3.6. The acceleration of the key head during the key movements depicted in Fig 7.3.5. Rose Hill Methodist Chapel, Middle c^1 full organ less Dulciana.

It can again clearly be seen that, with the exception of number six, the peak velocities are in inverse relationship to the "speeds" perceived by the player, varying between 0.30 ms^{-1} and 0.55 ms^{-1}. The "kink" in the upward slope of some of the curves appears to be characteristic of this organ and is either due to friction in the action or possibly to vibration.

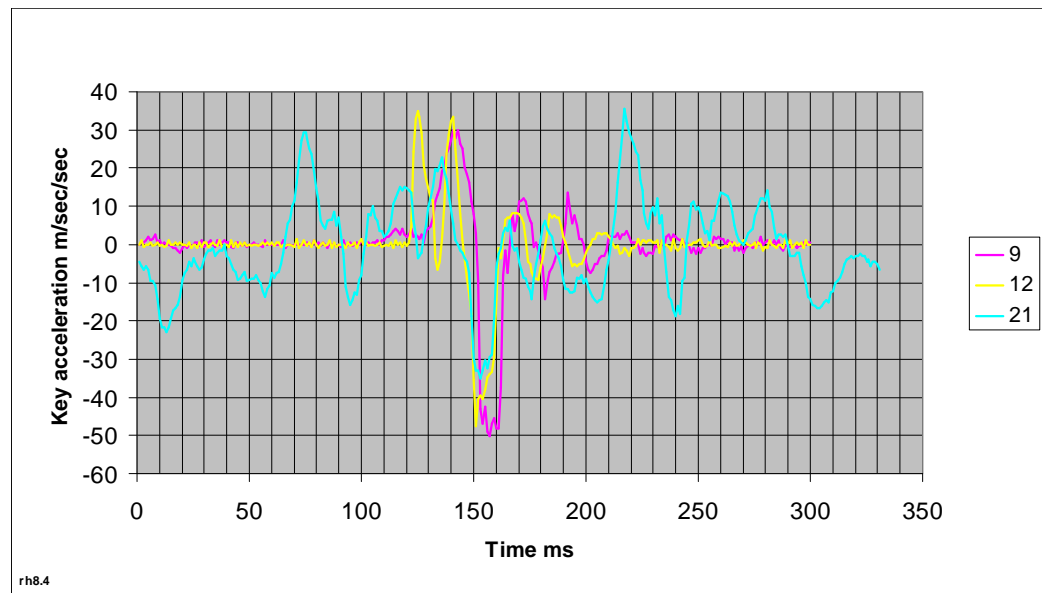The accelerations of the same movements are shown in Fig 7.3.7.

Fig 7.3.7 Graph showing the acceleration of the key head for the key movements shown in Fig 7.3.5.

The peak acceleration is approximately 35 m/s². The peak deceleration is approximately 50 m/s² when the key hits the key bed. Although the inertia of such an action may not be large, it nevertheless has to stop quickly – an important factor in action design.

7.3.3   J S Bach fugue

The next stage considered how this relates to what this player does during actual performance since he does not appear to vary the speed of movement to the extent that believed that he was in an exercise he designed to demonstrate that he did.

The player chose to play a Fugue from the Eight by J S Bach in order to demonstrate the expression due to change of key speed. The outputs from all working sensors are

shown in Fig 7.3.8. These have all been smoothed over ten data points. Figs 7.3.9 to
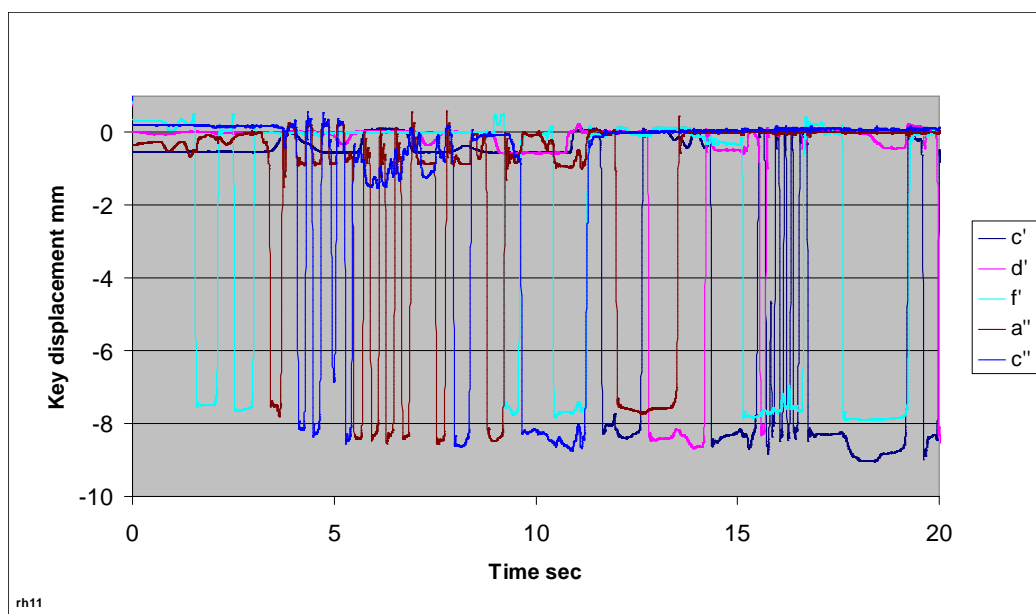7.3.13 show each key in isolation.

Fig 7.3.8 Graph showing all recorded key movements during performance of a J S Bach
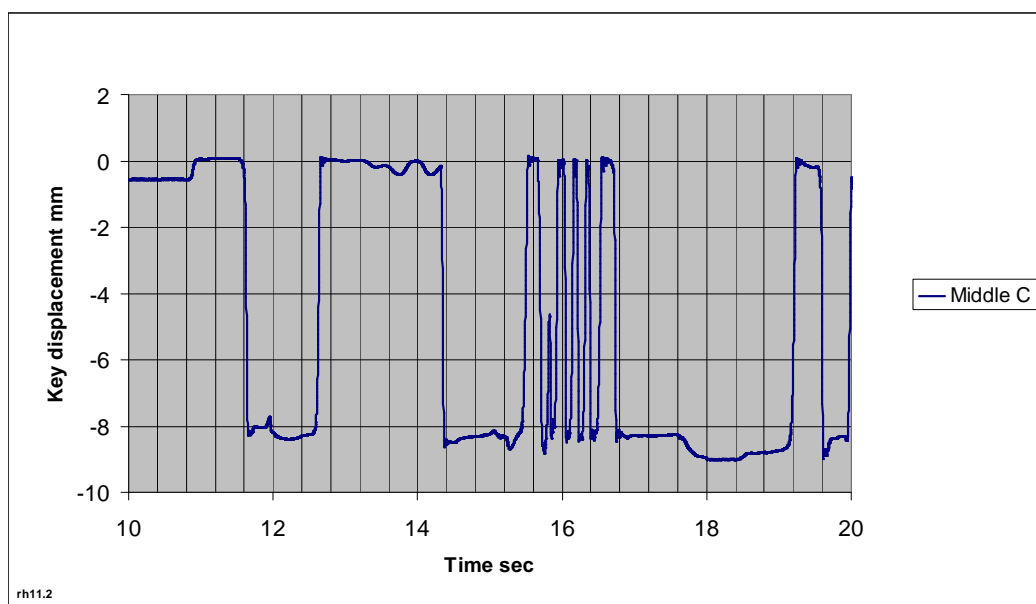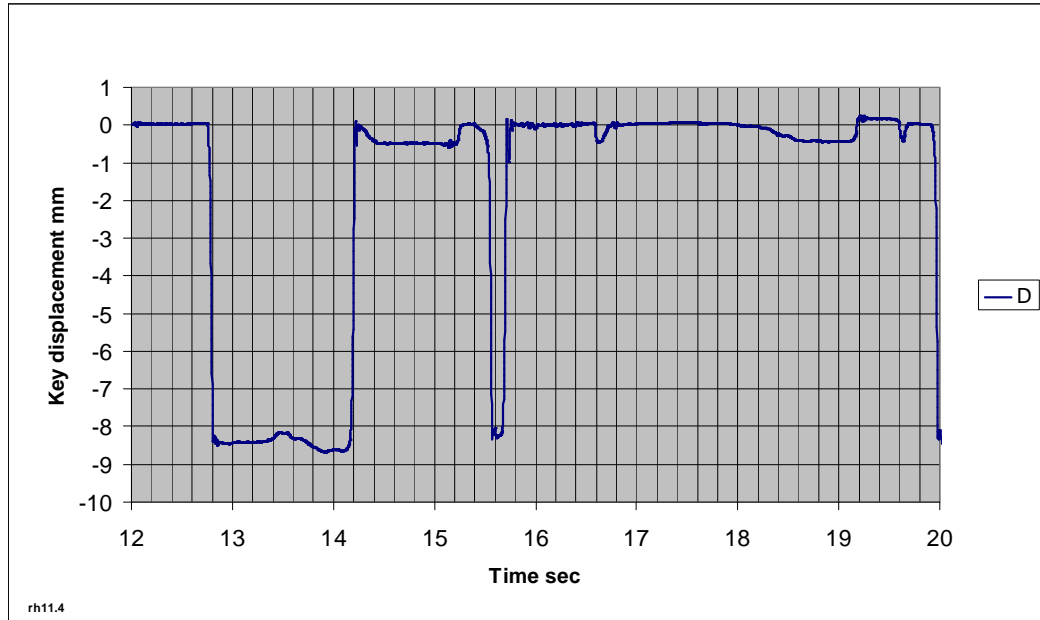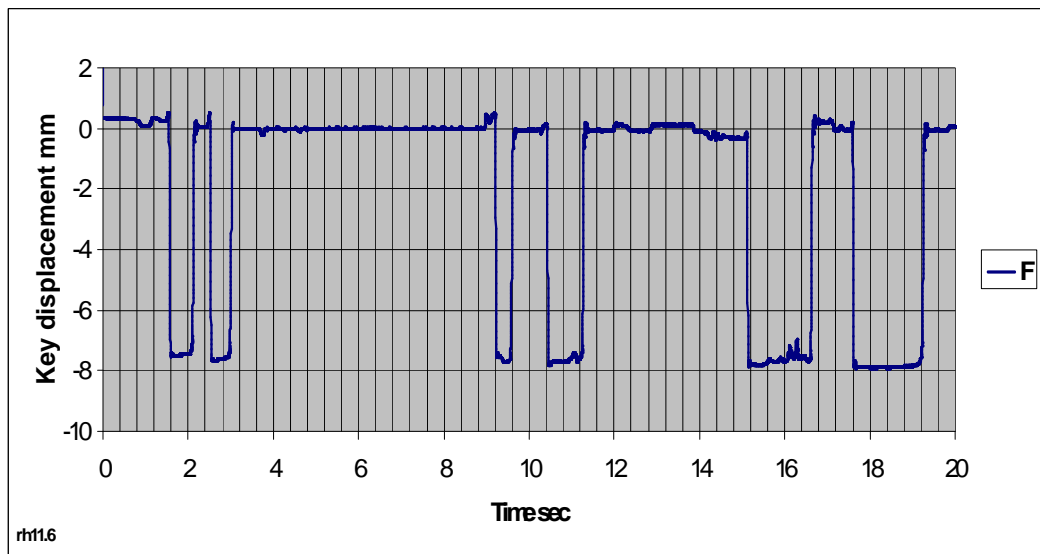fugue. Rose Hill Methodist Chapel, Stopped Diapason

Fig 7.3.9 Middle c^1 key movements from Fig 7.3.8

Fig 7.3.10 d^1 key movements from Fig 7.3.8

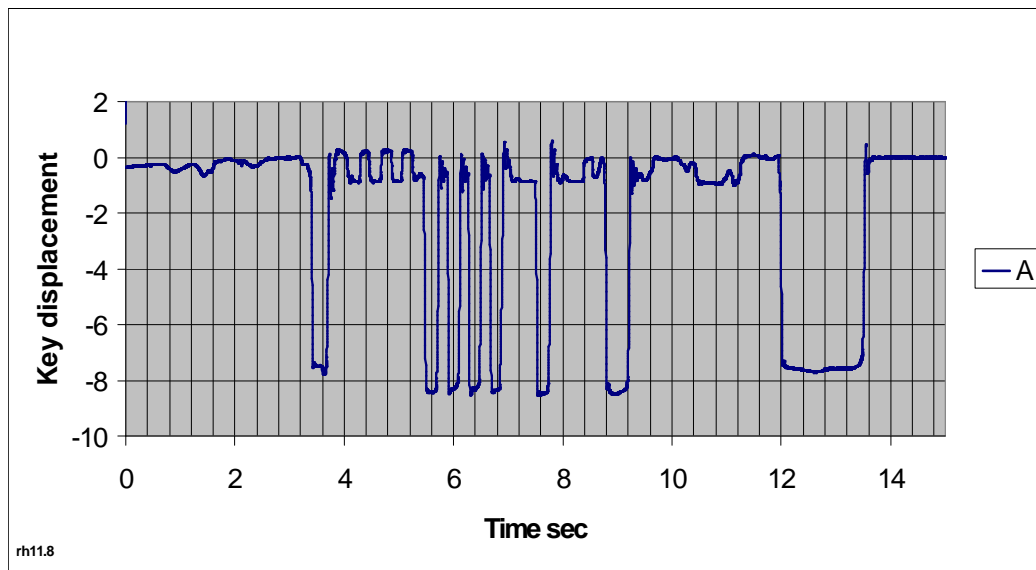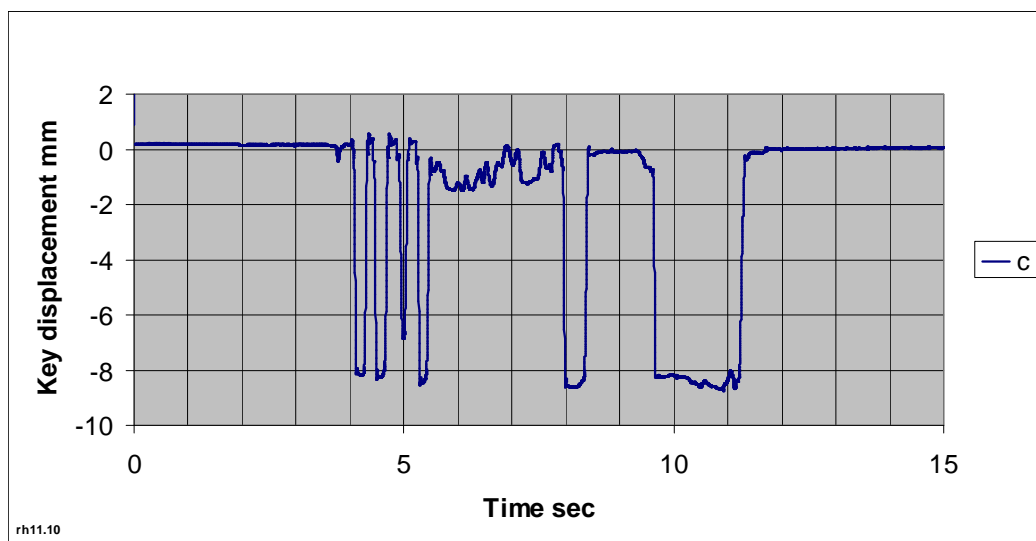Fig 7.3.11 f^1 key movements from Fig 7.3.8

Fig 7.3.12 a^2 key movements from Fig 7.3.8

Fig 7.3.13 c^2 key movements from Fig 7.3.8

Fig 7.3.14 shows all Middle c^1 key depressions in the order in which they were made. Assuming that pluck is overcome at 0.8 mm, the times of travel post-pluck are 37 ms, 33 ms, 39 ms, 25 ms, 27 ms, 23 ms, 25 ms and 31 ms.
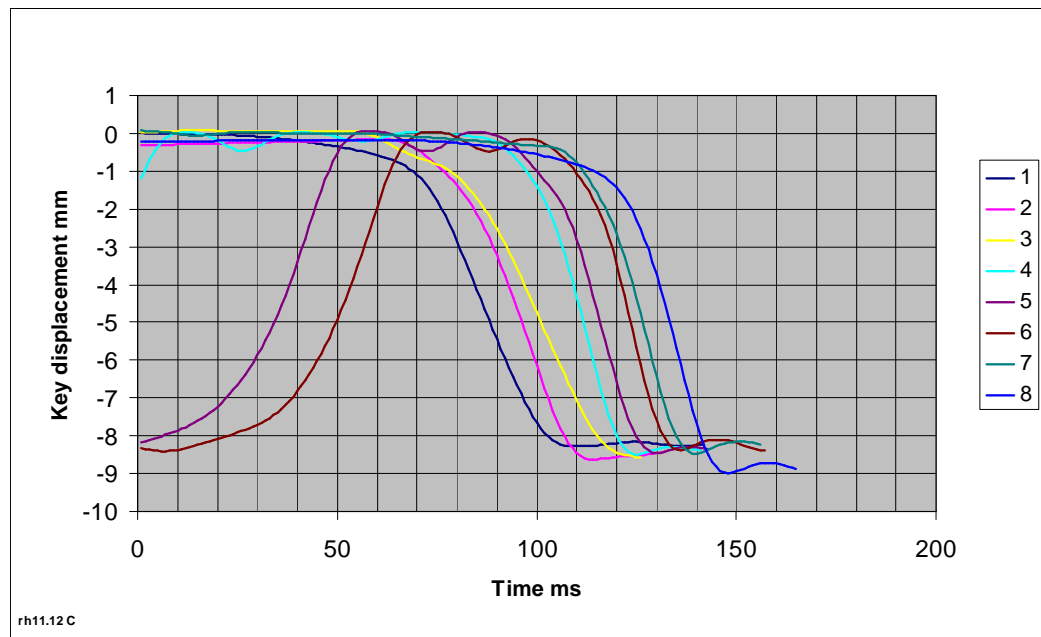
Fig 7.3.14 Graph showing the key movements of all the Middle c[1] notes played in the Bach fugue recorded in Fig 7.3.8. The number of the curve represents the order in which the note was played. Rose Hill Methodist Chapel.

Fig 7.3.15 shows the same information for all the f[1] notes recorded in Fig 7.3.8
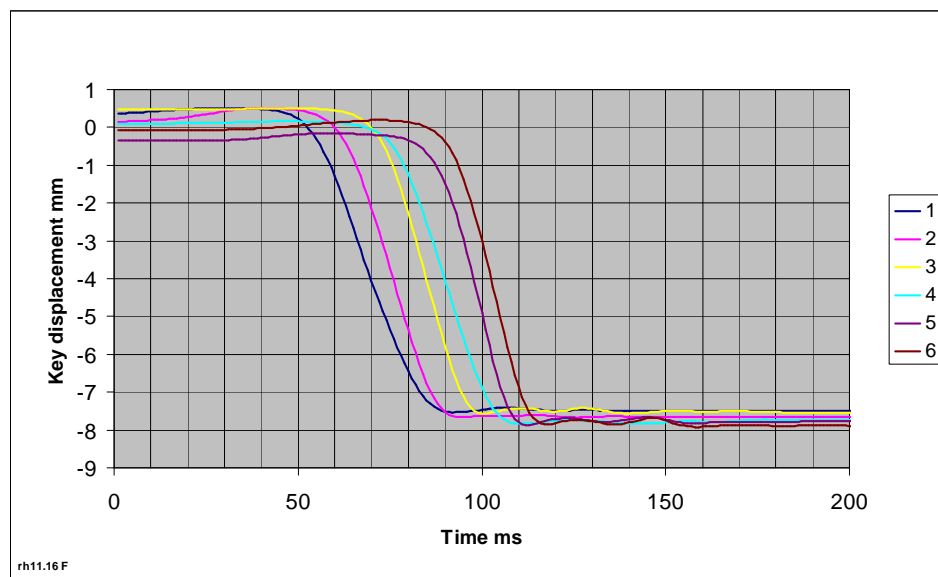

Fig 7.3.15 Graph showing the key movements of all the f[1] notes played in the Bach fugue recorded in Fig 7.3.8. The number of the curve represents the order in which the note was played. Rose Hill Methodist Chapel

Fig 7.3.16 shows the same information for all the d^{1}s recorded in Fig 7.3.8

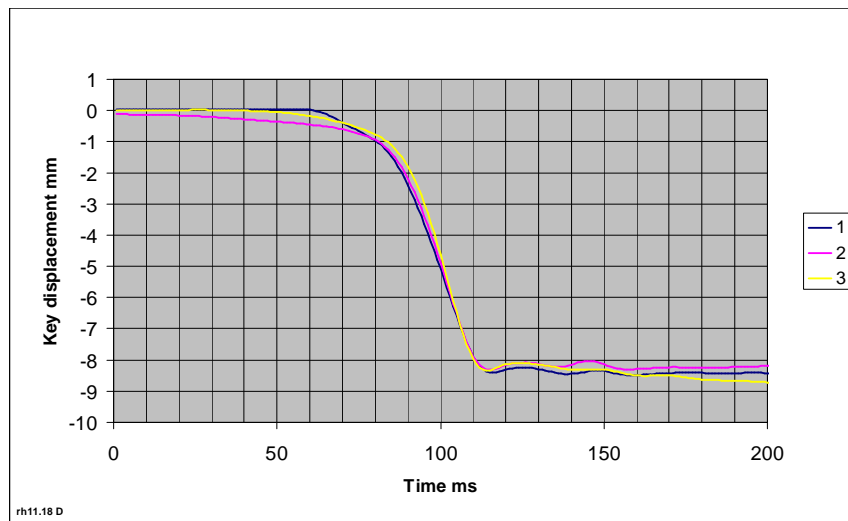
Fig 7.3.16 Graph showing the key movements of all the d^{1}s recorded in Fig 7.3.8. The number of the curve represents the order in which the note was played.

Fig 7.3.17 shows the acceleration of the key head of the three key movements depicted in Fig 7.3.16.
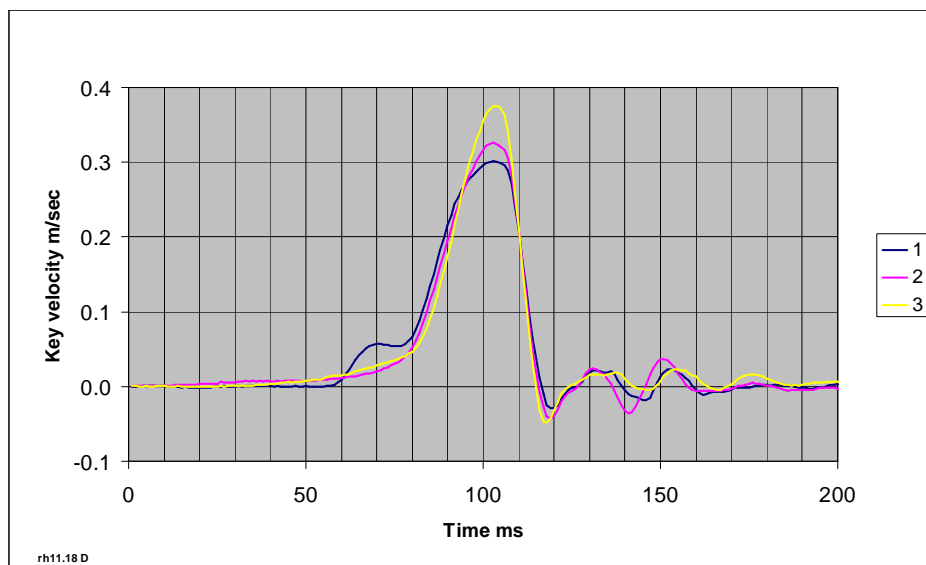
Fig 7.3.17 Graph showing the acceleration of the key head in the key movements shown in Fig 7.3.16. d^1 Rose Hill Methodist Chapel

7.3.4   Finale

Following the session at Rose Hill, Dr Singleton wrote, with a copy to the editor of the IBO Newsletter:

> Having played for you, watched the measurements and seen the data coming out on the screen, I am partly convinced that some of the things that I thought that I was doing whilst playing are illusory![1]

---

[1] E-mail to author

7.4 Radley College, Radley, Oxfordshire

7.4.1 Introduction

The organ was built by Hill Norman and Beard in 1980 and, with the exception of the en chamade (horizontal) trumpet, the manual action is mechanical. The façade is shown in Fig 7.4.1.

Fig 7.4.1 The façade of the organ in the Chapel of St Peter, Radley College, Radley Oxfordshire, Hill, Norman and Beard 1980.

The organ is looked after by John Bailey of Bishop and Sons. With the permission of the School authorities and under the direct supervision of Mr Bailey, sensors were installed inside the wind chest. The Swell organ was selected as being most readily accessible and middle c^1 selected as a representative note.

The cables were fed round the edge of the face board. The resultant air leak was not considered to be a problem and well within the capacity of the wind system.

Fig 7.4.2 The console of the organ in the Chapel of St Peter, Radley College. John Bailey, curator of the organ, is checking the force required to move a key using a set of key weights.

7.4.2   Measurements of key and pallet movements

This first set of measurements was taken on the 15th February 2005 and was intended to obtain some information about how a mechanical action organ of significant size behaves in practice. The sampling rate was 10 kHz. The microphone was placed over one of the swell shutters and there is considerable background noise.

Since these key movements were made in isolation it is not possible to categorise them in terms of how they might relate to "normal" playing. They can simply be used as a reference. Any descriptions of speed of movement are purely subjective.

The first graph, Fig 7.4.3, shows the key movement, pallet movement and waveform envelope for a "slow" key movement – sequence A. The trigger point is such that the first part of the key movement has not been recorded.
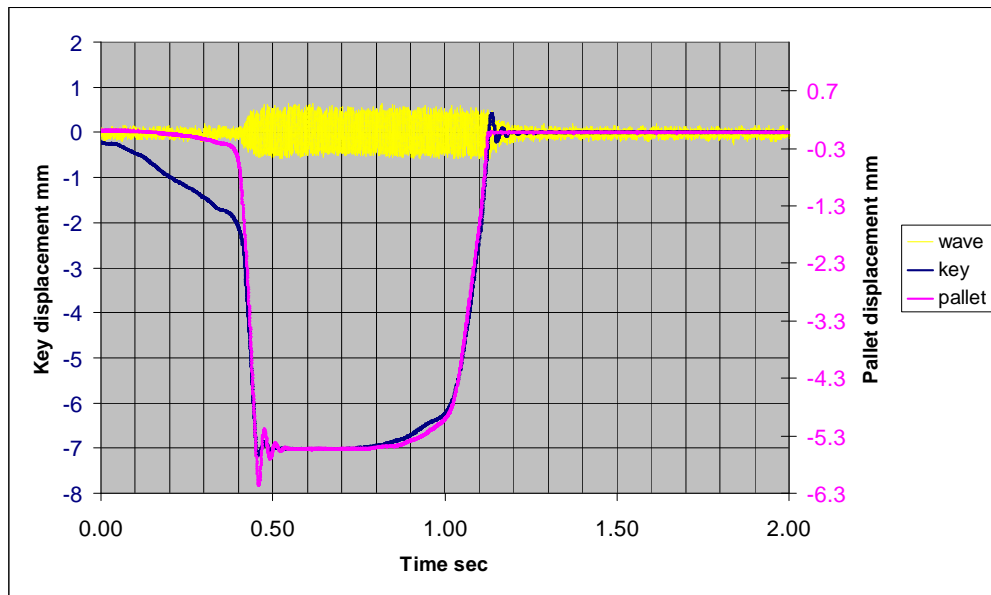

Fig 7.4.3 Sequence A. Graph showing the key movement, pallet movement and sound recording for a "normal" key movement. The sound recording amplitude is to an arbitrary scale. Radley College
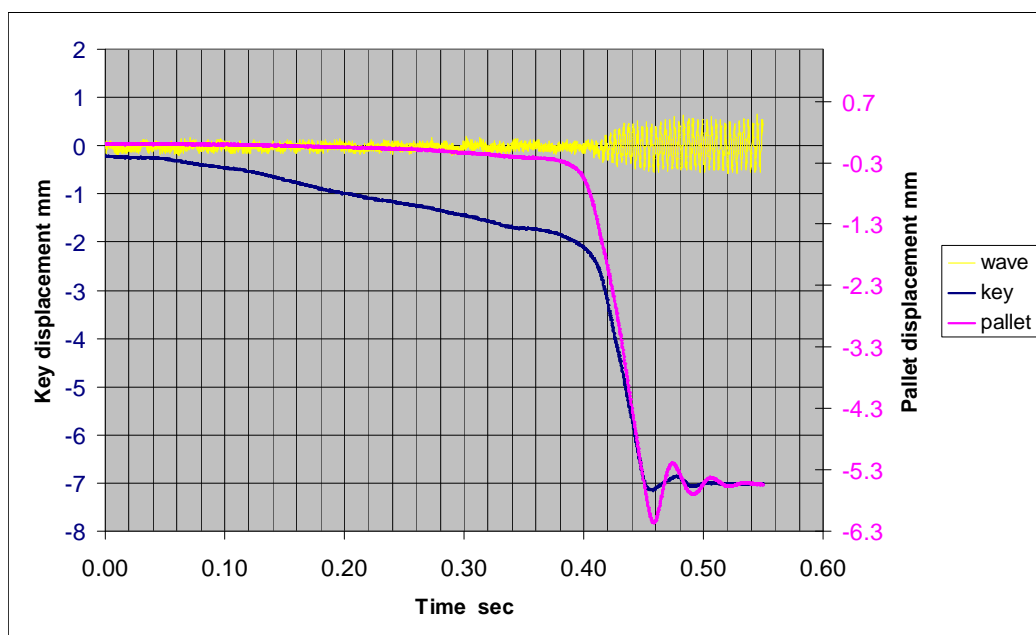
Fig 7.4.4 shows the key depression on an expanded scale.

Fig 7.4.4 Sequence A. Graph showing key depression, pallet movement and sound envelope
for a "normal" key movement. Radley College. Middle c[1] Great Stopped Diapason

The key rest position is at zero displacement. There is a very clear point at which the pallet starts moving more quickly but the pallet actually starts moving before this point allowing a flow of air to the pipe. This may be due to the leather and felt facing expanding and the air leaking through the gaps in the leather facing (this suggestion was made by Dr David Wylde of Henry Willis and Sons in a private conversation). The pluck point comes after approximately 2mm travel out of a total of 7mm (a very shallow key dip). There is an overrun by the pallet of approximately 0.7mm and with a frequency of oscillation of approximately 30 ms, which is similar to the total travel time of the pallet. The key follows the same pattern of oscillation at lower amplitude. It is not clear whether this is due to it following the oscillations of the rest of the action. The waveform envelope starts developing at approximately the same time as the pallet starts opening.
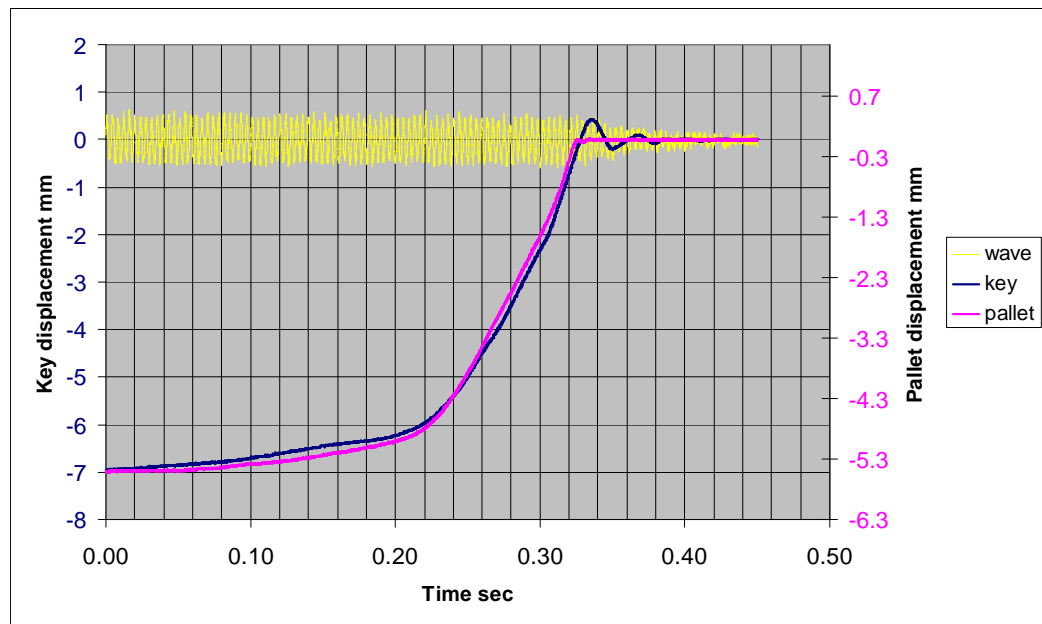
Fig 7.4.5 Sequence A. Key release from the complete "normal" movement shown in Fig 7.4.3. The pallet initial lags behind the key probably due to friction.

Fig 7.4.5 shows the key release. The pallet lags slightly behind the key in the early stages but, due to the effect of the pressure differential across the pallet, reaches its rest position about 3 ms ahead of the key. The pallet shows only a very small degree of oscillation due to it being held firmly closed by the pressure differential whereas the key shows a much greater amount. Despite the slow release of the key and thus closure of the pallet, the sound envelope does not start decaying until the pallet is firmly shut.

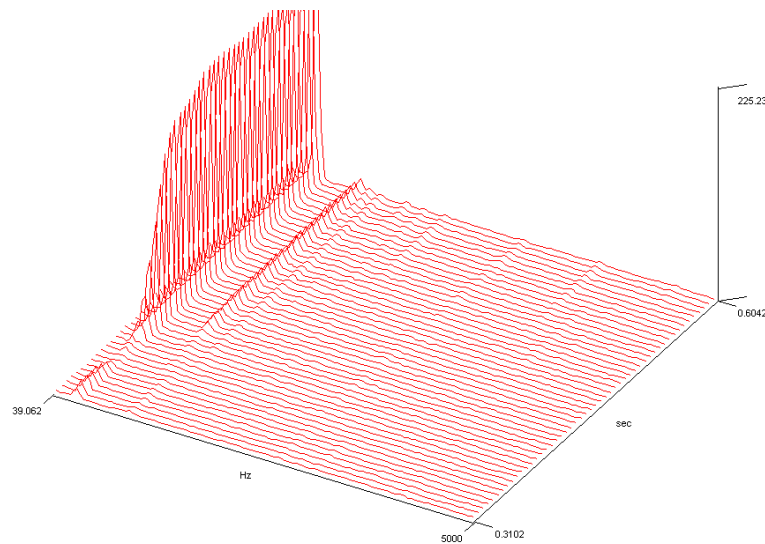Fig 7.4.6 shows a 3D spectral visualisation of the initial transient.

Fig 7.4.6. 3D visualisation of the spectrogram of the initial transient from Fig 7.4.5. The frequency limits are 39 and 5000 Hz. Linear amplitude, arbitrary scale.

The initial movement of the pallet has resulted in a murmur before the main speech of the pipe.

The next sequence of graphs, sequence B, shows a quicker key movement. Fig 7.4.7 shows the complete key movement.
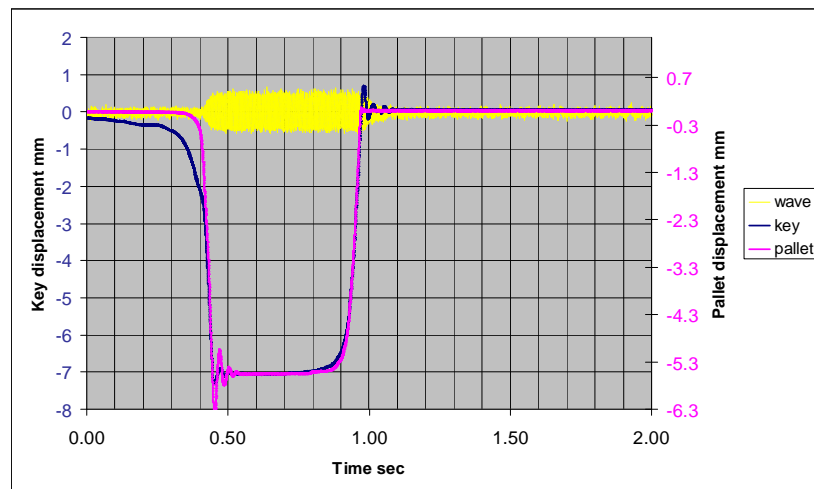

Fig 7.4.7 Sequence B. Graph showing the key movement, pallet movement and sound recording for a "quicker" key movement. The sound recording amplitude is to an arbitrary scale. Radley College

The pluck point remains constant at about 2 mm key travel. As in the previous example there is a further change of gradient at about 0.5 mm. This will be commented on in the next sequence of graphs and will, for the moment, be disregarded. In this key movement the pre-pluck movement is very much shorter and there is only a barely measurable movement of the pallet until the pluck point. Although less clear than in the first example, there is a clear change of gradient in the key movement at the point at which the pallet starts opening.

Fig 7.4.8 shows the opening part of the sequence.
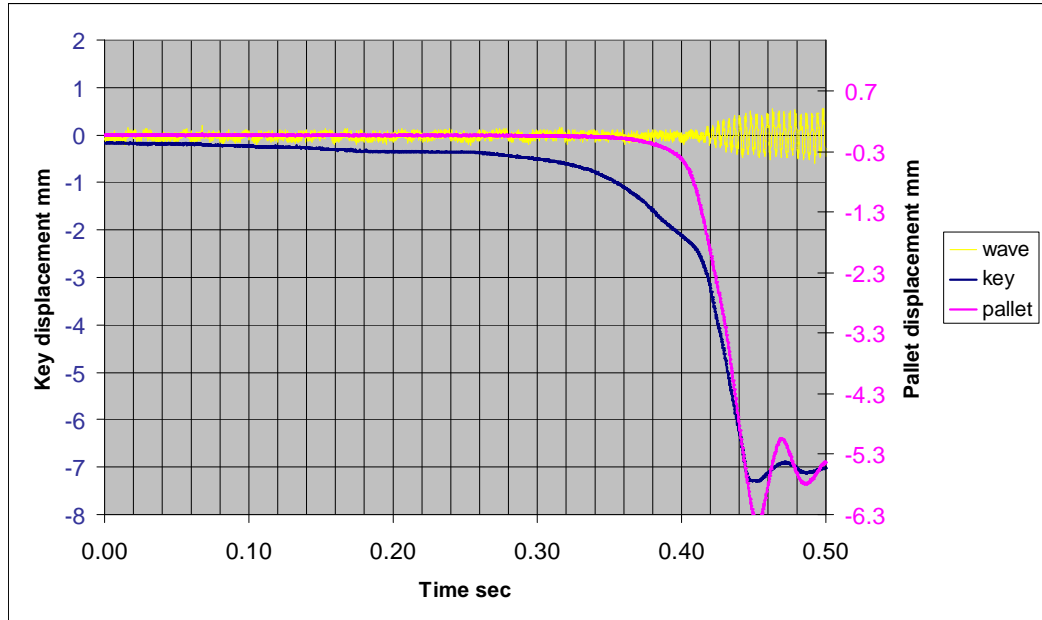

Fig 7.4.8 Sequence B. Graph showing key depression, pallet movement and sound envelope for a "quicker" key movement. Radley College. Middle c[1] Great Stopped Diapason

The pallet overrun is now 1 mm and takes 0.1 s to damp. This could affect the repetition of the note. The sound envelope does not start developing until the pallet has started moving.

Fig 7.4.9 shows the key release.
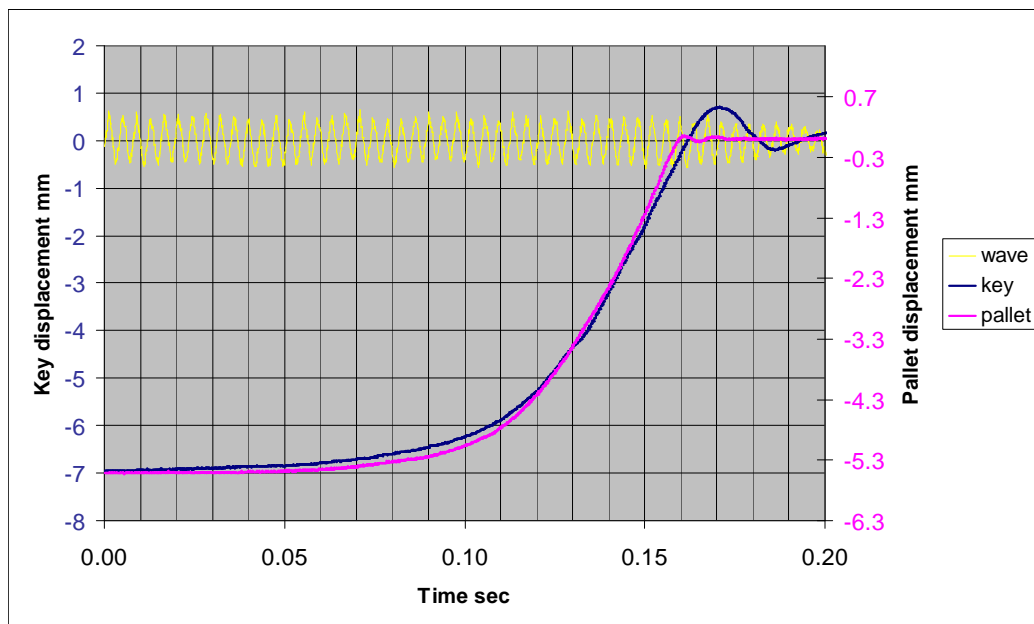
Fig 7.4.9 Sequence B. Key release from the complete "quicker" movement shown in Fig 7.4.6. The pallet initial lags behind the key probably due to friction.

This graph covers half the time scale of Fig 7.4.5 showing the equivalent phase of the first slower sequence A. Again, the sound envelope does not start diminishing until after the pallet has closed.

Fig 7.4.10 shows the 3D spectral analysis of the initial transient of sequence B covering the same time span as Fig 7.4.6. There is some noise on this recording.

Fig 7.4.10 Sequence B. 3D visualisation of the initial transient shown in Fig 7.4.8 using
Sigview 1.91. The frequency limits are 39 and 5000 Hz. Linear amplitude, arbitrary scale.

Sequence C represents a further increase in perceived speed of movement and Fig
7.4.11 shows the complete movement.
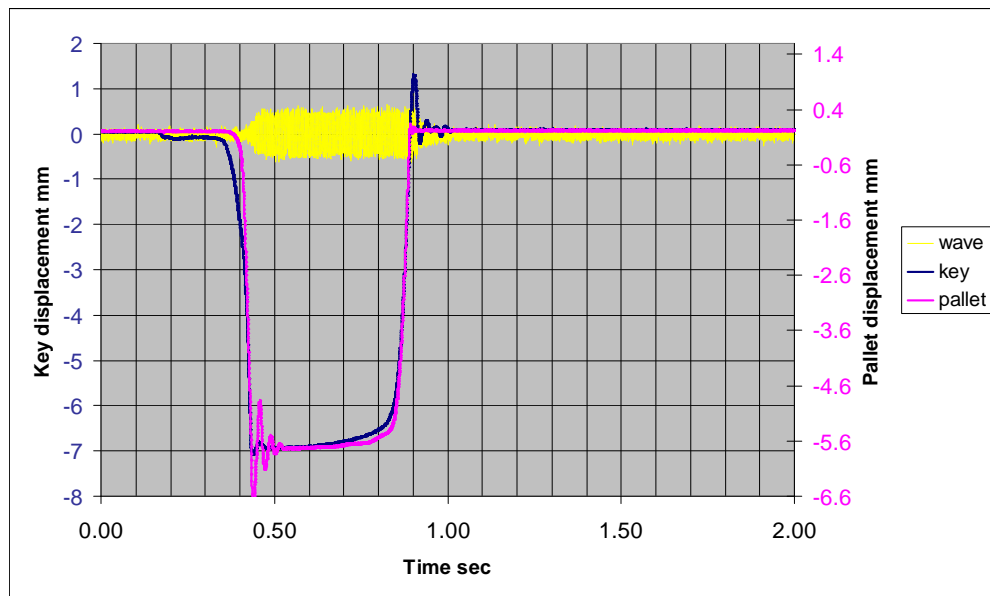
Fig 7.4.11 Sequence C. Graph showing the key movement, pallet movement and sound
recording for a "quicker" key movement than Sequence B. The sound recording amplitude is
to an arbitrary scale. Radley College

The pluck point in the key movement is less distinct but still apparent. The initial movement of the key is, however, very distinct and there is a clear plateau. This is probably due to a small amount of slackness leading to some free movement in the action. The organ's curator told the author that the action had previously been modified to reduce free play by removing lead weights from the backs of the keys. This would have been compensated for by increasing the tension of the pallet springs.

Fig 7.4.12 shows the key depression.

Fig 7.4.12 Sequence C. Graph showing key depression, pallet movement and sound envelope of the movement recorded in Fig 7.4.11. Radley College. Middle c^1 Great Stopped Diapason

The pallet overrun is now 1.25 mm.

Fig 7.4.13 shows the key release.
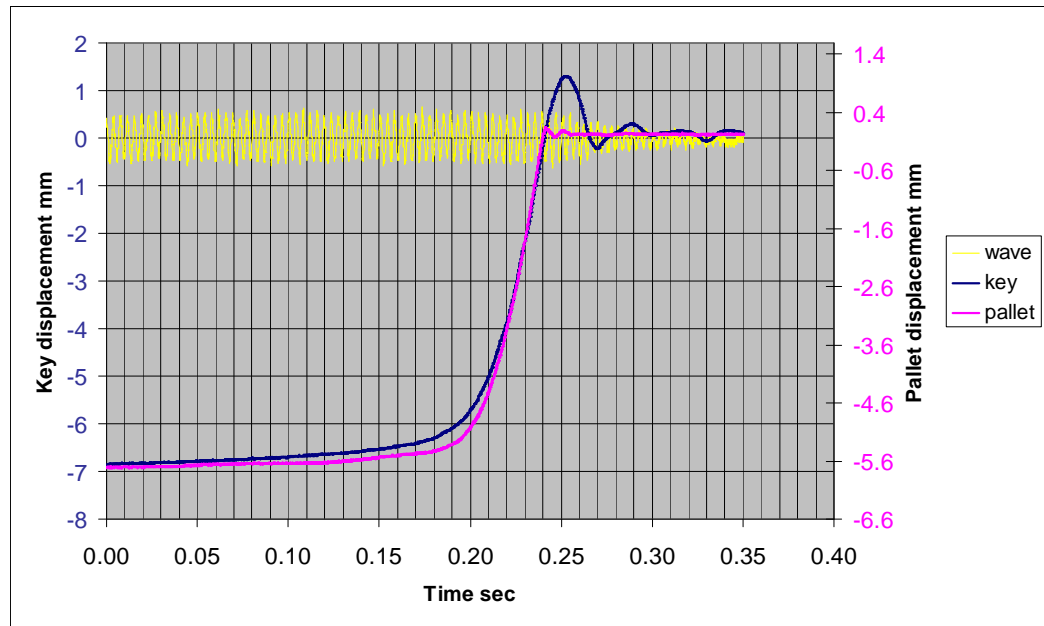
Fig 7.4.13 Sequence C. Key release from the complete movement shown in Fig 7.4.10.
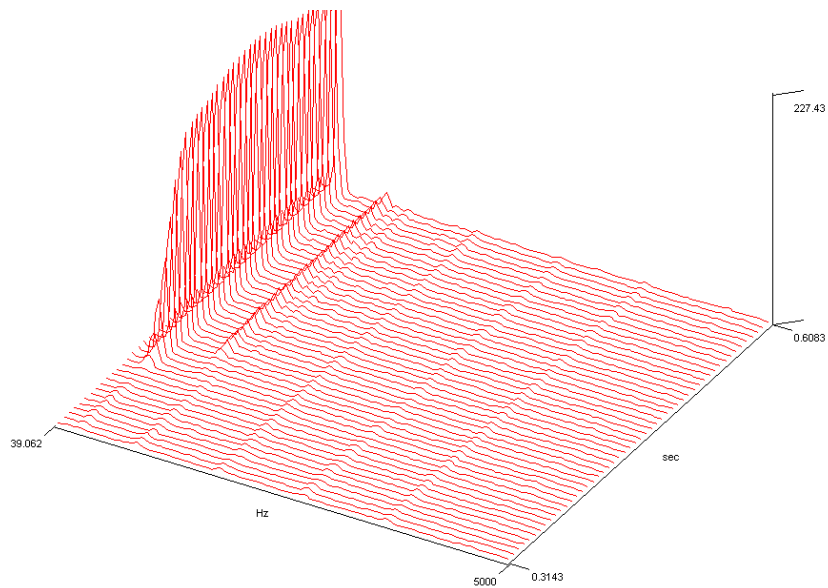
Fig 7.4.14 shows the spectrogram.

Fig 7.4.14 Sequence C. 3D visualisation of the initial transient shown in Fig 7.4.11 using
Sigview 1.91. The frequency limits are 39 and 5000 Hz. Linear amplitude, arbitrary scale.

Sequence D is a "fast" key movement and Fig 7.4.15 shows the overall movement.
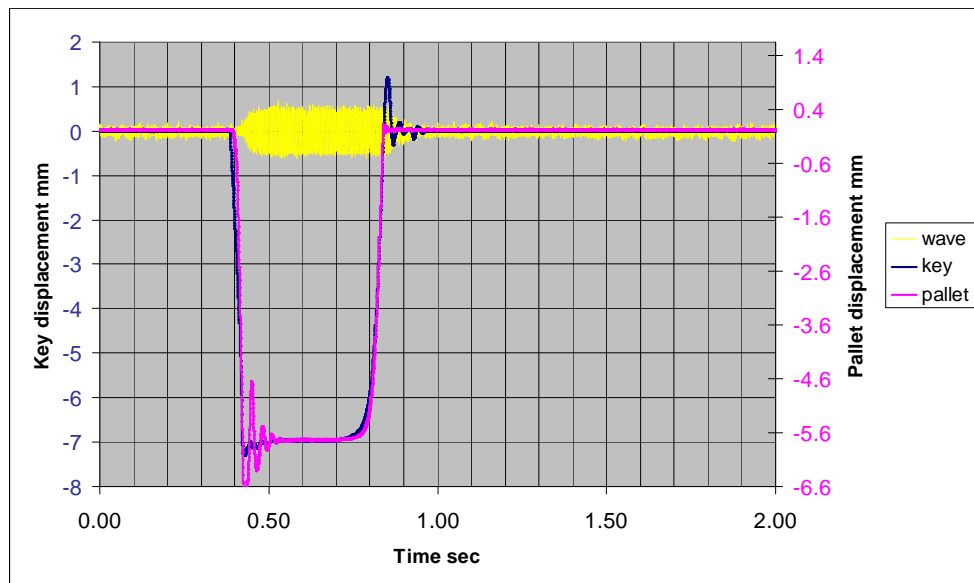
Fig 7.4.15 Sequence D. Graph showing the key movement, pallet movement and sound
recording for a "fast" key movement. The sound recording amplitude is to an arbitrary scale.
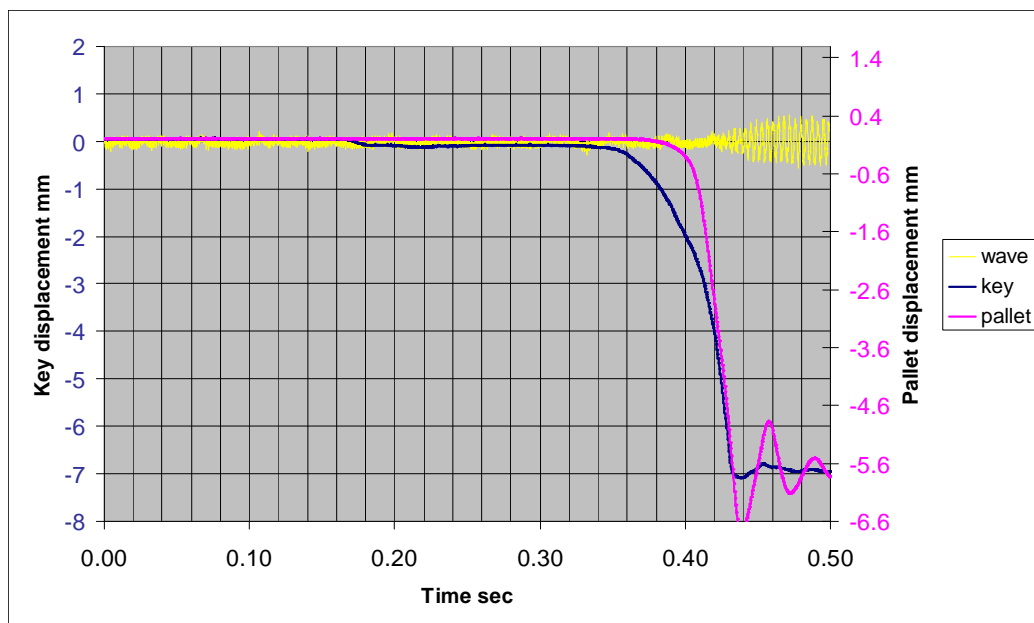
Fig 7.4.16 shows the key depression.
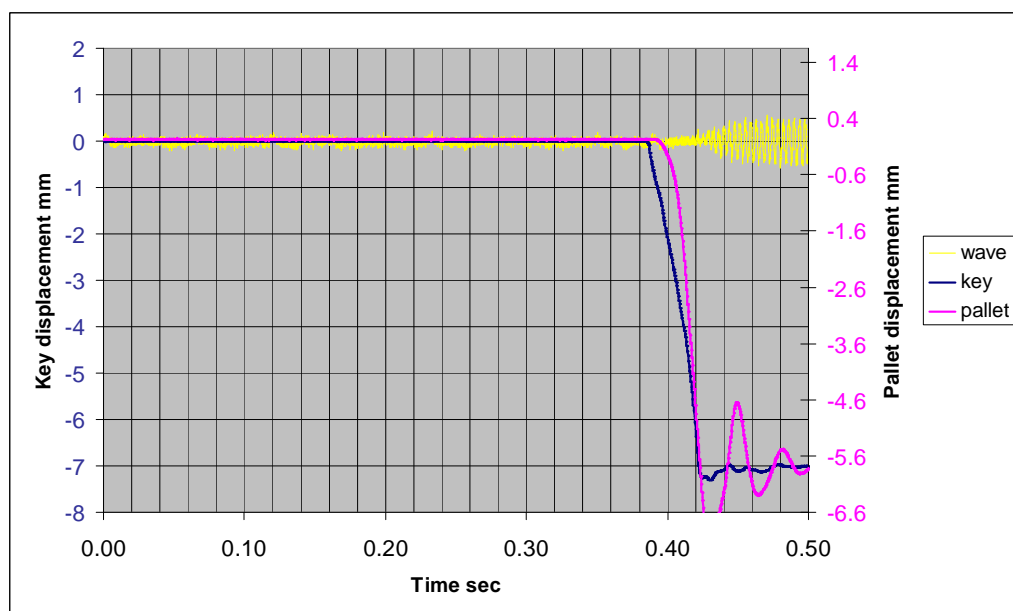
Fig 7.4.16 Sequence D. Graph showing key depression, pallet movement and sound
envelope of the "fast" movement recorded in Fig 7.4.14. Middle c[1] Great Stopped Diapason

Here, the pluck point is not apparent suggesting that this note was played by moving the whole hand rather than just one finger. The result is a "constant velocity" movement rather than a "constant force" movement.

The release is shown in Fig 7.4.17.
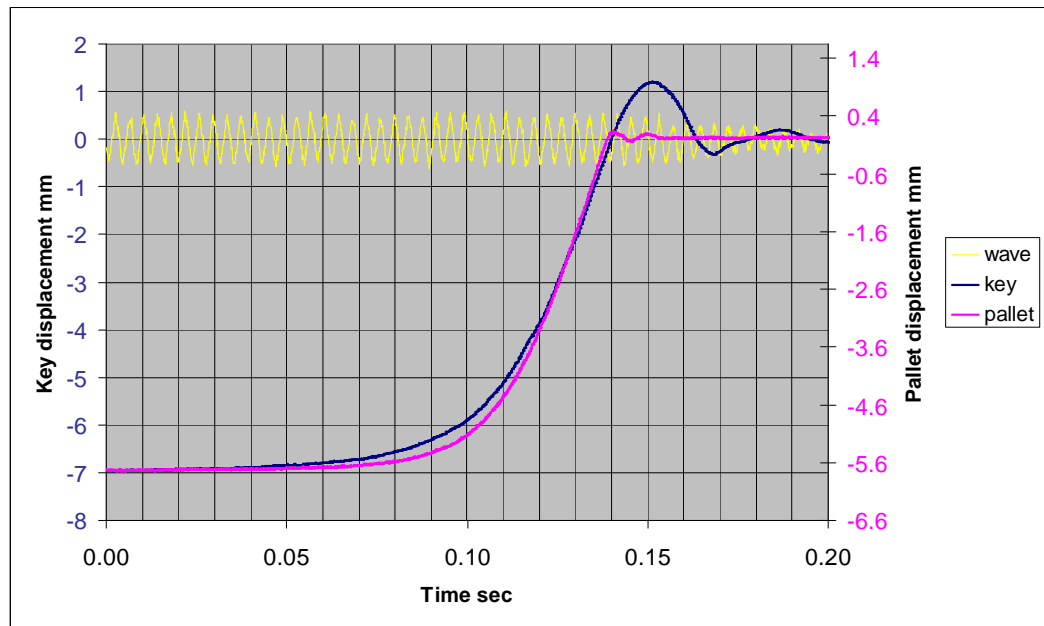
Fig 7.4.17 Sequence D. Key release from the complete "fast" movement shown in Fig 7.4.15.

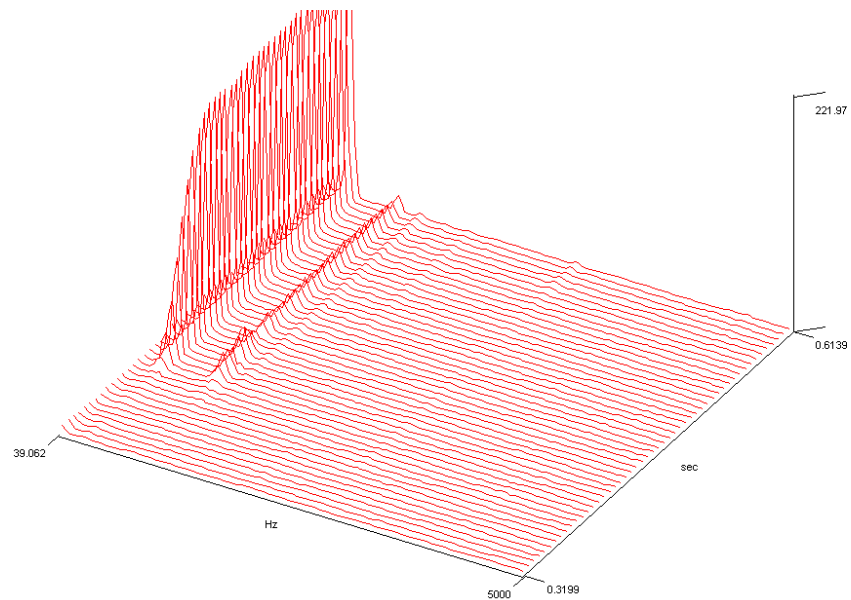Fig 7.4.18 shows the spectrogram of the depression.
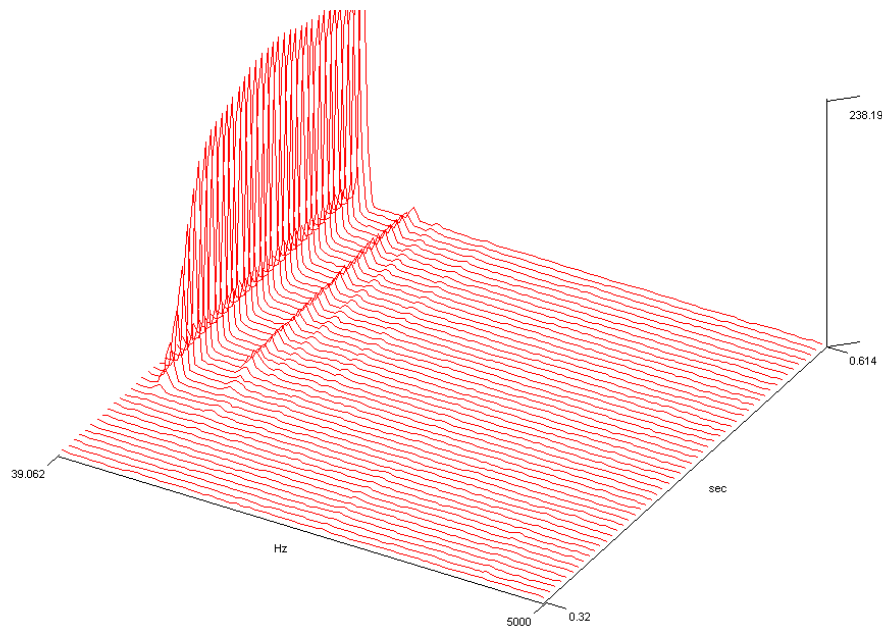
Fig 7.4.18 Sequence D. 3D visualisation of the initial transient shown in Fig 7.4.14 using
Sigview 1.91. The frequency limits are 39 and 5000 Hz. Linear amplitude, arbitrary scale.

Fig 7.4.19 shows the movement of the same pallet (Swell middle c^1) through the
electric Swell to Choir coupler. The coupler is a simple action magnet arranged to
pull down the tracker near the chest. Due to self-inductance it does not allow a good
repetition rate. Part way through its travel the key moves as the slack in the action is
taken up.
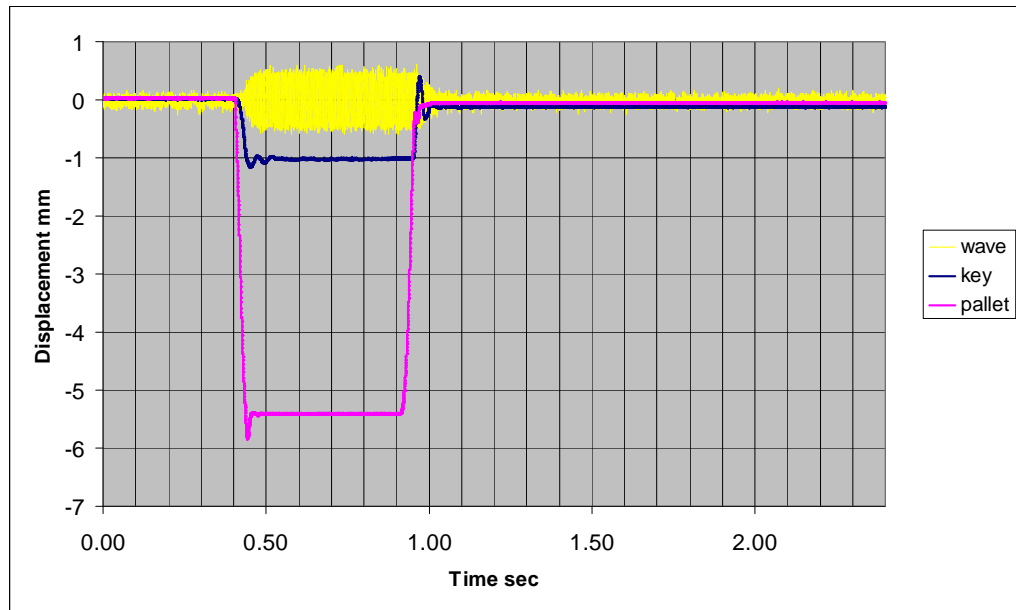
Fig 7.4.19 Movement of the Swell Middle c[1] key and pallet with the note played through the electric Swell to Choir coupler.

Fig 7.4.20 shows the pallet opening. The slowing of the pallet in the later part of its travel may be due to the additional force required to move the key as well.
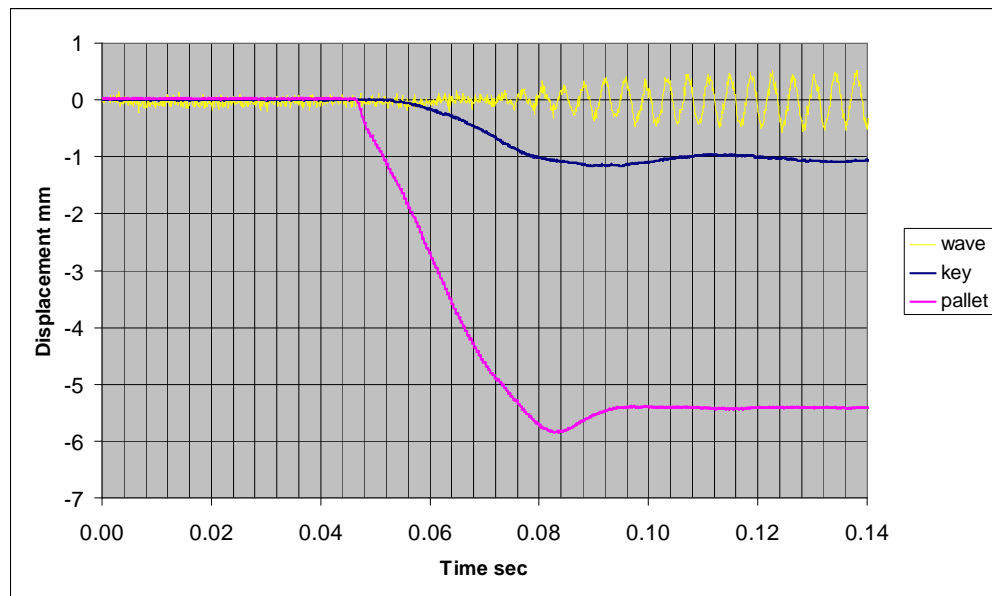
Fig 7.4.20 Initial movement of the Swell Middle c[1] key and pallet with the note played through the electric Swell to Choir coupler.

Fig 7.4.21 shows the pallet return of the Swell Middle C played through the Swell to Choir coupler.
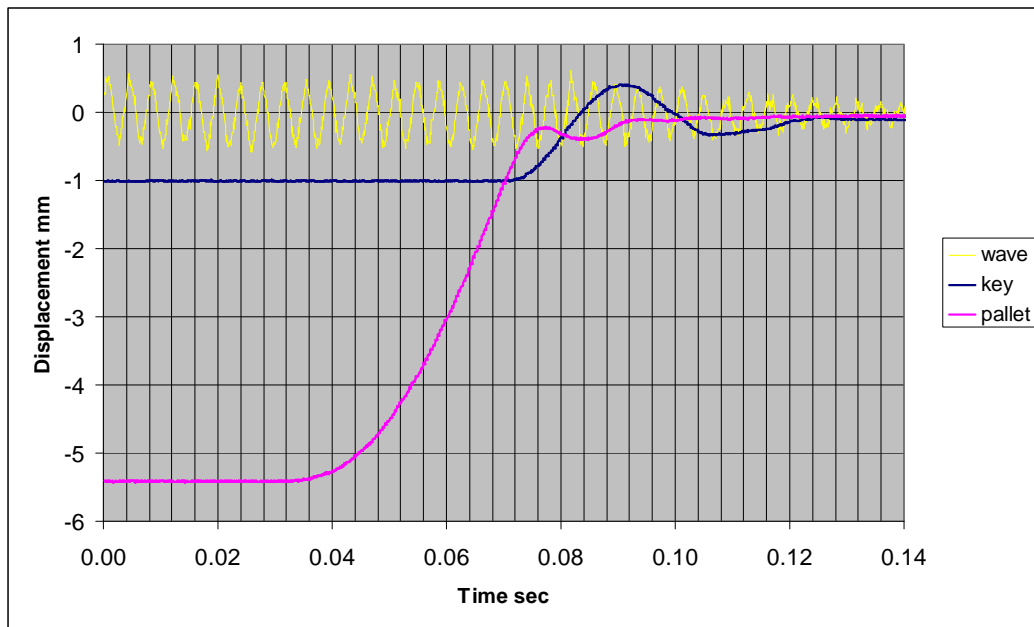
Fig 7.4.21 Pallet return of the Swell Middle c^1 played through the electric Swell to Choir coupler. The initial part of the key curve is coincident with the "-1" displacement gridline.

The movement of the pallet is checked just before it fully closes at the point at which the key starts returning to its rest position. This is possibly not significant in this case but is a phenomenon to be borne in mind in similar installations.

Fig7.4.22 shows a visualisation the 3D spectrogram of the initial transient shown in Fig 7.4.20.
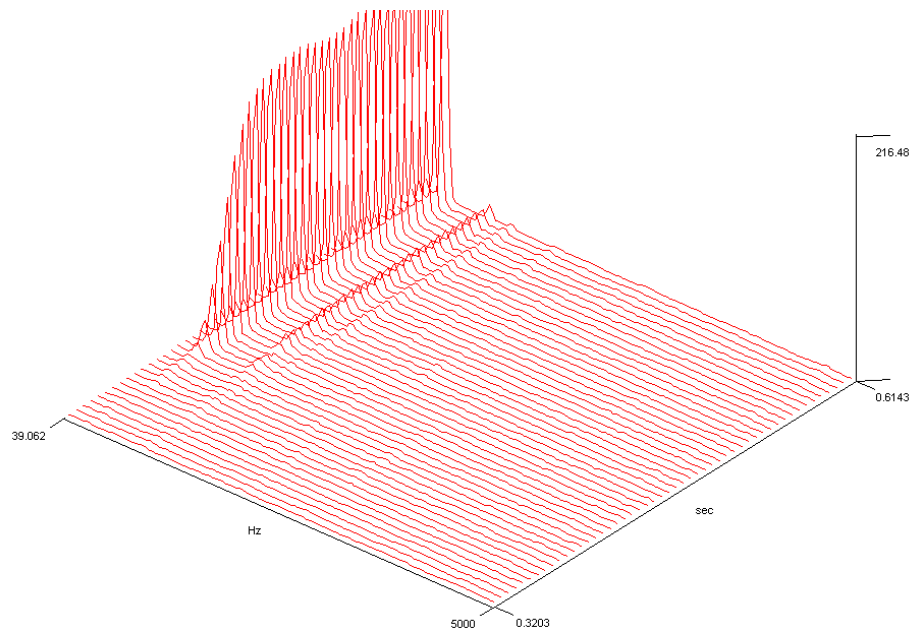
Fig 7.4.22 3D visualisation of the initial transient shown in Fig 7.4.20 in which the Swell pallet was moved using the Swell to Choir coupler. The frequency limits are 39 and 5000 Hz. Linear amplitude, arbitrary scale.

Fig 7.4.23 shows the four key depressions from sequences A, B, C, and D. The perceived speed of movement increases from sequence to sequence.
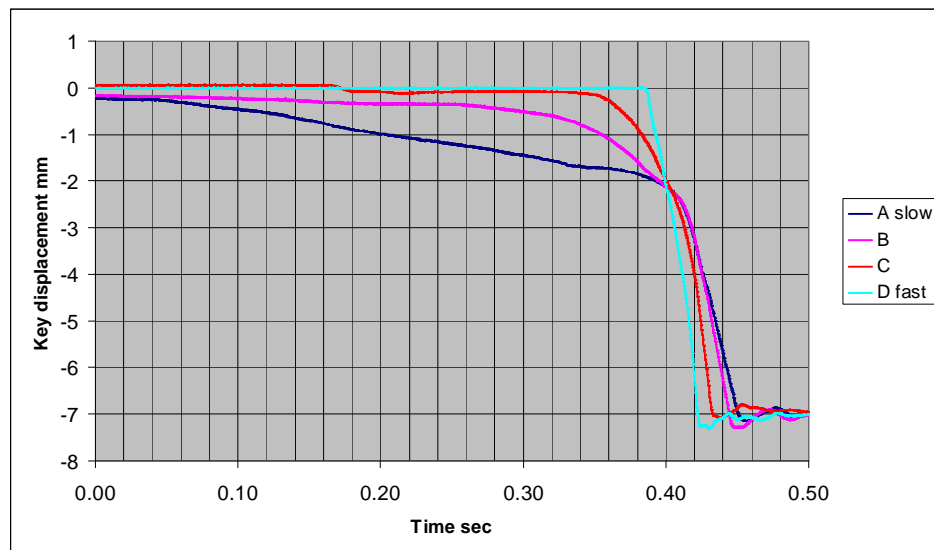
Fig 7.4.23 Graph showing the key movements for the four sequences described above. The speed of movement increases from A to D.

The perception of the speed at which the player is moving the key relates to the time from the key starting to move to the time at which the key hits the key bed. There is a clear difference in the time of post-pluck travel but it is significantly smaller than the difference in pre-pluck movement.

The corresponding movements of the pallets are shown in Fig 7.4.24 with the addition of the pallet movement through the Swell to Choir coupler.

Fig 7.4.24 Graph showing the pallet movements corresponding with the key movements in Fig 7.4.23 with the addition of the movement played through the Swell to Choir coupler.

The pallet movement through the Swell to Choir coupler falls in the middle of the range of "manual" movements.

The envelopes of the five initial transients are shown adjacent to each other in Fig 7.4.25 in order to indicate the similarity. There are clear differences in the shape of the envelope after it has reached its maximum amplitude. It is not clear whether this is due to pressure variations in the chest or due to the speed of opening of the pallet. What is clear is that the initial development of the sound envelope does not

reflect the key movement and does not even show the variation of the pallet movement.

Sequence A (Fig 7.4.6)
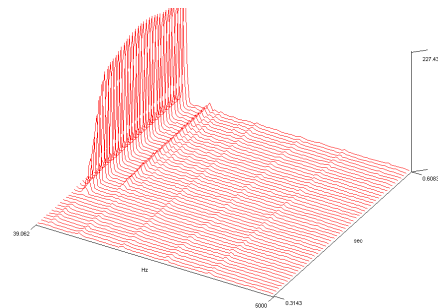
Sequence B (Fig 7.4.10)
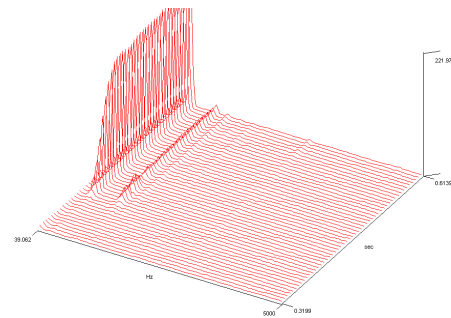
Sequence C (Fig 7.4.14)
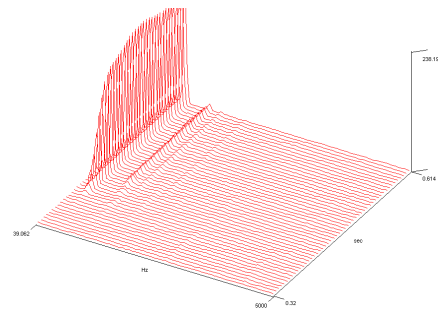
Sequence D (Fig 7.4.18)
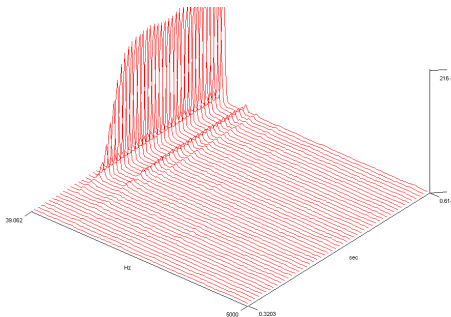
Swell to Choir coupler (Fig 7.4.22)

Fig 7.4.25 Diagram comparing the shapes of the initial transients of Middle c^1 of the Stopped Diapason on the Swell at Radley College with the key moved at different speeds and through the Swell to Choir coupler. Linear amplitude, arbitrary scale.

The closing pallet movements are shown in Fig 7.4.26. Despite the differences in opening movement, the closing movements are much more closely related with the exception of Sequence A, the slowest opening movement.
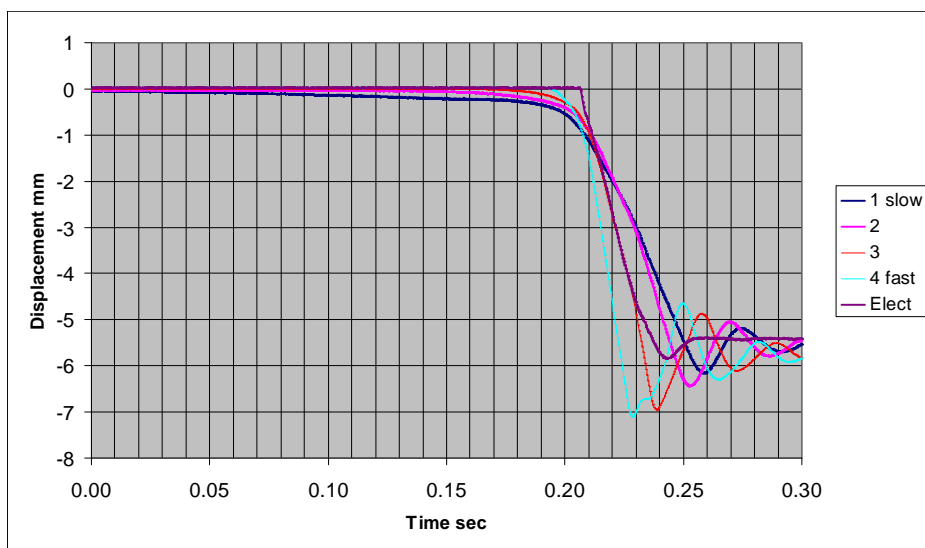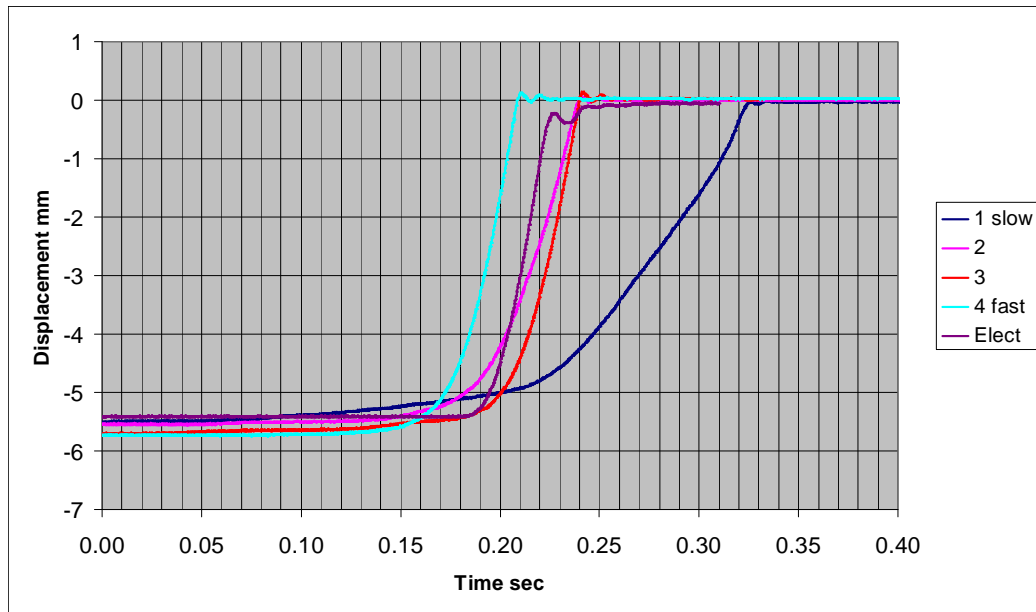
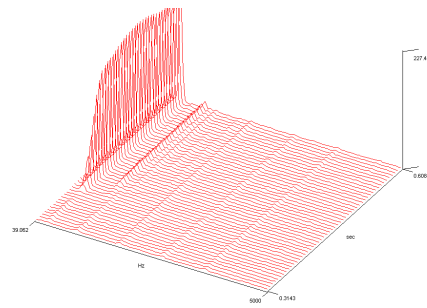Fig 7.4.26 Graph showing the closing pallet movements corresponding with the key movements shown in Fig 7.4.23 with the addition of the movement with the note played through the Swell to Choir coupler.

The spectrograms of the closing transients are shown in Fig 7.4.27. Again, there is some variation in the envelope before the amplitude starts reducing overall, but the shape of the decay is constant between examples.
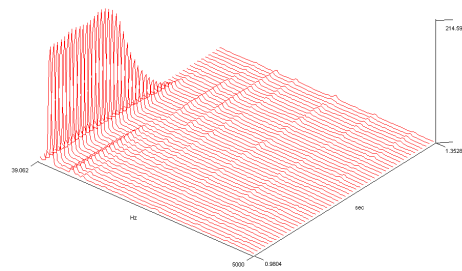
Sequence A
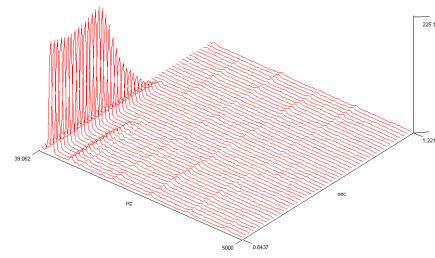
Sequence B
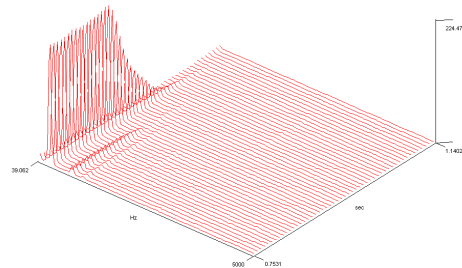
Sequence C
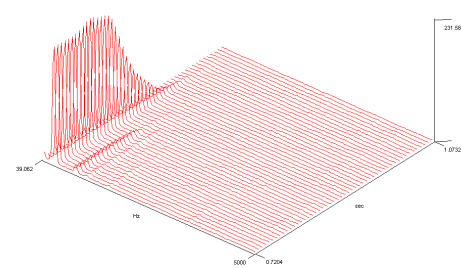
Sequence D
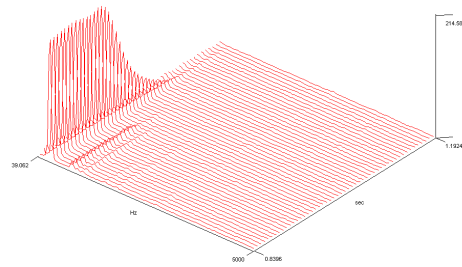
Swell to Choir coupler

Fig 7.4.27 Diagram comparing the shapes of the closing transients of Middle c[1] of the
Stopped Diapason on the Swell at Radley College with the key moved at different speeds
and through the Swell to Choir coupler. Linear amplitude, arbitrary scale.

The particular pipe chosen for these measurements (middle c[1] of the Swell Stopped
Diapason) did not have an audible chiff and there was no difference between the
notes audible to the author or organ builder.

7.4.3   Key movements of various standards of player

7.4.3.1 Introduction

A series of measurements were then made of a number of players of varying standards but who were familiar with the organ. The LED sensors were used for these measurements.

7.4.3.2 School Succentor

The first measurements were of Dr Tim Morris, Succentor to the School and formerly Organ Scholar at New College, Oxford. He is a Fellow of the Royal College of Organists (FRCO).

The first sample was of J S Bach's fugue BWV 545, bar 29. This contains the sequence e,d,e,c,d,e. This was selected because Dr Morris stated that the middle of the three "e"s should be played "faster". Fig 7.4.28 shows the recording of the three complete notes.
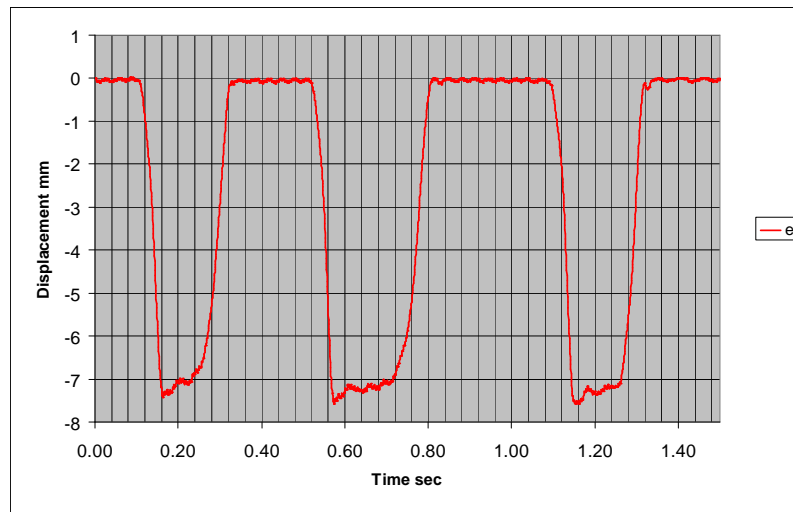
Fig 7.4.28 Recording of the movement of the e^1 key during the performance of an extract from J S Bach's fugue BWV 545, bar 29. The organist was trying to play the second note "faster". LED sensors

Fig 7.4.29 shows the three key depressions from Fig 7.4.28.
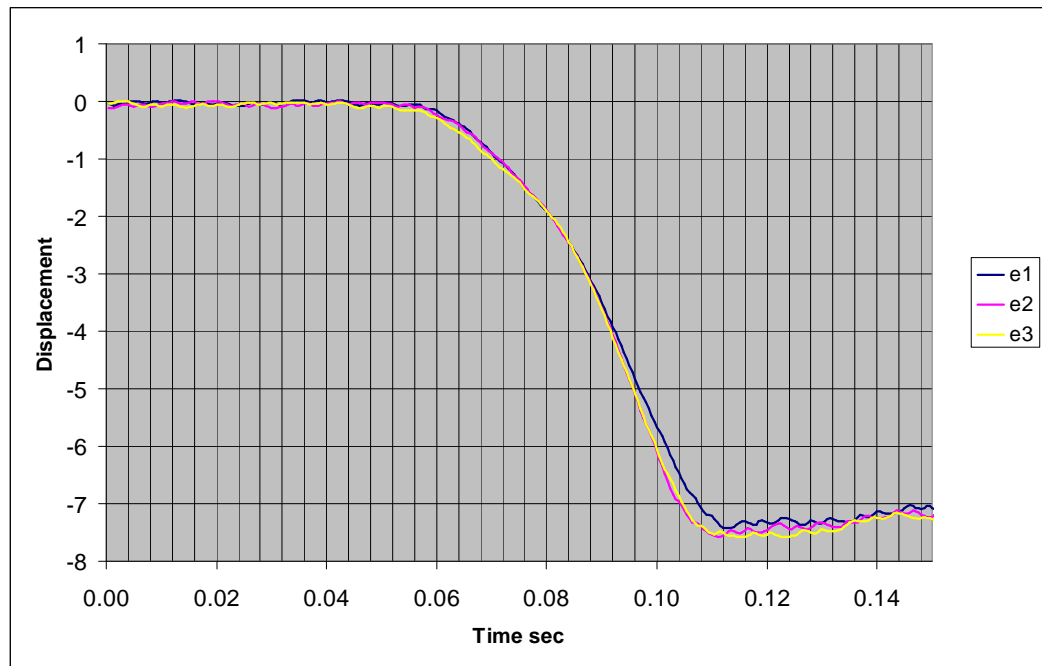
Fig 7.4.29 The three key depressions from Fig 7.2.28. The organist was trying to move the key of the second note (pink) faster than the other two.

Subject to the limitations imposed by the noise on the signal it appears that the speed of key movement of the second note is almost identical to note one at 24 ms and slightly shorter than note three at 28 ms but that the note was held down longer. The three notes were held down for 0.179, 0.236 and 0.187 seconds respectively, measured at 2mm key movement, which is approximately the pluck point.

In order to make a more accurate measurement, the same exercise was carried out using the laser sensors. The three depressions of the "e" key are shown in Fig 7.4.30. Compare this with Fig 7.4.28.
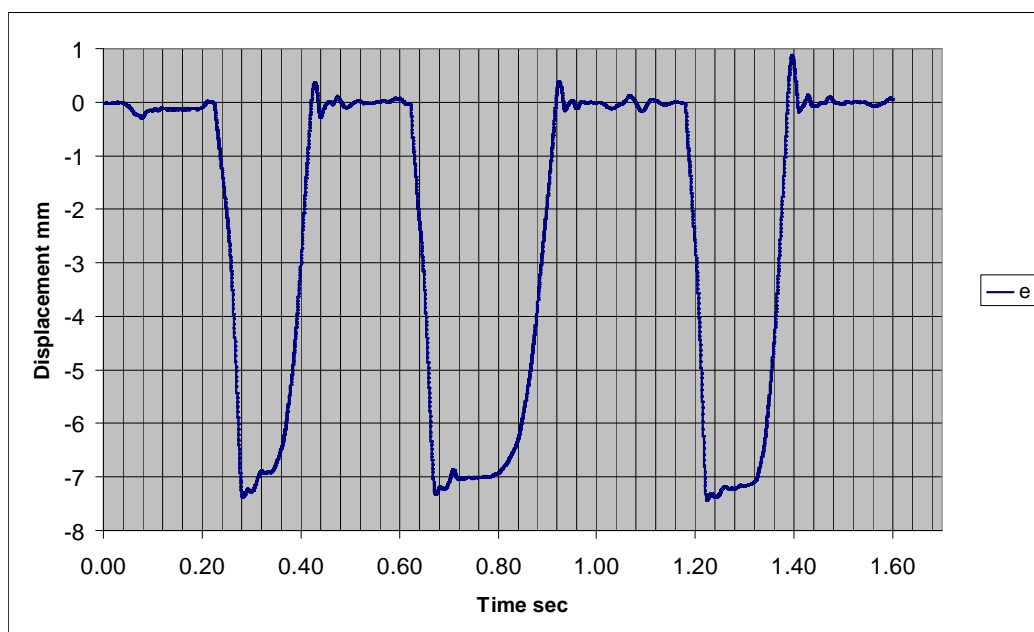
Fig 7.4.30 Recording of the movement of the e[1] key during the performance of an extract from J S Bach's fugue BWV 545, bar 29. The organist was trying to play the second note "faster". Laser sensors.

The lengths of the three notes are 0.163, 0.264 and 0.185 seconds respectively at 2 mm key travel. Here again the first note is slightly shorter than the third but the second, emphasised, note is significantly longer.

The three key depressions are shown in Fig 7.4.31 there is some difference in the pre-pluck movement but the post-pluck movements are very similar – 24.5 ms for notes one and two and 30 ms for note three measured from 2 mm travel to the key bed. The relation between the pre- and post-pluck phases of the three notes in the two sets of measurements is not consistent and there is no evidence that Dr Morris was moving the key faster. He was, however, clearly extending the length of the note.
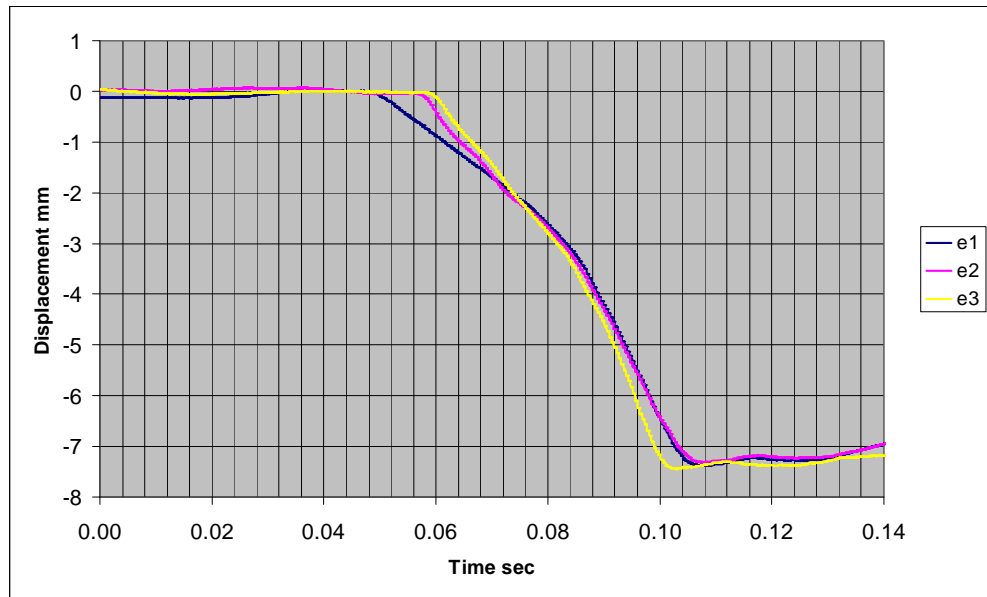
Fig 7.4.31 The three key depressions from Fig 7.2.30. The organist was trying to move the key of the second note (pink) faster than the other two. Laser sensor

The key releases are shown for the two sequences in Fig 7.4.32 for the LED sensor and Fig 7.4.33 for the laser sensor.
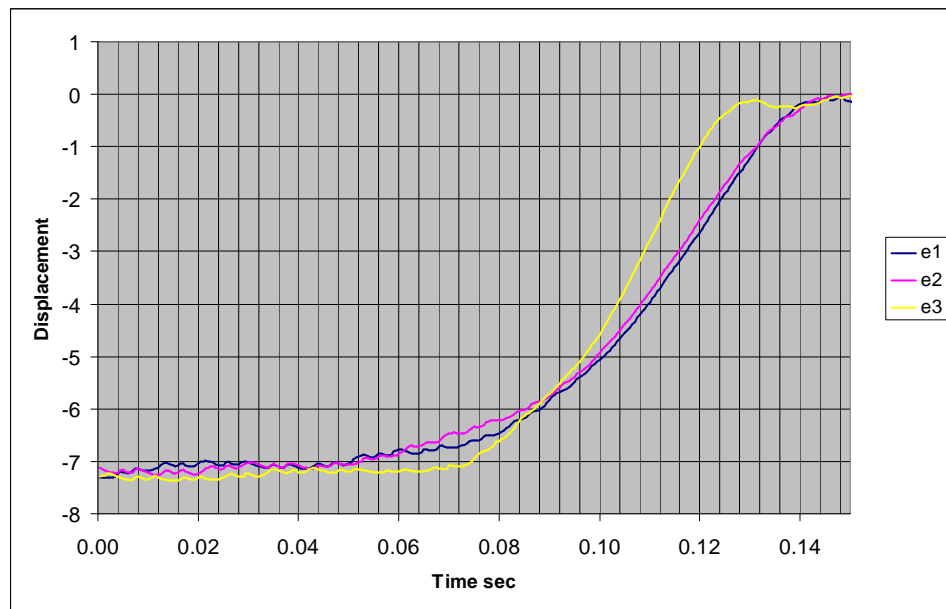
Fig 7.4.32. Key releases from the complete key movements depicted in Fig 7.4.28. LED sensors. The pink curve, note two, was played with a "faster" key movement than the other two
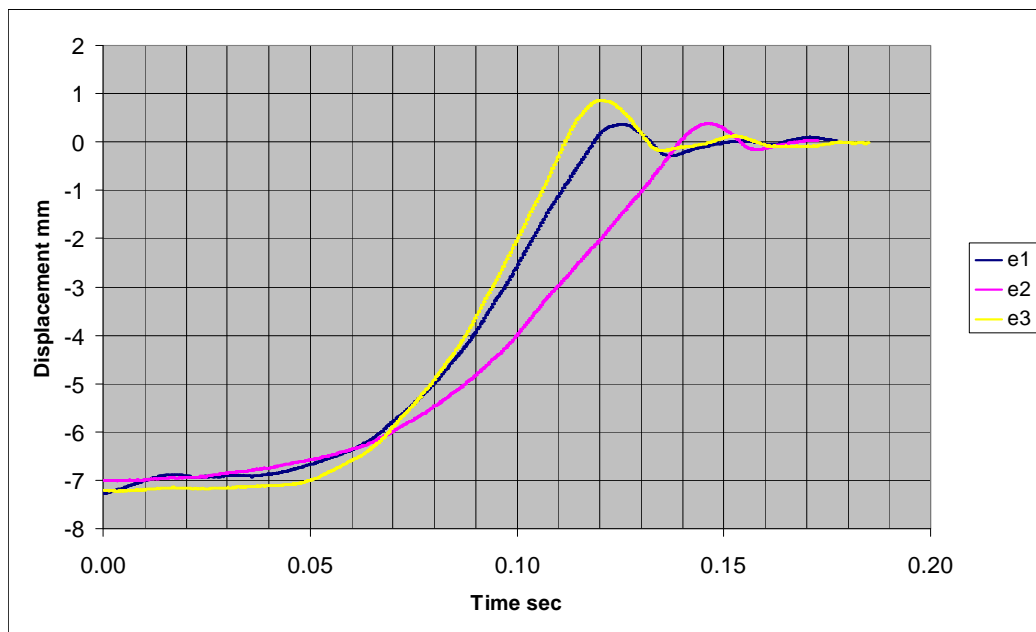
Fig 7.4.33. Key releases from the complete key movements depicted in Fig 7.4.30. Laser sensors. The pink curve, note two, was played with a "faster" key movement than the other two

Again, there is no correlation between the actual relative key speeds and those that Dr Morris was trying to achieve.

Dr Morris then played a series of notes with increasing speed of key movement. The key depressions are shown in Fig 7.4.34. After the first three of the eight notes, the times become similar and only vary by around 3 to 4 ms. This is unlikely to be of any significance. This result should be compared with a similar exercise at Rose Hill Methodist Chapel, Fig 7.3.1.
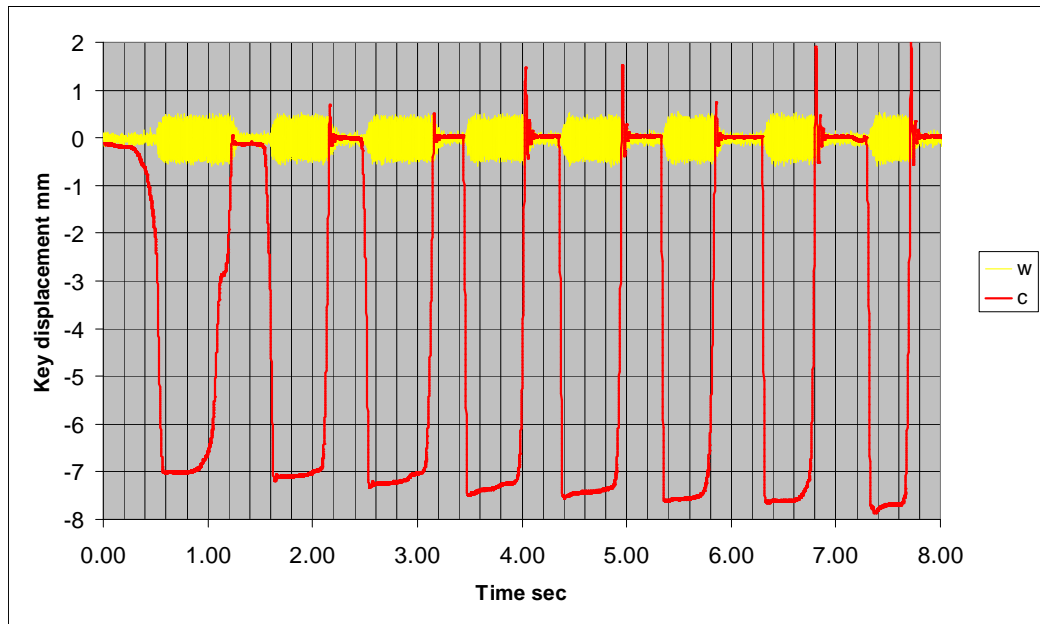
Fig 7.4.34 Sequence of Middle c^1s on the Swell, Radley College, played with increasing
speed of key movement. Laser sensor.
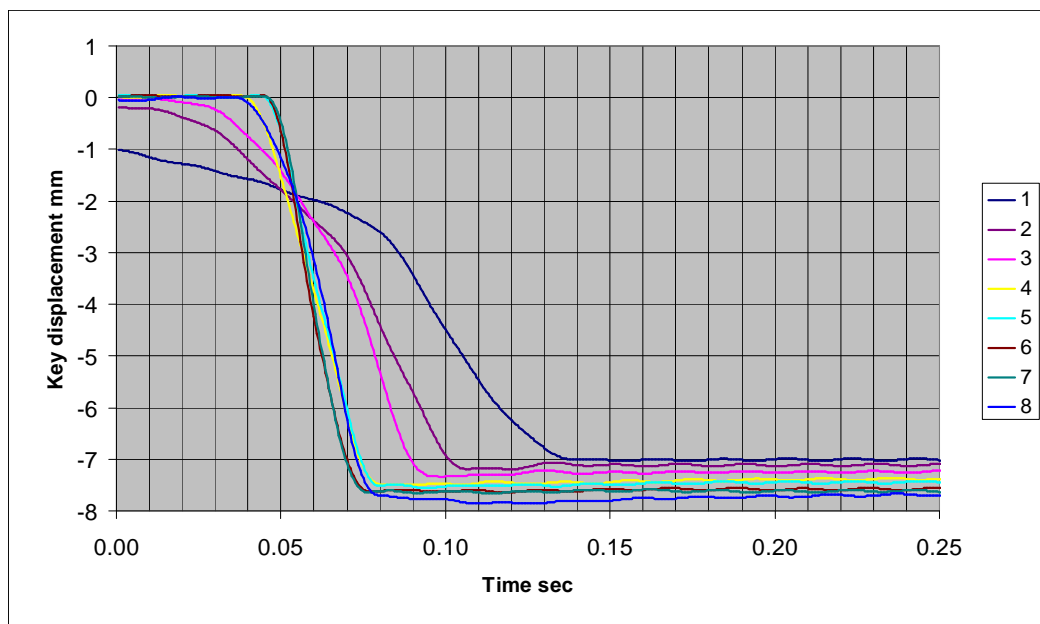
Fig 7.4.35 Sequence of Middle c^1 key depressions on the Swell, Radley College, played with
increasing speed of key movement from 1 to 8. Laser sensor.

Despite the small variations in key travel time, the key is pushed further into the key
bed with each successive movement.

In Dr Morris's final exercise the second of two successive f^1s was played "very deliberately".

The first playing of this sequence is shown in Fig 7.4.36. Although the post-pluck travel is slightly faster, it can clearly be seen that the main difference is in the pre-pluck movement. In the case of the first (not "very deliberate") note, Dr Morris appears to have been applying pressure to the key before the main key movement in order to take up the slack. He was observed to do this on a number of occasions.
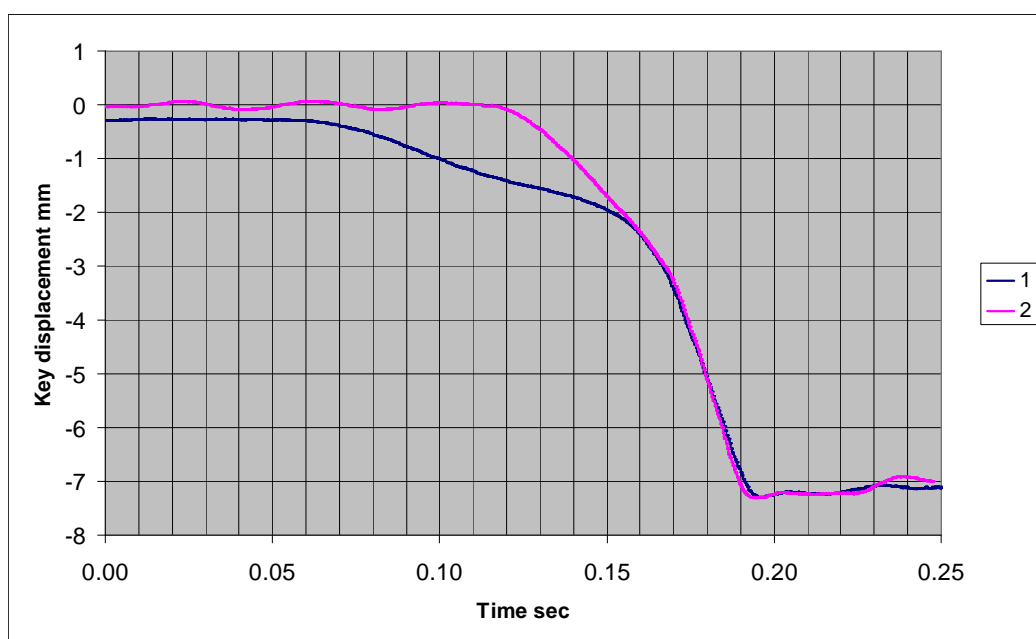
Fig 7.4.36 Two key depressions in which the second was made "very deliberately". Laser sensor, f^1 Swell organ, Radley College

The second playing of the sequence, Fig 7.4.37, shows a more marked increase in speed post-pluck but again clearly shows that the main difference is pre-pluck. In both cases the second key movement was made from the key bed and shows vibration from the movement of other keys.
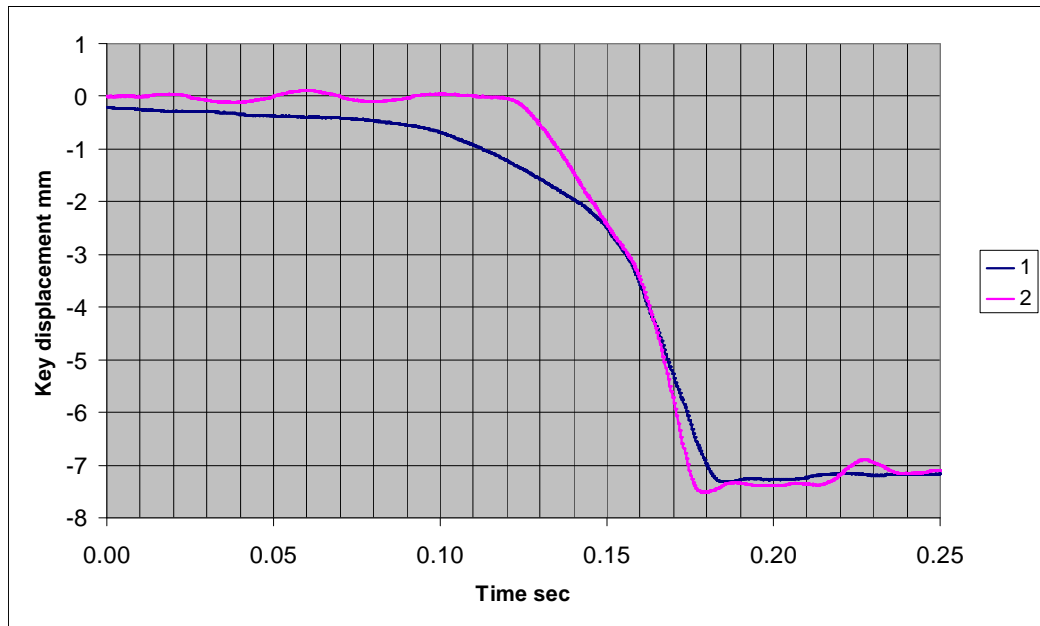
Fig 7.4.37 Two key depressions in which the second was made "very deliberately". Laser sensor, f^1 Swell organ, Radley College

7.4.3.3 Former organ scholar

The second player was Luke Bartlett, former organ scholar at Chichester Cathedral and ARCO playing standard.

Mr Bartlett was first asked to play three notes in isolation – "normal", "legato" and "staccato" – in the way that he would if playing a piece of music. The note was middle C on the Choir organ. These are shown to the same scale in Fig 7.4.38. It is not practical to line the complete curves up at the pluck point of approximately 2 mm but Fig 7.4.39 shows as much of the curves as possible aligned at 2 mm travel.
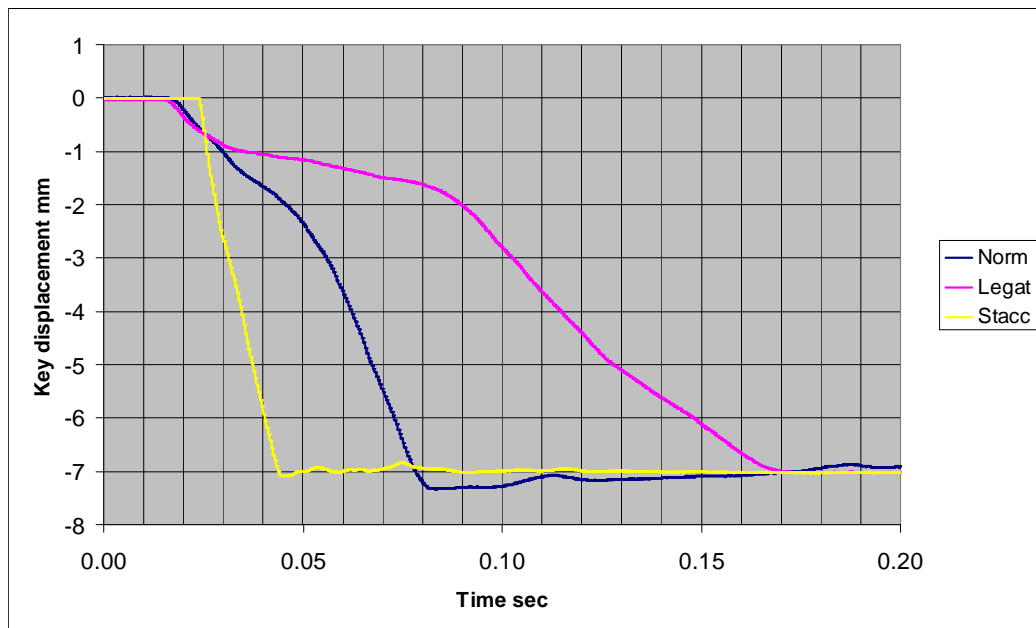
Fig 7.4.38 Middle c[1] on the Choir organ, Radley College, played "normally, "legato" and "staccato"
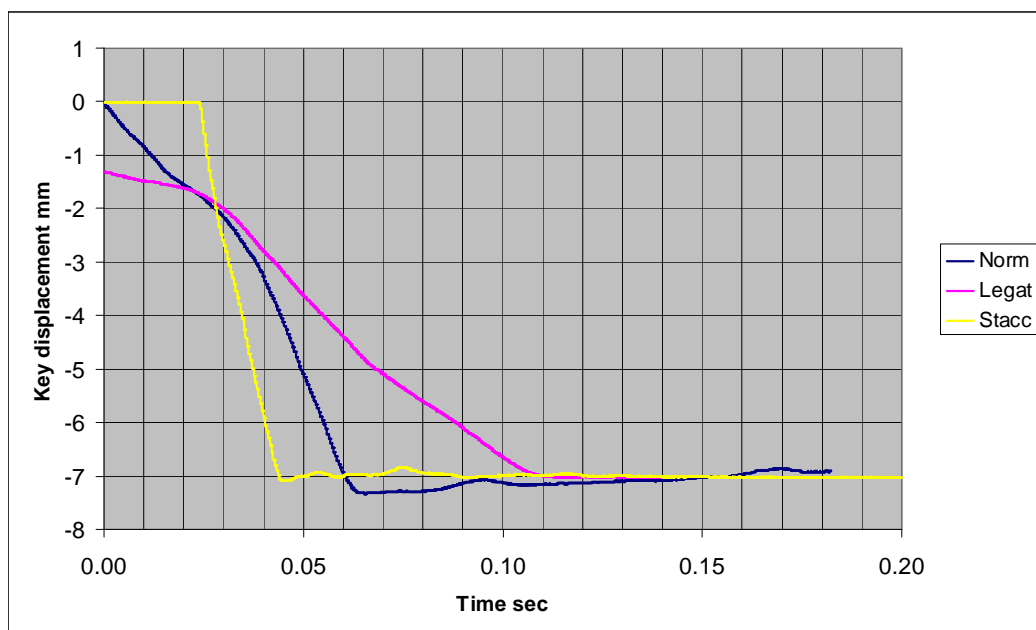
Fig 7.4.39 Middle c[1] on the Choir organ, Radley College, played "normally, "legato" and "staccato" with the curves aligned at the pluck point of approximately 2mm key travel.

There is a very clear difference between these three notes both pre- and post-pluck.

Mr Bartlett then played a piece of music (J S Bach BWV 733) in the same three styles. Two successive middle c^1s were recorded. The "normal" playing of the complete sequence is shown in Fig 7.4.40. From this graph it can be seen that the first note is short and the second one long – exceeding the length of recording.
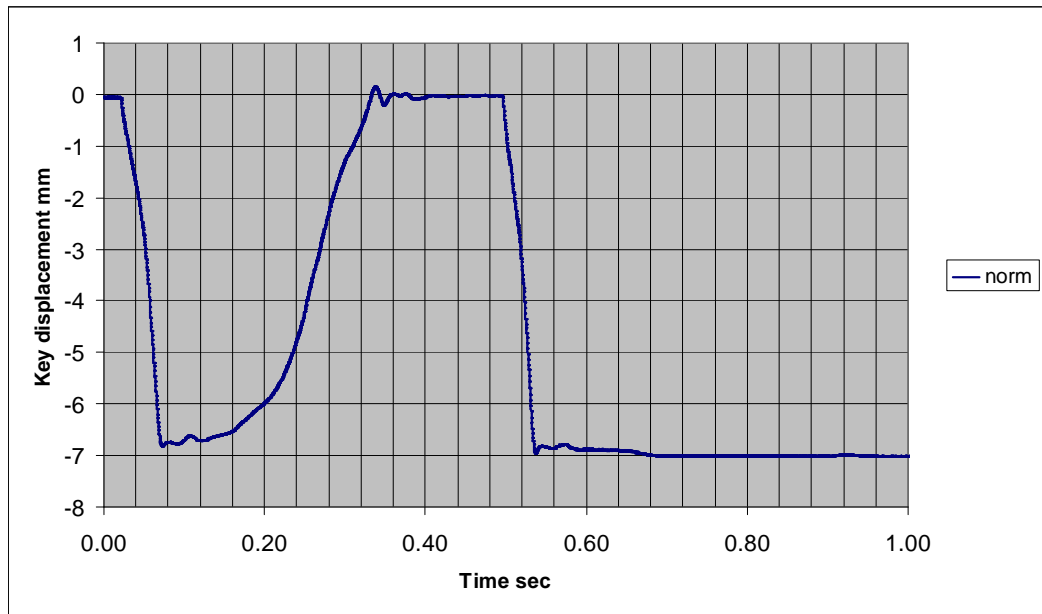
Fig 7.4.40 J S Bach BWV 733 played "normally". Middle c^1 Choir organ, Radley College. Laser sensor.

Fig 7.4.41 shows the sequence played "legato"
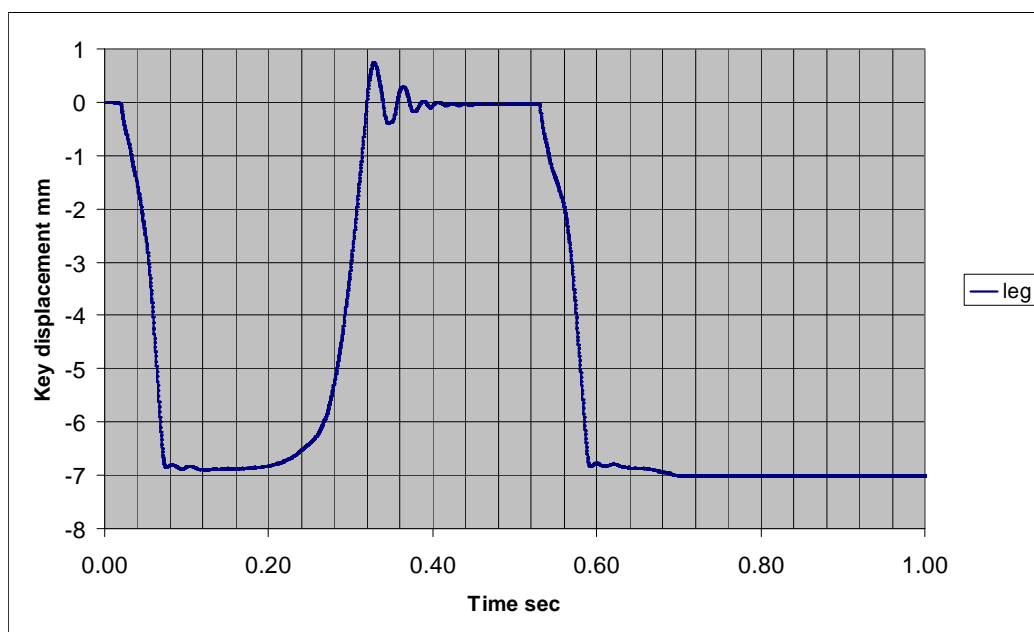
Fig 7.4.41 J S Bach BWV 733 played "legato". Middle c[1] Choir organ, Radley College. Laser sensor.

Fig 7.4.42 shows the sequence played "staccato".
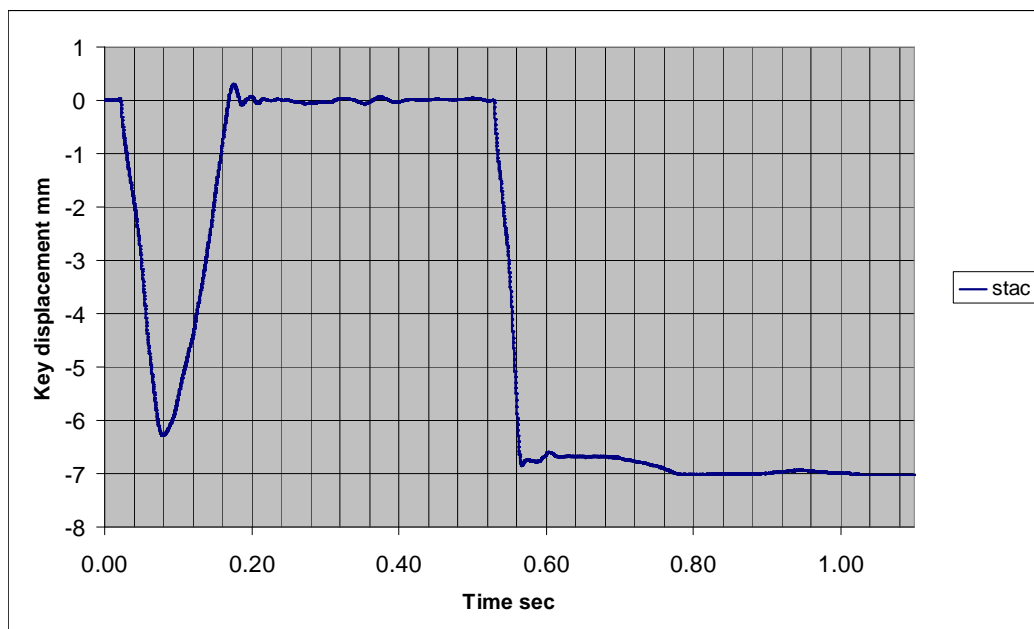
Fig 7.4.42 J S Bach BWV 733 played "staccato". Middle c[1] Choir organ, Radley College. Laser sensor.

210

The most obvious difference between the "normal" and "legato" sequences is the speed of the release. The "staccato" note is clearly shorter in duration.

The key depressions are shown in the next series of graphs. Fig 7.4.43 shows the "normal" depressions.
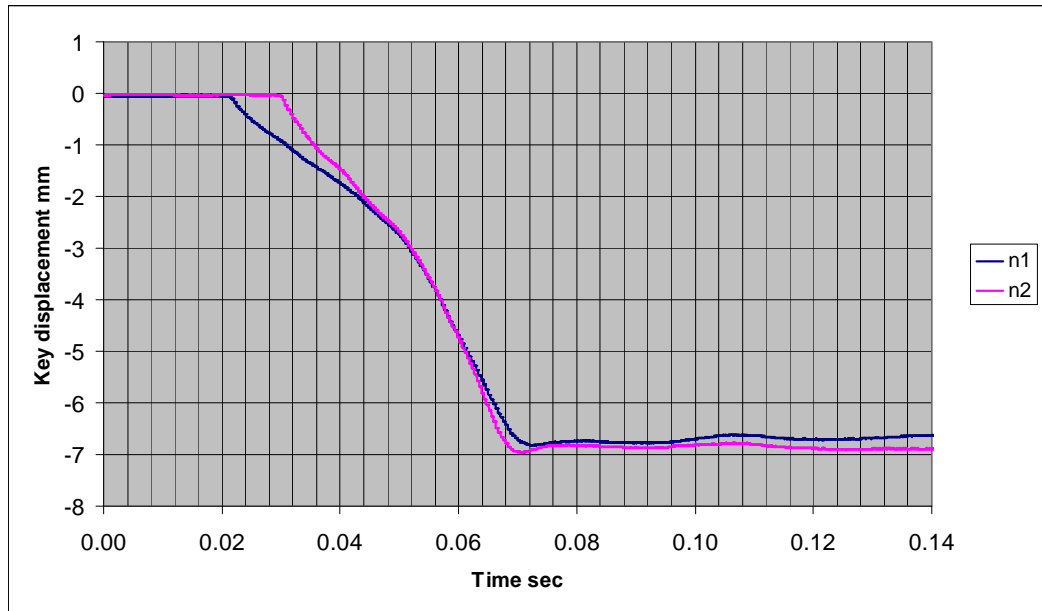
Fig 7.4.43 Key depressions in "normal" playing BWV 733. Middle c[1] Choir organ, Radley College. Laser sensor.

Fig 7.4.44 shows the "legato" key depressions.
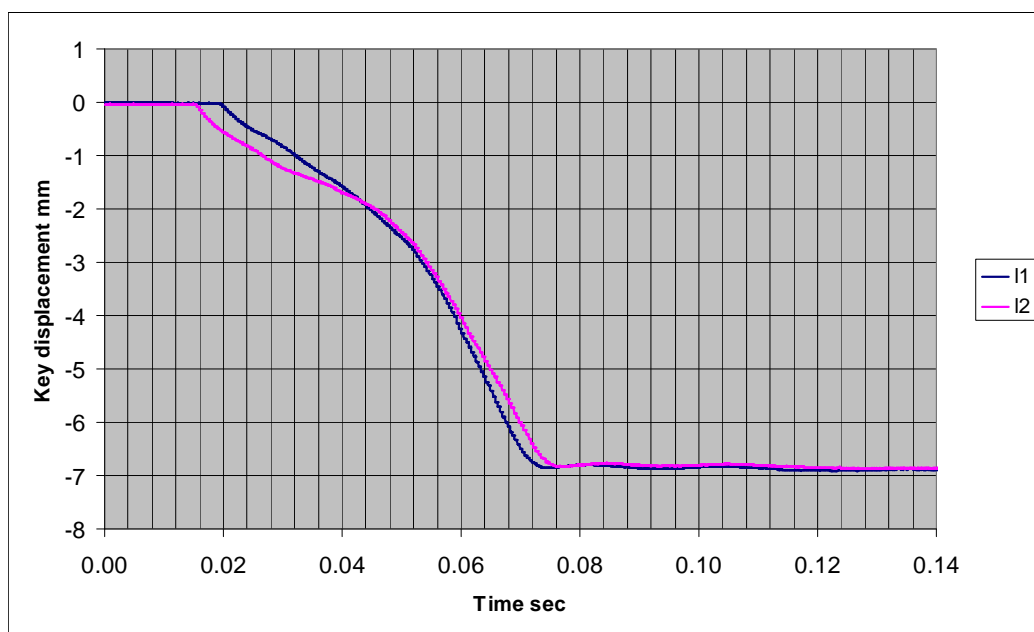
Fig 7.4.44 Key depressions in "legato" playing BWV 733. Middle c[1] Choir organ, Radley College. Laser sensor.

Fig 7.4.45 shows the "staccato" key depressions.
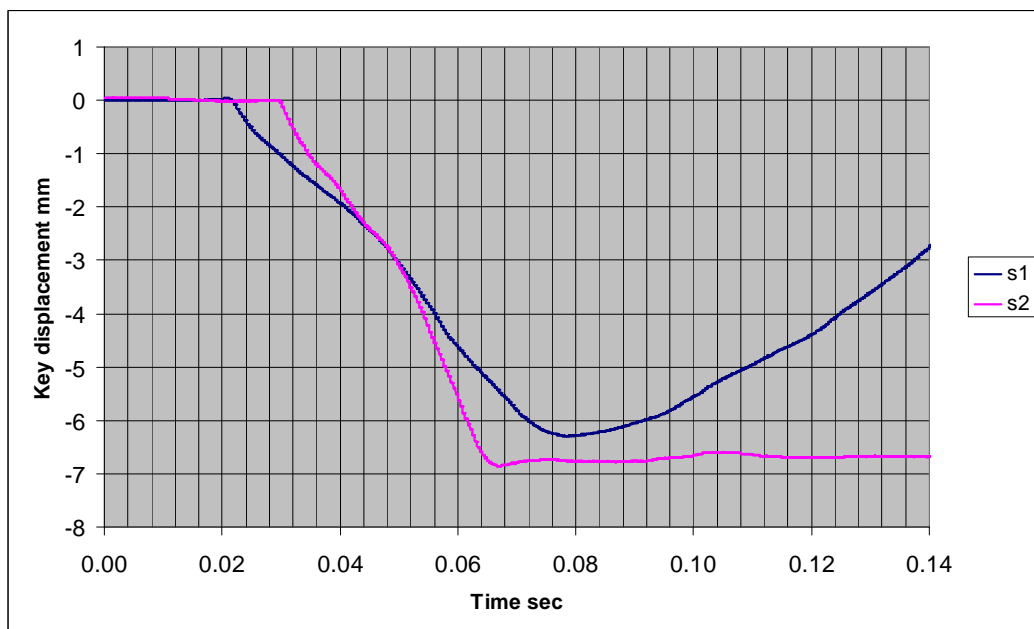
Fig 7.4.45 Key depressions in "staccato" playing BWV 733. Middle c[1] Choir organ, Radley College. Laser sensor.

The first depression in which the key did not reach the key bed is shallower than the second depression.

Fig 7.4.46 shows all six keystrokes shown in Fig 7.4.43 to Fig 7.4.45 on the same graph.
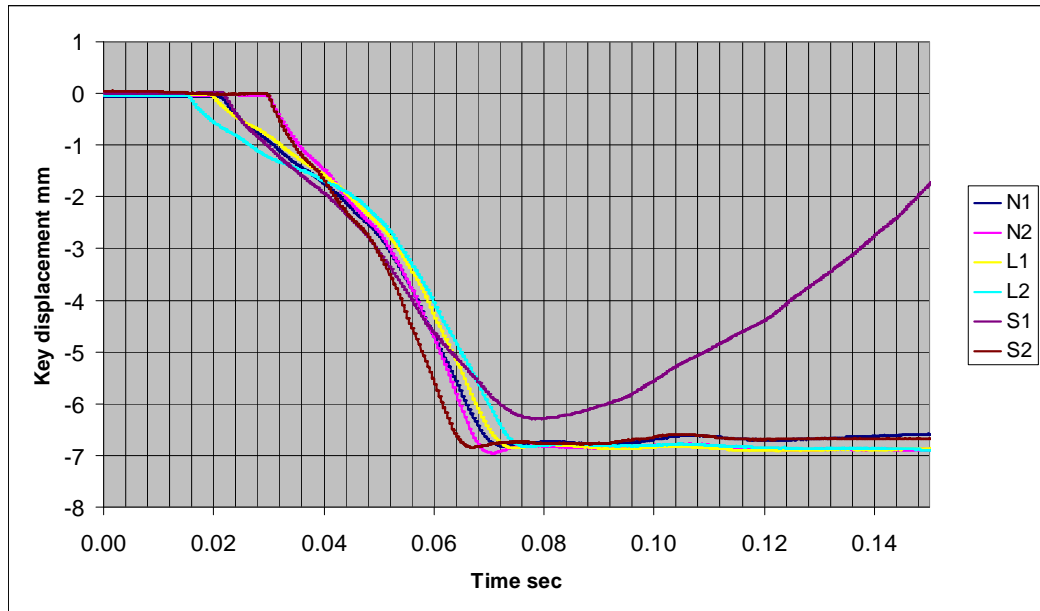
Fig 7.4.46 Middle c^1 key on the Choir organ, Radley College, played in three different styles. The letters N, L and S represent normal, legato and staccato playing respectively and the numbers indicate the first or second note in the sequence.

These curves do not show the same degree of variation that was demonstrated in the isolated key movements, Fig 7.4.39.

7.4.3.4 Student

The next subject was Ben Sheen, a year nine student at the College and of about Grade 5 standard.

He was asked to play middle C on the Stopped Diapason on the Choir organ trying to move the key "normally", "slowly" and "fast". LED sensor.

Fig 7.4.47 shows the result.
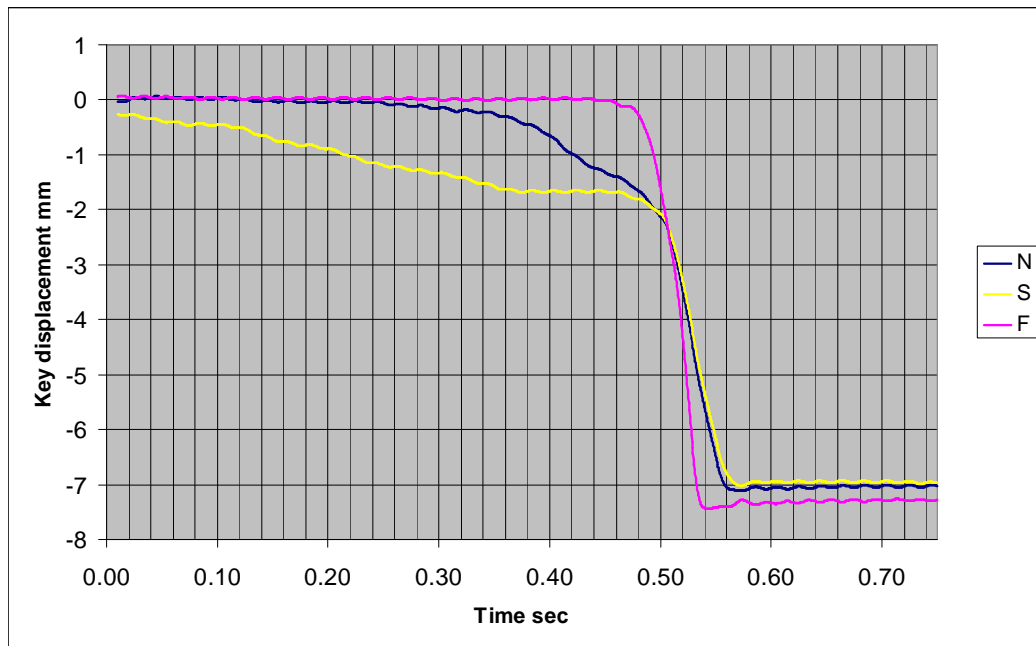
Fig 7.4.47 Middle c[1] on the Stopped Diapason on the Choir organ, Radley College played in three different styles in isolation by a pupil at the College. N, S and F represent normal, staccato and fast key movements respectively.

The pre-pluck movements vary significantly but, whilst the "fast" post-pluck movement is quicker, "normal" and "slow" are almost indistinguishable.

Ben then played the sequence improvised by Dr John Kitchen (Fig 7.2.3.) in the same three styles.

Fig 7.4.48 shows the complete "normal" sequence.
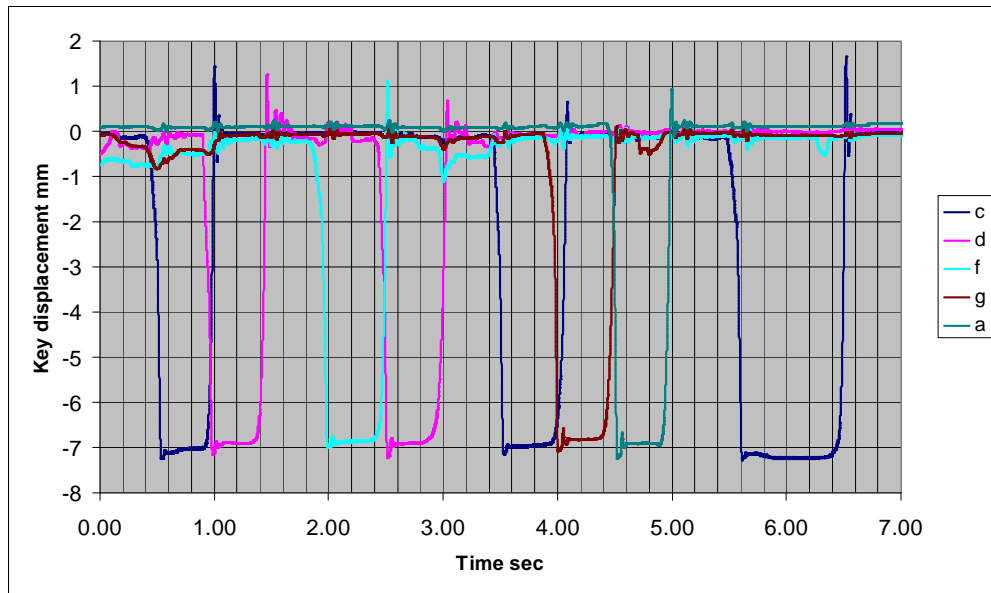
Fig 7.4.48 Theme (Fig 7.2.3) played by a pupil at Radley College in a "normal" style.

Fig 7.4.49 shows the theme played "slowly". Ben was clearly applying pressure to the keys in advance of the actual movement. This also makes it difficult to define the point of starting of the movement and may well give the player the impression of a longer overall time of travel.
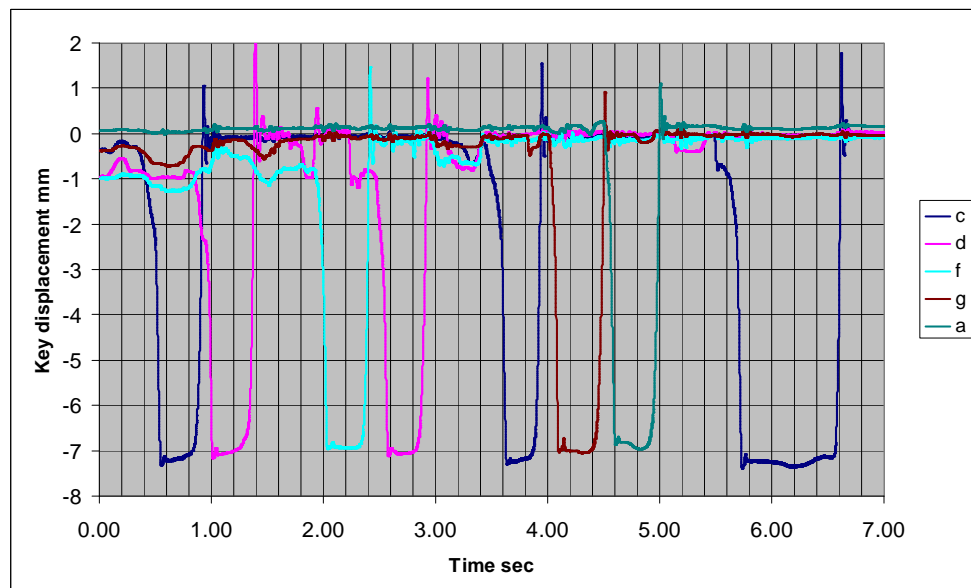
Fig 7.4.49 Theme (Fig 7.2.3) played by a pupil at Radley College in a "slow" style.

The "fast" playing of the theme is shown in Fig 7.4.50. The obvious difference is that the beginnings of the keystrokes are much "cleaner".
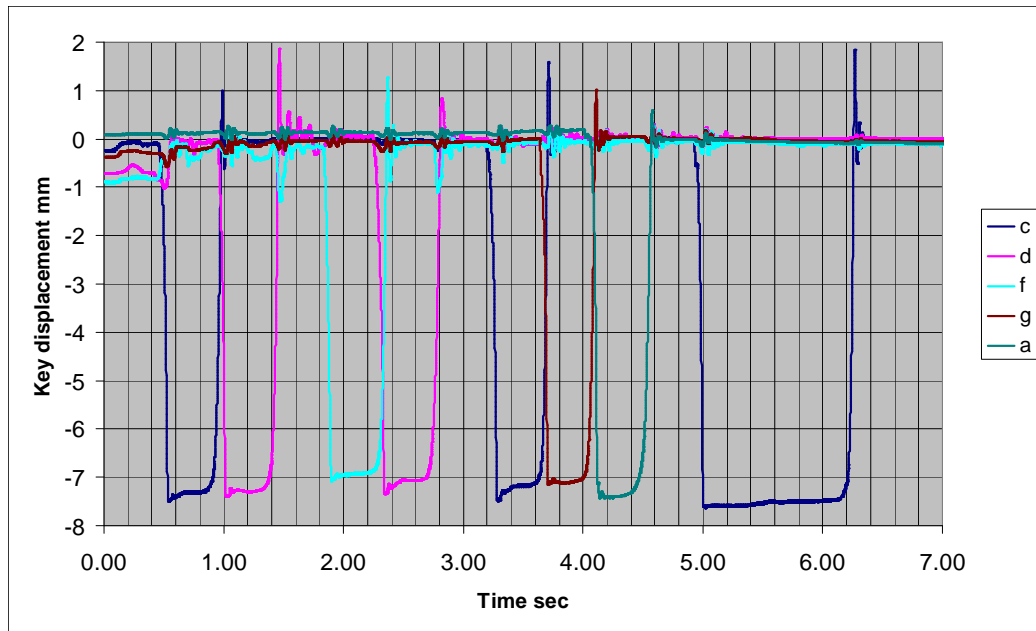
Fig 7.4.50 Theme (Fig 7.2.3) played by a pupil at Radley College in a "fast" style.

It is of interest that the "slow" key movements resulted in the shortest note lengths and least overlap of notes.

Fig 7.4.51 shows the "normal" key depressions. Note that the pluck point appears to differ between notes. Given that the action is well regulated, this is probably due to differences in the action runs between notes, and, in particular, differences in the length of the rollers.
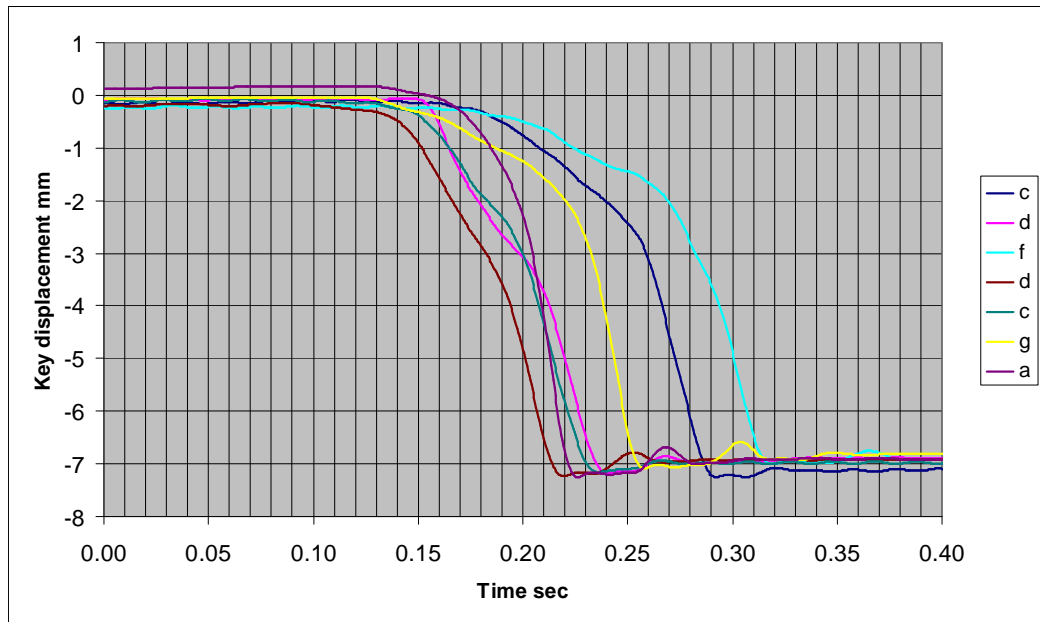
Fig 7.4.51 Key depressions from Fig 7.4.48. Theme improvised by Dr John Kitchen, played "normally" by a pupil at Radley College.

The "slow" depressions from Fig 7.4.49 are shown in Fig 7.4.52.
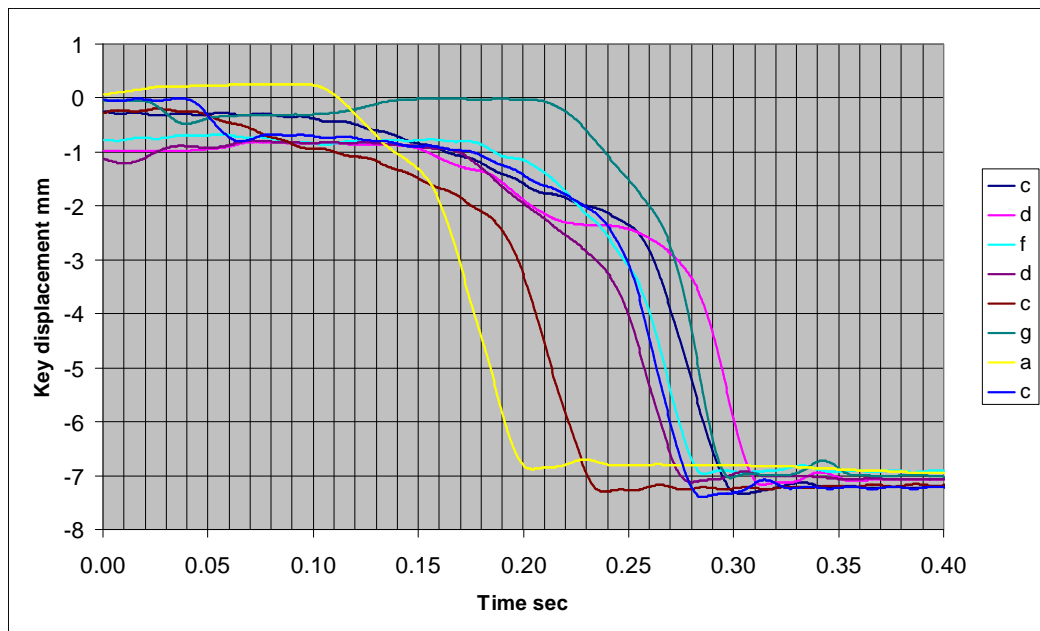
Fig 7.4.52 Key depressions from Fig 7.4.49. Theme improvised by Dr John Kitchen, played "legato" by a pupil at Radley College.

217

The variation in pre-pluck movement is apparent here but a visual comparison of the post-pluck movement suggests that the keys move at a similar speed but that the pluck points vary significantly.

Fig 7.4.53 shows the "fast" key depressions from Fig 7.4.50.
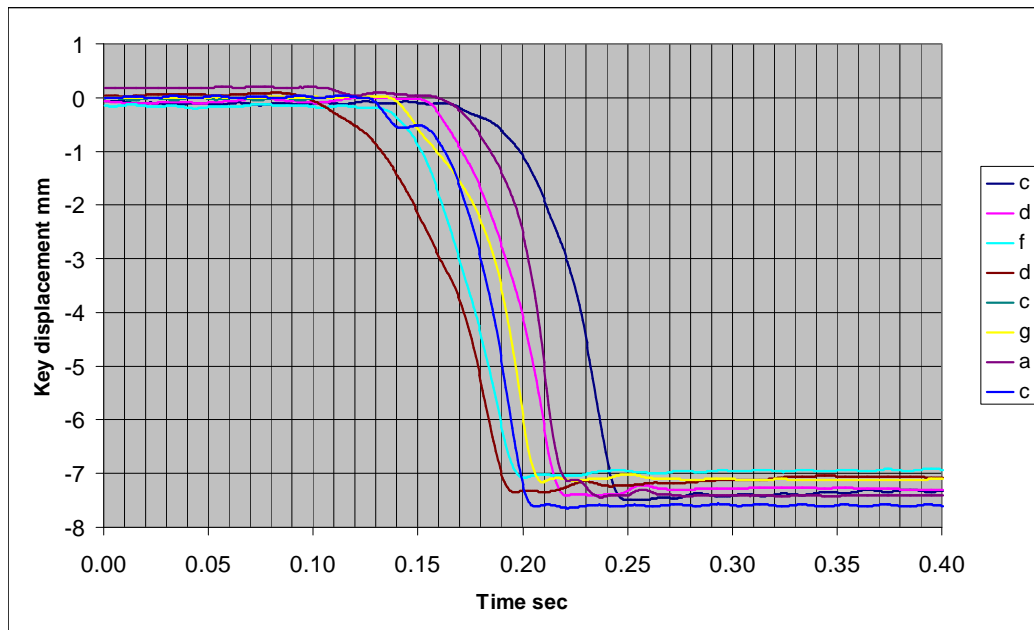
Fig 7.4.53 Key depressions from Fig 7.4.50. Theme improvised by Dr John Kitchen, played "fast" by a pupil at Radley College.

Again, there is a very clear difference in the pre pluck movements from the other two sequences.

Fig 7.4.54 shows the first four notes with the three different styles grouped together. The other four notes would give a similar result.
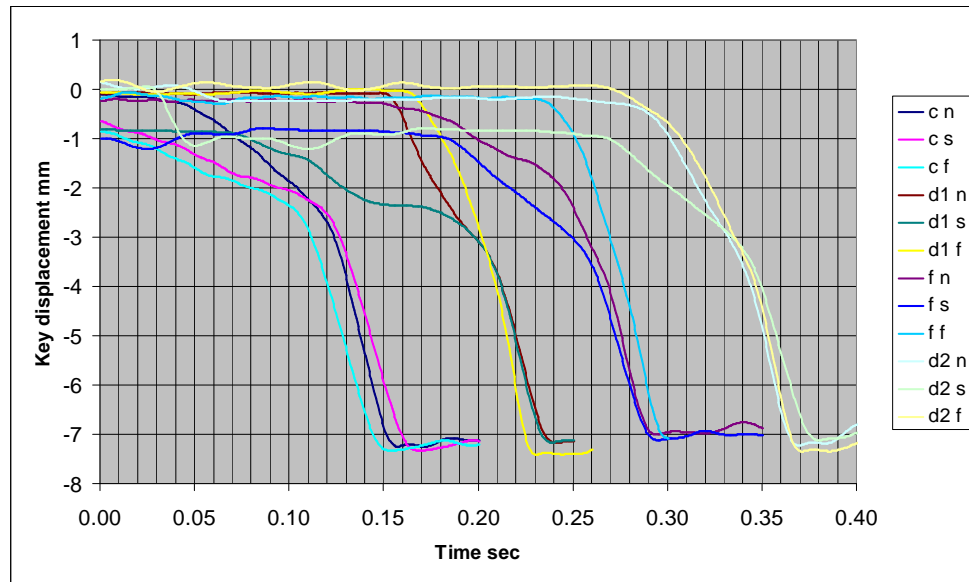
Fig 7.4.54 The first four noted from the theme improvised by Dr John Kitchen and played by a pupil at Radley College in each of three styles – "normal", "slow" and "fast". The first letter indicates the key being played and n, s and f represent the speed.

It can clearly be seen that the majority of the variation in key movement occurs in the pre-pluck phase and that the post-pluck movements do not vary to the same extent.
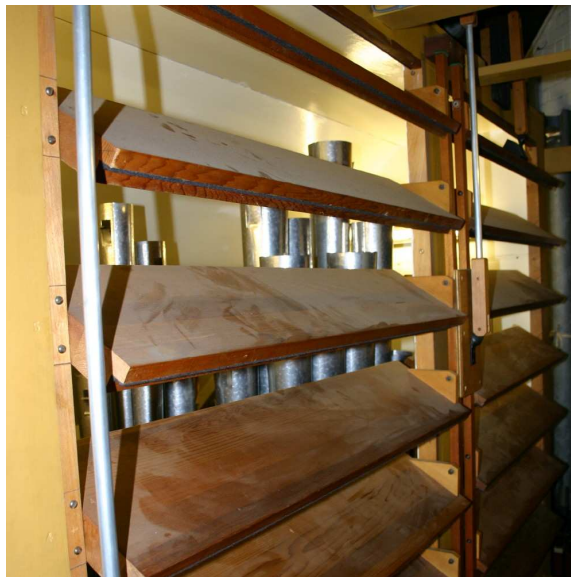
Fig 7.4.55 Photograph of the Swell organ Radley College showing the swell shutters, which are opened and closed to control the volume of the enclosed pipes.

7.5 St Margaret's Church, Ipswich

7.5.1 Introduction

This is a three manual organ of 27 speaking stops originally built by J W Walker in 1868. Its specification is shown in Appendix 1. Apart from being a suitable size for study, this organ was chosen because it is located opposite Bishop and Son's workshop on Bolton Street, Ipswich, so that it was convenient for John Bailey, manager of the workshop, to supervise access, and because the organist, John Parry, was very interested in the project. It was possible to locate a laser sensor inside the windchest of this organ, although the lack of space meant that it was not practical to take a photograph of the installation. The façade is shown in Fig 7.5.1.

Fig 7.5.1 The façade of the organ in St Margaret's Church, Ipswich. Originally built by J W Walker in 1880.

7.5.2 Measurements of key and pallet movements

Fig 7.5.2 shows the console with the music desk removed and a laser sensor in place over the Great middle c^1 key. The organ was played by John Parry, organist of the church.

Fig 7.5.2 The console of the organ in St Margaret's Church, Ipswich. The music desk has been removed and a laser sensor is in place over the Middle c^1 key of the Swell organ.

Fig 7.5.3 shows a "slow" isolated Middle c^1 using a laser sensor over the key and under the pallet. The sound recording has been noise-reduced using Cooledit Pro with an fft of 512 and a reduction level of 70db
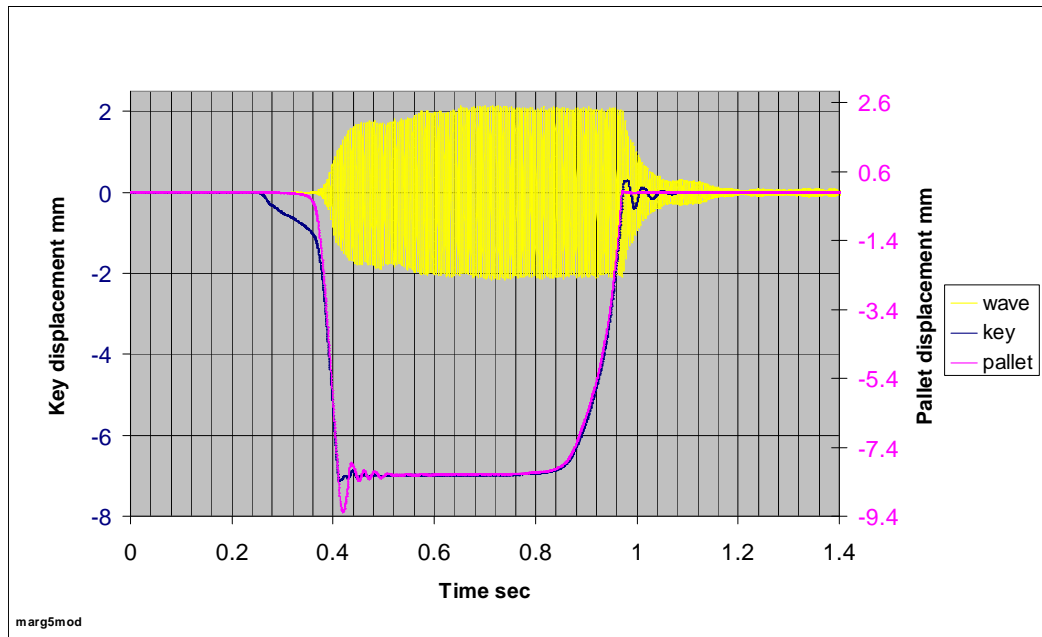
Fig 7.5.3 St Margaret's Ipswich. "Slow" movement of the Middle c^1 key showing the movement of the key before the pluck point at approximately 1 mm travel due to flexibility in the action. The amplitude of the sound recording is arbitrary and it has been noise reduced.

The key depression of the sequence in Fig 7.5.3 is shown in Fig 7.5.4.
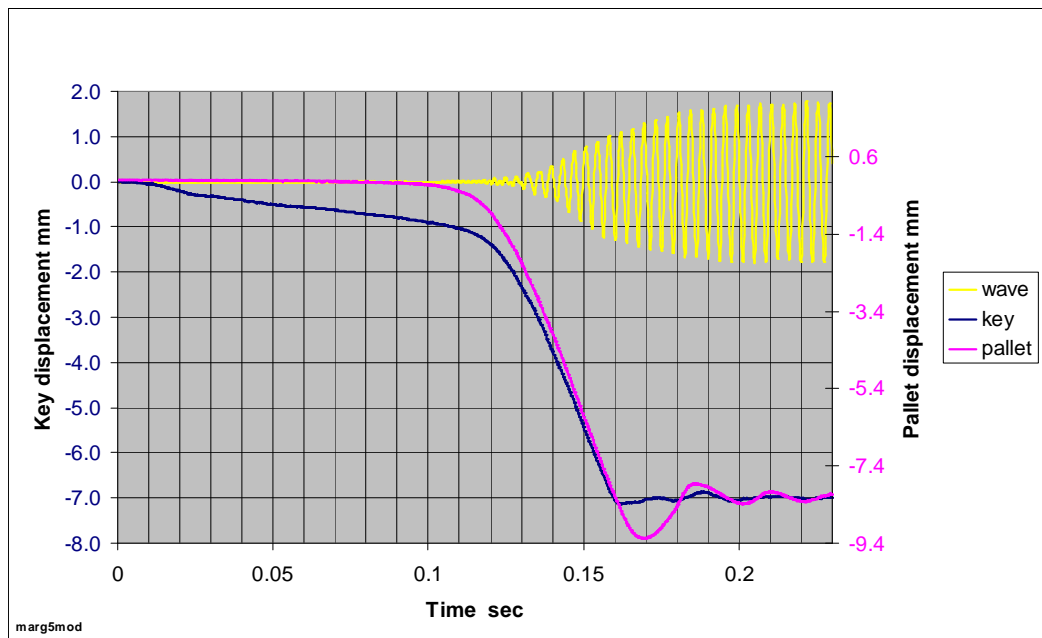
Fig 7.5.4 The key depression in Fig 7.5.3 shown to a larger scale.

These curves show the characteristic shape of the key movement due to flexibility in the action.

The key release is shown in Fig 7.5.5.
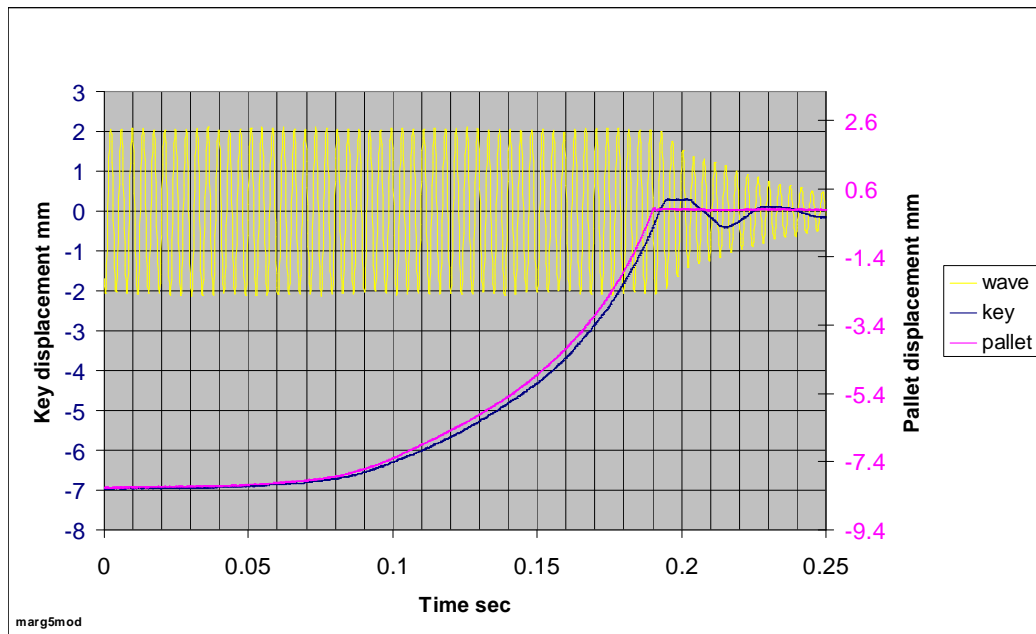
Fig 7.5.5 The key release form Fig 7.5.3 shown to a larger scale

The sound envelope does not start diminishing until the point at which the pallet returns to its seat even with a slow and steady key release as used here. The pallet returns in advance of the key, the key rest position being coincident with the pallet rest position in this graph.

Fig 7.5.6 shows a "faster" movement. The sound recording has not been noise-reduced.
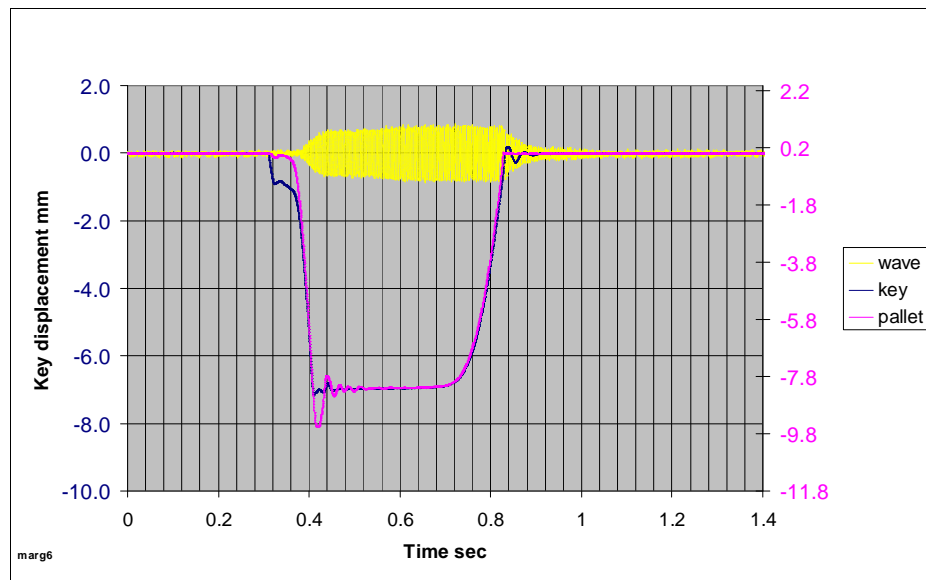
Fig 7.5.6 "Faster" movement of the Middle c^1 key showing the movement of the key before the pluck point at approximately 1 mm travel due to flexibility in the action. The amplitude of the sound recording is arbitrary and it has not been noise reduced.

The key depression is shown in Fig 7.5.7. There is a distinct movement and return of both the key and the pallet at the beginning of the sequence as if the player's movement is "bouncing" off a resistance. This was also apparent in other recordings not reproduced here.
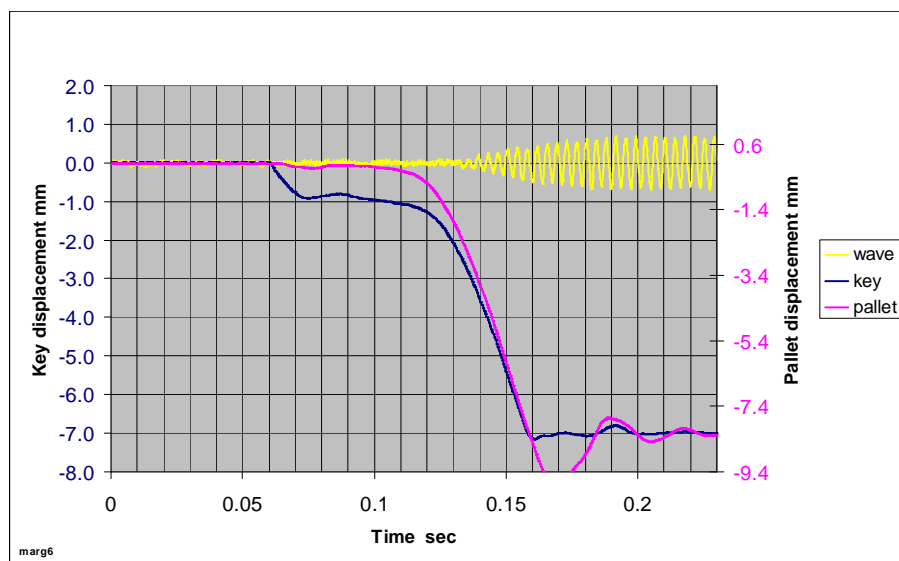
Fig 7.5.7 The key depression in Fig 7.5.6 shown to a larger scale.

The key release from the sequence shown in Fig 7.5.6 is shown in Fig 7.5.8. Again, the sound envelope does not start to diminish until the pallet is almost seated.
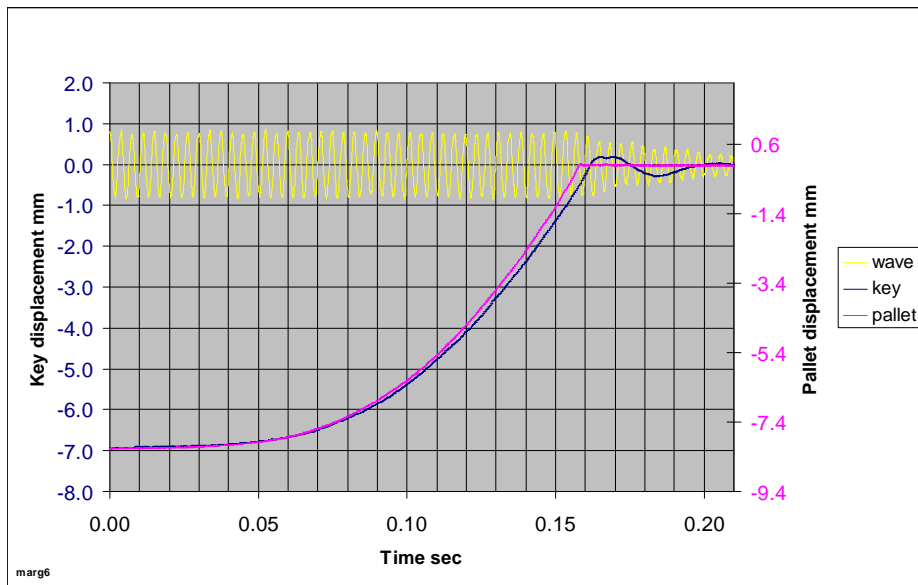
Fig 7.5.8 The key release form Fig 7.5.6 shown to a larger scale

A "fast" key movement is shown in Fig 7.5.9.
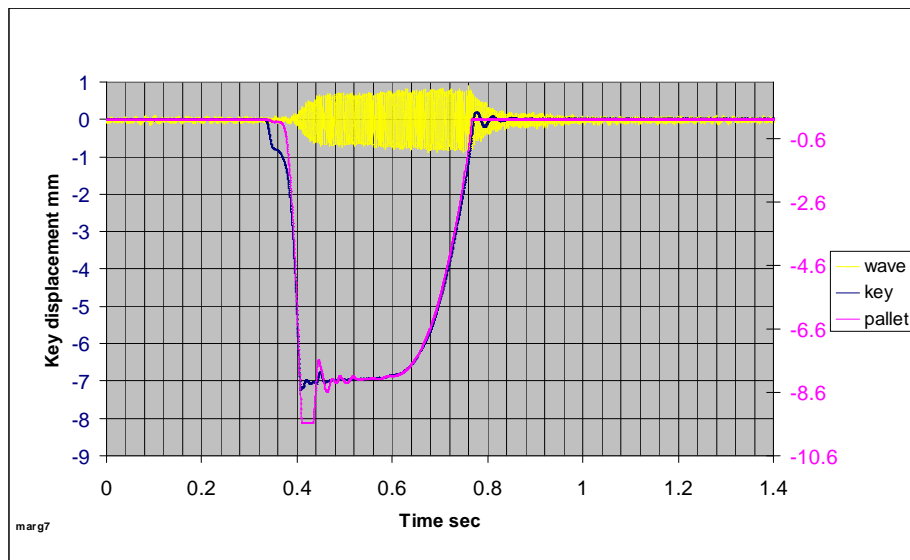
Fig 7.5.9 St Margaret's Ipswich. "Fast" movement of the Middle c[1] key showing the movement of the key before the pluck point at approximately 1 mm travel due to flexibility in the action. The amplitude of the sound recording is arbitrary and is not noise reduced.

226

The key depression is shown at a larger scale in Fig 7.5.10
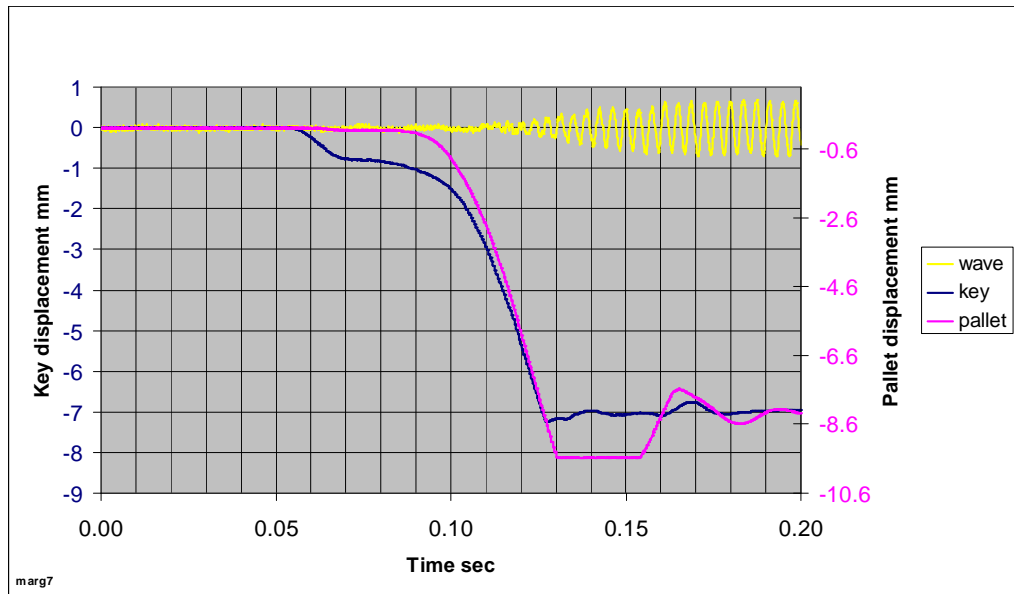
Fig 7.5.10 The key depression in Fig 7.5.9 shown to a larger scale.

This still shows the characteristic key movement with the key not quite stopping its movement. The key release is shown in Fig 7.5.11.
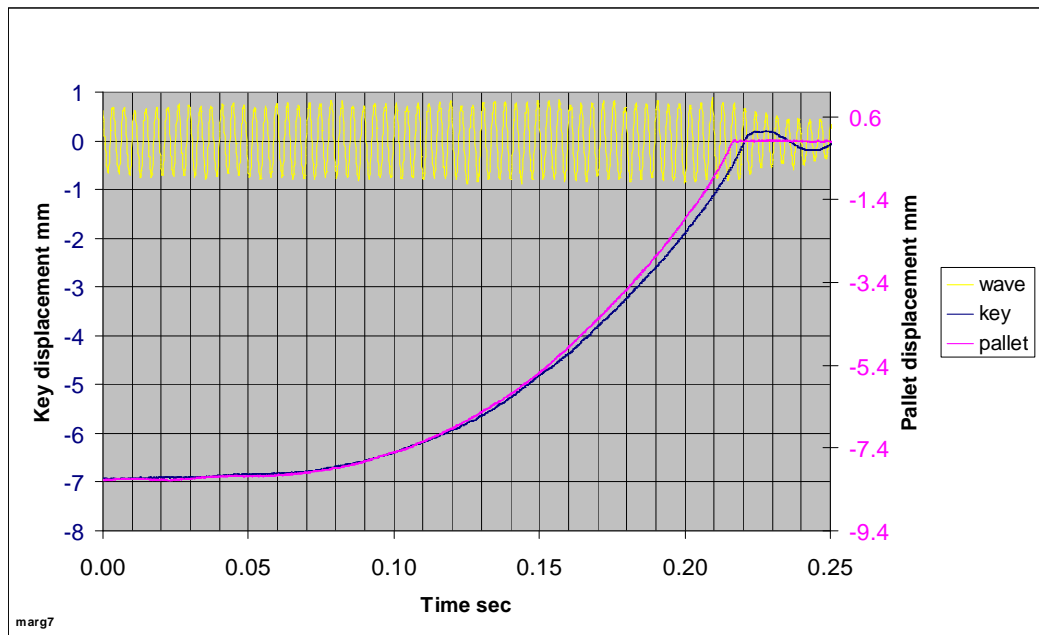
Fig 7.5.11 The key release form Fig 7.5.9 shown to a larger scale

The three key depressions are shown superimposed in Fig 7.5.12.
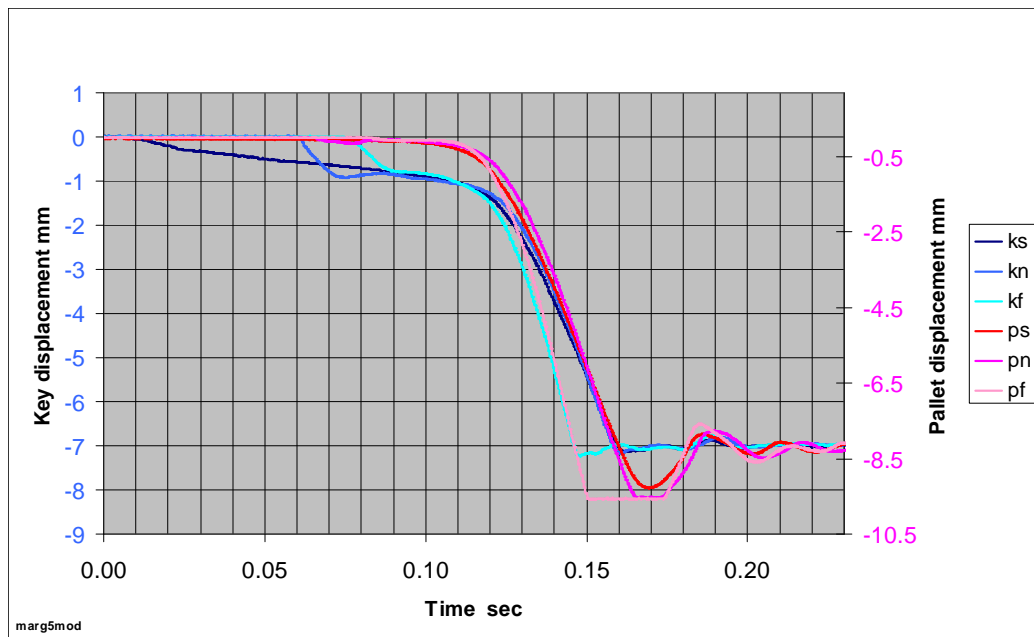
Fig 7.5.12 The key and pallet movements from Fig 7.5.3, 7.5.6 and 7.5.9 presented on the same graph for comparison. K and p represent the key and pallet movements respectively and s, n and f represent the increasing speeds of movement depicted in the three previous graphs.

The key and thus the pallet movement post-pluck for the "fast" movement are faster than the other movements, the key movement reducing from 48ms to 35ms (taking 1 mm as the pluck point). The pre-pluck time reduces from 110ms to 66ms.

The next graph, Fig 7.5.13, shows the movement of the Middle c^1 key when two notes were played together "with the fist".
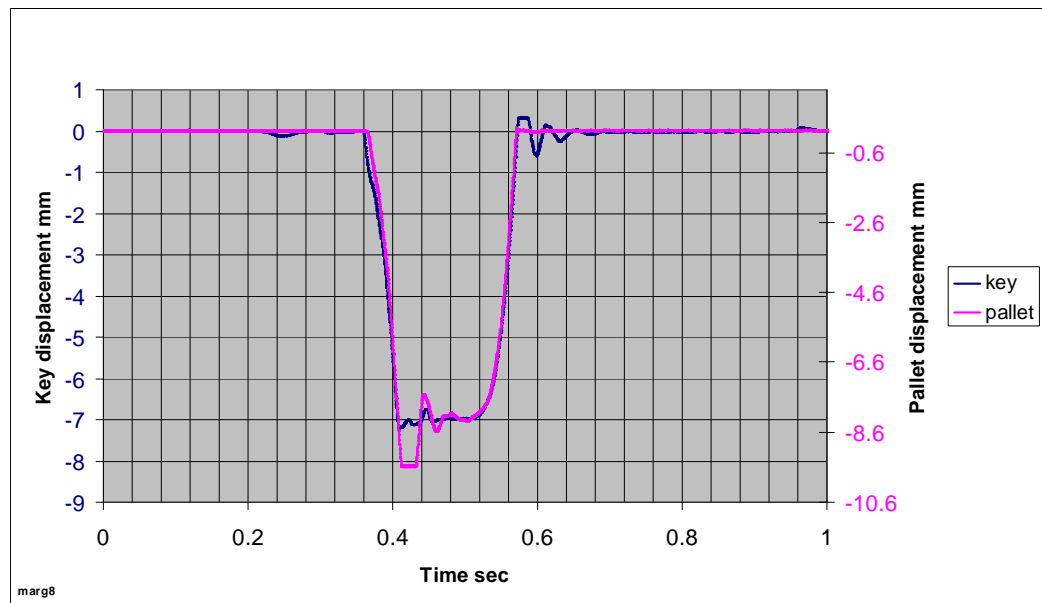
Fig 7.5.13 St Margaret's Ipswich. Movement of the Middle c^1 key using the "fist". There is still a distinct movement of the key before the pluck point at approximately 1 mm travel due to flexibility in the action.

The key depression is shown in Fig 7.5.14. The "fist" movement is faster pre-pluck and after a slight check around the pluck point, continues at a similar speed post-pluck which is actually slower than the "fast" movement allowing the fingers to do the work. This is a further example of the transition from "constant force" to "constant velocity" playing – the "inertia" of the whole hand overcomes the variations in resistance through the key's travel and the finger goes through the pluck in a more controlled manner.
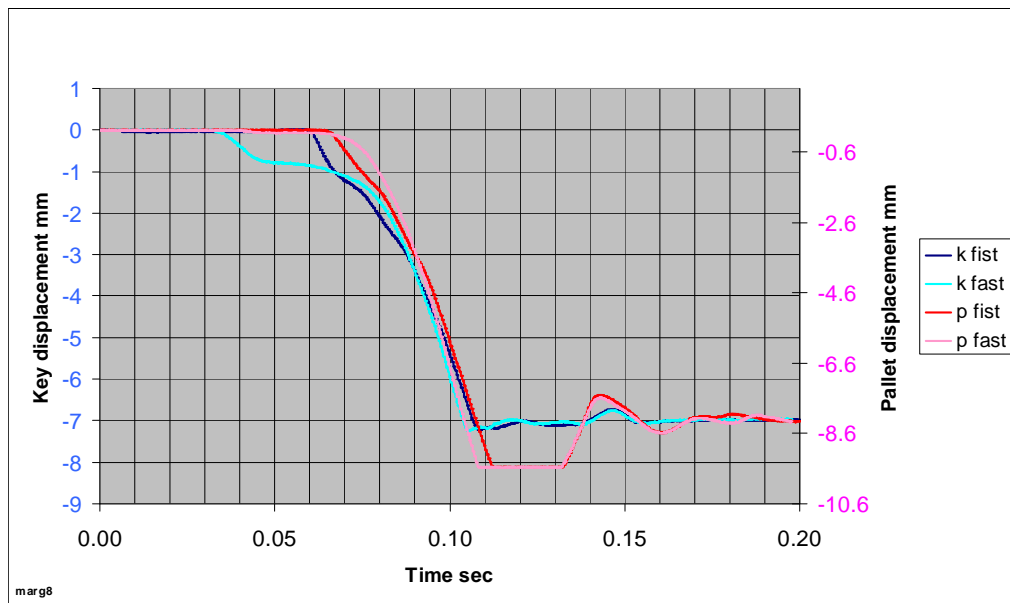
Fig 7.5.14 Graph comparing the movements of the key and pallet with a "fast" finger
movement and with a "fist" movement

Fig 7.5.15 shows the movement of the key and pallet and a recording of the sound
for a full chorus on the Great organ
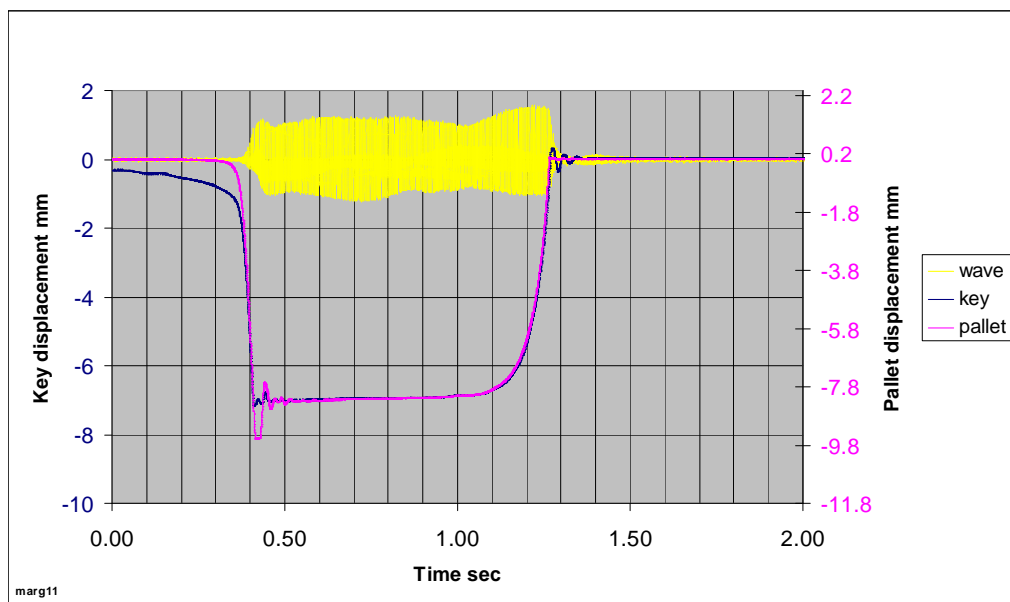
Fig 7.5.15 St Margaret's Ipswich. Movement of the Middle c^1 key plated normally using the
full chorus. There is a distinct movement of the key before the pluck point at approximately
1 mm travel due to flexibility in the action

The key depression from Fig 7.5.15 is shown at larger scale in Fig 7.5.16 and the key release in Fig 7.5.17.
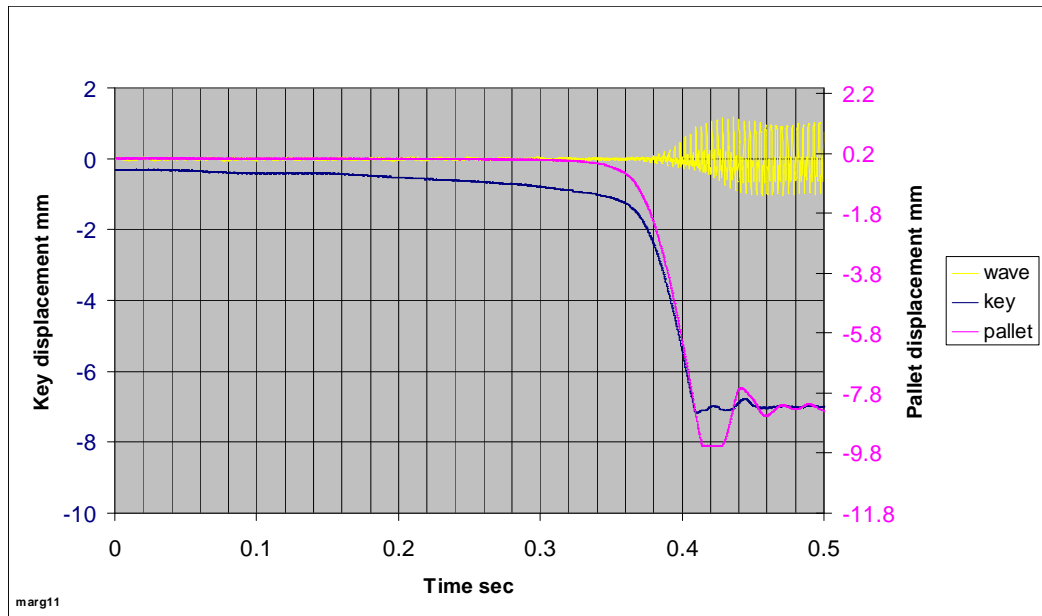
Fig 7.5.16 The key depression in Fig 7.5.14 shown to a larger scale.
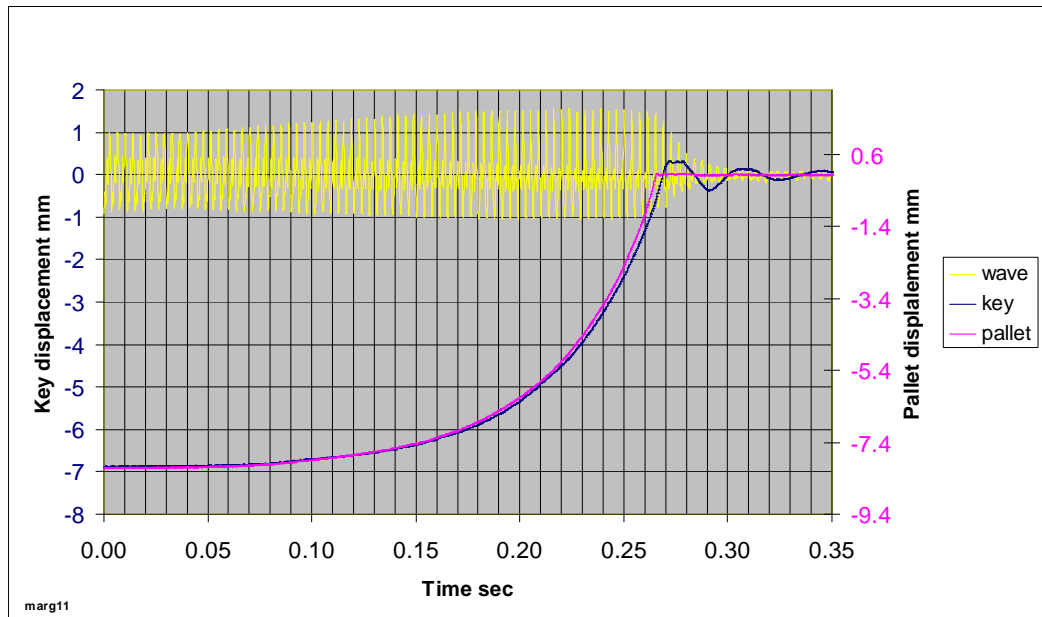
Fig 7.5.17 The key release form Fig 7.5.14 shown to a larger scale. Despite the increased air demand of the full chorus, the waveform envelope does not start diminishing until the pallet is nearly closed.

The key releases of the first four notes are shown in Fig 7.5.18.
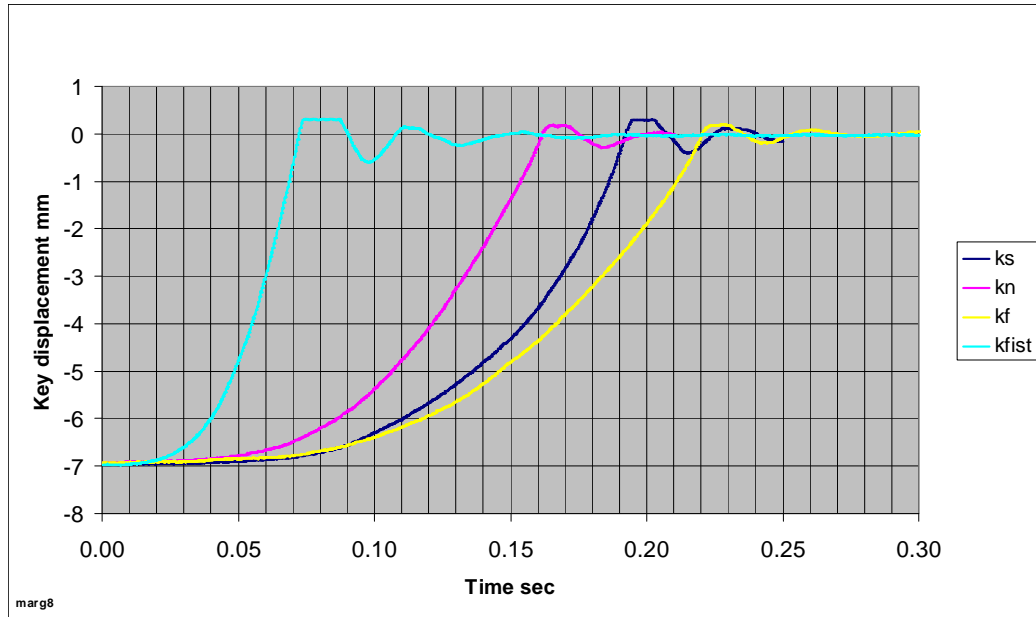
Fig 7.5.18 The key releases from the first four exercises shown in Figs, 7.5.3, 7.5.6, 7.5.9
and 7.5.12

The "fist" action is obviously faster than the other three but the "fast" key movement
has resulted in the slowest release.

7.5.3   Measurement of key movement during normal playing

A separate exercise was undertaken on the 12th May 2005. Mr Parry played a variety
of pieces of music in different styles with the LED sensors in place over the Great
manual. The sampling rate was 2kHz. There was a particular problem with the
sensors being knocked during playing and there are some obvious discontinuities in
the curves. These do not prevent conclusions from being reached.

The first piece played was *Jesus meine Zuversicht* by J S Bach, BWV 728. This was played without ornaments and Mr Parry believed that it would exhibit a significant variation in key speed.

The complete recording is shown in Fig 7.5.19.
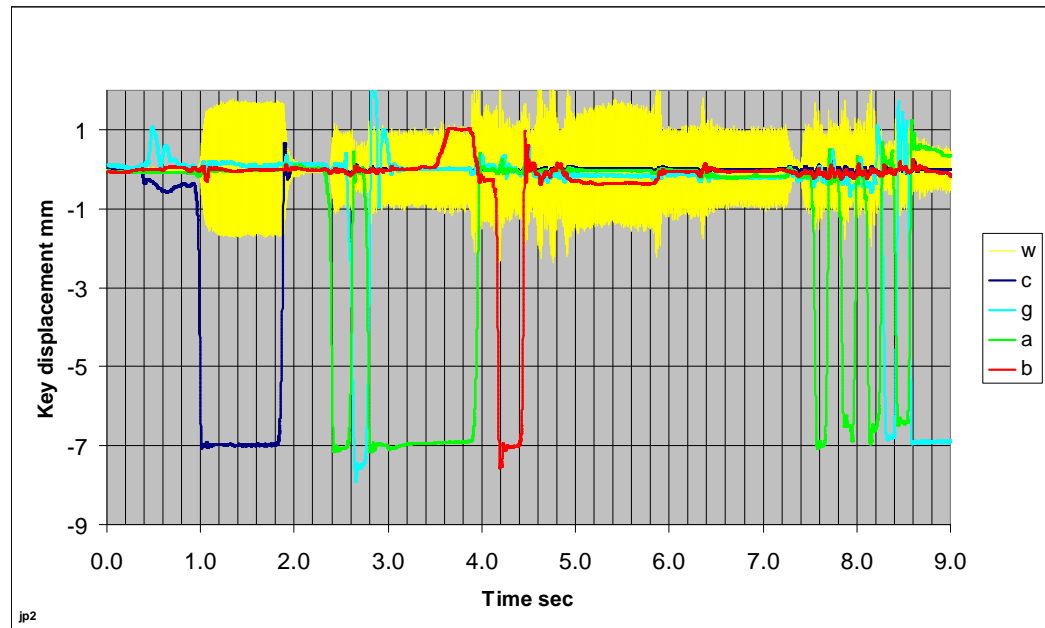
Fig 7.5.19 Recording of *Jesus meine Zuversicht* by J S Bach, BWV 728. The amplitude of the sound recording, w, is arbitrary.

All of the key depressions are shown in Fig 7.5.20. Their position along the time axis is arbitrary. It is not clear why the first g^1, the brown line, is displaced in the way that it is. It may have been moved during the playing of this note and then partially returned to its starting position or there may have been a fault with the sensor. This curve should be disregarded for analysis but is included in order to show all of the key movements recorded. It can be seen that, although there is some variation in speed of movement, it is not large.
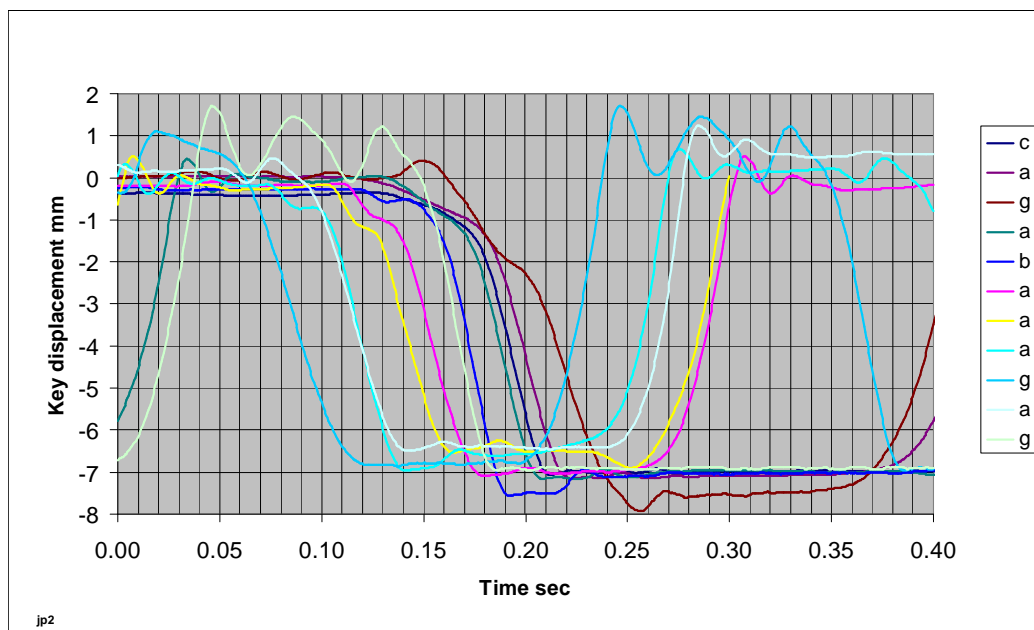
Fig 7.5.20 All of the key depressions From Fig 7.5.19 recorded on one graph. The horizontal position is arbitrary. The legend at the right indicates the order in which the notes were played.

The second representative piece of music was Boellman's Toccata, which was selected by Mr Parry as a "fast" piece that he would expect to significantly affect the way that he played compared to the Bach Chorale Prelude. The complete recording is shown in Fig 7.5.23. This shows the same overruns on the G key recording.

Fig 7.5.21 J S Bach,"*Jesus meine Zuversicht*", BWV 728. Third bar, played with modification in Fig 7.5.19. (Novello Book 18)

Fig 7.5.22. Boellman, Toccata from "*Suite Gothique*". Transposed in Fig 7.5.23. (Paxton)
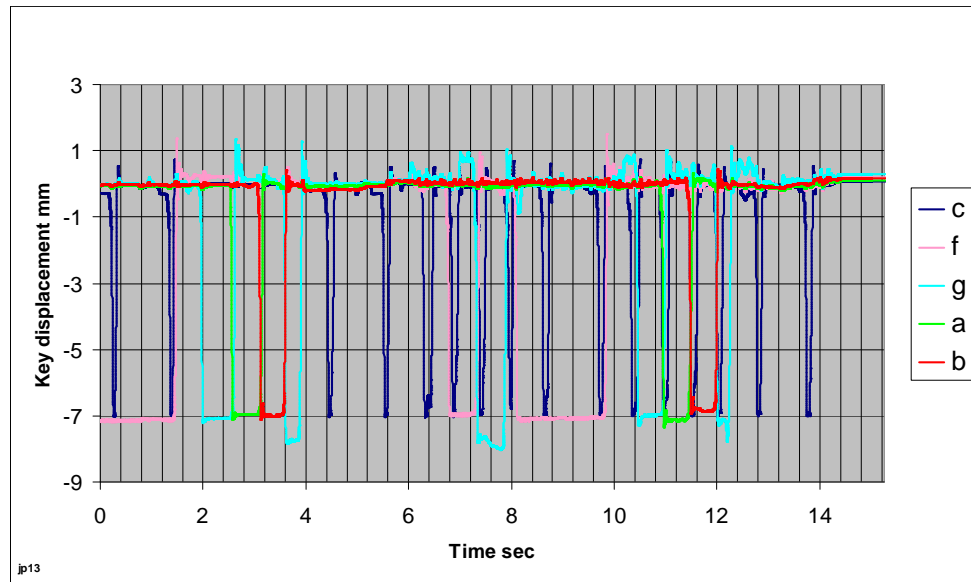
Fig 7.5.23 Recording of key movements in Boellman's Toccata, played at St Margaret's
Ipswich by John Parry.

A visual inspection of these curves indicate that they do not vary to a significant
extent and so the first occurrence of each note has been isolated and the key
depressions shown in Fig 7.5.26.
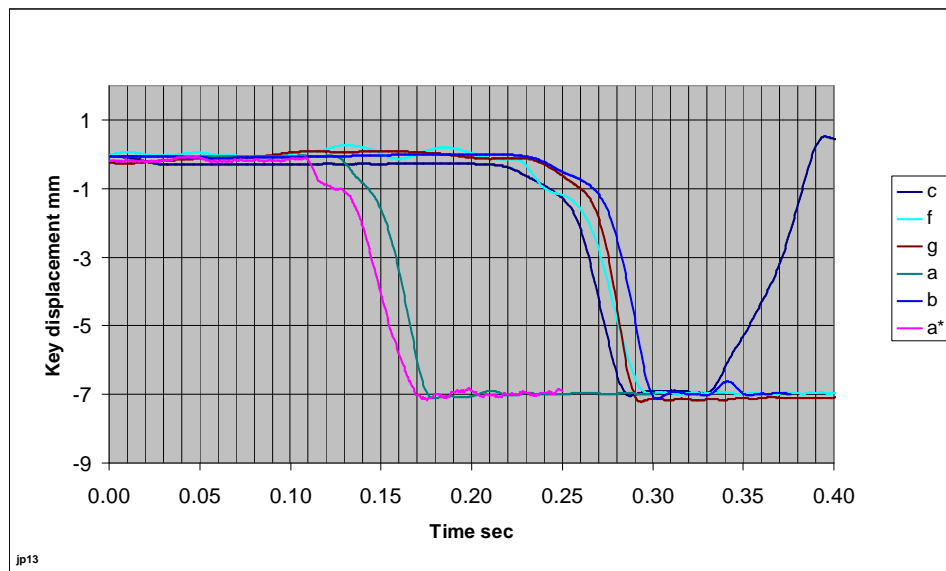
Fig 7.5.24 Key depressions from Fig 7.5.20 showing the first playing of each note. The a^2
has been isolated in order to compare it with an a^2 (shown here as a*) from the recording of
the Bach Chorale Prelude in Fig 7.5.19 in which it is also the pink line.

The pink curve a* has been superimposed from the previous exercise and is the pink curve from Fig 7.5.20. It has been placed next to the representative a^2 from the Boellman toccata. The curve from the "slower" piece starts off more slowly and slows down in the last third or so of its travel, but for the majority of its movement, follows the key movement from the "faster" piece closely.

The releases of the two a^2 key movements in Fig 7.5.23 above are shown in Fig 7.5.25.
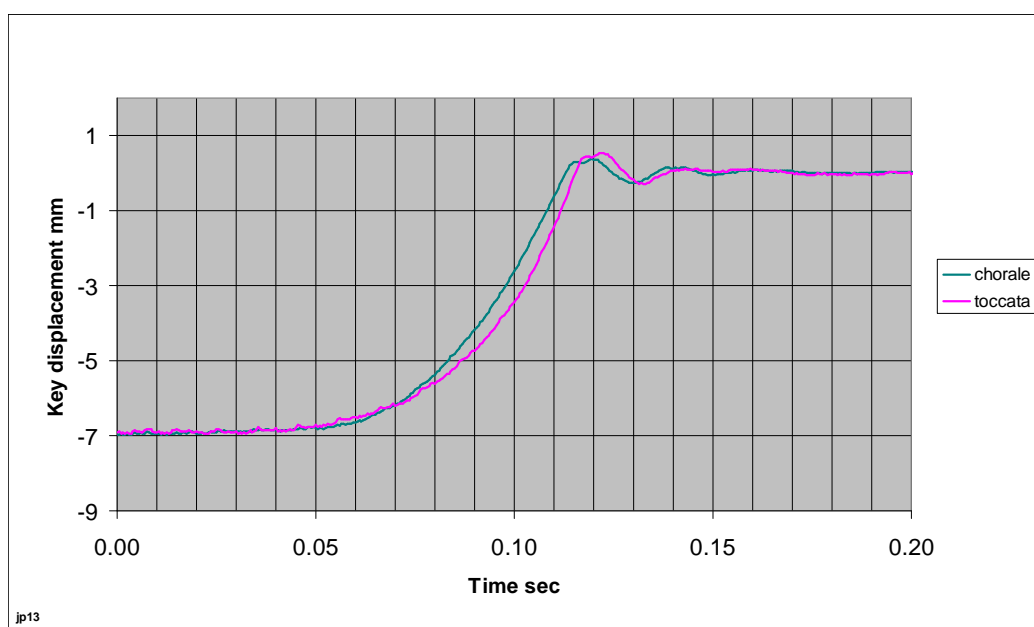
Fig 7.5.25 The key releases from the a^2 notes highlighted in Fig 7.5.23. The pink line is from the faster piece.

It can first of all be seen that the two releases do not differ greatly and that the key release of the Chorale Prelude is, in fact, slightly faster than that in the Toccata. Taking the start of the release as 0.20 sec, the total time of travel is approximately 0.10 sec. This should be compared with Fig 7.5.19 showing key releases in isolation where the "finger" movements resulted in a release time of between 0.14 and 0.20 sec and the "fist" movement gave a release time of 0.07 sec.

7.6 St Mary's Church, Haddington

7.6.1 Introduction

The organ in St Mary's Church Haddington was built by Lammermuir Pipe Organs and completed in 1990. The specification is shown in Appendix 1. The action is mechanical throughout.

The organ is very much in the North European style with a Hauptwerk and Rückpositiv, and with the pedal in separate towers to both sides, Fig 7.6.1.
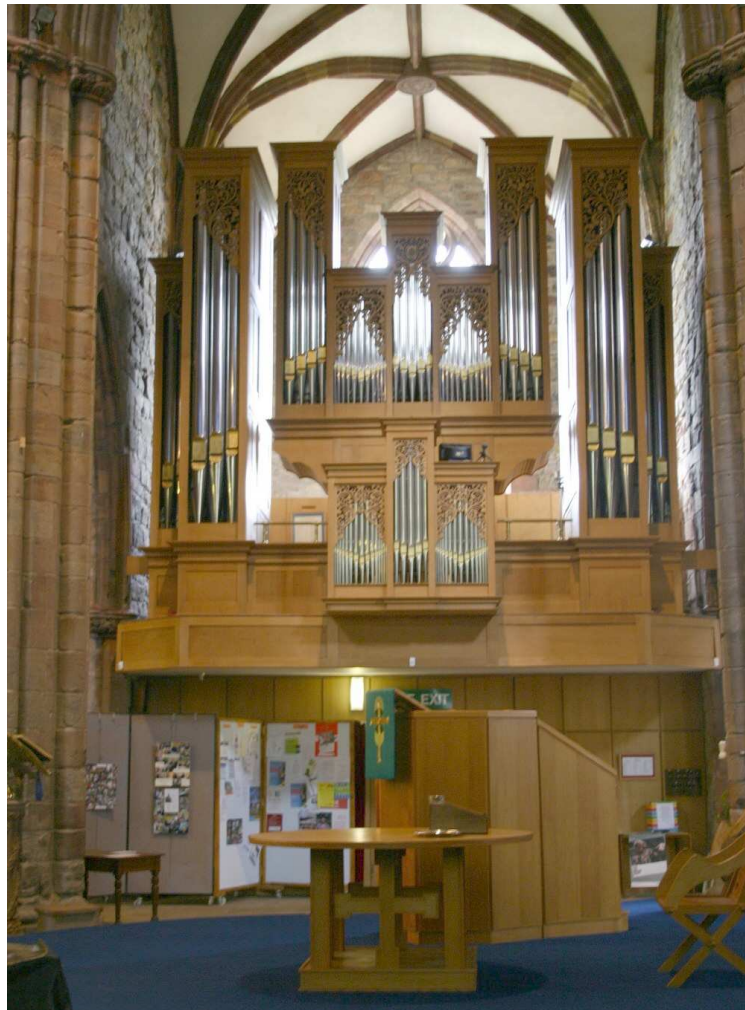
Fig 7.6.1 St Mary's Church, Haddington. Organ by Lammermuir Pipe Organs 1990

For this exercise Alan Alexander, who had studied the organ to an advanced level in New Zealand before becoming a vet, played the instrument. He was very familiar with the organ. The studies were planned to take place on the 2nd August 2005, but a problem with the LED sensors (later identified as a partial failure of the power supply) meant that the results were of limited use. Mr Alexander is pictured at the console in Fig 7.6.2. The Rückpositiv stop knobs are on the back of the Rückpositiv case behind the player's back, and the pedal board is of the straight flat form with "German" style accidentals.

Fig 7.6.2 Alan Alexander at the console, St Mary's, Haddington. The Rückpositiv drawstops are behind the player's back and the pedals have "German" style undercut accidentals. The Rückpositiv to Pedal coupler can be seen to be depressing the bottom E key of the lower manual as the bottom EE of the pedal is played.

Although some further measurements were taken with the LED sensors, the majority of the work was done with the laser sensors and these are shown in position above the Rückpositiv keys in Fig 7.6.3. The reflective strips required by the LED sensors can be seen attached to the keys. The geometry of this console meant that the laser sensors could be positioned relatively far back on the keys, thus minimising the interference to the player. The key dip was measured as 8mm and the movement was thus well within the range of the sensors.
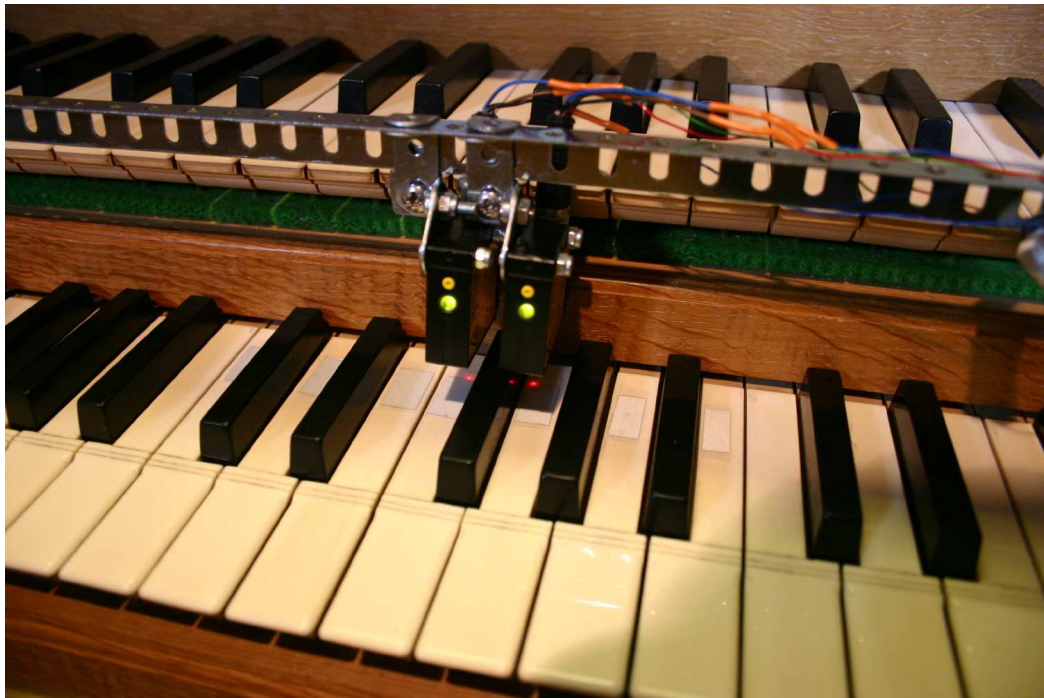
Fig 7.6.3 Laser sensors mounted over the Rückpositiv keys, St Mary's, Haddington. The reflective strips were for the LED sensors.

7.6.2 LED sensors

Due to the problem with the power supply, the quality of the signal from the LED sensors rapidly deteriorated. However, the first three sets of measurements during the second session are adequate for making comparisons of the important parts of the movement.

These measurements are of a scale of C major starting at Middle c^1. The first graph, Fig 7.6.4, shows the key movements in "normal" playing.
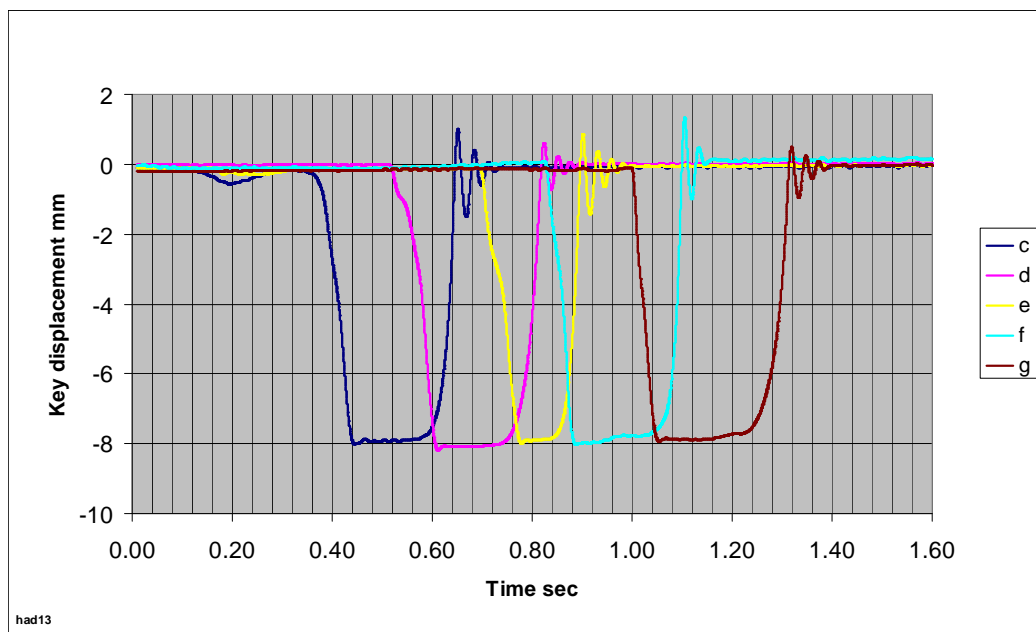
Fig 7.6.4 Recording of the key movements during a scale of c major played "normally".

Fig 7.6.5 shows the key movements during "legato" playing.
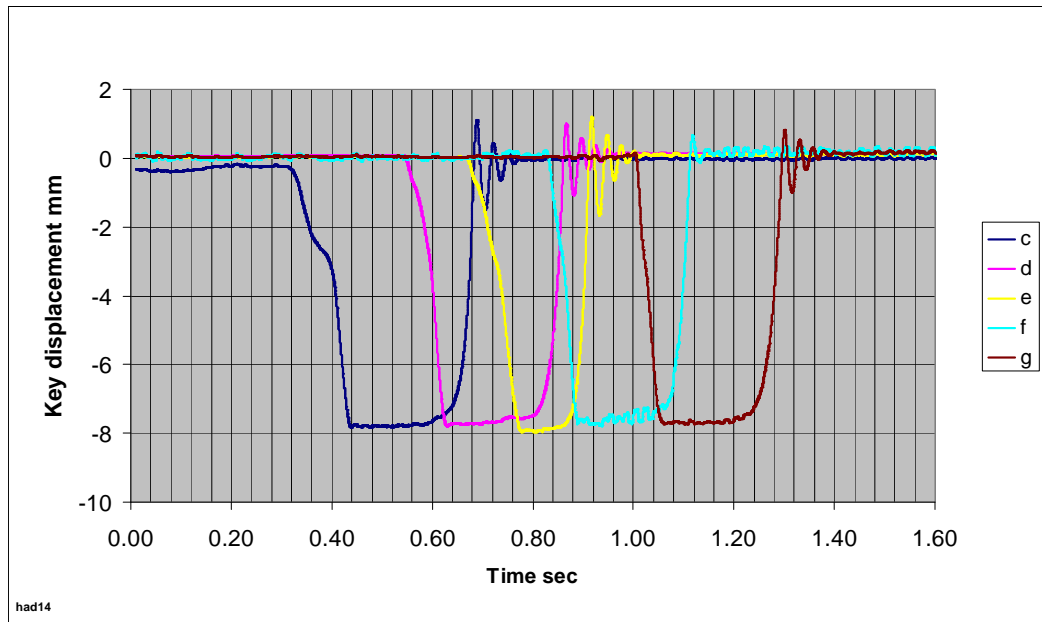
Fig 7.6.5 Recording of the key movements during a scale of c major played "legato".

A visual comparison indicates the following:

- There is little difference in the post pluck movement
- The initial note in the legato playing has an elongated pre-pluck movement
- There is little difference in the timings of the notes
- The "e" in both cases is shortened. This is the note, in normal scale fingering, after which the thumb is brought underneath the third finger.

Fig 7.6.6 shows the same scale played "staccato".
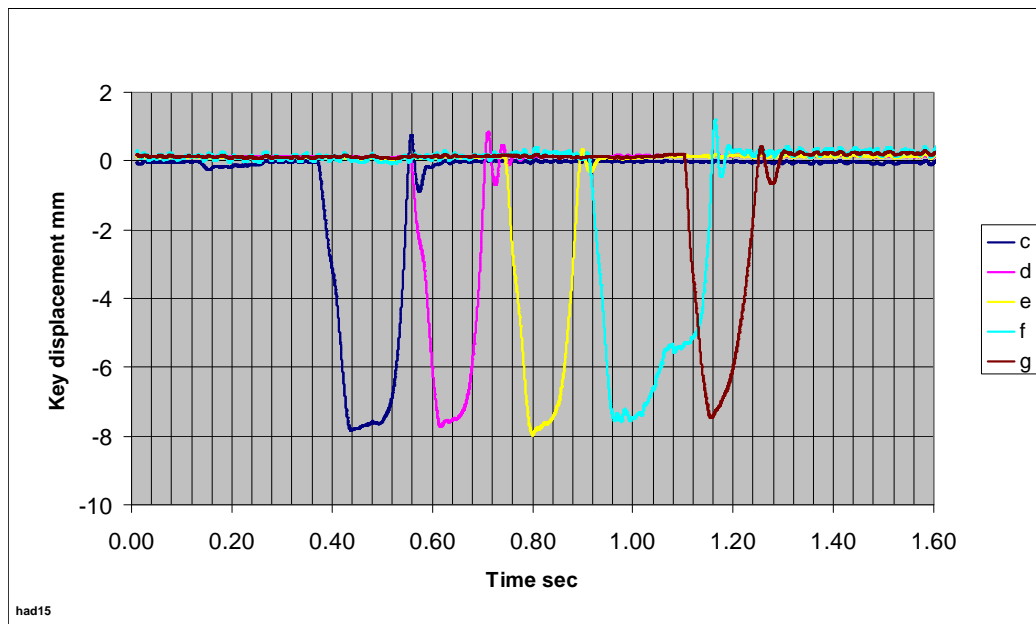
Fig 7.6.6 Recording of the key movements during a scale of c major played "staccato".

Here the e^1 is not shortened relative to the other notes but the subsequent f' is elongated.

Fig 7.6.7 shows the three c^1s and e^1s for comparison. Despite the noise, it can clearly be seen that in the case of the three c^1s there are significant differences in the pre-pluck movements (pluck occurring at around 3mm) and that the post-pluck movements are very similar. The e^1s show a similar pre-pluck difference and slightly larger post-pluck differences. These are still small relative to the total differences and are unlikely to be significant.
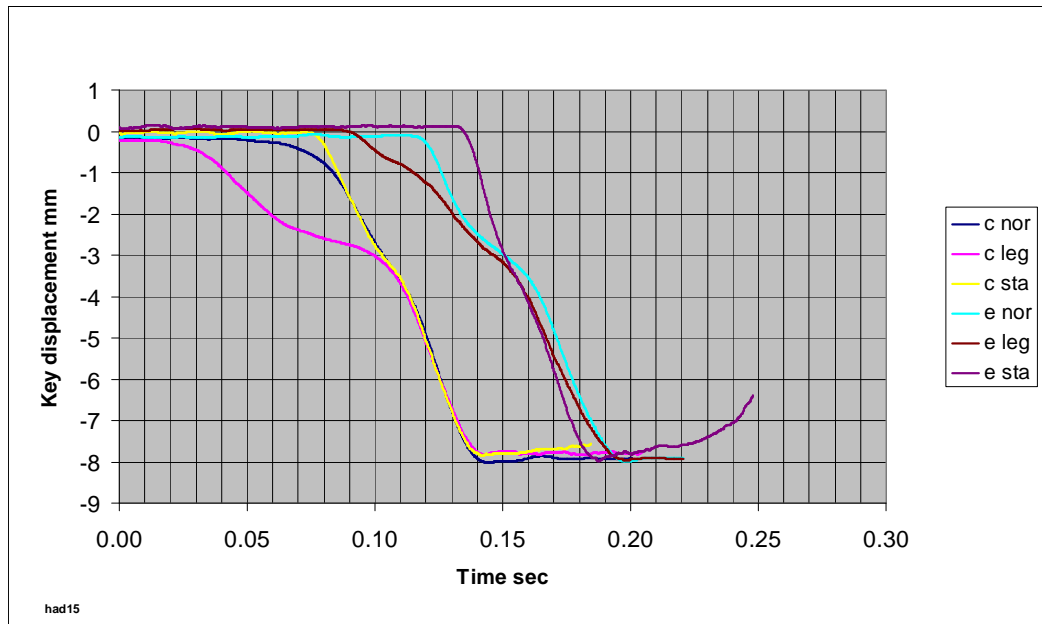
Fig 7.6.7 The three e[1]s and three c[1]s from the Figs 7.6.3 to 7.6.6 superimposed. The three different styles of playing of the same note, normal, legato and staccato are grouped together.

7.6.3   Laser sensors

Some measurements were then taken using the laser sensors. In the first exercise, a scale was played starting from a[1] below Middle c[1] so that the two notes being recorded were in the middle of the sequence. The results are summarised in the graph below, Fig 7.6.8, which shows the movements of the c[1] and d[1] keys when played "normal" legato" and "staccato".
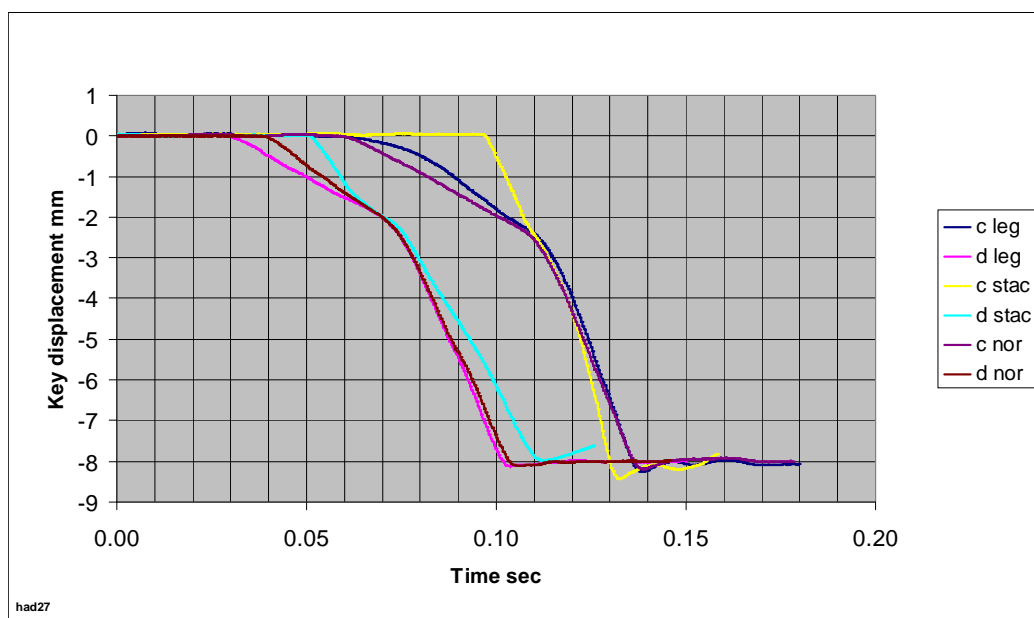
Fig 7.6.8 Graph showing the movements of the c^1 and d^1 keys in the middle of a scale and played "legato", "normal" and "staccato"

From this graph it can be seen that the "normal" and " legato" curves are very similar after pluck for both notes. The c^1 legato curve shows a distinct elongation whereas the d^1 curves start at about the same point but follow a slightly different shape. The staccato curves both show a distinctly shorter pre-pluck movement but still show the characteristic shape at the pluck point. The c^1 key moves more slowly post-pluck whereas the d^1 key moves more quickly. This is probably a random phenomenon possibly due to the change of hand position between the two notes.

In the next exercise the c^1 key was depressed three times in each of the three styles ("normal", "legato" and "staccato"). For this exercise the sound was also recorded using an Edirol R1 solid-state sound recorder with the microphone (Shure PG81) suspended over the front of the Rückpositiv case. The recording format was 44.1 KHz 16bit.

The first graph, Fig 7.6.9 shows the three key movements during "normal" playing. The waveform on this graph was recorded through the DAQ box at 10 KHz. There is very considerable variation in the waveform envelopes. This is probably due to the

unsteady wind in this organ brought about by the use of wedge bellows. This unsteadiness makes analysis of the sound difficult because it is was not possible to ascertain the cause of particular variations.
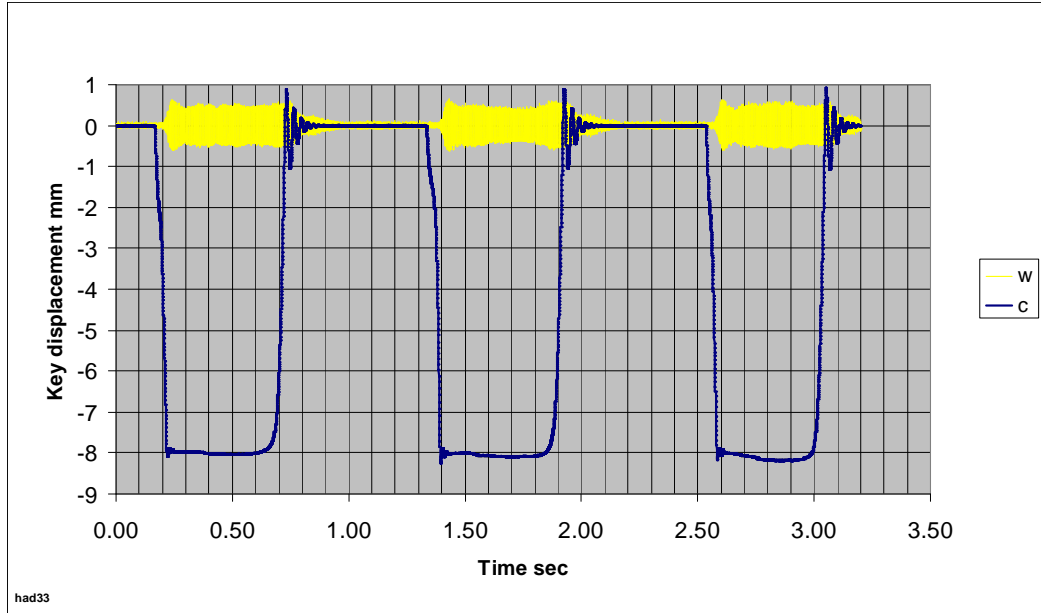
Fig 7.6.9 Graph showing the key movements and sound envelope, Middle c[1] played "normally" on the Rückpositiv.

What can be deduced from this graph is that the sound envelope does not start developing until the key has moved a significant distance and that at the end of the note the envelope continues until the key has returned to its start position. This organ would potentially appear to provide the source of a great deal of information if pallet movements and pressures could also be measured.

The three key depressions are shown in Fig 7.6.10. The first and third key movements are very similar post-pluck and this is unlikely to contribute to any differences in the sound. The second curve is flatter pre-pluck and steeper post-pluck with some difference in shape around the pluck point. The sound envelope from the first depression has been added in order to indicate where it starts developing. It can be seen that this is not until the key is approximately half way through its travel. Tests on other organs and in the laboratory indicate that on this organ the

Rückpositiv Middle c^1 pallet starts opening after approximately two millimetres of key travel, i.e. 25% of its movement.
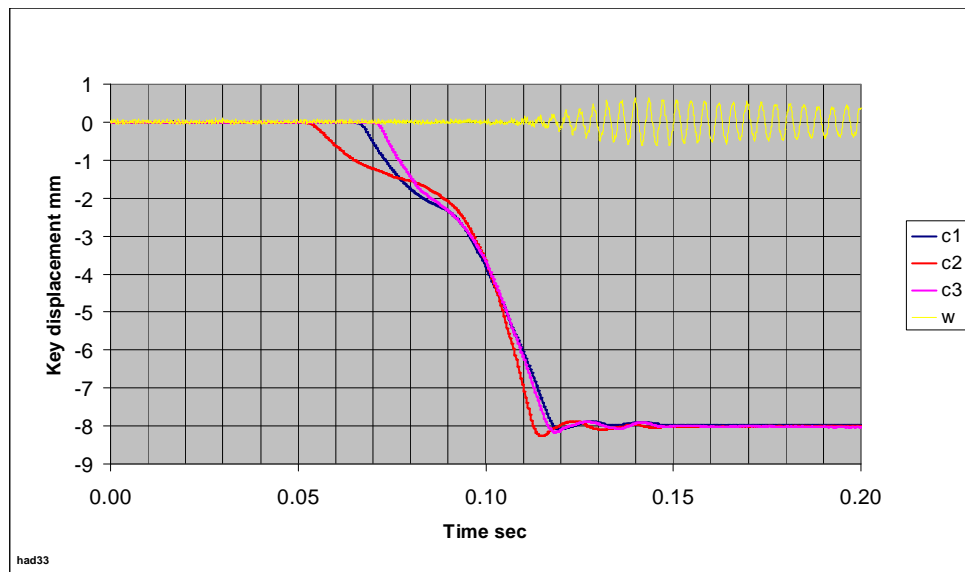
Fig 7.6.10 The three key depressions from Fig 7.6.9

Fig 7.6.11 shows the three "legato" key movements.
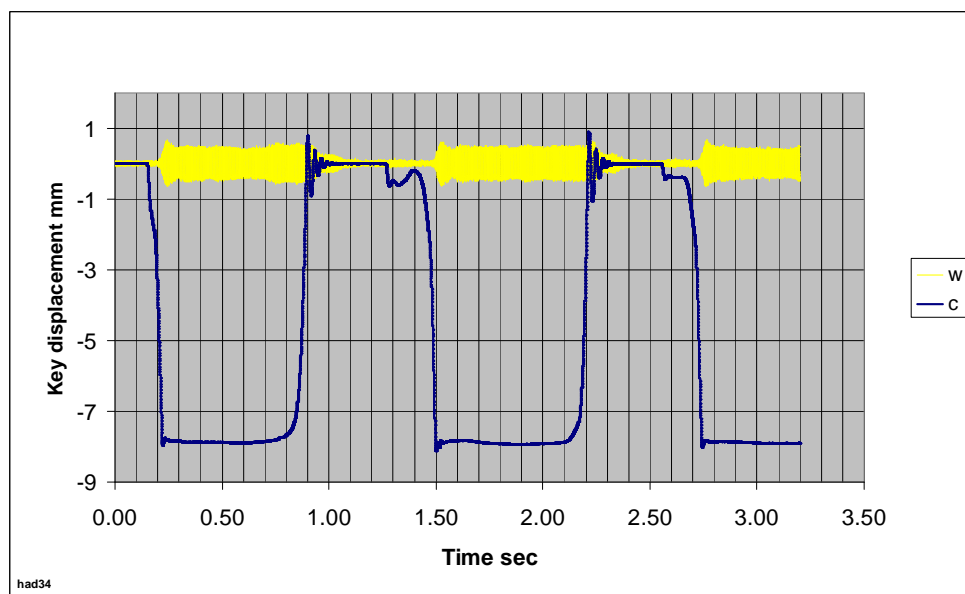
Fig 7.6.11 Graph showing the key movements and sound envelope Middle c^1 "legato" playing on the Rückpositiv.

The second and third movements show a very distinct movement of the key before the actual depression. The second one is reversed almost to the rest position and is shown in Fig 7.6.12. The increase in sound level corresponding with this movement appears to be the aftermath of the previous note since it appears at about the same time after every key movement including the last one. It is not clear whether this is due to echoes or whether it is an artefact of the organ. The latter is unlikely because the pallet should be firmly closed at this point and the frequency is very close to the steady state frequency.
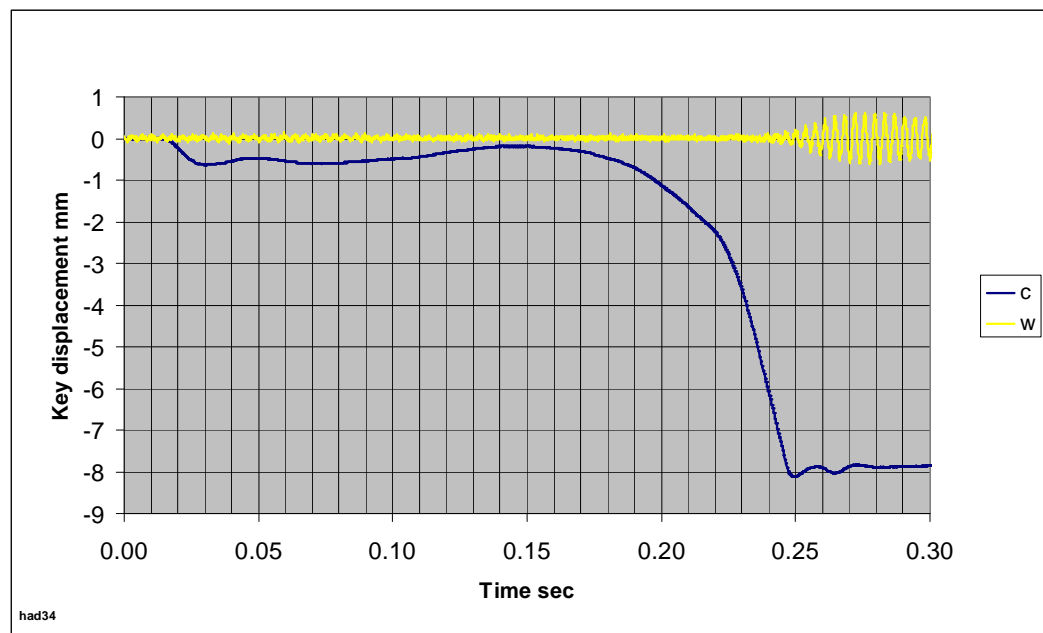
Fig 7.6.12 The second key movement from Fig 7.6.11 shown to a larger scale

Fig 7.6.13 shows all three key movements. It will be noted that the normal and staccato movements are very similar post-pluck and that the legato movement is slightly slower. The waveform envelopes have been superimposed to indicate the relative timings of the three key movements. At this level of approximation and with the proviso noted above about the quality of the recording, the three waveforms are similar.

Fig 7.6.14 shows the main part of the key movement in more detail. The three curves have been aligned approximately at the estimated pluck point. This has resulted in the waveform envelopes also coinciding.
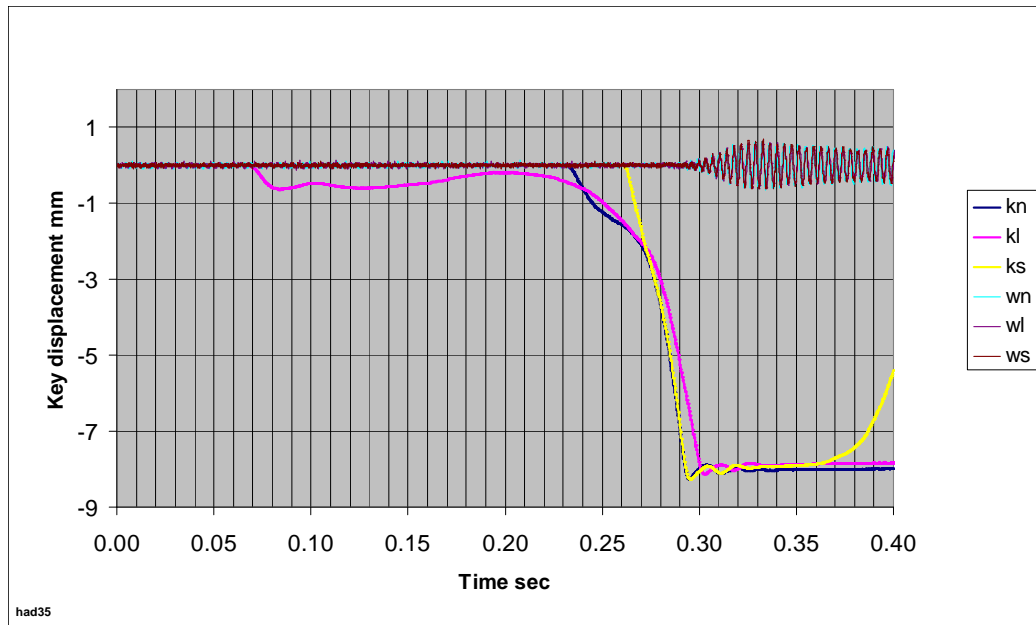
Fig 7.6.13 The three key depressions from Fig 7.6.11
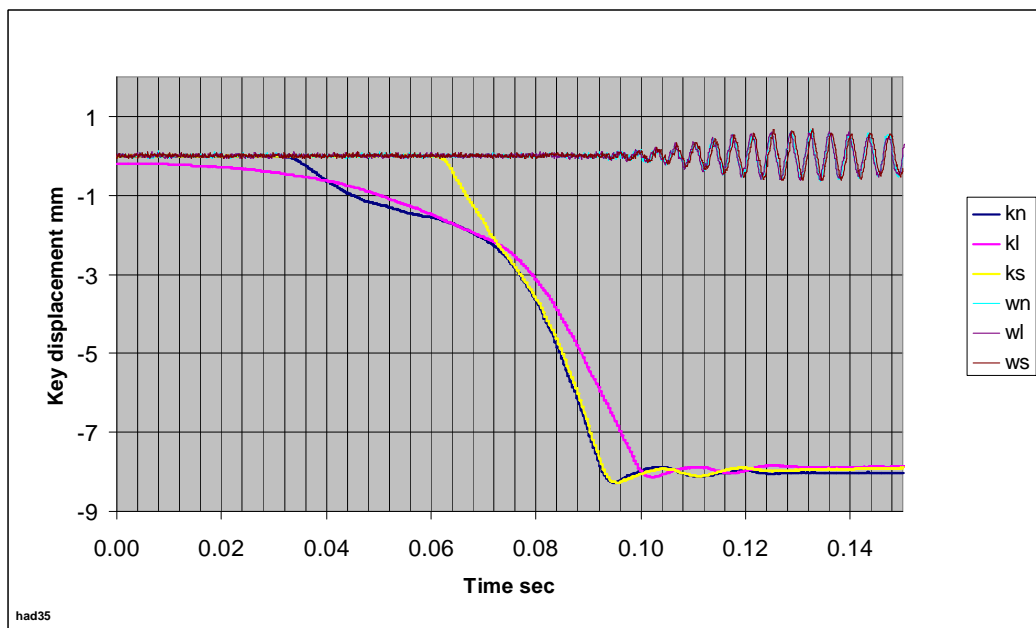
Fig 7.6.14 The three key depressions from Fig 7.6.13 without the elongated pre-pluck movement of the second curve.

The lengths of the pre- and post-pluck phases are tabulated in Fig 7.6.15.

Style	a Total time sec	b Pre-pluck time sec	c Post-pluck time sec	d % c of a
Legato	0.230	0.202	0.028	12.2
Normal	0.059	0.038	0.021	35.6
Staccato	0.031	0.010	0.021	67.7

Fig 7.6.15 Tabulation of pre- and post-pluck key movement times of the movements shown in Fig 7.6.13

The release of the second key movement is shown in Fig 7.6.16. It can clearly be seen that the envelope does not appear to start reducing in amplitude until after the key has returned to its rest position.
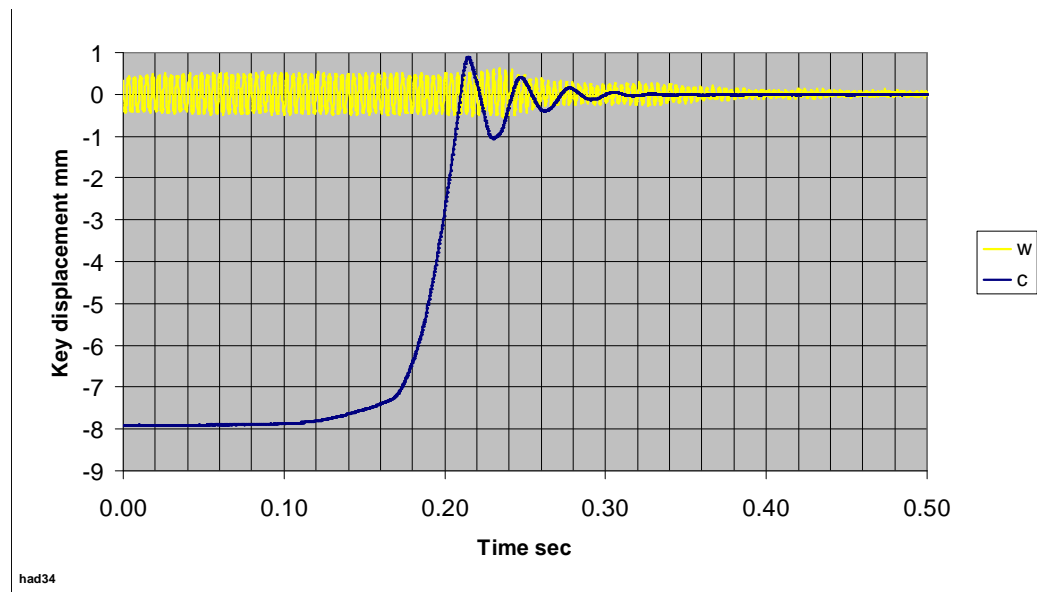
Fig 7.6.16 The key release of the second key movement in Fig 7.6.11.

Fig 7.6.17 shows the three staccato key movements of Middle c^1. Fig 7.6.18 shows the key depressions and the curves have been superimposed in order to highlight their similarity, the first two being indistinguishable. This would suggest that any variation in the sound between these three notes, and certainly the first two, is not due to the way in which the key is moved. The waveform envelope from the first movement has been superimposed.
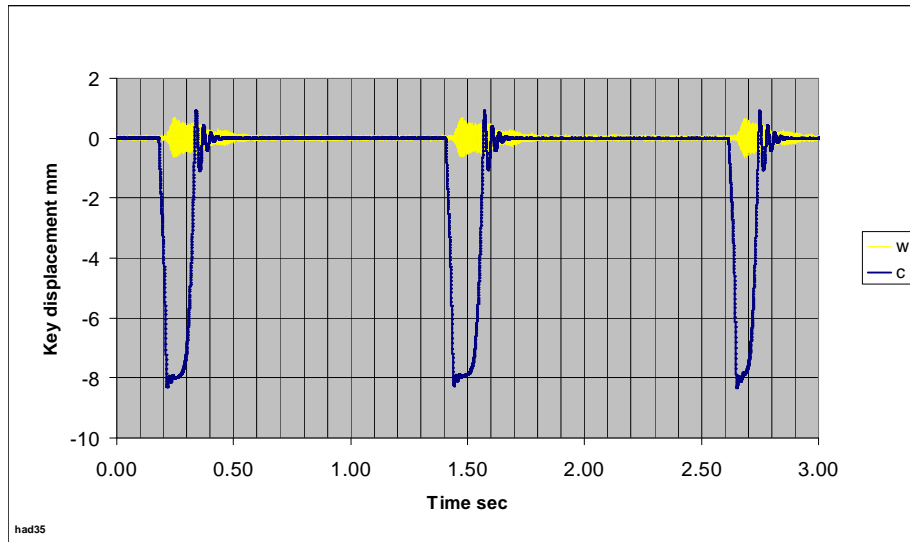
Fig 7.6.17 Graph showing the key movements and sound envelope. Middle c^1 "staccato" playing on the Rückpositiv.
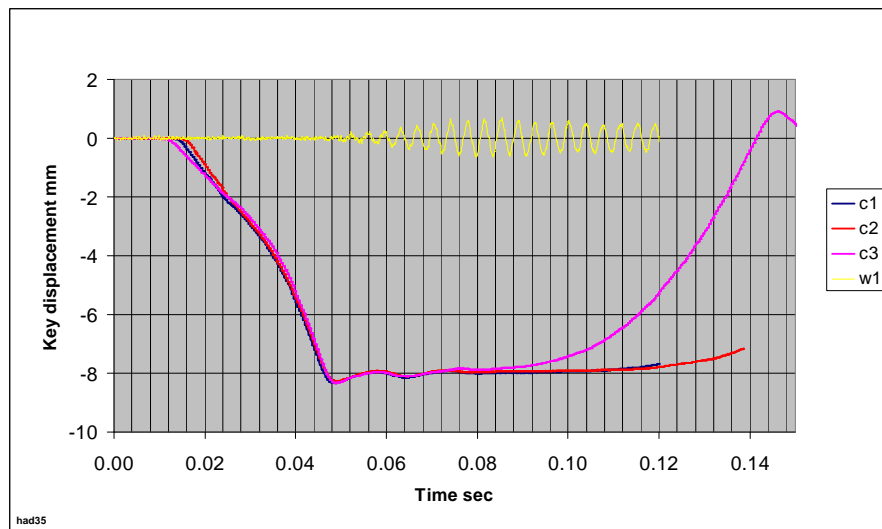
Fig 7.6.18 The three key depressions from Fig 7.6.17

250

Fig 7.6.19 shows the CD quality sound recordings from the three "normal" key movements (Fig 7.6.9) as a 3-dimensional visualisation of the spectral analysis using Sigview 1.91 with an fft of 1024, divided into 100 segments and with an upper frequency limit of 5 kHz.
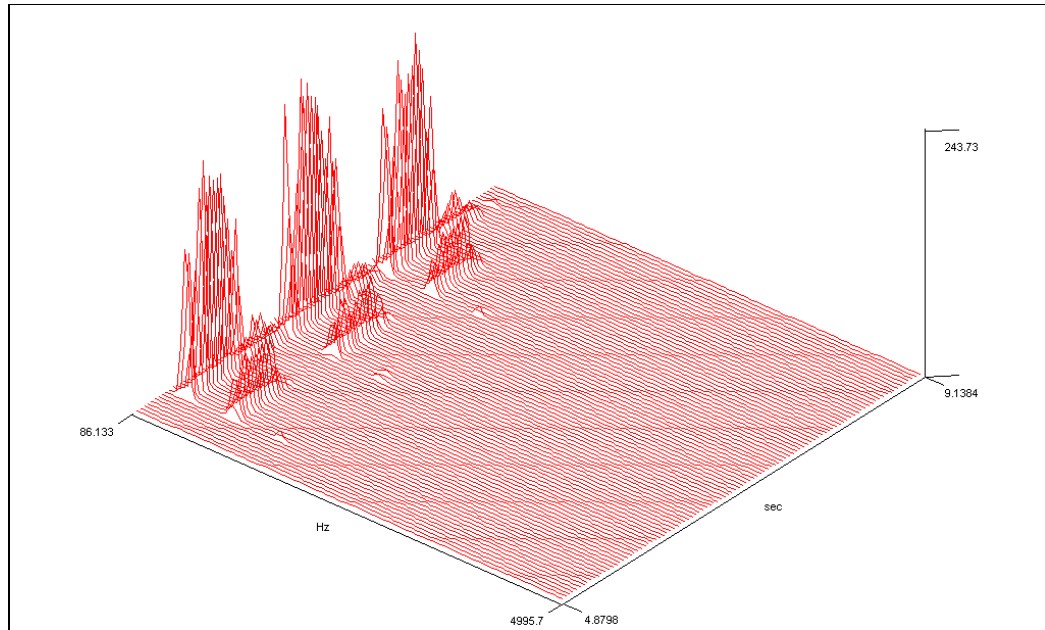
Fig 7.6.19 3D visualisation of the spectral analysis of the "normal" playing shown in Fig 7.6.9. The frequency limits are 86 and 5000 Hz. Linear amplitude, arbitrary scale.

Fig 7.6.20 shows the three legato movements from Fig 7.6.11 as a 3-dimensional visualisation of the spectral analysis.
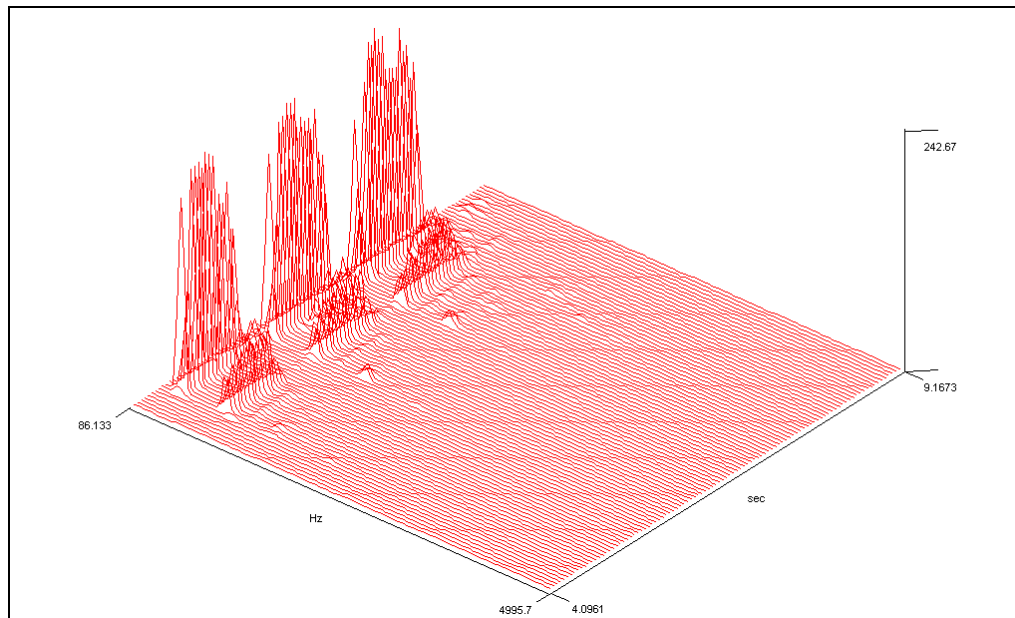
Fig 7.6.20 3D visualisation of the spectral analysis of the "legato" playing shown in
Fig 7.6.11.The frequency limits are 86 and 5000 Hz. Linear amplitude, arbitrary scale.

Fig 7.6.21 shows the three staccato movements from Fig 7.6.17 as a 3-dimensional
visualisation of the spectral analysis.

.
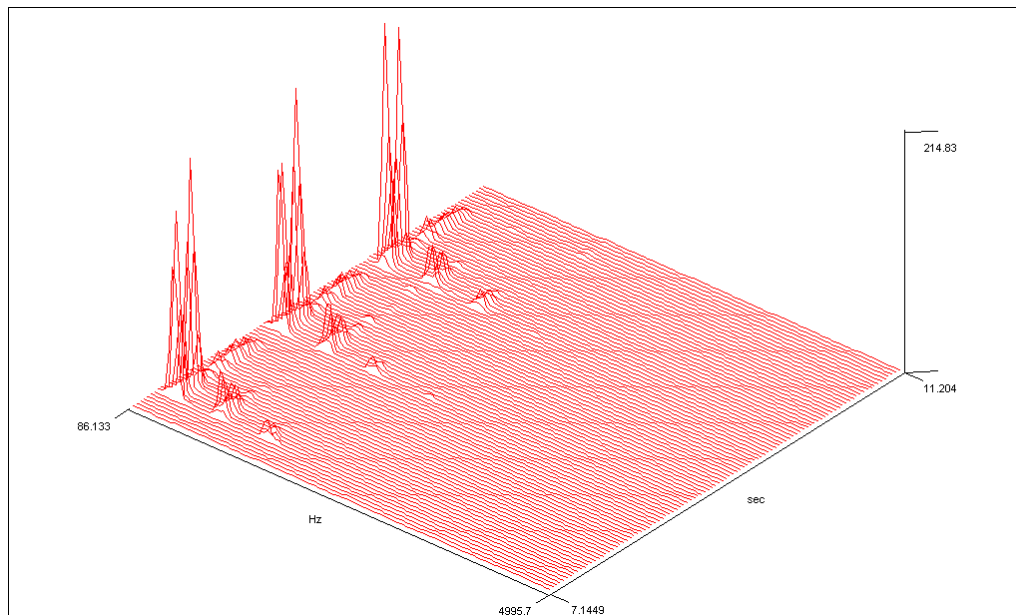
Fig 7.6.21 3D visualisation of the spectral analysis of the "staccato" playing shown in
Fig 7.6.17.The frequency limits are 86 and 5000 Hz. Linear amplitude, arbitrary scale.

The next sequence of spectrograms shows the initial 0.12 second of the first envelope in each sequence. This time period was chosen because this is time between the start of the envelope and the key returning to its rest position in the first staccato note. The fft was set at 512 in order to maximise the time resolution, but at the expense of frequency resolution, which is 86.13 Hz. The sampling time range is approximately 0.012 sec., and it must be noted that this still means that the signal is averaged over 10% of the envelope and there will be distortion.

The first three diagrams show the first note, which will be unaffected by any previous note.

Fig 7.6.22 shows the first 0.12 second of the first "normal" key movement from Fig 7.6.9.
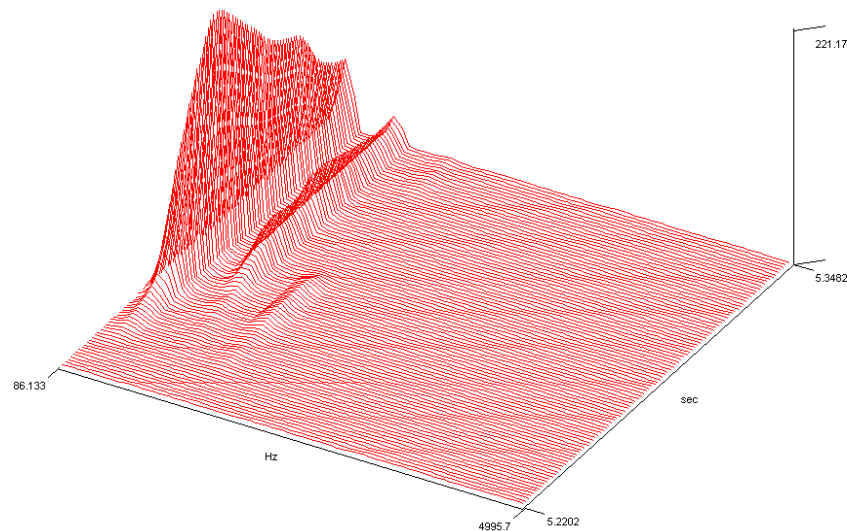
Fig 7.6.22 3D visualisation of the spectrogram of the first note from the "normal" sequence shown in Fig 7.6.9. Linear amplitude, arbitrary scale.

Fig 7.6.23 shows the first 0.12 second of the first "legato" key movement from Fig 7.6.11.

.
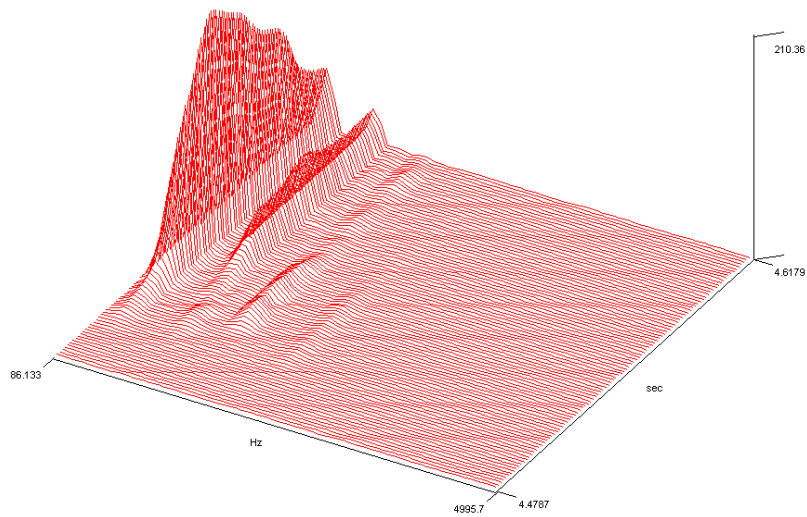
Fig 7.6.23 3D visualisation of the spectrogram of the first note from the "legato" sequence shown in Fig 7.6.11. Linear amplitude, arbitrary scale.

Fig 7.6.25 shows the first 0.12 second of the first "staccato" key movement from Fig 7.6.17.
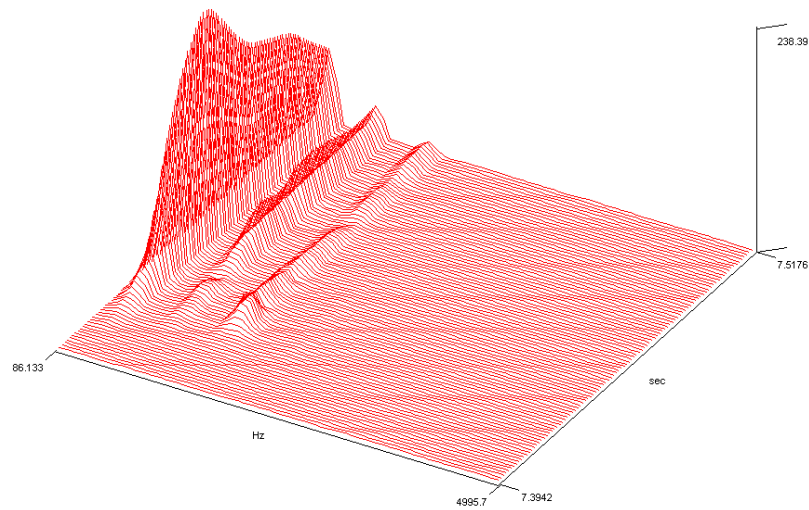
Fig 7.6.24 3D visualisation of the spectrogram of the first note from the "staccato" sequence shown in Fig 7.6.17. Linear amplitude, arbitrary scale.

These three spectrograms are shown side by side in Fig 7.6.25 in order to facilitate comparison.

normal   legato   staccato
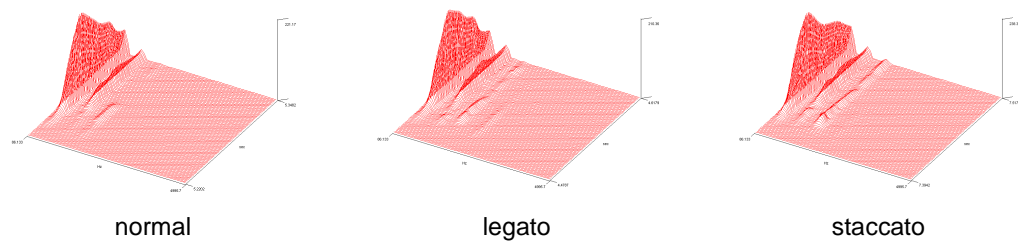
Fig 7.6.25 The three 3D spectral analyses from Figs 7.6.22 to 7.6.24 presented together for comparison. The corresponding key movements are shown in Fig 7.6.13. Linear amplitude, arbitrary scale.

The rise of the fundamental is similar in each case and does not reflect the key movement. There are some differences in the harmonics and also in the fundamental after it has reached a peak, which may be due to the winding system.

7.7 All Saint's, Epping Upland, Essex

7.7.1 Introduction

Epping Upland is a small village in Essex about 14 miles north of central London. The organ in All Saints Church (Church of England) started out as a barrel organ by Bevington but has been extensively rebuilt since. It is located in a chamber to the north of the chancel and has two manuals and pedals with 12 speaking stops (IIP12).

The pedal action is electric with a compass of 30 notes, CC to f, and the manual action is mechanical with a compass of 54 notes, C to f^3. The key dip at Middle c^1 is 13.5mm, which is very deep particularly on a small organ. The organist of the church is Dr Rodney Matthews.

The organ façade is shown in Fig 7.7.1, the console in Fig 7.7.2 and Dr Matthews is pictured playing in Fig 7.7.3.

Fig 7.7.1. The façade of the organ in All Saints Church, Epping Upland, Essex
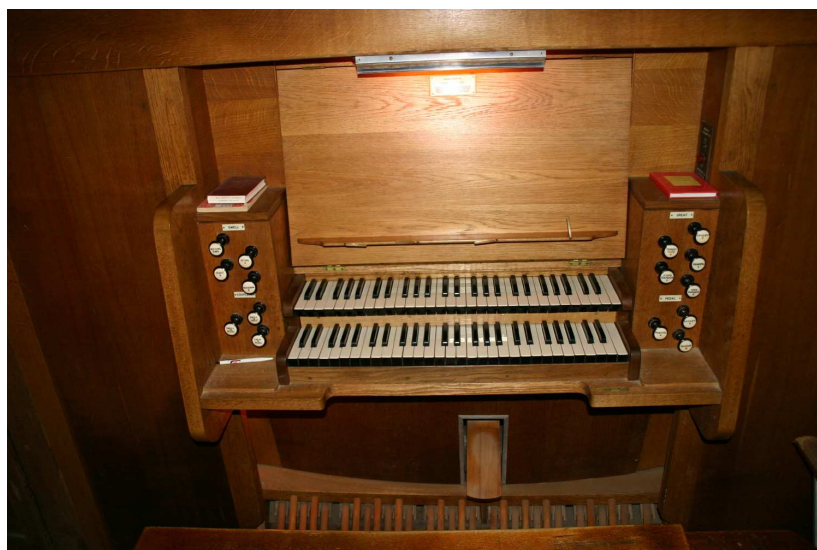
Fig 7.7.2. The console of the organ in All Saints Church, Epping Upland, Essex

Fig 7.7.3. Dr Rodney Matthews, organist of All Saints, Epping Upland, Essex, at the console.

7.7.2 Key movement during scales

In the first exercise, Dr Matthews played a scale in three styles – "normal", "legato" and "staccato" on the Great organ using the Stopped Diapason. Dr Matthews considered that playing in these three styles would result in a difference in key movement speed. Fig 7.7.4 shows the complete recording of the "normal" sequence.
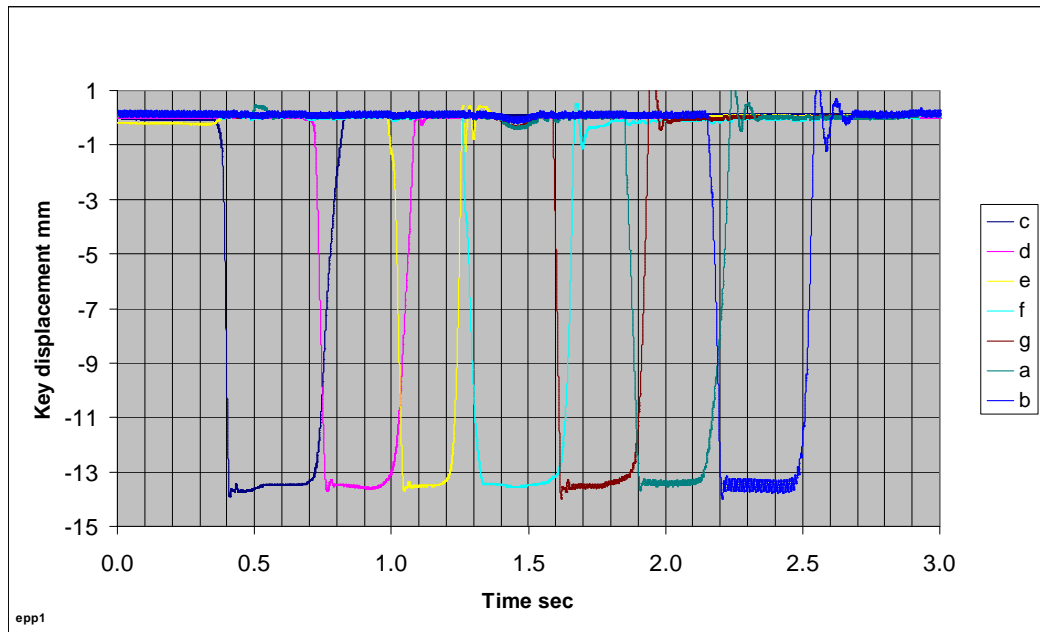
Fig 7.7.4 Key movements from a scale played "normally", Great Stopped Diapason

Fig 7.7.5 shows the complete recording of the scale played "legato".
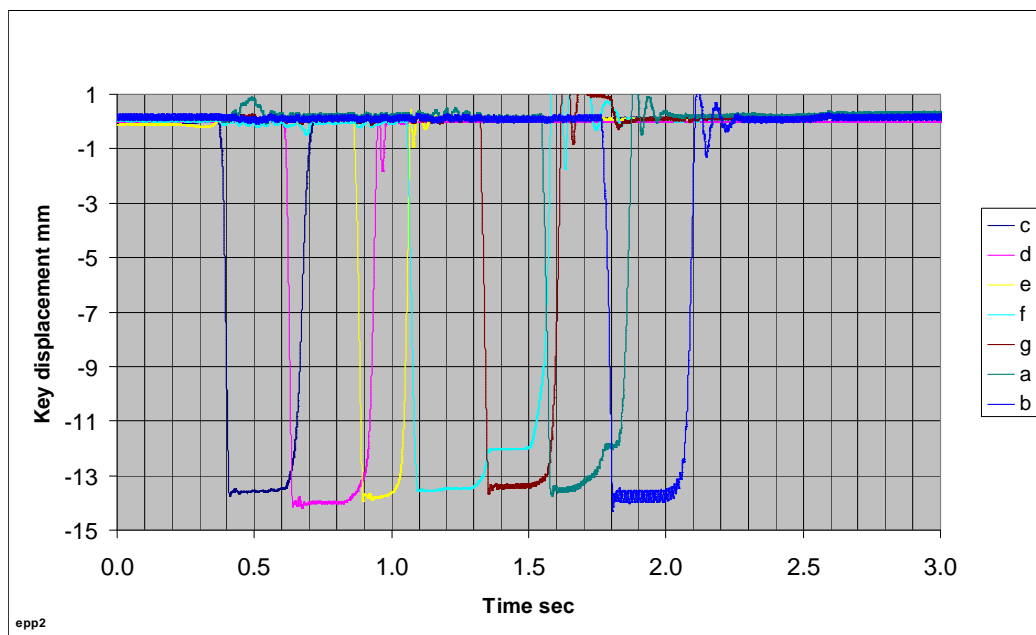
Fig 7.7.5 Key movements from a scale played "legato", Great Stopped Diapason

Fig 7.7.6 shows the complete recording of the scale played "staccato".
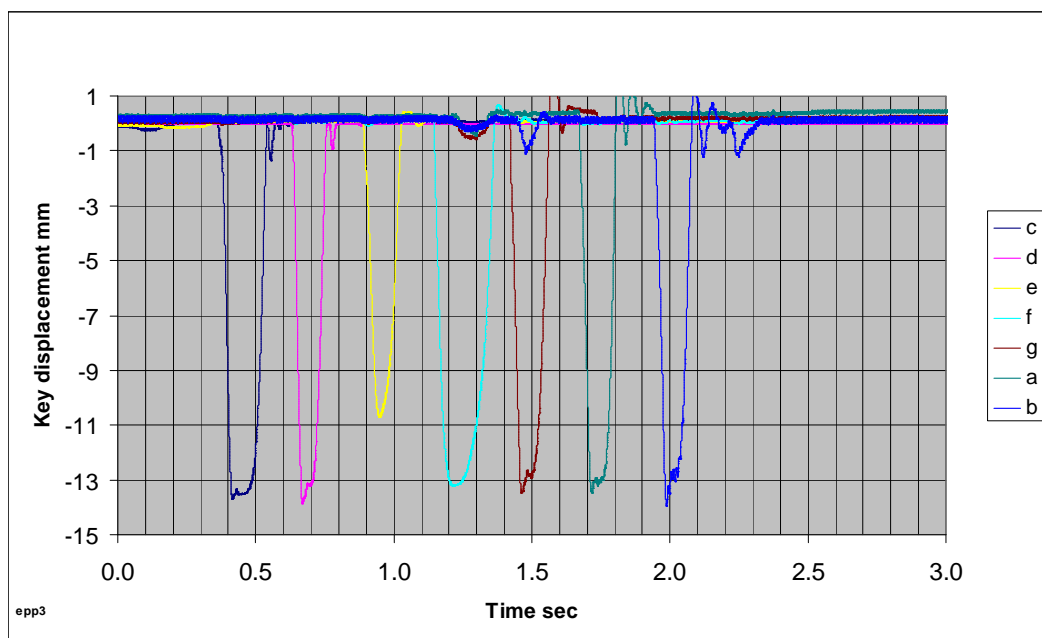
Fig 7.7.6 Key movements from a scale played "staccato", Great Stopped Diapason

Fig 7.7.7 shows the three c^1 and the three g^1 key movements superimposed. In both cases the normal and legato movements are effectively identical with a slight pre-pluck difference evident in the c movement. There is a greater pre-pluck movement in the g action run. In both cases the staccato key movement is slower both pre- and post-pluck despite expecting it to be faster. This has been observed elsewhere in the site visits and appears to be due to a change from playing with flexible fingers to playing with the whole hand.
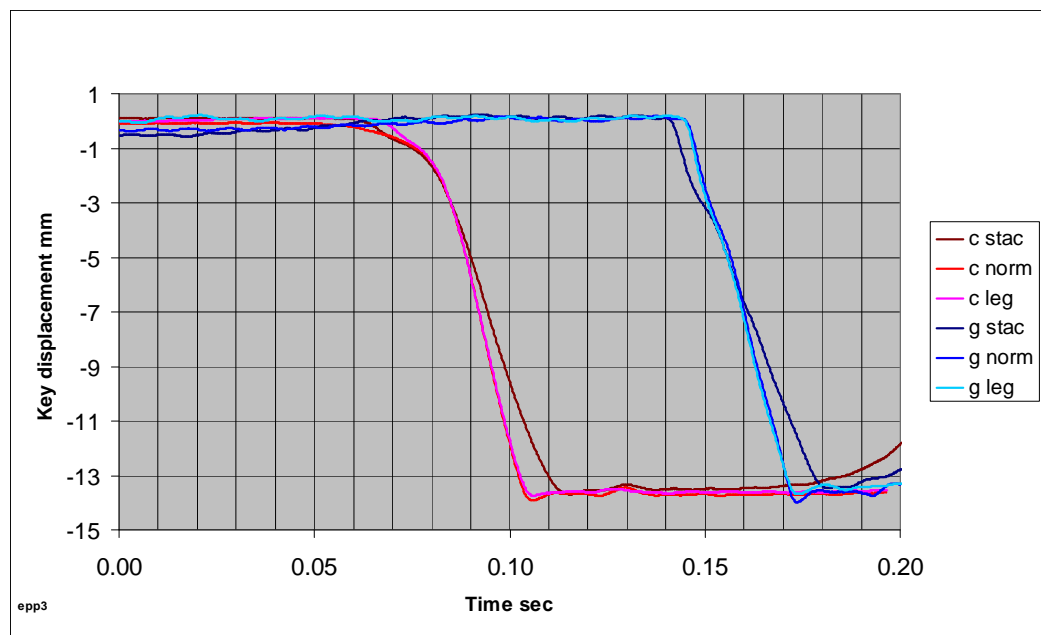
Fig 7.7.7 The three c^1 and three g^1 key movements from Figs 7.7.4 to 7.7.6.

7.7.3 Key movement during normal playing

In the next exercise, Dr Matthews played an improvised sequence in the same three styles. Fig 7.7.8 shows the "normal" playing, Fig 7.7.9 shows the "legato" playing and Fig 7.7.10 shows the "staccato" playing.
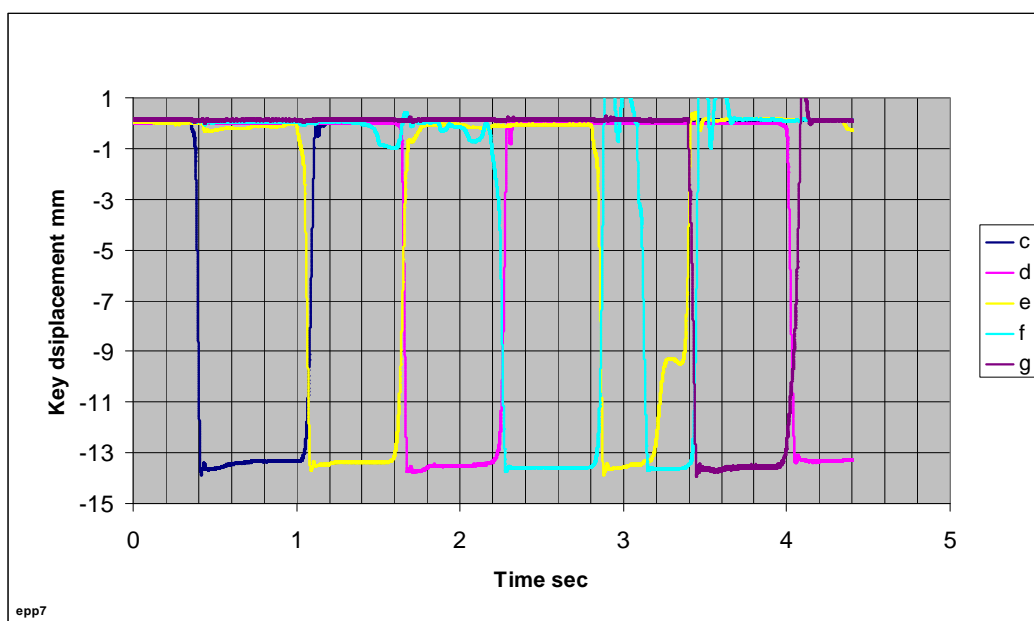
Fig 7.7.8 Recording of key movements of improvised theme played "normally". Great Stopped Diapason
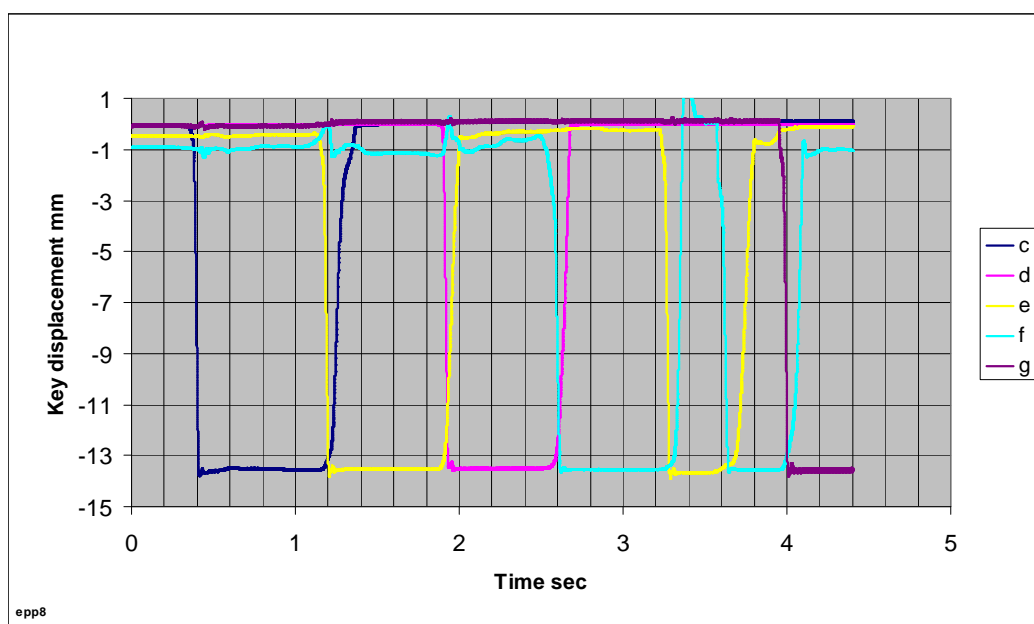
Fig 7.7.9 Recording of key movements of improvised theme played "legato". Great Stopped Diapason
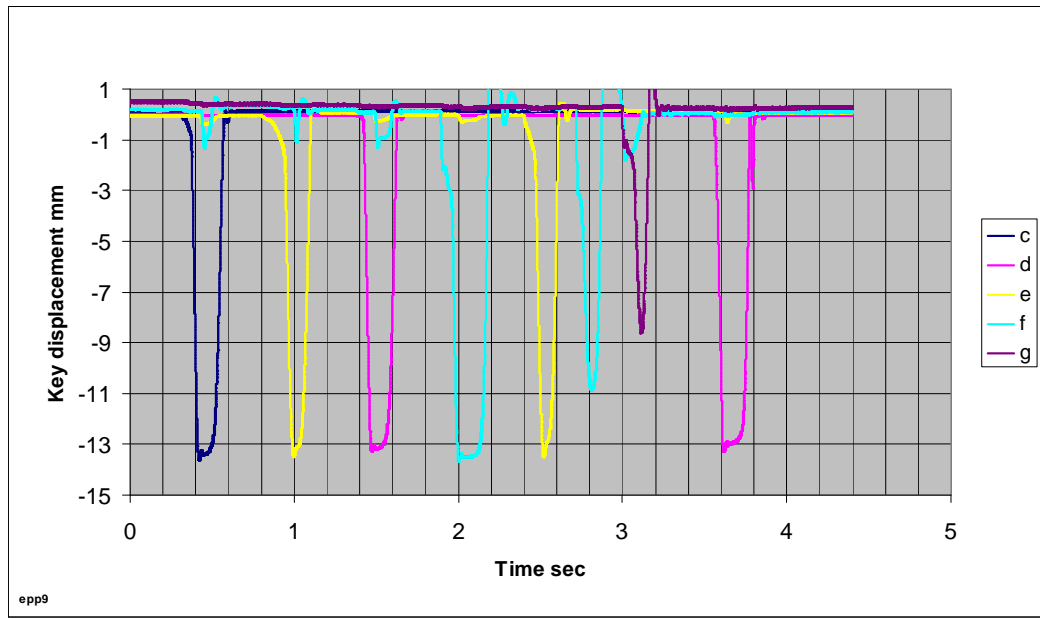
Fig 7.7.10 Recording of key movements of improvised theme played "staccato". Great Stopped Diapason

Fig 7.7.11 shows the three c^1 and the three e^1 key movements superimposed.
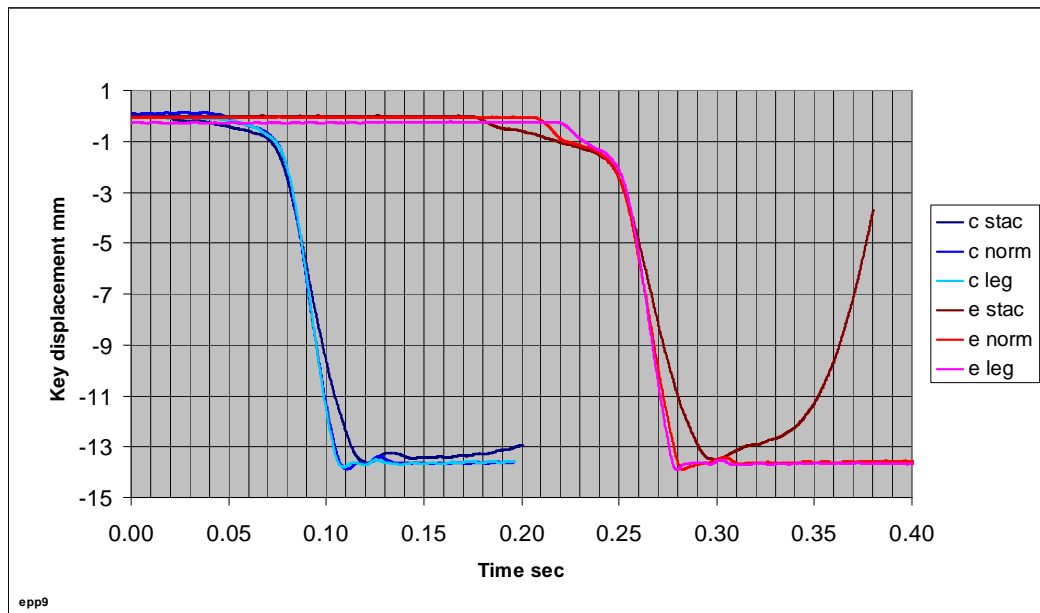
Fig 7.7.11 The three c^1 and e^1 key movements from an improvised theme played "normally", "legato" and "staccato".

This again shows the "legato" and "normal" key movements being effectively identical with, in this case, a longer pre-pluck movement on the normal e^1 depression. The two "staccato" movements are slower than the other two styles.

263

7.8 Carlops Chapel

7.8.1 Introduction

Carlops is a small village about sixteen miles south of Edinburgh. The chapel contains a small one manual organ, which had been moved from another chapel.

Fig 7.8.1 shows the organ with its front casework removed and the LED sensors in place.

Fig 7.8.1 The organ in Carlops Chapel with the LED sensors in place.

The organist of the chapel is Professor Murray Campbell, Professor of Musical Acoustics at the University Edinburgh and who played for this exercise.

7.8.2   Isolated notes

The first series of measurements was made using a laser sensor and a sampling frequency of 10kHz. The sound was recorded through the computer's soundcard with a standard computer microphone. The position of this can be seen from Fig 7.8.1 and resulted in a considerable amount of background noise, which was reduced using Cooledit Pro with an fft of 1024 and a reduction level of 60dB. In this series Prof Campbell played a sequence of two Middle c^1s with either "slow" followed by "fast" or "fast" followed by "slow" key movements. Each was repeated five times.

An example of the fast followed by slow sequence is shown in Fig 7.8.2.

carlops4nr
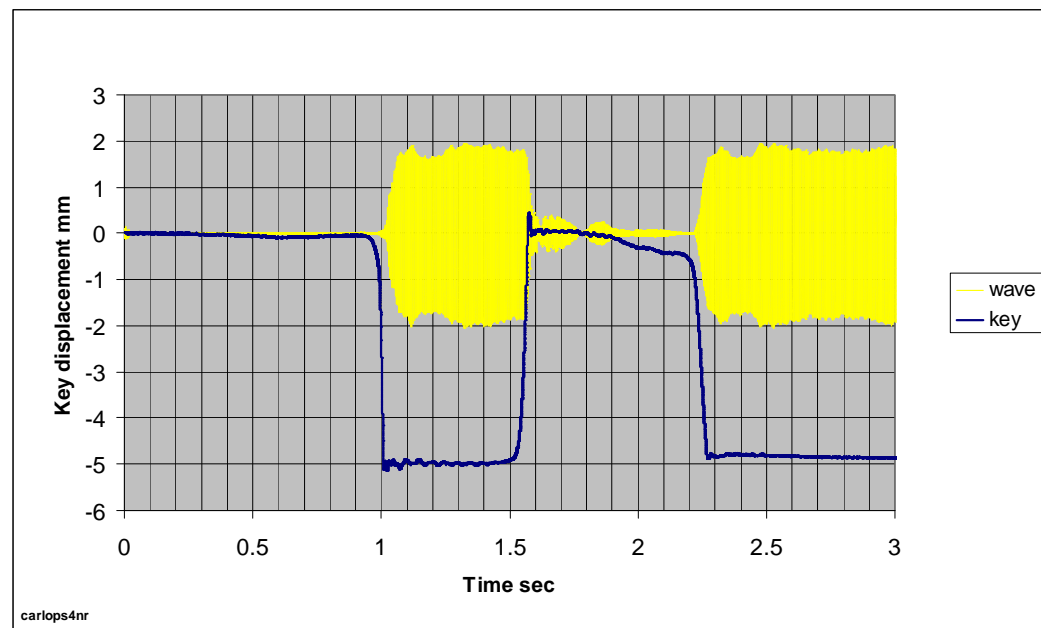
Fig 7.8.2 Graph showing key movement and diagrammatical representation of sound envelope for a sequence of two notes, the first with a "fast" key movement followed by a "slow" key movement. Carlops Chapel, Middle c^1 Stopped Diapason.

It can readily be seen that "slow" movement exhibits the characteristic shallower initial gradient before the pluck point, which occurs after approximately 0.5mm key movement. Note that there is a small displacement of the key before the "fast" movement due to the player's finger resting on the key. These movements are shown at a larger scale in Fig 7.8.3. The curves for the slow and fast movements were roughly aligned at the pluck point of approximately 0.5 mm movement and then finely adjusted so that the waveforms were brought into phase. The waveform at the beginning of the "slow" (pink) sound envelope is due to the previous note and is not as the result of the key depression represented here. In the "slow" movement, the sound envelope starts at approximately 0.5mm movement and there is a distinct increase in the rate of build up at approximately 1mm movement, a time difference of approximately 0.02 second.
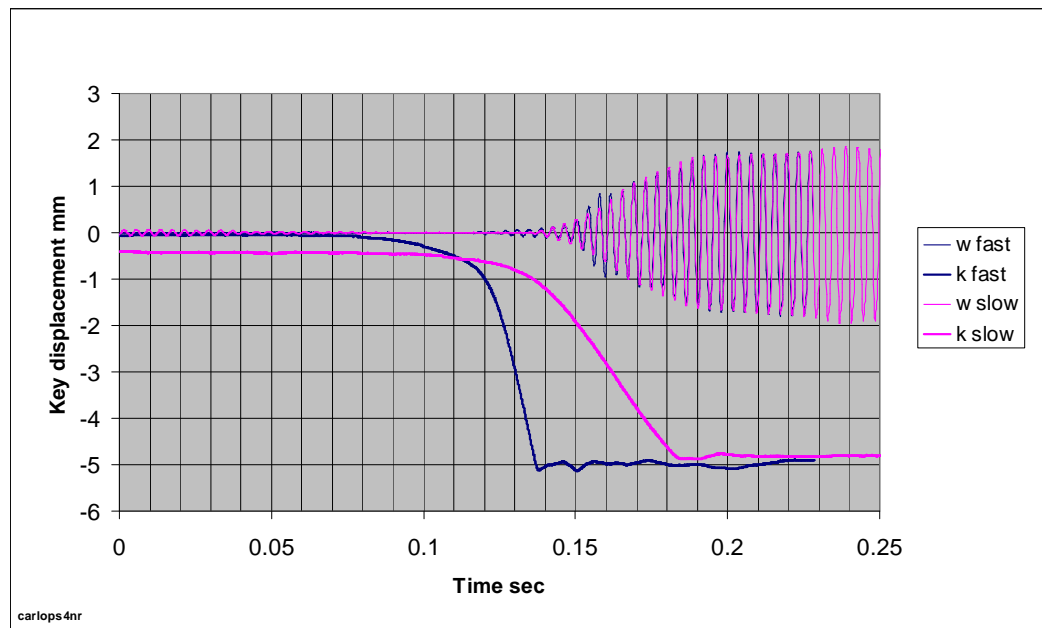
Fig 7.8.3 "Fast" (blue line) and "slow" (pink line) key movements and representations of the corresponding sound envelopes to an arbitrary scale. The key movements cross at the estimated pluck point. W indicates the sound recording, the amplitude of which is arbitrary and k indicates the key movement. Carlops Chapel, Middle c^1 stopped diapason.

The sound envelope of the "fast" movement is visually very similar but doesn't start until the key has moved approximately 2mm. It does not start full development until after the key has hit the key bed. The main part of the sound envelope starts developing at the same time post-pluck in both cases. Visualisations of the three-dimensional spectrograms of the two sounds from Fig 7.8.2 are shown in Fig 7.8.4. These were produced using Sigview version 1.9.1.0 with an fft of 256, 30 steps and limiting the upper frequency to 2kHz as there was no visible information above this frequency. Despite the time difference relative to the key movement, there are only small differences between the two sounds and there is no apparent consequence of the elongated initial "slow" key movement.

Fast   Slow
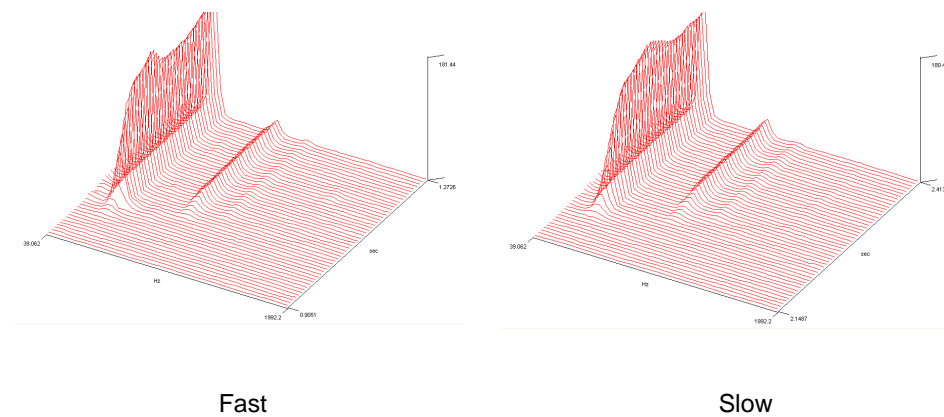
Fig 7.8.4 3D visualisation of the spectral analyses of the two notes shown in Fig 7.8.2 with "fast" and "slow" key movements.

The next results show the results of a "slow" movement followed by a "fast" one. Fig 7.8.5 shows the overall sequence.
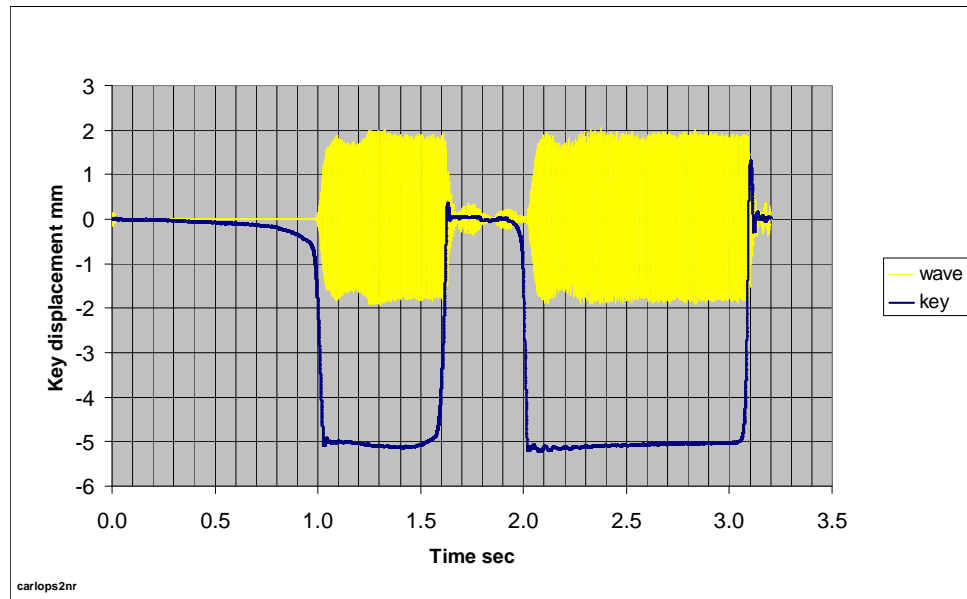
Fig 7.8.5 Graph showing key movement and diagrammatical representation of sound envelope for a sequence of two notes, the first with a "slow" key movement followed by a "fast" key movement. Carlops Chapel, Middle c^1 Stopped Diapason.

These movements are shown at larger scale in Fig 7.8.6.
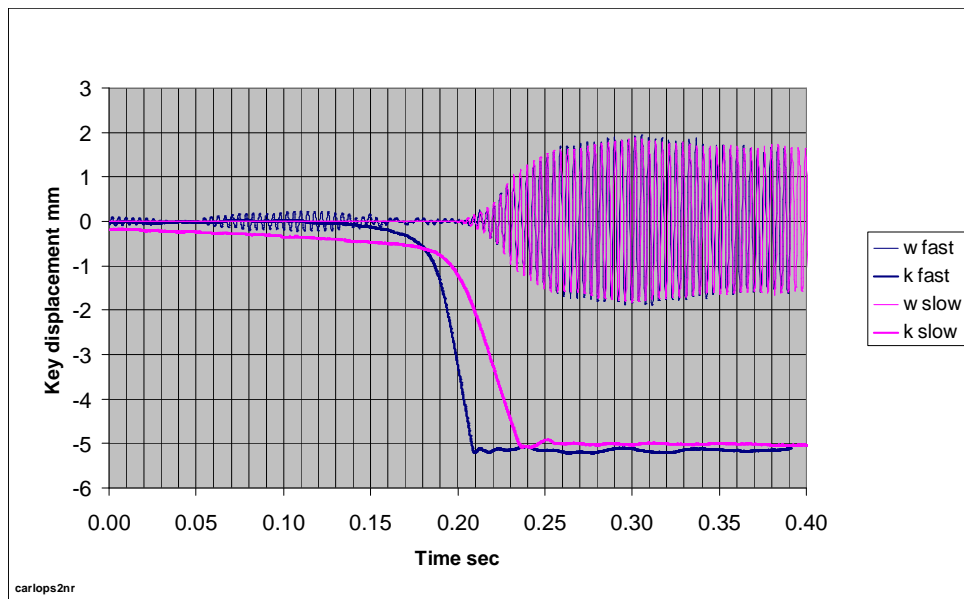
Fig 7.8.6 Graph showing key movement and diagrammatical representation of sound envelope for a sequence of two notes, the first with a "slow" key movement followed by a "fast" key movement. Carlops Chapel, Middle c^1 Stopped Diapason.

.

There may well be some interference to the start of the "fast" sound envelope due to the decay of the first note but this would be expected to start the pipe speaking sooner. There appears to be a similar but shorter delay in the speech of the pipe when the key is moved "fast".

The spectrograms in Fig 7.8.7 again show that, although there are differences, they do not reflect the key movements. The initial slope of the "fast" envelope is, in fact, shallower then the "slow" one.

Slow   Fast
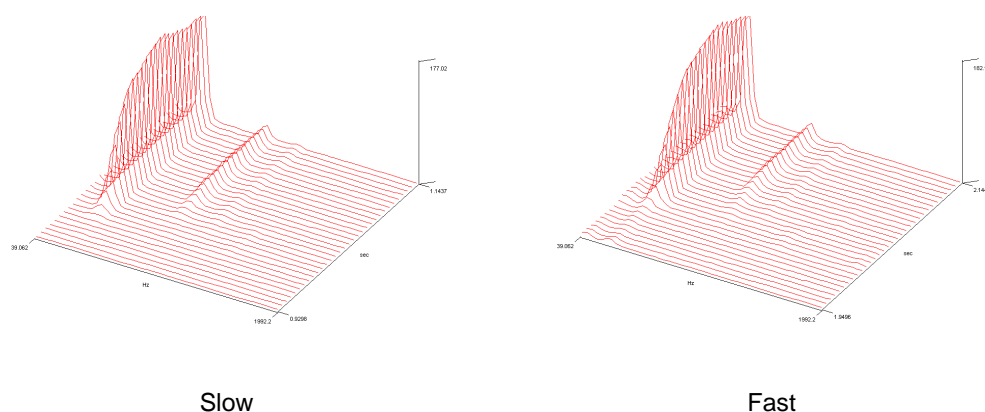
Fig 7.8.7 3D visualisation of the spectral analyses of the two notes shown in Fig 7.8.6 with "slow" and "fast" key movements.

Fig 7.8.8 shows all the first key depressions in this sequence. From this it can clearly be seen that the difference between "slow" and "fast" movements is predominantly accounted for by variations in the pre pluck movement. In the case of curve 10, and assuming a critical point of 1mm key travel as the point at which the sound envelope starts developing when the key is depressed "slowly", curve 10 has a pre-pluck time of approximately 0.986s and a post-pluck time of 0.048s – a ratio of 20.5:1. Curve 4

has a pre-pluck time of 0.041s and a post-pluck time of 0.016s – a ratio of 2.5:1. The ratio of the two ratios is 8.2:1.

The difference between the slowest and fastest time is 24:1 pre-pluck and 3:1 post pluck.

Using a different reference point, e.g. 0.5mm travel, would produce different numbers but still indicate a significant difference between the fast and slow movements. The shallow gradient of the pre-pluck curve makes it impossible to assess the pluck point accurately.
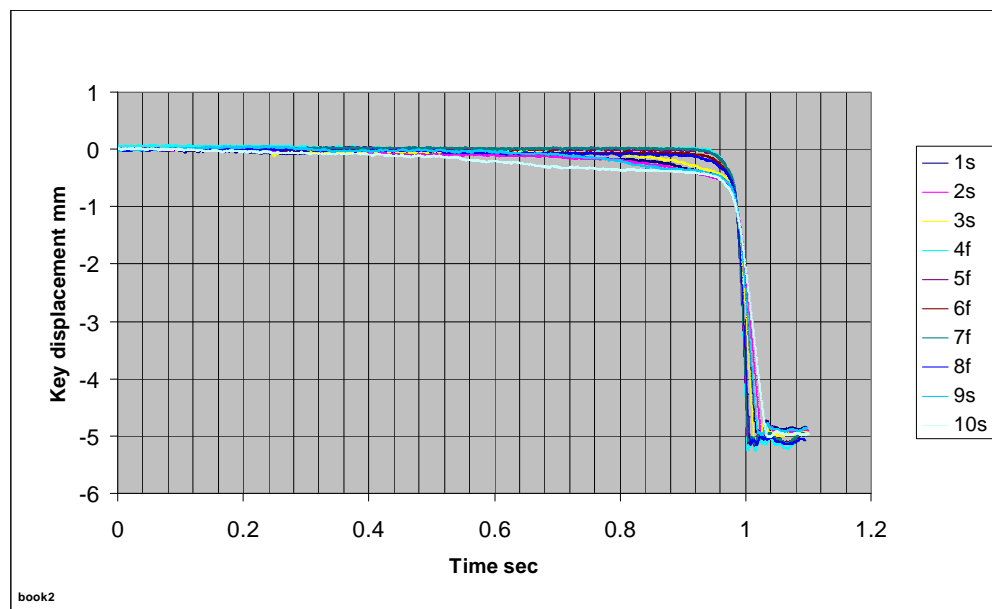
Fig 7.8.8 The first key depression from each of the ten exercises (indicated by the number in the legend) in which the key was depressed twice either "fast" followed" by "slow" or vice versa. Carlops Chapel. The letter indicates whether the note recorded here was fast or slow.

Fig 7.8.9 shows the post-pluck movements at a larger scale. The five "fast" movements are grouped together at the left of the graph. The "slow" movements are more spread out but are all towards the right of the graph. These have been plotted to cross over at about 0.7 mm in order to emphasise the differences.
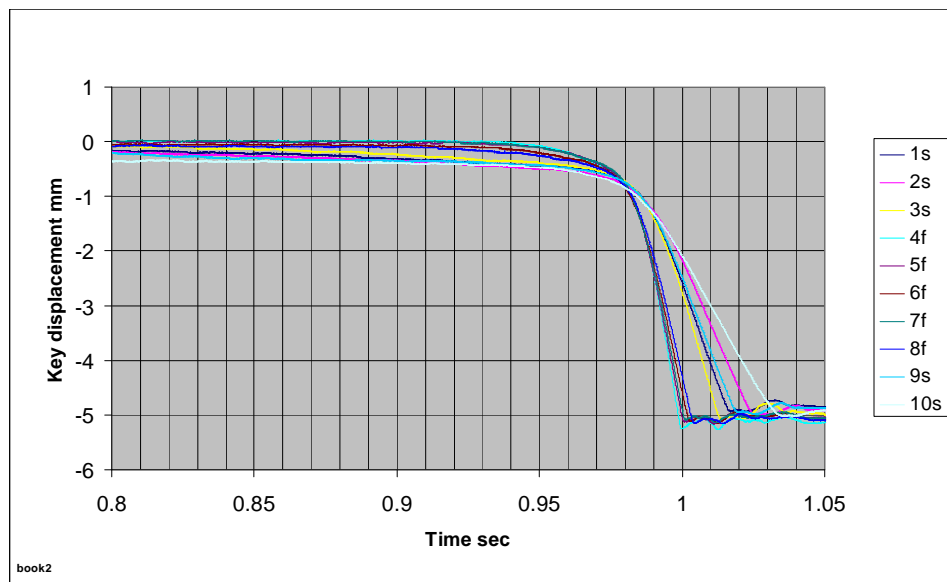
Fig 7.8.9 The post-pluck movements from the key movements shown in Fig 7.8.8 to a larger scale.

Fig 7.8.10 shows the second note in the sequences of two. Slow and fast playing is reversed from that in Figs 7.8.8 to 7.8.9. Again, there is a clear difference in both the pre-pluck and post-pluck movements, with only one "slow" movement, number 5, not being closely grouped with the rest. Curve 5 is also the only "slow" movement on which the previous key release appears (at the left of the graph), and it also shows a very much less smooth pre-pluck movement.
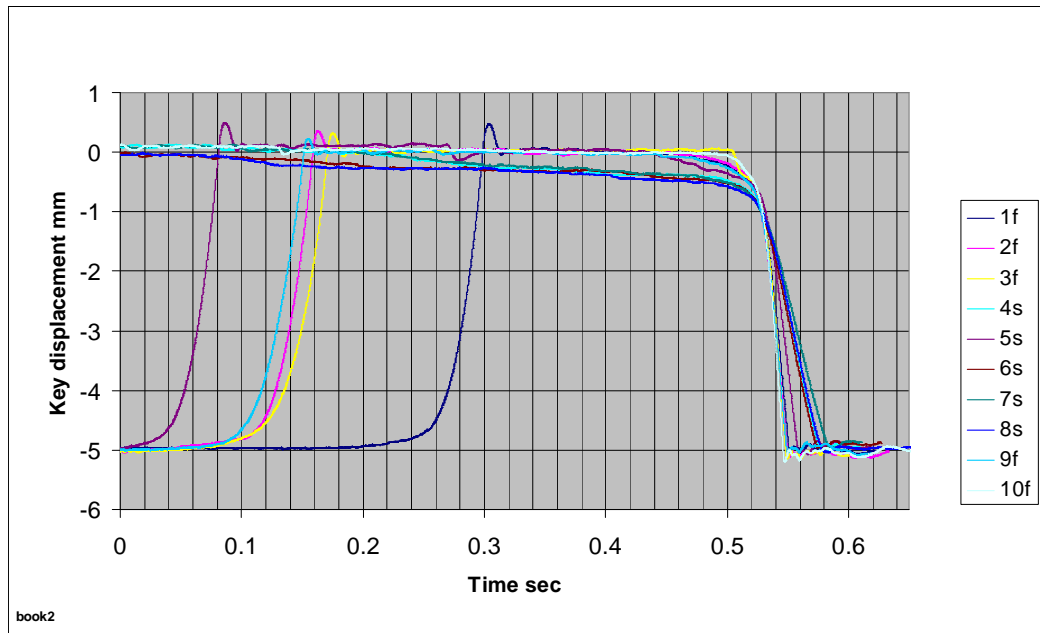
Fig 7.8.10 The second key depression from each of the ten exercises (indicated by the number in the legend) in which the key was depressed twice either "fast" followed" by "slow" or vice versa. Carlops Chapel. The letter indicates whether the note recorded here was fast or slow.

The post-pluck movements are clearly divided into two groups. These are shown at larger scale in Fig 7.8.11. They vary between 0.21s and 0.60s, i.e. the same proportion 3:1 as for the first note in each pair, but overall slightly slower. Curve 3 shows very clearly the characteristic shape of a mechanical action key movement up to the pluck point. Curve 5, a slow one, is in the middle of the two groups and is the only one that does not fall into one of two distinct groups.
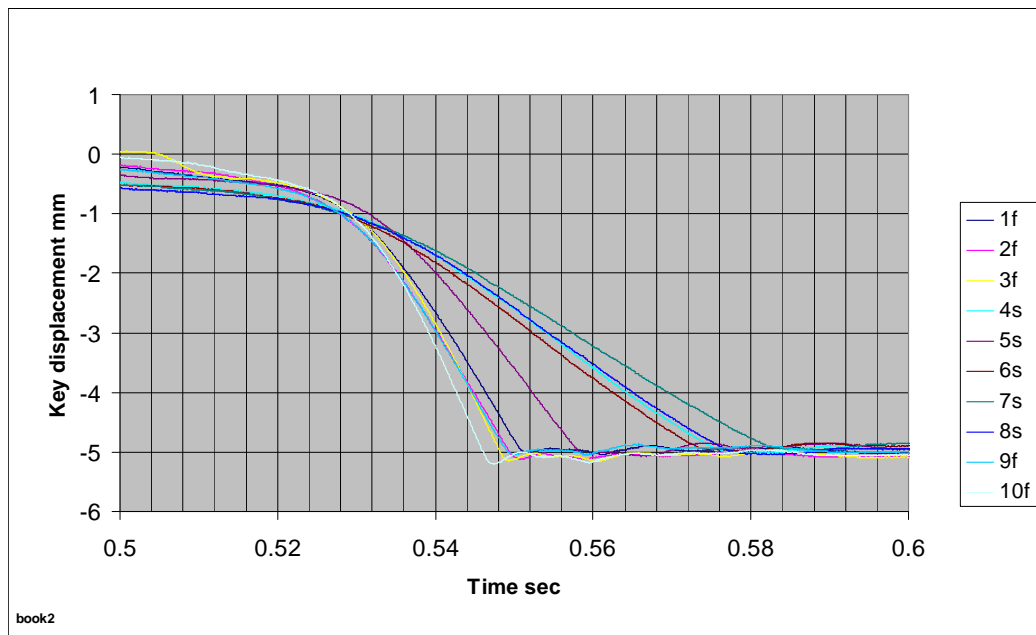
Fig 7.8.11 The post-pluck movements from the key movements shown in Fig 7.8.10 to a larger scale.

Fig 7.8.12 The LED sensors in position above the keys at Carlops Chapel. The sensor mountings are an earlier version and the sensors are not adjustable sideways.

7.8.3   Measurement of key movement during normal playing

In the next exercise Prof Campbell played a tune (Londonderry Air) in two different styles, which he described as being "decisive" and "expressive" and which he believed resulted in different speeds of key movement. The tune was repeated eleven times with the style alternating as requested. The movements of a Middle c^1 and d^1 were recorded. These were in the middle of the piece so that the player was not able to give undue consideration to the first note. Nevertheless, the first note of the first playing follows a different shape from the others, although this may be random and its overall length is no greater than other curves. The curves are centred on 1 mm key travel and are shown in Fig 7.8.13. The order of the post-pluck times is ddddedeeeee where e and d represent expressive and decisive respectively. The times vary from 19ms to 44ms. The "expressive" post-pluck times vary from 27ms to 44ms and the "decisive" times vary from 19ms to 28ms. Taking a simple average gives 38.3ms for the expressive key movements and 22.2ms for the decisive key movements.
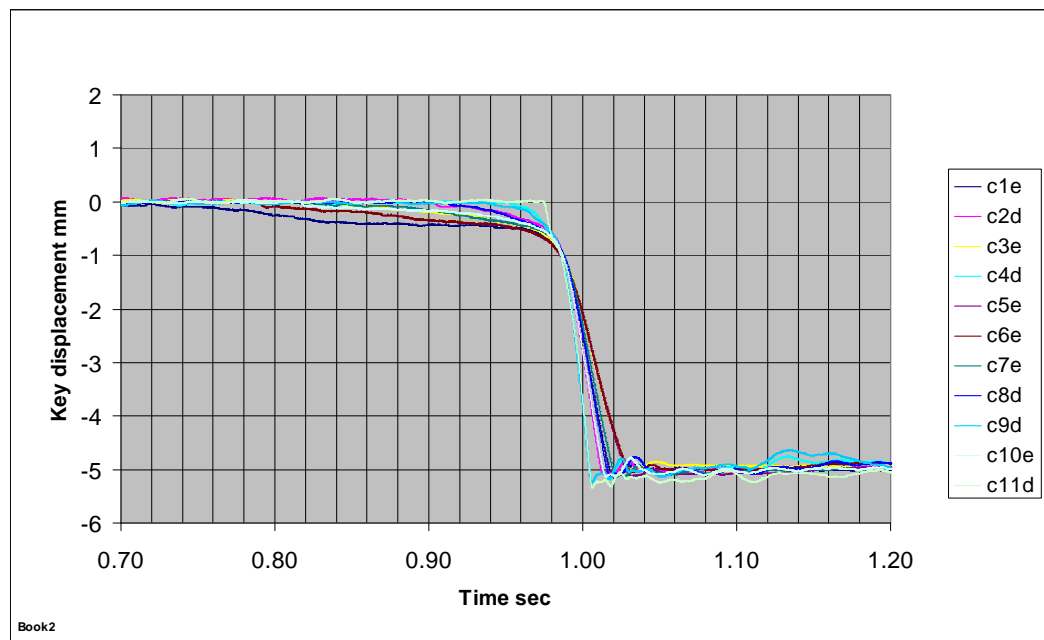
Fig 7.8.13 Key movements from a selected note (Middle c^1) from a tune (Londonderry Air) played eleven times either "expressively" or "decisively".

From the results above, these differences in post-pluck movement are unlikely to have any significant effect on the sound.

Fig 7.8.14 shows the key movements of the d^1 key to the same scale as Fig 7.8.13.
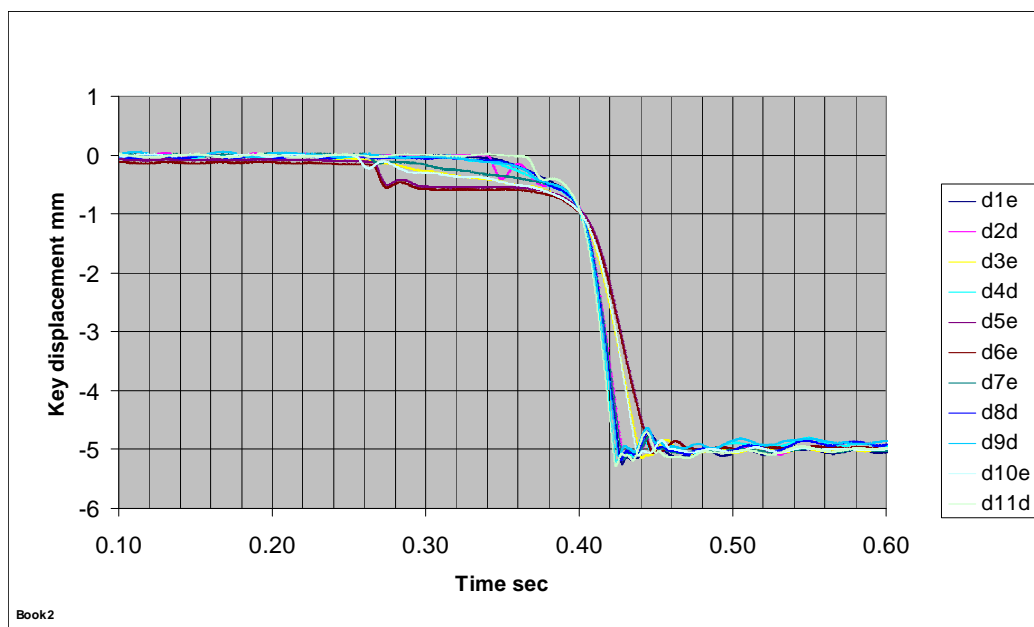
Fig 7.8.14 Key movements from a selected note (d^1) from a tune (Londonderry Air) played eleven times either "expressively" or "decisively".

The pre-pluck movements are of a consistently shorter length than the c^1 key movements shown in Fig 7.8.13. This is presumably influenced by the previous note. Notes 5 and 6 show an almost identical characteristic shape. Notes 2 and 11 also show distinct checking of the movement at the pluck point in which the key appears to "bounce" off the point of maximum resistance.

Fig 7.8.15 shows that there are two groupings of pre- and post-pluck times according to whether the movement was decisive or expressive with the exception of note 7 (expressive), which is at the fast end of the "expressive" pre-pluck grouping but is second slowest in the "decisive" post-pluck grouping. The order from fastest to slowest is dddddedeeee. The overall range of post-pluck times is from 23ms to 47ms,

the "decisive" times vary from 23ms to 28ms and the "expressive" times vary from 27ms to 47ms.
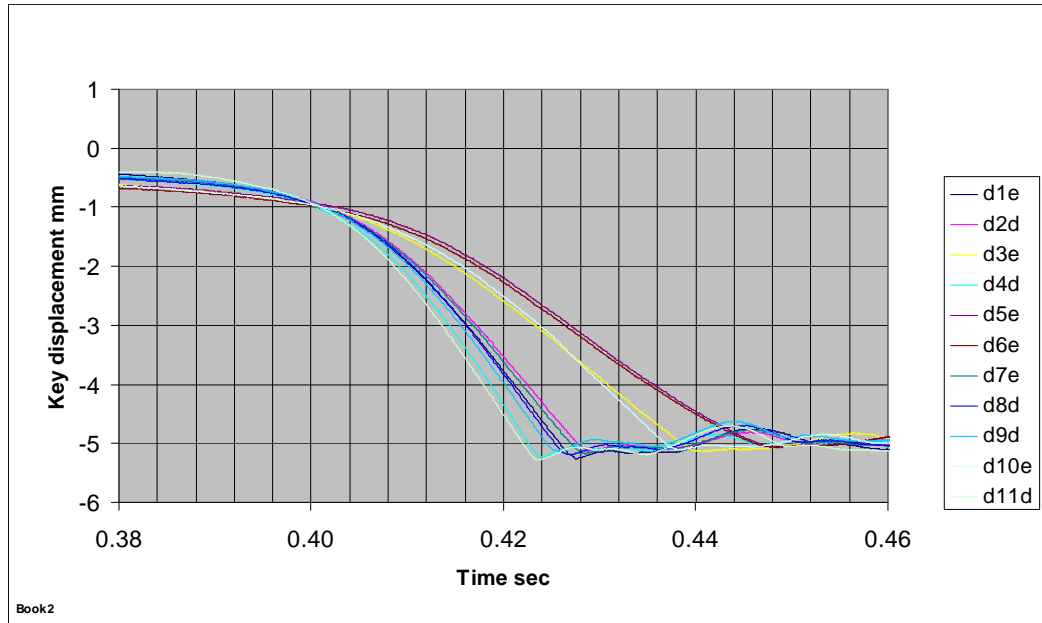
Fig 7.8.15 The post-pluck movements of the d^1 key from Fig 7.8.13 shown to a larger scale.

In the final exercise Prof Campbell played a section from a J S Bach Chorale Prelude, again in both "decisive" and "expressive" styles. The LED sensors were used for this exercise. Due to teething problems with the equipment, only three of the channels gave satisfactory outputs. The results from these three are sufficient to determine differences in the playing style.

The first graph, Fig 7.8.16 shows the complete sequence of "expressive" playing split into two sections because of limitations in producing graphs with more than 32,000 data points in Microsoft Excel. Movement transmitted through the organ case due to other key depressions can clearly be seen.
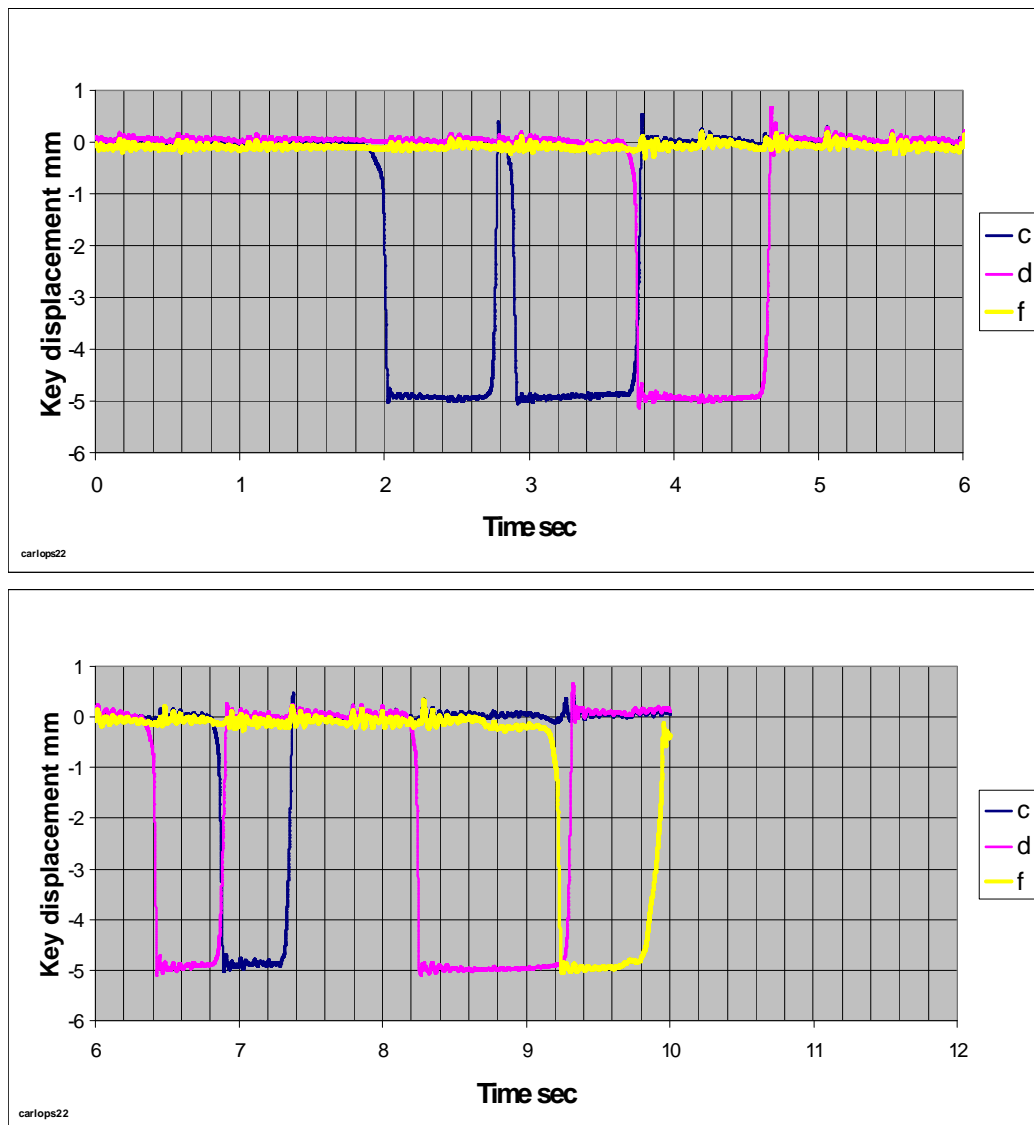
Fig 7.8.16 Key movements from a performance of a J S Bach Chorale Prelude played "expressively" spread over two graphs.

Fig 7.8.17 shows the comparative data from the "decisive" playing presented in the same way. The "expressive" playing clearly shows longer pre-pluck movement. There is little difference in the overlapping of the notes but the "decisive" playing is faster overall. The final chord in the "decisive" sequence shows that the movements of two notes were the same.
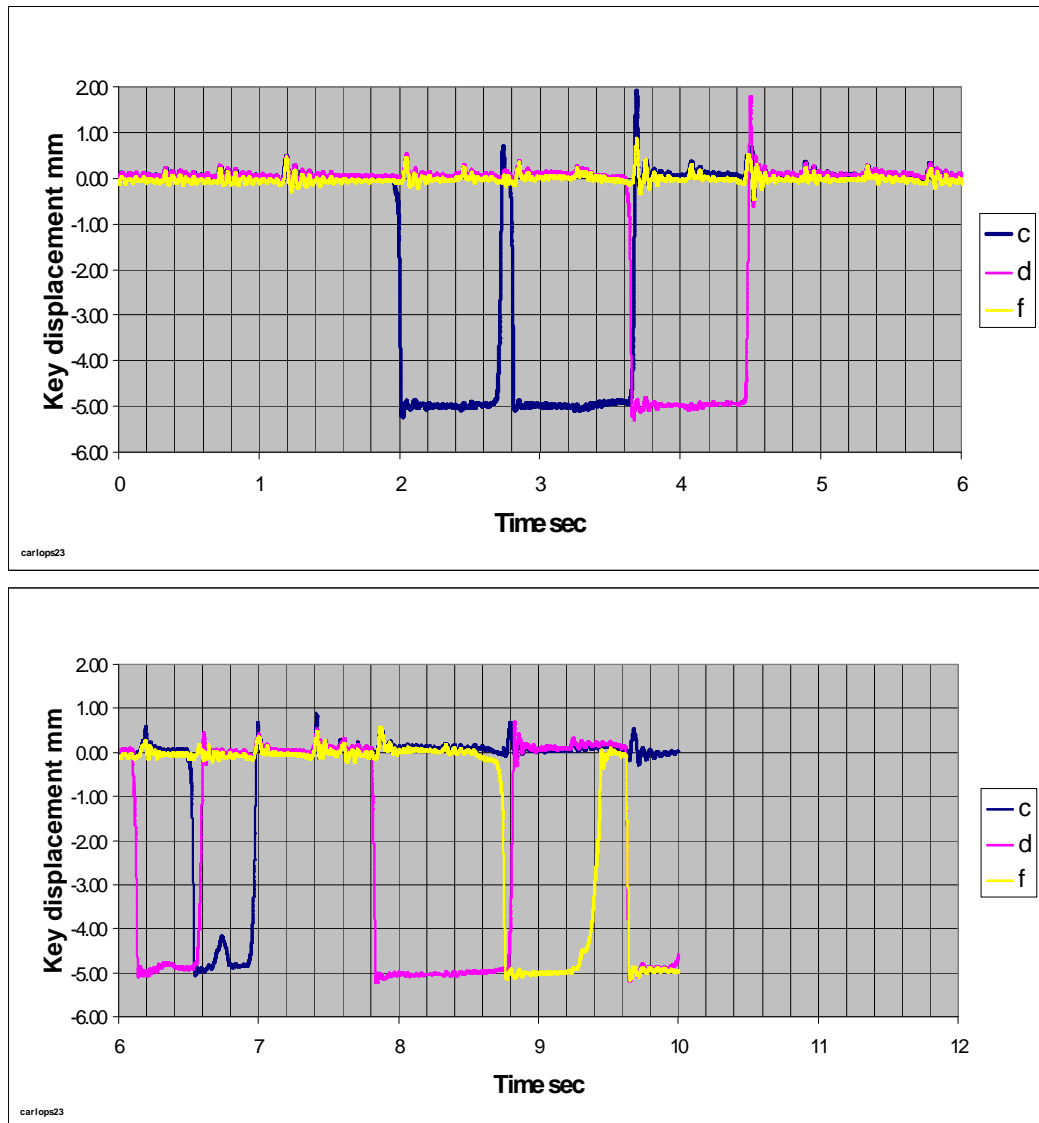
Fig 7.8.17 Key movements from a performance of a J S Bach Chorale Prelude played
"decisively" spread over two graphs.

The key movements for the "expressive" movement are shown in Fig 7.8.18, with
the curves for the same key grouped together. The pluck point of the f^1 key appears
to lower than the other two keys.
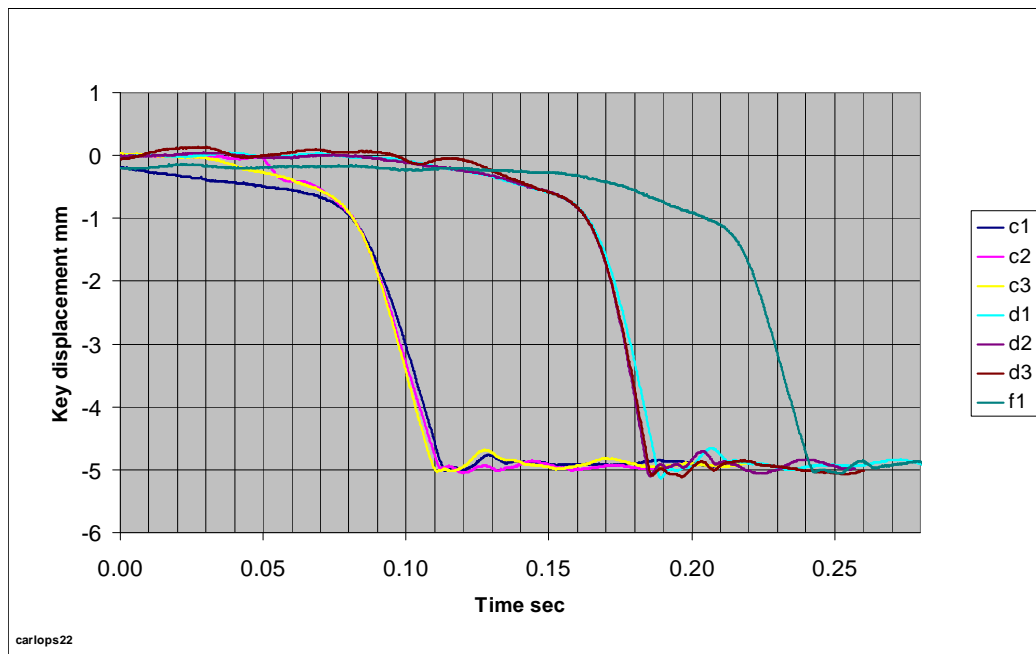
Fig 7.8.18 Key depressions from the "expressive" playing shown in Fig 7.8.16. The numbers
in the legend indicate the order of playing of that particular note.

Fig 7.8.19 shows the same information for the "decisive" sequence in Fig 7.8.17.
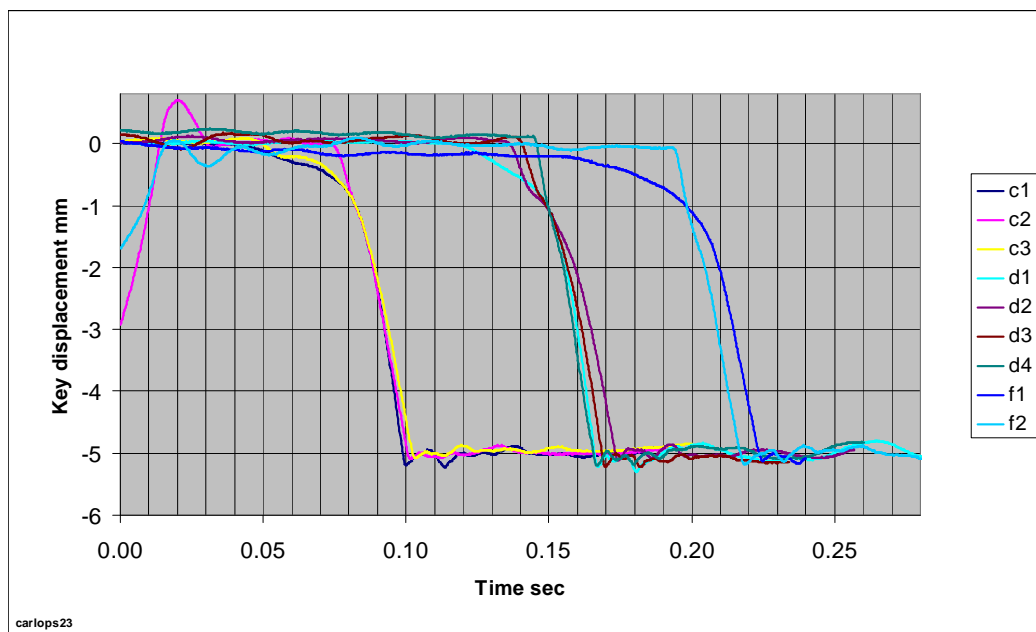
Fig 7.8.19 Key depressions from the "decisive" playing shown in Fig 7.8.17

The shorter pre-pluck movement is apparent in some of the movements.

Fig 7.8.20 shows all of the "expressive" movements from Fig 7.8.18 superimposed.
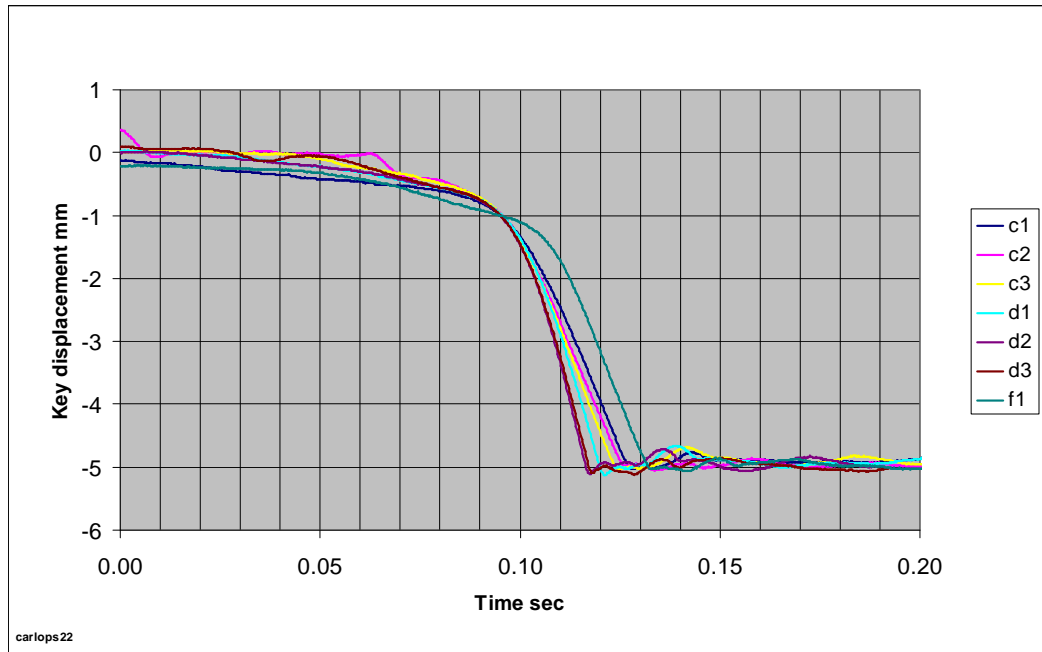
Fig 7.8.20 All the "expressive" curves from Fig 7.8.17 superimposed.

Adjusting the f^1 curve for a different pluck point would bring it closer to the other curves.

Fig 7.8.21 shows the same information for the "decisive" movements from Fig 7.8.19.
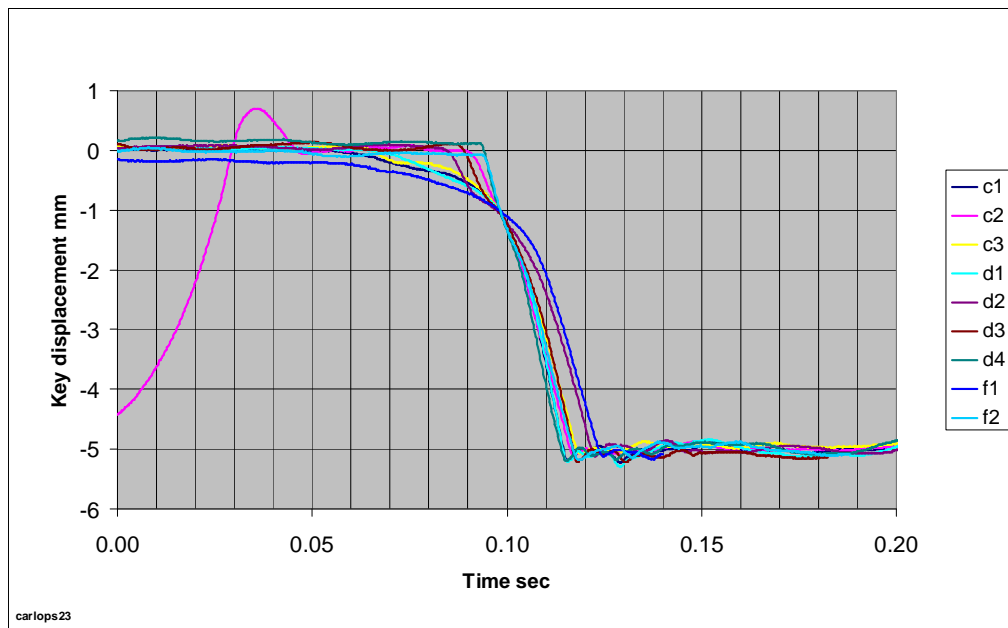
Fig 7.8.21 All the "decisive" curves from Fig 7.8.18 superimposed.

Fig 7.8.22 shows all of the movements from both sequences on the same graph with the expressive and decisive curves from Figs 7.8.16 and 7.8.17 grouped together.
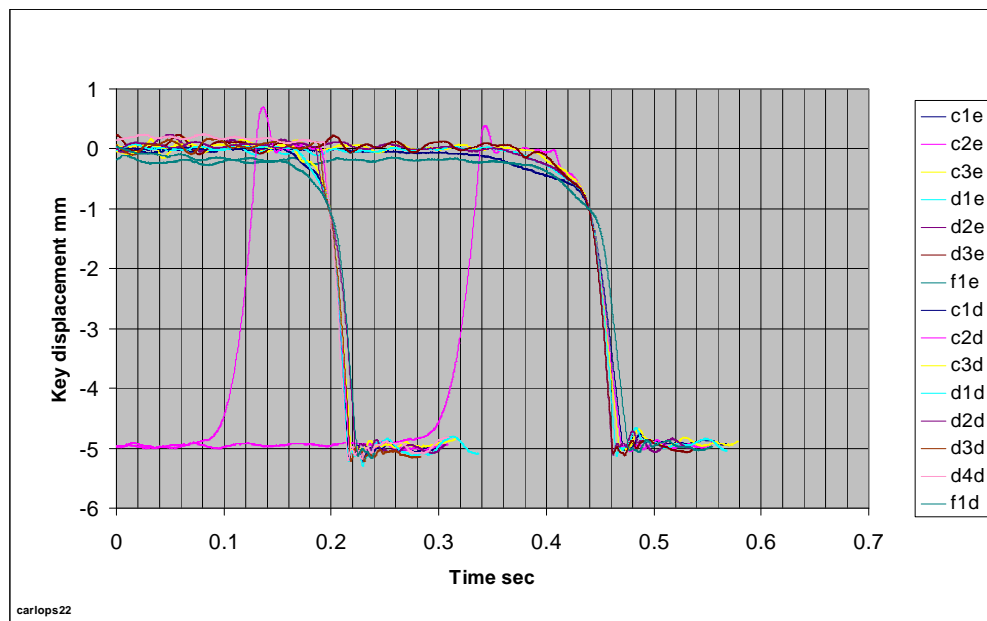
Fig 7.8.22 Key movements from a J S Bach Chorale Prelude played "expressively" (indicated by a final "e" in the legend) and "decisively" (indicated by a final "d"). The number refers to the order in which a particular key was depressed. The decisive curves are to the left.

The "expressive" post-pluck times vary from 21ms to 36ms and the "decisive" post-pluck times vary from 15ms to 27ms. The pre-pluck times are longer in the "expressive" playing.

7.9 St Stephen's Centre, Edinburgh

7.9.1 Introduction

St Stephen's Centre is a former Church of Scotland church that is now used as a community centre and retains its three manual organ of 32 stops (IIIP32) built in 1880 by Father Willis essentially unaltered (Fig 7.9.1).

Fig 7.9.1 The façade of the "Father" Willis organ in the St Stephen's Centre, Edinburgh

This organ is of particular interest not only because of its size but also because it incorporates Barker levers in the Great action. The National Pipe Organ Register states that Willis's ledgers record it as having originally cost £1,245. Its stop list is shown in Appendix 1.

The manual compass is C to g^3, 56 notes, and the pedal compass is CC to f, 30 notes. The console, with a laser sensor over the Middle c^1 key on the Great, is shown in Fig 7.9.2.

Fig 7.9.2 Console of the organ in St Stephen's Centre, Edinburgh

Dr John Kitchen played the organ for this exercise. David Page and Jim Smail of Forth Pipe Organs very generously gave a day of their time in order to allow access to the inside of this instrument. It had been hoped to place a laser sensor inside the windchests but both the Swell and Great divisions are divided into high- and low-pressure chests with the tracker leading most directly to the high-pressure reed chest, which was the only part accessible. There was, in any case, insufficient room in either the Great or the Swell high-pressure windchest for the sensors and it was, therefore, decided to clip a reflective flag to the Middle c^1 tracker of the Swell organ and to secure the laser sensor to a conveniently located structural member. The flag itself is made of balsawood laminated between sheets of card firmly glued to phosphor bronze action wire and is light but rigid. This is shown in Fig 7.9.3. Note the circular trackers and the additional masking tape used to secure the flag because the trackers are very much thicker than the modern trackers for which the clips were designed. This was not ideal because of the additional action leading to the low-pressure flue chest and there is thus a significant degree of flexibility in the action after the point at which measurements were taken. The flag appeared to remain rigid throughout.

Fig 7.9.3 A laser sensor measuring the movement of a tracker by means of a "flag" attached to the tracker.

The two backfalls and intermediate sticker are shown in Fig 7.9.4. The tracker from the console is at the extreme right with the tracker to the high-pressure chest just behind it. A tracker goes from beyond the far end of the visible action to the low-pressure pallet.
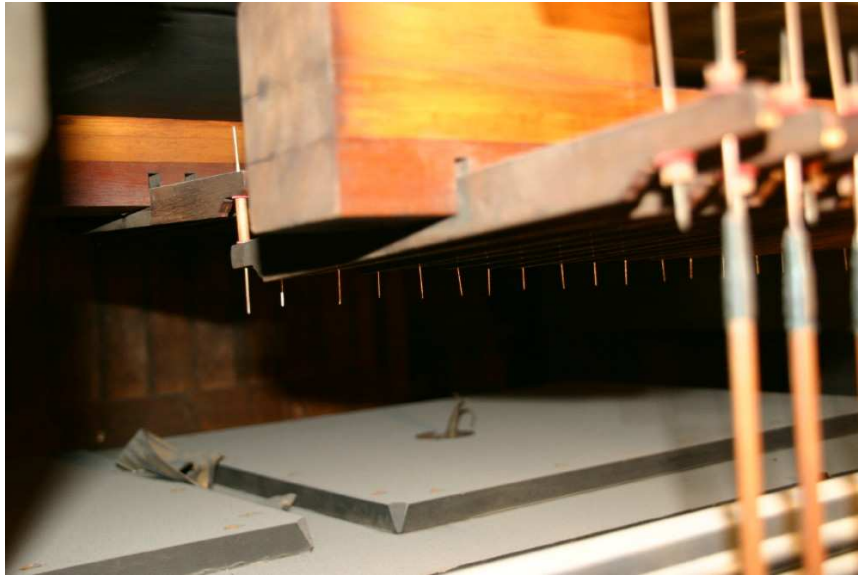
Fig 7.9.4 Trackers and backfalls in the Great action, St Stephen's Centre, Edinburgh. The tracker from the key, bottom left, pulls down the backfall Just behind this tracker is another tracker leading to the high pressure reed chest. The backfall is connected via a short sticker to another backfall, the far end of which pulls down a further tracker (not visible) that opens the pallet in the low-pressure flue pipe chest.

The pallets of the high-pressure chest of the Great organ can be seen in Fig 7.9.5. The ends are roughly sawn off square, with the note numbers hand written on them. The thickly felted pallet tops, the leather hinges, the guide pins on either side of the pallets and the substantial pallet rail to restrict their movement can be seen.

Fig 7.9.5 The pallets of the high-pressure reed pipe chest in the Great organ at the St Stephen's Centre. Edinburgh. The trackers at the bottom are the continuation of those going out of the top right of Fig 7.9.4.

Sound recordings were made using a small condenser microphone placed in front of the main case as it was not possible in the time available to place it near the pipes. Its position resulted in considerable noise that was reduced using Cooledit Pro with an fft of 512 and a reduction level of 70dB. A sample of the recorded and noise-reduced signals is shown in Fig 7.9.6.
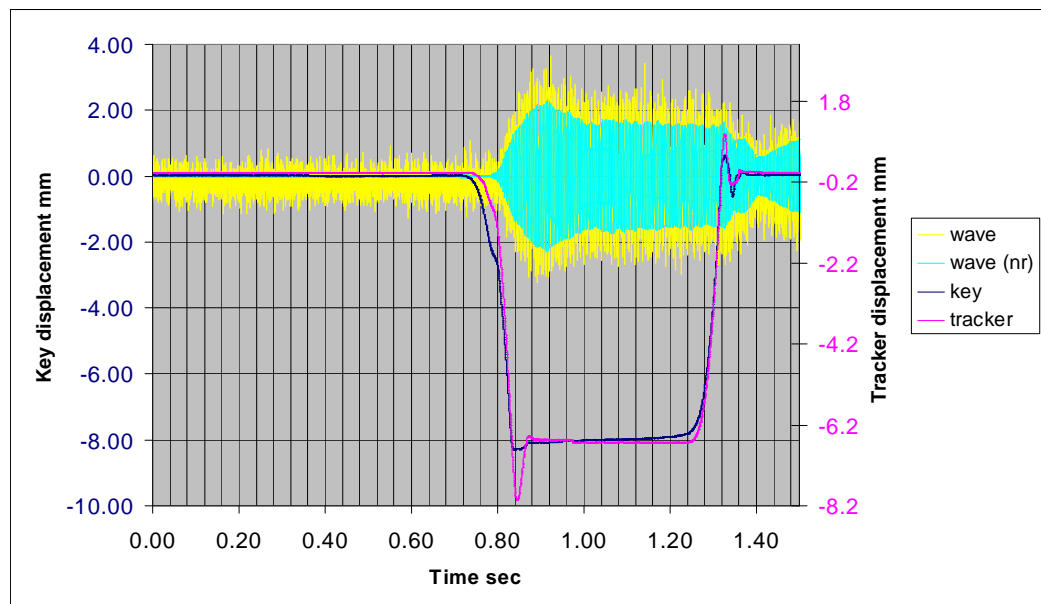
Fig 7.9.6 Diagram to show the effect of noise reduction using CooleditPro on a sample sound recording at St Stephen's Centre. The yellow outline is the recorded sound and the pale blue outline is the noise reduced recording.

The small sound starting shortly before the key starts moving can clearly be identified as spurious noise as the tracker being measured has not moved.

7.9.2   Isolated key movement

In the first exercise, Dr Kitchen moved the Middle c^1 key of the Swell organ in isolation.

The first movement is "normal" and is shown in Fig 7.9.7.
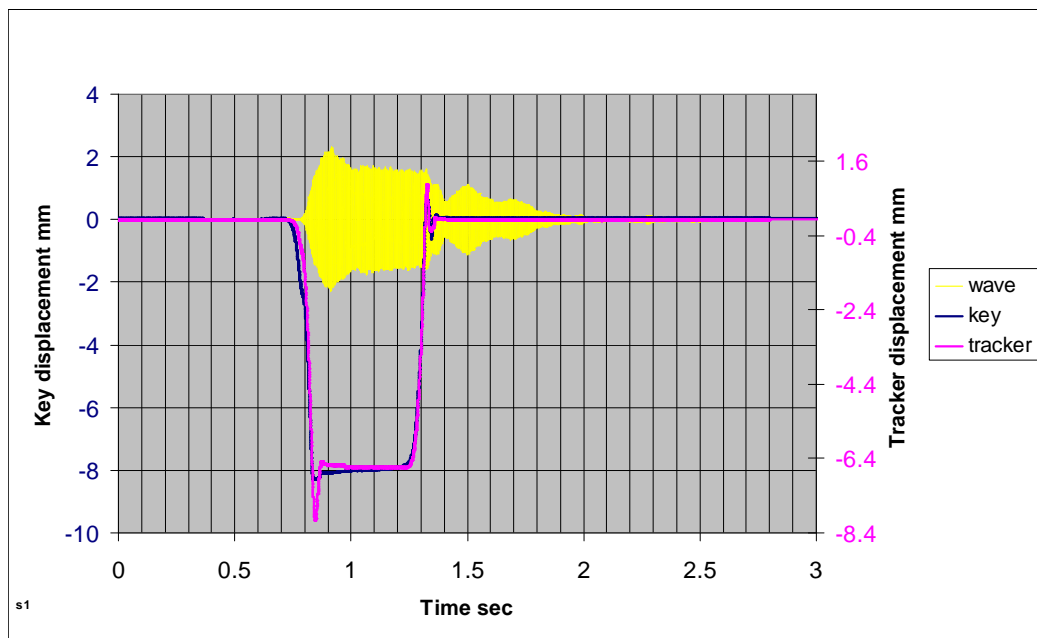
Fig 7.9.7 Diagram showing the key movement, tracker movement and noise reduced sound recording of a Middle c^1 played "normally".

The initial movement from Fig 7.9.7 is shown to a larger scale in Fig 7.9.8.
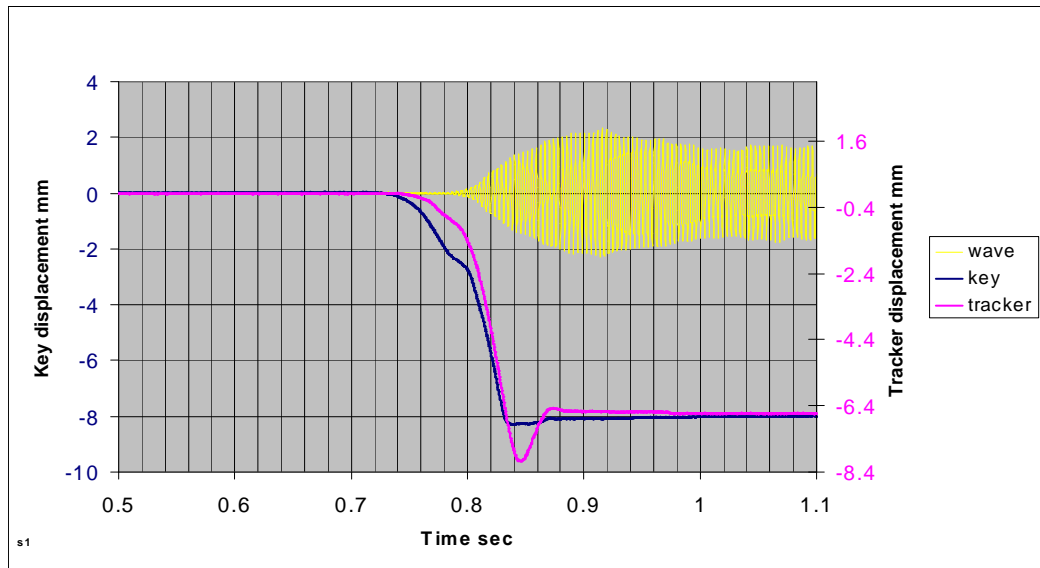
Fig 7.9.8 The initial movement from Fig 7.9.7 shown to a larger scale.

The shape of the key release is more apparent in the "slow" movement and is discussed below.

The effects of the flexibility after the sensor mounting point are more clearly seen in the "slow" movement represented in Fig 7.9.9.
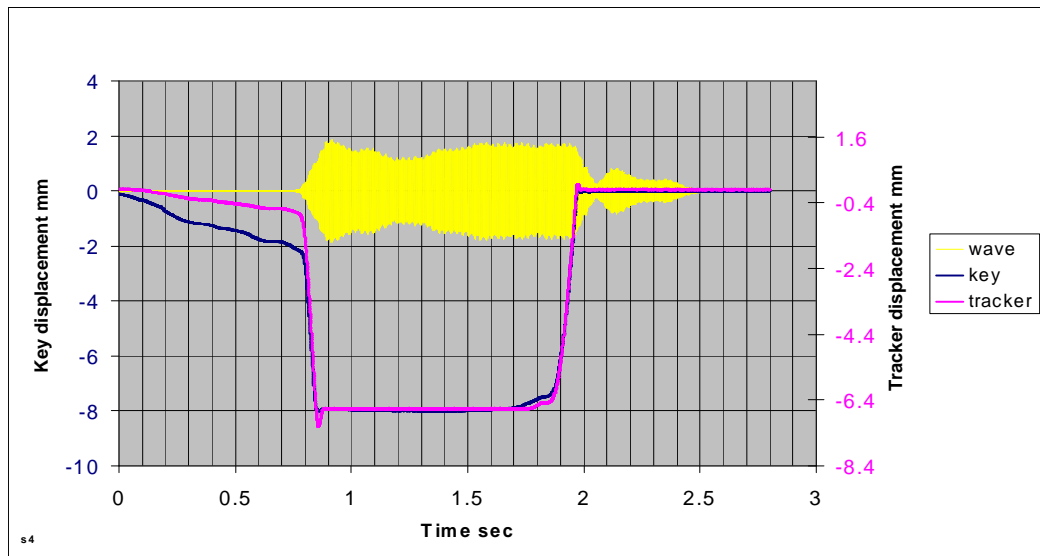
Fig 7.9.9 Diagram showing the key movement, tracker movement and noise reduced sound recording of a Middle c^1 played "slowly".

There is a clear point at which the pallet can be deduced to start opening and this corresponds with the point at which the sound starts developing. There is considerable flexibility in the short section of the action from the position of the sensor to the pallet. The initial movement is shown in more detail in Fig 7.9.10.
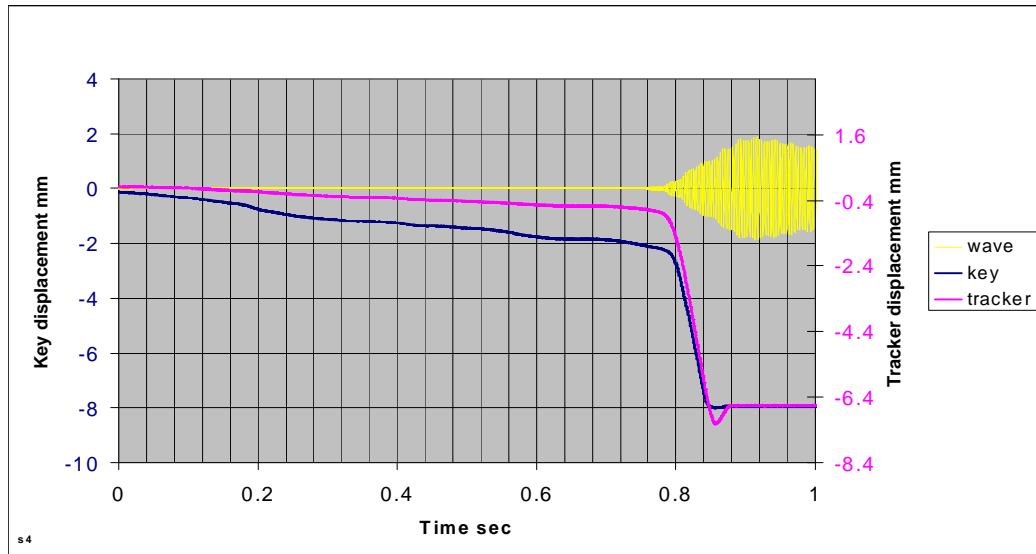
Fig 7.9.10 The initial movement from Fig 7.9.9 shown to a larger scale.

The key release of the "slow" playing (Fig 7.9.9) is shown in Fig 7.9.11.
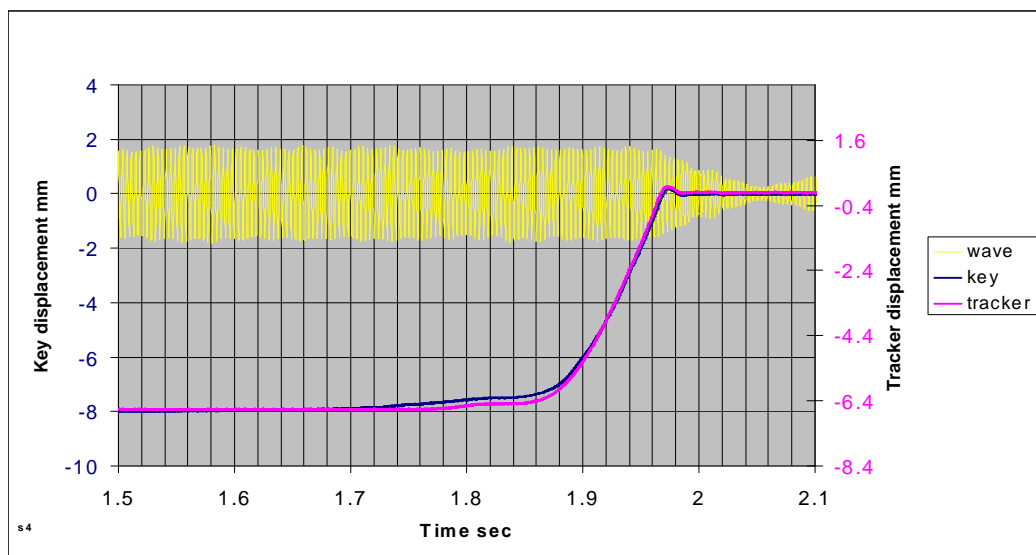
Fig 7.9.11 The key release of the movement shown in Fig 7.9.9

The key leads the measuring point on the tracker initially but the tracker does not then lead the key in the final stages as seen when measuring pallet movement elsewhere. Because of the apparent considerable flexibility in the final part of the action run it is not possible to determine precisely what is actually happening to the pallet.

A "fast" key movement is shown in Fig 7.9.12.
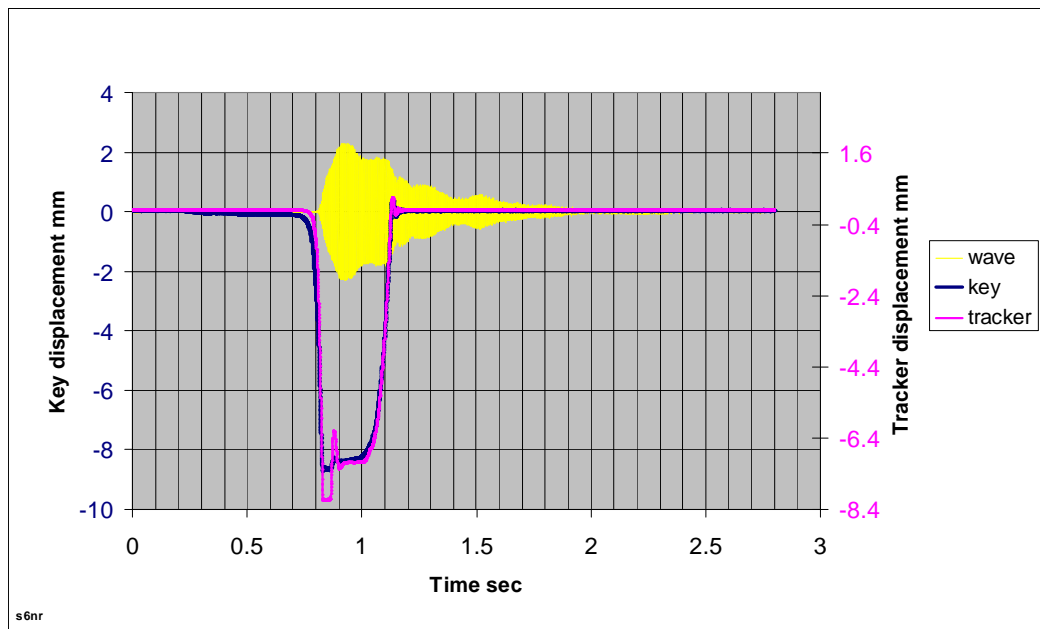
Fig 7.9.12 Diagram showing the key movement, tracker movement and noise reduced sound recording of a Middle c[1] played "fast"

The key depression from Fig 7.9.12 is shown in Fig 7.9.13.
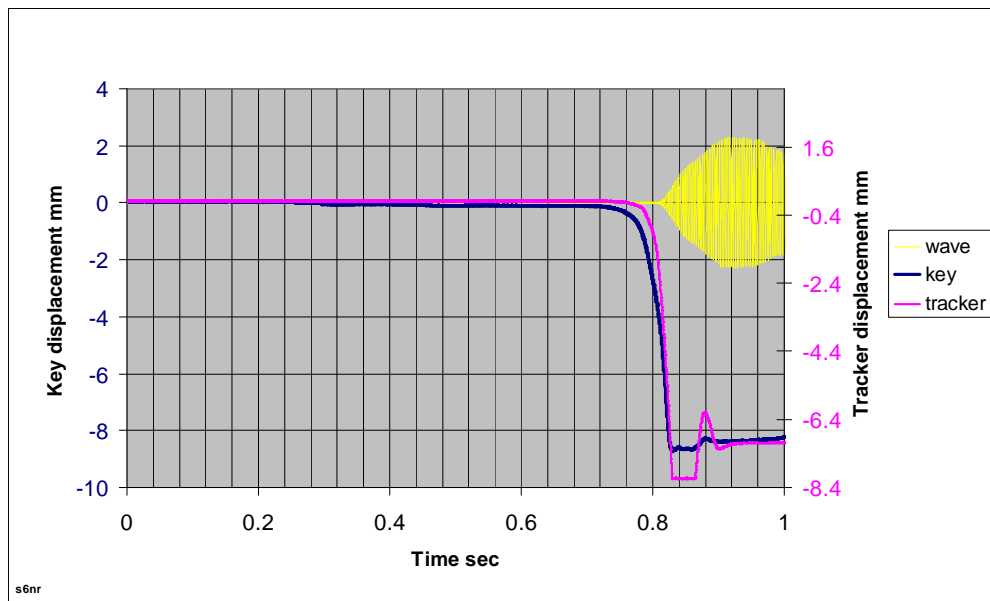
Fig 7.9.13 The initial movement from Fig 7.9.2 shown to a larger scale.

All of the key depressions and associated pallet movements are superimposed on one graph in Fig 7.9.14. They are arbitrarily centred on the trigger point of the daq box which approximately corresponds with the pluck point at about 2 mm key travel.
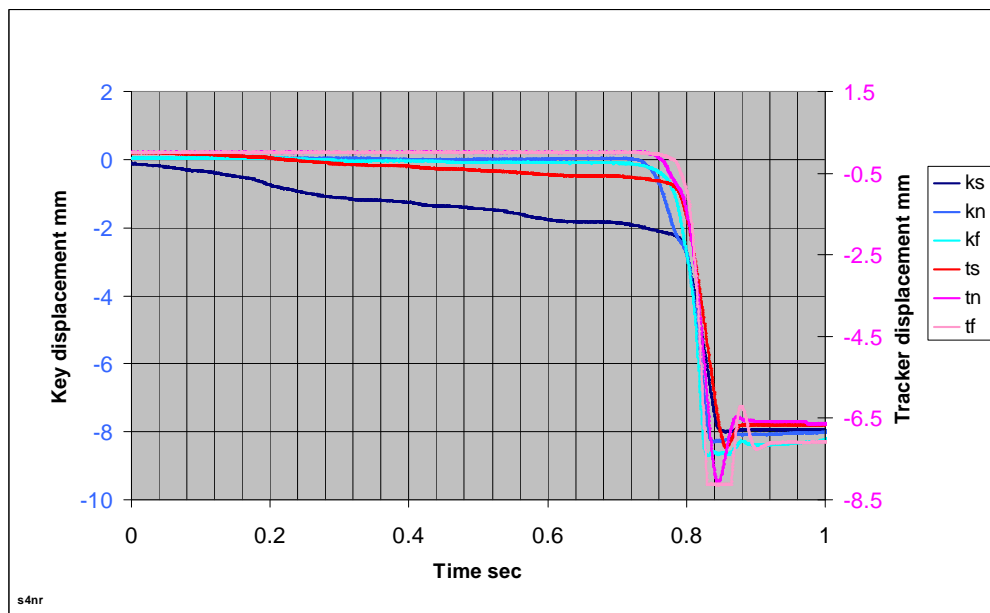
Fig 7.9.14 Diagram showing all the movements of the key and the tracker for a note played "normal", "slow" and "fast"

The "slow" movement is clearly not representative of normal playing and the "normal" and "fast" times are close together.

Dr Kitchen then played a theme (the same as used at the Reid Concert Hall Fig 7.2.3) with "spontaneous", "slow" and "fast" key movements. Recordings of the key and tracker movements are all presented in the same graph as Fig 7.9.15. The key movements are on the left. The key movements are shown crossing at 2.5 mm in order to emphasise the similarity of the latter part of the travel. A visual inspection and spectroscopic analysis of the sound recording shows that the sound envelope starts developing at approximately 2.50mm. At this point there is some difference in the initial movement of the key, however, note the remarkable similarity between curves ks1 (slow) and kf1 (fast) and the difference between the two "slow" curves ks1 and ks2. This, along with similar results elsewhere, indicates that there is a degree of randomness in the movements.
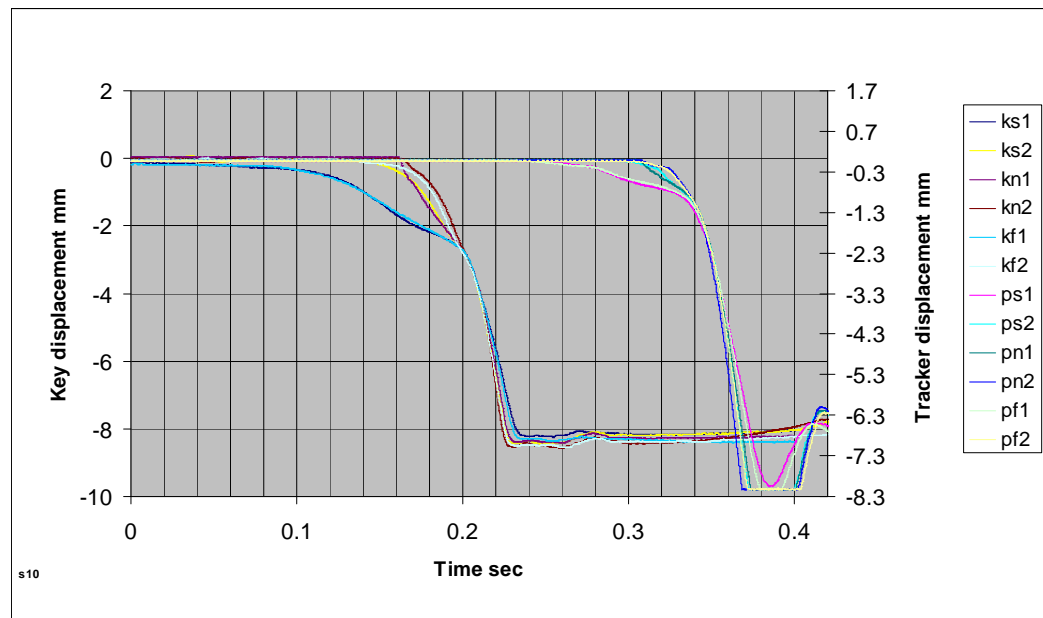
Fig 7.9.15 Key and tracker (indicated by "p" in the legend) movements for a theme played "slow", "normal" and "fast". There are two readings of the Middle c^1 key in each playing denoted by the numbers 1 and 2.

7.9.3   Barker lever

The final set of measurements was made from the Great manual in order to attempt to determine how the Barker Lever operated. In view of the difficulty of attaching a sensor to the Great action, the sensor was left on the Swell Middle c^1 tracker and the Swell to Great coupler used.

Fig 7.9.16 shows the Barker machine from Reading Town Hall organ (Willis 1864), restored by Harrison and Harrison 1999, who made the machine available for examination in their workshop during 1998). Its size can be gauged from the electric drill resting on the top. Fig 7.9.17 is a diagram taken from Audsley, Fig CLXXXI, of a typical Barker machine similar to the one at Reading Town Hall but apparently more complicated than the St Stephen's Centre one appeared to be – it being somewhat inaccessible. The principle of operation is the same. The tracker, I, at the right is connected to the key and opens the pallet G to admit air to the bellows at the top. Backfall H closes the air dump valves Q and R at the same time. As the top of the bellows top L rises, it moves the tracker W that is connected to the pallet in the windchest. M is a check valve to prevent the bellows opening too far. The dump valve is split and opposed so that there is no pluck effect when it opens. At St Stephen's Centre the tracker W is replaced by a sticker and a pushing movement taken from the bellows. The machine is rotated through 90° with the left hand end of the machine in the diagram being at the top with the bellows opening away from the keys. The sticker U is replaced with a braided strip, which appeared to pull the dump valve open against a spring.

Fig 7.9.16 Barker machine from Reading Town Hall organ (Henry Willis 1864) under restoration in Harrison and Harrison's workshop during 1998.
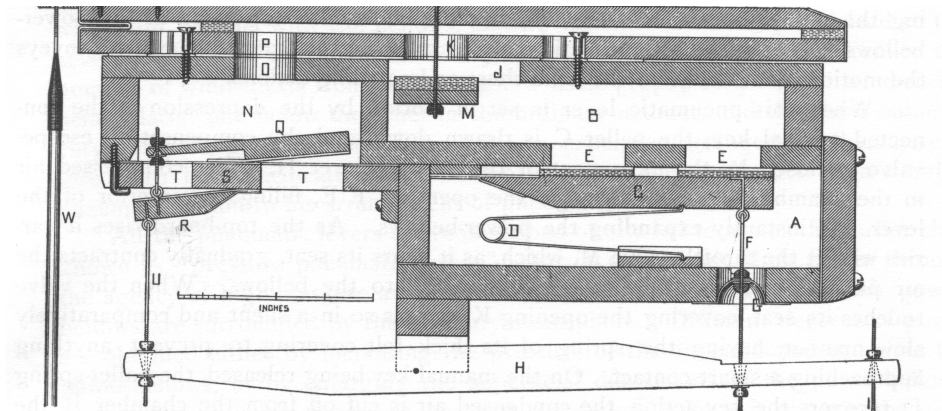
Fig 7.9.17 Illustration of a Barker similar to the one in the St Stephen's Centre. Audsley Fig CLXXXI

Fig 7.9.18 shows braided strips (equivalent of U in Fig 7.9.17) and the dump pallet R in the Barker machine from Reading Town Hall.

Fig 7.9.18 Detail from the Barker machine from Reading Town Hall shown in Fig 7.9.16 showing the braided strip (equivalent to tracker U in Fig 7.9.17), attached to a backfall, which opens the dump valve R in Fig 7.9.17

The first graph Fig 7.9.19 shows a "slow" key movement. This exhibits a very characteristic shape to the key movement with two distinct checks to the movement. This effect could not be felt through the finger by any of the people present who tried moving the key (Dr Kitchen, David Page and the author) and was not consistently reproducible – it tended to occur when the player was not trying "too hard" to move the key in a particular way. It is not clear whether it is due to friction in the mechanical link or whether it is due to the way the Barker machine works e.g. the staged opening of the pallets. An inspection with David Page indicated that the air admittance valve opened in advance of the air dump valve closing. The pallet starts opening at about the 4.8 mm key position i.e. more than two thirds of its way down.
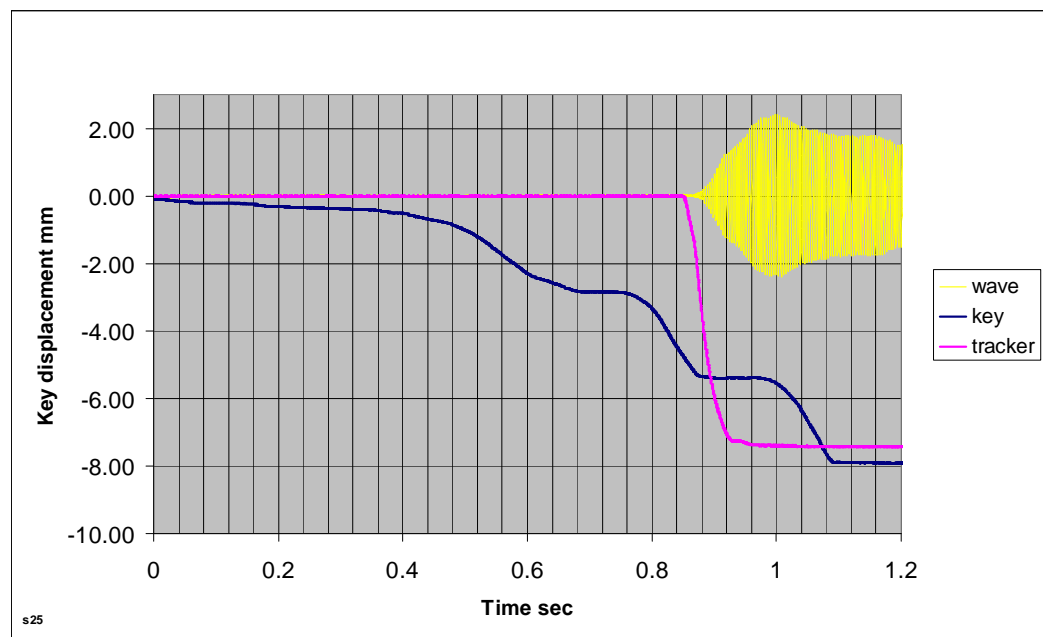
Fig 7.9.19 Diagram showing the Great key and Swell tracker movement of the St Stephen's Centre organ using the Swell to Great coupler, which operates through the Barker lever mechanism. The key movement was "slow".

Fig 7.9.20 shows a "fast" key movement. In this case the pallet does not start moving until the key has moved about 7.7 mm, i.e. virtually at the end of its travel.
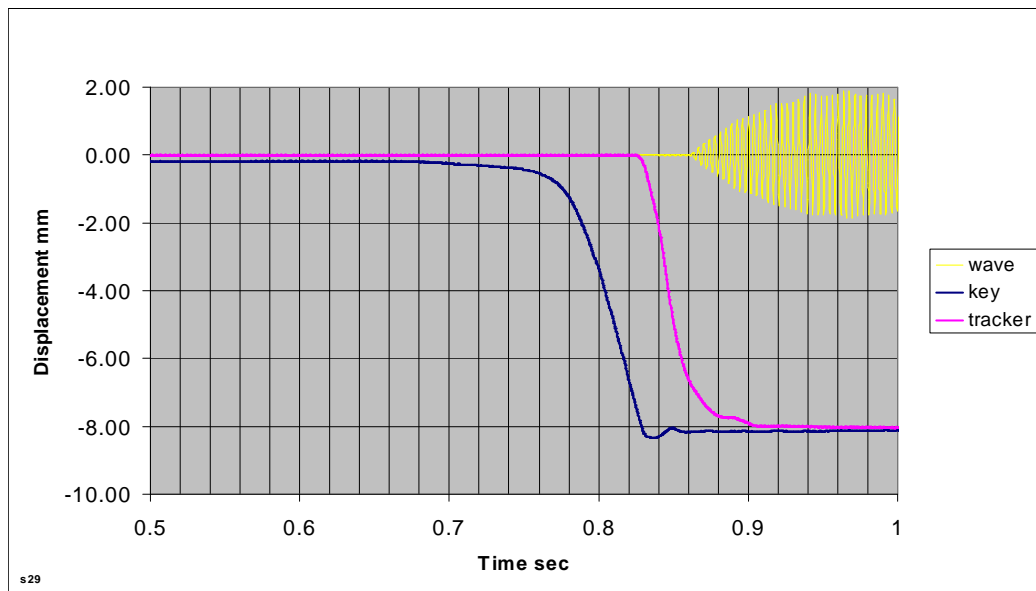
Fig 7.9.20 Diagram showing the Great key and Swell tracker movement of the St Stephen's Centre organ using the Swell to Great coupler, which operates through the Barker lever mechanism. The key movement was "fast".

Fig 7.9.21 shows a " normal" movement being the first note of a sequence during which the player said that he was "thinking about something else".
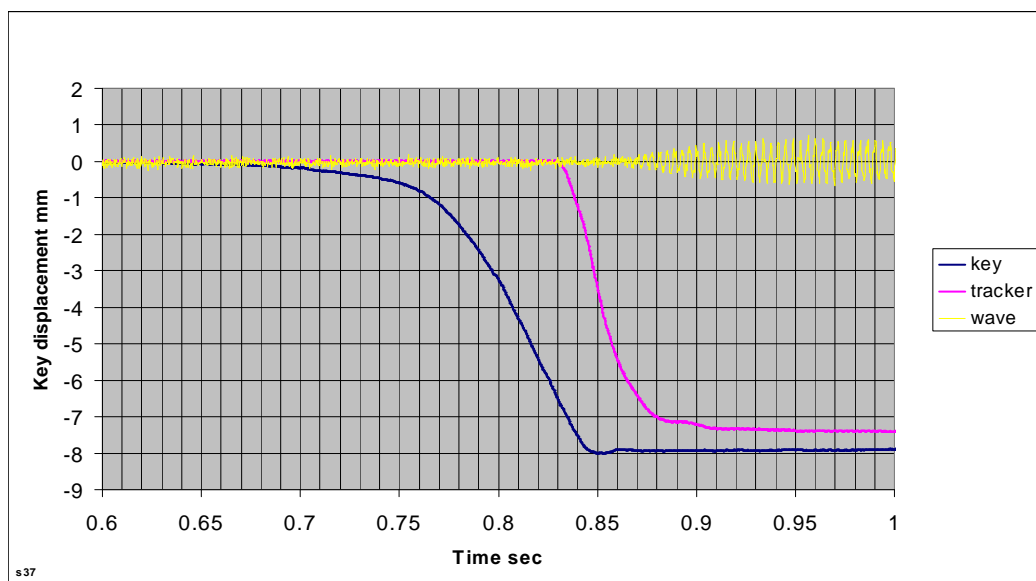
Fig 7.9.21 Diagram showing the Great key and Swell tracker movement of the St Stephen's Centre organ using the Swell to Great coupler, which operates through the Barker lever mechanism. The key movement was "normal, with the player thinking about something else".

300

These three movements are shown superimposed in Fig 7.9.22. Of particular interest is that the tracker movement with the slow key movement is slightly slower than for the other two movements. This was also the case with other slow key movements and whilst the slow movements are somewhat exaggerated, there is some modification to the movement leaving the Barker machine.
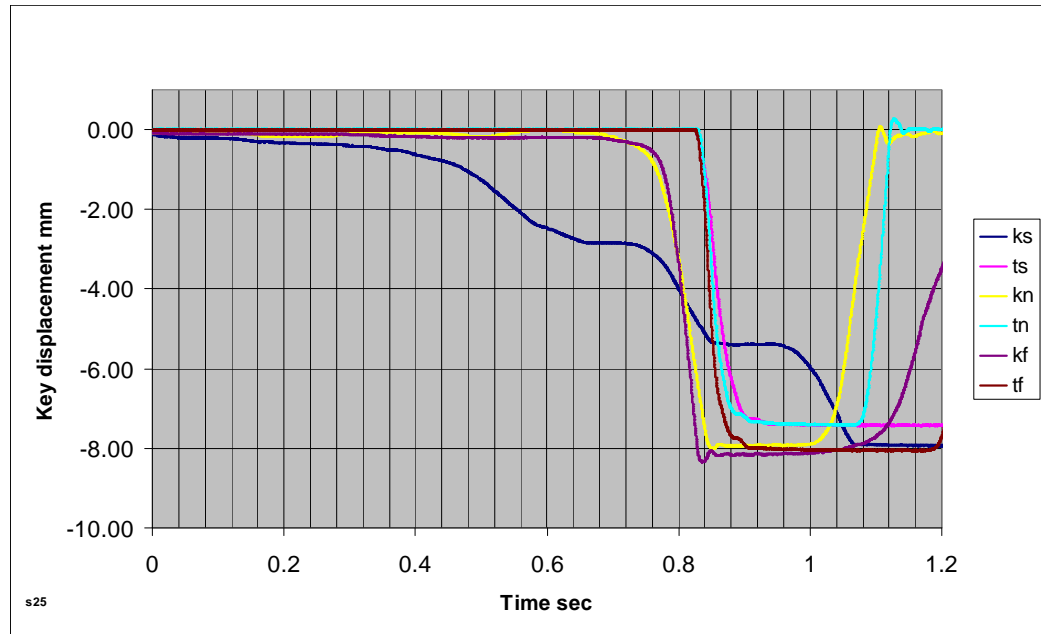
Fig 7.2.22 Diagram showing the three sets of measurements of the key and tracker using the Swell to Great coupler through the Barker lever at St Stephen's Centre. The key movements were "slow", "normal" and "fast" denoted by s, n and f respectively.

Of even more interest is are some of the results using the Swell Sub Octave to Great coupler and playing c^2 on the Great. An example is shown in Fig 7.9.23. The displacement of the key rest position after the note may be due to the sensor being knocked during playing. Despite the key movement being no slower than the example illustrated in Fig 7.9.19 above, there is a very clear and distinctly shaped slower initial movement of the tracker. Discussion with David Page came up with the suggestion that it is due to the dump valve (R in Fig 7.9.17) not closing promptly enough resulting in a constant flow of air through the inlet valve and out through the dump valve during the initial movement. It is well known that the Barker machine of

this organ is in need of overhaul and so a misalignment of this sort might be expected and is a common problem due to the complexity of the machines. This phenomenon was apparent in other slow movements through this key but not in faster ones.
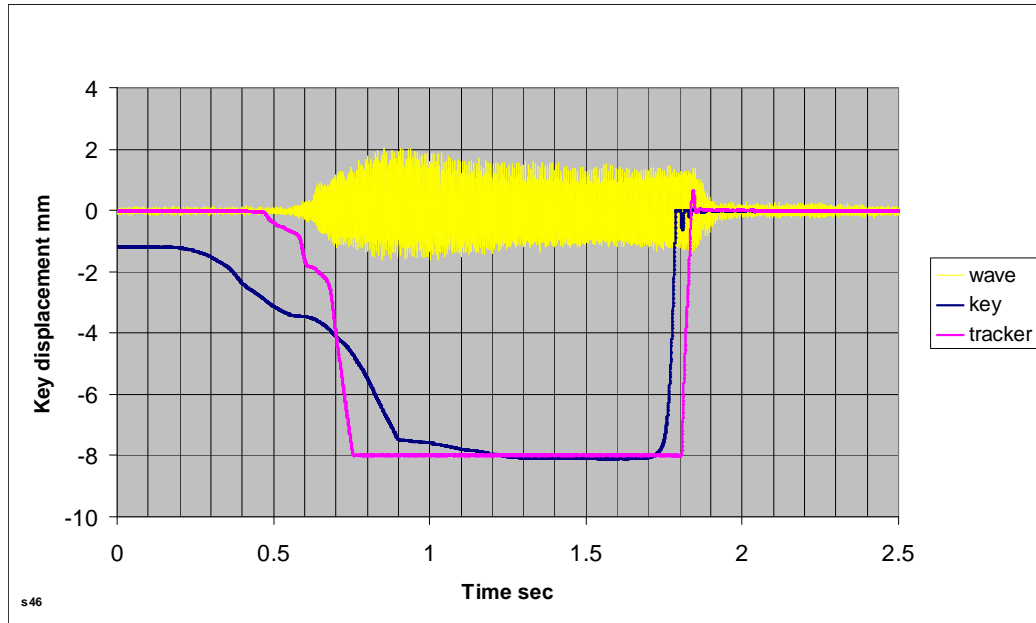
Fig 7.9.23 Diagram showing the Great key and Swell tracker movement of the St Stephen's Centre organ using the Swell sub octave to Great coupler, which operates through the Barker lever mechanism. The shape of the tracker movement appears to be due to incorrect phasing of the opening and closing of the valves in the Barker machine.

Chapter 8

Conclusion

Comments on the results

The diversity of opinion given in the literature reviewed in Chapter 3 gives an indication of the complexity of the issues involved in trying to establish to what extent organists can control the pallet and thus potentially the initial transient of a note by the way in which they move the key. This project was prompted by comments about some of the larger mechanical action organs built recently, but the first organ measured was one of the smallest in this study (Rose Hill Methodist Chapel, Oxford, Chapter 7.3). The organist believed that he could control the key and thus the pallet, but even on this fairly small (seven manual stops) organ the characteristic effect of the flexibility of the action pre-pluck can clearly be seen to be the dominant factor (Fig 7.3.5). When playing a sequence of "increasingly fast" key movements, the player reached a steady speed by the sixth key movement out of thirty-four (Fig 7.3.2). At the end of the session, the organist conceded that some of the things that he thought that he was doing were illusory (Paragraph 7.3.4). This organ also showed an apparently fundamental change in the way that the player moved the key above a certain speed. There appeared to be a move from a "constant force" type of playing to a "constant velocity" one. The latter was characterised by not exhibiting the slowing down of the key pre-pluck and by being slower overall.

The study of this change was outside the scope of this project because there was no equipment available with to undertake it but it is clearly an area for future study.

The organs used were those for which the opportunity to use them arose during the project. There are no very large organs represented and only by using a variety of different organs and organists can a valid conclusion be reached in the case of an empirical study such as this. Ideally each organist would have played similar material on more than one organ, but this was not possible (except at the Reid Concert Hall and St Stephen's Centre, but these are not directly comparable because the latter was intended to show the effects of the Barker lever).

At the Reid Concert Hall, University of Edinburgh (Chapter 7.2), an organ with a very "light" action, the organist demonstrated that, whilst he thought that he was varying the speed of key movement, he was actually changing the rhythm and length of notes. The effect of pre-pluck flexibility can again be seen very clearly in Fig 7.2.13 where the post-pluck movement can be seen to remain constant. The player however had a very clear perception that he was "doing something different".

Radley College (Chapter 7.4) has a larger organ and Fig 7.4.3 very clearly shows the characteristic shape of key and pallet movement demonstrated on the model organ (Fig 6.24). The spectrograms in Fig 7.4.25 show that very differently perceived key movements are not reflected in the sound envelope. An attempt to accent a note by moving the key faster (Figs 7.4.28 and 7.4.31) shows that this simply did not happen. The note was, however, elongated.

A similar exercise to the one at Rose Hill (Chapter 7.3) in which the organist played a sequence of notes with increasing key speed produced the same result at Radley College (Fig 7.4.34) – the key speed reached a constant by the fourth movement out of eight. A student at the college played more detachedly when trying to play slowly because the pre-pluck movement was elongated and the pluck occurred late in the note.

At St Margaret's Ipswich it was again possible to place sensors under the pallets and Figs 7.5.3 to 7.5.5 shows the characteristic shape of the key and pallet movements. A comparison between a Bach Chorale Prelude and Boellman's Toccata (Fig 7.5.24), which the organist believed would result in very different key movements, showed an elongation of the pre-pluck movement and a slowing down of the final part of the key movement in the Bach, but very similar initial post-pluck movements.

St Mary's Haddington is a relatively new organ in the North European style (Chapter 7.6). The results here, again, show that variations in style produce significant differences in the pre-pluck movement that are either totally absent or very much reduced in the post-pluck movements (Fig 7.6.7). Sound envelopes and spectrograms do not reflect the variations in key movement.

All Saint's Epping Upland (Chapter 7.7), a fairly small organ, showed distinct differences in pre pluck key travel between notes (Fig 7.7.7) as well as distinct differences in pre-pluck times. The organist consistently moved the keys more slowly in staccato (fast) playing.

Carlops Chapel was the smallest organ investigated, but even here the difference between slow and fast key movements could be seen to be predominantly in the pre-pluck area even though there was only about 0.5 mm pre-pluck movement (Fig 7.8.2 etc). The sound envelopes do not reflect the key movements. In "expressive" playing some of the pre-pluck movements are relatively long and not always reflected in the post-pluck movements (Fig 7.8.13).

The organ at the St Stephen's Centre in Edinburgh was selected because it has a Barker lever on the Great organ. The purely mechanical Swell organ showed the now expected characteristics (with the proviso that the second sensor was measuring the movement of a tracker outside the windchest) (Fig 7.9.9). The results using the Barker lever were less conclusive (it was known that this action needed some overhaul). Fig 7.9 20 shows that the tracker starts to move at the very end of the key movement.

Some of the authors quoted in Chapter three (Jude, Harrison etc) clearly understood what was happening to the pallet, and describe what happens when the key moves through the pluck point. They did not, however, back this up with experimental data and many organists continued to believe that they could control the pallet.

Norman (1966) suggests that a well-voiced pipe on low wind pressure and open toe voicing "no doubt" allows some control of the intonation. Again, this is an area for future study but the results of this study suggest that the player does not vary the speed of key and thus pallet movement greatly during actual performance. A sensitive pipe on a light action may well respond to careful movement of individual keys, but none of the players in this study could demonstrate any systematic variation of transient. Changes in a "sensitive" pipe might be due to random slight variations - this needs to be ascertained.

The result from the model (Fig 6.24) shows that there is only a very small part of the key movement between the pallet starting to open and the pressure in the groove reaching a maximum in which there is a theoretical possibility of exerting any control over the pallet.

Specific conclusions

The results from the measurements in this paper, taken on a variety of organs using a number of organists, most of who believed that they could control the pallet to a meaningful extent, lead to a number of clear conclusions.

The first conclusion is that organists do vary the way in which they move the key. This does not however mean that they vary the way in which they move the pallet or even that part of the key movement that controls the pallet. Their perception of the variations that they were making did not always agree with what they were actually doing.

The second conclusion is that the pallet does not precisely follow the key. The most important factor here is pluck. Even in short and rigid actions, the measurements showed that there was a movement of the key head as the action flexed up to the point at which pluck was overcome. The key then started moving more rapidly and there was no indication that the players could significantly slow the key down before it hit the key bed. A typical time of travel of a pallet was 30 ms. For the player to control the pallet, he would have to reduce the force that he had been applying to get through the pluck during the first part of this movement. The International Amateur Athletic Federation[1] considers that a reaction time for runners off the block of less than 120 ms indicates a false start.

The third conclusion is that the variation in the player's movements was almost entirely in the part of the movement before the pallet started opening. This may very well influence how they "feel" about playing the music but it has no audible effect.

The fourth conclusion is that the variations in pallet movement that were observed did not have an audible effect. None of the players could give an audible demonstration of variations in sound.

The fifth conclusion is that there is only a very small proportion of the key movement, between the pallet starting to open and the pressure in the groove reaching a maximum, in which control of the transient might be possible.

The sixth conclusion is that those few variations in sound that could be observed did not appear to be related to the key movement.

The seventh conclusion is that the speed of closing the pallet had little effect on the closing transient even in extreme cases.

---

[1] [IAAF]

The eighth conclusion is that players clearly varied the rhythm of playing when they were asked to vary the speed of moving the key.

The ninth conclusion is that there appears to be a transition from playing with the fingers to playing with the whole hand or arm above a certain speed.

The excess force required due to pluck means that the player can keep his fingers in contact with the keys with the certain knowledge that he will not move them, whilst keeping the force required to move the key after pluck has been overcome to a comfortable level. The same end is achieved on an electric keyboard by making the contact point a third to half way down the key's travel. This means that the player can "feel" the key by moving it slightly, again with the certain knowledge that the note will not sound until he wants it to. The practice of superimposing artificial "tracker touch" on standard electric keyboards may be unsatisfactory because the tactile feedback no longer coincides with the audible feedback but this needs investigating. A typical electric keyboard also lacks the inertia of a mechanical action.

The overall conclusion is that there appear to be characteristics of mechanical organ actions that give important feedback to the player but do not necessarily influence the sound.

Further work to be done

There is clearly a great deal of further work that could valuably be done.

There appears little doubt that organists empirically prefer mechanical actions unless they are too "heavy". Given that they have little control over the pallet, it would appear that it is the tactile feedback that is critical. Experiments to determine whether there is any consensus as to the most comfortable amount of pluck should be undertaken. This could be combined with an analysis of other important

characteristics such as key force, EDM and friction since there is a compromise between flexibility and mass.

If is possible to identify the characteristics that organists need in order to play "musically" it may be possible to superimpose these on an electric keyboard in order to provide the best compromise when a mechanical action is not practical. Bicknell (1997) states that it has not been possible to develop an electric switch that operates at the beginning of the key movement. This may be of great importance to producing a good electric action and should be pursued.

All the work in this project has been limited to the action itself. In practice, the player's finger may bend as well and this could be measured.

Measurement of the time that it takes for a player to react to going through the pluck point should be undertaken by using a force transducer and measuring the reaction time to a stimulus similar to pluck.

More extensive tests on organs with unsteady wind systems should be undertaken in order to establish whether changes in the transient are due to random fluctuations of pressure or the effect of the timings of adjacent notes.

Tests with fully proportional actions may indicate whether the ability to control the transient may be a potentially useful factor in organ playing.

In general, the pipes of a mechanical action organ are, of necessity, relatively close to the player. The effect of a significant time delay to the sound might help indicate to what extent the audible feedback is important.

There may be other things that give the player an impression that what he is doing at the keys is changing the sound that is being produced. This may include more action noise when a key is hit harder.

The effect of friction on action components and how it might be minimised should be investigated.

The exercises undertaken in this project were limited by the instruments that were made available. More work should be done on larger organs in particular and on organs with assisters of various sorts such as balanciers.

No consideration was given to how differently voiced pipes might affect the outcome although the variety of organs examined did not suggest that different pipes had a significant effect.

The instance of the player playing in a more detached way when attempting to play legato (section 7.4.3.4) should be studied further.

Bibliography

[Angster, Pitsch and Miklós 2004]   Angster J, Pitsch S, Miklós A. "The Influence of Different types of Wind Chests on the Sound Formation of Flue Organ Pipes" *CFA/DAGA'04* (Strasbourg March 2004)

[Anderson 1956]   Andersen, Poul-Gerhard. *Organ Building and Design* (London, George Allen and Unwin 1969) translation by Joanne Curnutt from *Orgelbogen* (Copenhagen 1956)

[Audsley 1905]   Audsley, George Ashdown. *The Art of Organ Building* (Mineola, Dover 1965 republication of 1905 edition, Dodd, Mead & Co)

[Baker 1993]   Baker, David. *The Organ* (Princes Risborough, Shire 1991 reprinted 1993)

[Barnes 1964]   Barnes, William H. *The Contemporary American Organ* (Miami, Warner 1964) Eighth edition

[Bellochio 1992]   Bellochio, Mathew-Michael. *Long Run Concerns* (The American Guild of Organ Builders Convention, Portland, Oregon 1992 video recording).

[Bethards 2005]   Bethards, Jack M. "A Brief for the Symphonic Organ" *The Diapason* (Des Plaines, Illinois, Scranton Gillette September 2005)

[Bicknell 1997]   Bicknell, Stephen. "Raising the Tone" *Choir and Organ* (March/April 1997)

[Bird and Ross 2002]   Bird J and Ross C. *Mechanical Engineering Principles* (Oxford, Newnes 2002)

[Blanton 1965]   Blanton, Joseph E. *The Revival of the Organ Case* (Albany Texas, Venture Press 1965)

[Bohn]   Bohn, David. Wisconsin Alliance for Composers – www.wiscomposers.org, *On the Nature of the Beast that does not Breathe – A composer's-Eye View of Writing for the Organ* (Newsletter date unclear)

[Bonavia-Hunt]   Bonavia-Hunt, Noel *The Modern British Organ* (London, Weekes, new and revised edition, undated)

[Caddy, Pollard and Howard 1957]   Caddy, Roy S, Pollard, Howard F. "An Objective Study of Organ Actions" *Organ Institute Quarterly* (Vol 7, No 2, Summer 1957) p44

[Calvert and Farrar 1999]	Calvert J R and Farrar R A. *An Engineering Data Book* (Basingstoke, Palgrave 1999)
[Challis 1953]	Challis, John. "The Slider and Pallet Wind Chest" *Organ Institute Quarterly* (Vol.3 No. 3 Summer 1953)
[Cobb 2004]	Cobb F. *Structural Engineer's Pocket Book* (Oxford, Elsevier 2004)
[Collins 1982]	Collins, Peter. "A Question of Touch" *JBIOS* (Oxford 1982, Vol 6) p 36
[Curley 1998]	Curley, Carlo *In the Pipeline* (London, Harper-Collins 1998)
[Dom Bedos 1766]	Dom Bedos (François Bédos de Celles). *L'art du Facteur d'Orgue* (Paris 1766-78) American translation by Ferguson, Charles *The Organ-Builder* (Raleigh NC, The Sunbury Press 1977)
[Donahue 1991]	Donahue, Thomas. *The Modern Classical Organ* (North Carolina, McFarland 1991)
[Ellerhorst 1965]	Ellerhorst, Winfred. *Handbuch der Orgelkunde* (Buren, Knuf 1965, reprinted 1975) in German
[Engineeringedge]	www.engineeringedge.com
[Fischetti 2004]	Fischetti, Mark. "*Working Knowledge – Pipe Organs*" Scientific American, (July 2004)
[Fisher 1997]	Fisher, Roger. "The New Marcussen Organ in the Bridgewater Hall, Manchester" *Organists' Review* (May 1997 p93)
[Forsyth-Grant 1987]	Forsyth-Grant, Maurice. *Twenty-One Years of Organ-Building* (Oxford, Positif Press 1987)
[French and Ebison 2000]	French A P and Ebison M. *Introduction to Classical Mechanics* (Dordrecht, Kluwer 2000)
[Gieck and Gieck 1997]	Gieck K and Gieck R. *Engineering Formulas 7th Edition* (Germering, Gieck 1997)
[Grantdesign]	www.grantdesign.com
[Grassin 2003]	Grassin, Didier. "Trackers – material evidence" *Organ Building* (Bury St Edmonds, Institute of British Organ Building 2003) p72-75
[Harrison 1953]	Harrison, G Donald. "Slider Chests?" *Organ Institute Quarterly* (Vol. 3, No. 3, Summer 1953)
[Hoffman 1986]	Hoffman, Ludwig. "Mechanical Action" *ISO Information* (No 26, June 1986) Translation by Keith Reginald Foster

[Hollick 1997]   Hollick, Douglas. "'Great Dane': Manchester's new Marcussen" *Choir and Organ* (March/April 1997)

[Hopkins and   Hopkins, Edward J and Rimbault, Edward F. *The Organ, Its*
Rimbault 1877]   *History and Construction* (London 1877, 3rd Ed. Republished, Bardon Enterprises 2000)

[Hull 1911]   Hull, A Eaglefield. *Organ Playing: its Technique and Expression* (Augener 1911)

[IAAF]   International Amateur Athletic Federation. www.iaaf.org 2006

[Jones 1999]   Jones, Kenneth. "Manual Coupling in Larger Organs" *Organists' Review* (November 1999)

[Jude 1922]   Jude, Alexander A. "The Barred and Barless Soundboards II" *The Organ* (Vol 1 No 4 April 1922) p207

[Klotz 1965]   Klotz, Hans. *The Organ Handbook* (St Louis, Concordia Publishing House 1969) Translated by Krapf, Gerhard from *Das Buch von der Orgel* (Kassel, Barenreiter) 7th ed 1965

[Laukhuff 2000]   Laukhuff, Aug. Catalogue 2000

[Legros 1976]   Legros, Henri, " The Manual Action of the Clicquot Organ at Souvigny" *ISO Information 15* (December 1976

[Lewis 1956]   Lewis, Walter and Thomas. *Modern Organ Building* (London, Reeves 1934 reprinted 1956)

[Lindhardt 1962]   Lindhardt. (Walcker Hausmitteilung Nr 28, 4 April 1962)

[Marsden Thomas   Marsden Thomas, Anne. *A Practical Guide to Playing the*
2001]   *Organ* (Cramer 2001)

[Matthews 2004]   Matthews, C. *Engineers' Data Book* (Bury St Edmonds, I Mech. E. 2004)

[Moyes 2002]   Moyes, Andrew. "Tracker or Electric" Letter in *Organists' Review* (November 2002 p373)

[Noehren 1993]   Noehren, Robert "Notes on the Design and Construction of a Modern Organ *The Diapason* (Des Plaines, Scranton Gillete May 1993 pp10-13

[Noehren 1999]   Noehren, Robert. *An Organist's Reader* (Michigan, Harmonie Park Press 1999)

[Norman 1966]   Norman, John and Norman, Herbert. *The Organ Today* (London, Barrie and Rockliff 1966)

[Norman 1977]   Norman, John. "The Design of Organ soundboard Pallet Valves" *JIMIT* (Spring 1977)

[Ochse 1988]   Ochse, Orpha. *The History of the Organ in the United States* (Bloomington, Indiana University Press 1988)

[Ogasapian 1990]   Ogasapian, John K. *Church Organs – A Guide to Selection and Purchase* (OHS & AGO 1990)

[Perrot 1971]   Perrot, Jean. *The Organ from the Hellenistic Period to the end of the Twentieth Century* (Oxford 1971)

[Pollard 1968]   Pollard, H F. "Time Delay Effects in the Operation of a Pipe Organ" *Acustica* (Vol 20 No 4 1968)

[Praet 2000]   Praet, Wifred. *Organ dictionary* (Nieuwkerken, Praet 2000)

[Pykett 2005]   Pykett, Colin "The Physics of Organ Actions" *Pykett.org.uk* (accessed 24th October 2005)

[Ritchie and   Ritchie, George and Stauffer, George. *Organ Technique*
Stauffer 2000]   (Oxford 2000)

[Romero]   Romero, R. *Fft for Dummies* (www.vlf.it)

[Sears, Zemansky   Sears F W, Zemansky M W and Young H D. *College Physics*
and Young 1991]   *7th Edition* (Reading, Mass. Adison Wesley 1991)

[Soderlund 1980]   Soderlund, Sandra. *Organ Technique an Historical Approach* (Hinshaw Music 1980)

[Speerstra 2003]   Speerstra, Joel. (Ed) *The North German Organ Research Project at Göteborg University* (Göteborg Organ Art Centre 2003)

[Stainer 1909]   Stainer, John. *Complete Organ Method* (Schirmer 1909)

[Sumner 1973]   Sumner, William Leslie. *The Organ* (London. Macdonald 4th Ed 1973)

[Taylor 2000]   Taylor, A J & L Ltd. Catalogue 2000

[Thisthlethwaite   Thistlethwaite, Nicholas. *The Making of the Victorian Organ*
1999]   (Cambridge 1999)

[van Oortmerssen   van Oortmerssen, Jacques. *Organ Technique* (Göteborg Organ
2002]   Art Centre 2002)

[Willcock and   Willcock and Booser. *Bearing Design and Application* (New
Booser 1957]   York, McGraw Hill 1957)

[Williams 1980]   Williams, Peter. *A New History of the Organ* (London, Faber and Faber 1980)

[Williams and   Williams, Peter and Owen, Barbara. *The Organ* The New
Owen 1997]   Grove Music Instrument Series (London, Macmillan 1997)

[Wills 1984]   Wills, Arthur. *Organ* Yehudi Menuhin Music Guides (London,
                       Macdonald 1984**)**

Publications

Woolley A G. Actions and Reactions, *Musical Instrument Technology* (Institute of Musical Instrument Technology, London September 2001). Pages 18 to 42

Woolley A G. Mechanical Pipe Organ Actions and their Interface with the Player, *Proceedings of the CFA/DAGA '04* (Strasbourg March 2004)

Woolley A G. Mechanical Pipe Organ Actions and their Interface with the Player, *IBO Newsletter* (Institute of British Organ Building, London No 34 June 2004)

Woolley A G. Mechanical Pipe Organ Actions and their Interface with the Player, *Proceedings of Forum Acusticum 2005* (Budapest September 2005)

Appendix 1

Specifications of the organs

Rose Hill Methodist Chapel, Rose Hill Oxford

This organ is believed by its tuner, John Bailey of Bishop and Son, to have been built by Hill around 1845. The pedal was added in 1918 (NPOR). The manual compass is C-f^3 54 notes and the manual action is mechanical.

Stopped Diapason Bass	8
Stopped Diapason Treble	8
Dulciana	8
Open Diapason	8
Principal	4
Twelfth	2 2/3
Fifteenth	2
Pedal Bourdon	16

Reid Concert Hall of the University of Edinburgh

The following description is reproduced from the leaflet published by the University of Edinburgh with permission.

The firm of Jürgen Ahrend [of Leer, Germany], renowned for the sensitive restoration of historic instruments, built the organ in the University's Reid Concert Hall (opus 98) in 1977-78, in consultation with Peter Williams. It remains, at the time of writing, the only organ by this firm in the UK. The instrument derives inspiration from early 18th-century German models; the two manual divisions are separately encased, but the pedal pipes are included in the Hauptwerk case. The pedal board is straight and flat, the Rückpositiv stop-handles project from the case behind the player, and there are no aids to registration. The unbushed mechanical action is of exceptional refinement; the voicing is direct and clear, yet full of subtlety.

SPECIFICATION

HAUPTWERK		*RÜCKPOSITIV*	
Praestant	*8*	*Gedackt*	*8*
Hohlflöte	*8*	*Praestant*	*4*
Oktave	*4*	*Rohrflöte*	*4*
Spitzflöte	*4*	*Waldflöte*	*2*
Nasat	*2⅔*	*Quinte*	*1⅓*
Oktave	*2*	*Sesquialtera*	*II (from tenor G)*
Mixtur	*IV-V*	*Scharf*	*IV*
Trompet	*8*	*Dulzian*	*8*

PEDAL

Subbass	*16*
Oktave	*8*
Oktave	*4*
Posaune	*16*
Trompete	*8*

Compass: manual C-f'''; pedal CC-F

Tremulant to whole organ

Pedal coupler to Hauptwerk

Manual shove-coupler

Unequal temperament

Radley College, Radley, Oxfordshire. Chapel of St Peter.

The organ was built by William Hill and Son and Norman and Beard Ltd (Hill, Norman and Beard) in 1980. The manual compass is 58 notes C to a^3 and the pedal compass is CC to g. The pedal action is electric.

Pedal

1	Double Open Diapason	32	ext 3
2	Open Diapason	16	
3	Sub Bass	16	
4	Bourdon	16	From Great
5	Principal	8	
6	Flute	8	
7	Quint	5 1/3	
8	Fifteenth	4	
9	Nachthorn	2	
10	Sesquialtera	III	17.19.22
11	Trombone	16	
12	Trumpet	8	ext 11
13	Clarion	4	ext 11

Choir

14	Stopped Diapason	8	
15	Principal	4	
16	Chimney Flute	4	
17	Nazard	2 2/3	
18	Gemshorn	2	
19	Tierce	1 3/5	
20	Cymbal	IV	22.26.29.33
21	Regal	16	
22	Cremona	8	
23	Tremulant		
24	Trompeta Real	8	en chamade

Great

25	Bourdon	16	
26	Open Diapason	8	

27	Stopped Diapason	8	
28	Principal	4	
29	Wald Flute	4	
30	Fifteenth	2	
31	Sesquialtera	III	12.15.17
32	Furniture	III	19.22.26
33	Posaune	8	
34	Tremulant		

Swell

35	Open Diapason	8	
36	Gedact	8	
37	Gamba	8	
38	Voix Celeste	8	
39	Gemshorn	4	
40	Stopped Flute	4	
41	Piccolo	2	
42	Larigot	1 1/3	
43	Mixture	IV	15.19.22.26
44	Contra Fagotto	16	
45	Cornopean	8	
46	Tremulant		

East   Separate floating division on electropneumatic chest

47	Dulciana	16
48	Open Diapason	8
49	Flute	8
50	Gemshorn	4
51	Fifteenth	2
52	Mixture	III
53	Trumpet	8

St Margaret's Church, Ipswich, Suffolk

This organ was built by J W Walker in 1858. The manual compass is C to g^3 and the pedal compass CC to f

Pedal	1	Open Diapason	16
	2	Bourdon	16
	3	Principal	8
	4	Trombone	16
Great	5	Open Diapason	8
	6	Stop'd Diapason	8
	7	Principal	4
	8	Lieblich Flute Metal	4
	9	Piccolo	2
	10	Mixture	III
	11	Trumpet	8
Swell	12	Double Diapason	16
	13	Open Diapason	8
	14	Echo Gamba	8
	15	Vox Angelica	8
	16	Stop'd Diapason	8
	17	Principal	4
	18	Fifteenth	2
	19	Mixture	III
	20	Horn	8
	21	Oboe	8
Choir	22	Dulciana	8
	23	Gamba	8
	24	Lieblich Gedackt	8

25 Lieblich Flute   4

26 Flute   4

27 Clarionette & Bassoon   8

St Mary's Church, Haddington, East Lothian

The organ in St Mary's Church Haddington was built by Lammermuir Pipe Organs of Oldamstocks, East Lothian and completed in 1990. The manual compass is C to g^3 and the pedal compass CC to f.

Pedal	1	Principal	16
	2	Subbass	16
	3	Octave	8
	4	Mixture	IV
	5	Fagot	16
	6	Trompete	8
Hauptwerk	7	Principal	8
	8	Chimney Flute	8
	9	Octave	4
	10	Spill Flute	4
	11	Quinte	2 2/3
	12	Octave	2
	13	Mixture	V
	14	Cornet	III
	15	Trompete	8
Rückpositiv	16	Gedackt	8
	17	Principal	4
	18	Clear Flute	4
	19	Nazard	2 2/3
	20	Gemshorn	2
	21	Tierce	1 3/5
	22	Larigot	1 1/3
	23	Scharff	III
	24	Crumhorn	8

All Saints, Epping Upland, Essex

The organ in All Saints Church (CoE) started out as a barrel organ by Bevington but has been extensively rebuilt since. The manual compass is c to f^3 and the pedal compass CC to f

Pedal

1	Bourdon	16
2	Principal	8
3	Fifteenth	4

Great

4	Open Diapason	8
5	Stop'd Diapason	8
6	Principal	4
7	Chimney Flute	4
8	Fifteenth	2

Swell

9	Gedact	8
10	Salicional	8
11	Octave	4
12	Mixture	III

St Stephen's Centre, Edinburgh

The organ was built by "Father" Henry Willis in 1880. The manual compass is C to g^3 and the pedal compass CC to f

Pedal

1	Open Diapason	16
2	Bourdon	16
3	Violoncello	8

Great

4	Double Diapason	16
5	Open Diapason	8
6	Open Diapason	8
7	Claribel Flute	8
8	Principal	4
9	Flute Harmonique	4
10	Fifteenth	2
11	Mixture	III
12	Bombarde	8
13	Clarion	4

Swell

14	Lieblich Bourdon	16
15	Open Diapason	8
16	Lieblich Gedackt	8
17	Salicional	8
18	Vox Angelica	8
19	Gemshorn	4
20	Flageolet	2
21	Cornopean	8
22	Hautboy	8

23 Vox Humana   8

Choir

24 Lieblich Gedackt   8
25 Claribel Flute   8
26 Dulciana   8
27 Viola da Gamba   8
28 Gemshorn   4
29 Flute Harmonique   4
30 Lieblich Flöte   4
31 Piccolo   2
32 Corno di Bassetto   8
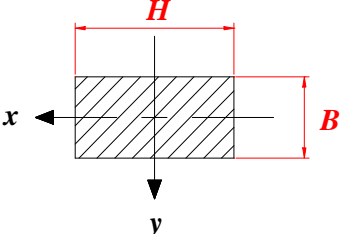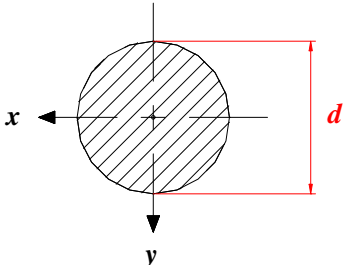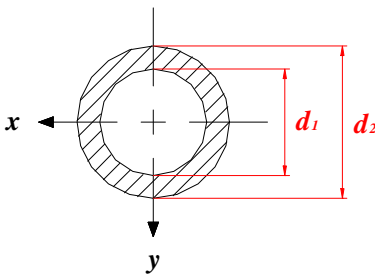
Appendix 2

Second moment of area, *J*
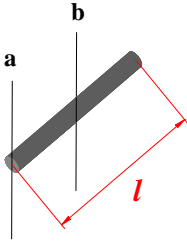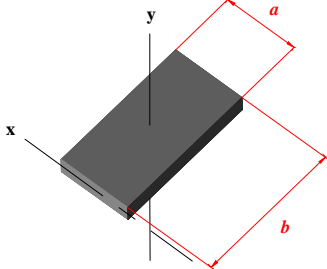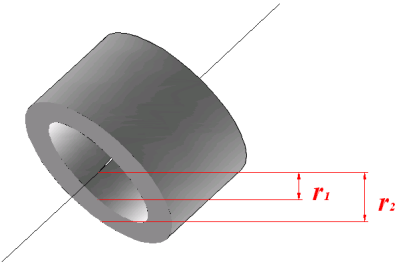
The second moment of area of a number of common cross sections is shown in the table below. Both *J* and *I* are used to denote polar second moment of area but *J* is used here in order to differentiate it from moment of inertia, which is also commonly denoted by *I*.

Cross section	**J**
	$J_x = \dfrac{BH^3}{12}$ $J_y = \dfrac{HB^3}{12}$
	$J_x = J_y = \dfrac{\pi d^4}{32}$
	$J_x = J_y = \dfrac{\pi\left(d_2^4 - d_1^4\right)}{32}$

Appendix 3

Moments of inertia, I

The moments of inertia of a number of common shapes with mass m is shown in the table below.

Shape	I
	Thin rod about end, a: $$I = \tfrac{1}{3}ml^2$$ Thin rod about centre, b: $$I = \tfrac{1}{12}ml^2$$
	Rectangular plate through centre: $$I_y = \tfrac{1}{12}m\!\left(a^2 + b^2\right)$$ Rectangular plate about an edge: $$I_x = \tfrac{1}{3}mb^2$$
	Hollow cylinder about axis: $$I = \tfrac{1}{2}m\!\left(r_1^2 + r_2^2\right)$$ Solid cylinder about axis: $$I = \tfrac{1}{2}mr_2^2$$

Appendix 4

Densities of materials

The densities of a number of common materials encountered in pipe organs is shown in the table below.

Material	Density g/cm³
Aluminium	2.7
Brass	8.5
Steel	7.7
Phosphor bronze	9.0
Pine	0.4
Oak	0.8

Appendix 5

Young's Modulus, Y

The Young's modulus of a number of common materials encountered in organ building is shown in the table below.

Material	Y GN/m²
Aluminium	70
Brass	102
Steel	207
Phosphor bronze	100
Pine	8
Oak	13

Appendix 6

Data sheets

RS
Data Sheet

Reflective and slotted opto switches 2601

Gallium Arsenide infra-red emitting diodes and spectrally matched detectors housed in moulded packages mechanically designed to enable sensing in a variety of applications, i.e. limit switching, paper/tape sensing and optical encoding.

Reflective opto switch
RS stock no. 307-913

Comprises a Ga As infra-red emitting diode with a silicon phototransistor in a moulded rugged package. The sensor responds to the emitted radiation from the infra-red source only when a reflective object is within the field of view of the sensor. The device is ideal for such applications as end of tape detection, mark sensing, etc. An infra-red transmitting filter eliminates ambient illumination problems.

Absolute maximum ratings at 25°C (unless stated)

Operating temp range _____ -40°C to +80°C
Storage temp range _____ -40°C to +80°C
Lead soldering temperature (5 sec) _____ 260°C

Input diode

Forward dc current _____ 40mA*
Reverse dc voltage _____ 2V
Power dissipation _____ 50mW**

Output sensor

Collector-emitter voltage _____ 15V
Emitter-collector voltage _____ 5V
Power dissipation _____ 50mW**

* Derate linearly 0.73mA/°C above 25°C
** Derate linearly 0.91mW/°C above 25°C

Applications
● Limit switch
● Paper sensor
● Counter
● Chopper
● Coin sensor
● Optical sensor
● Position sensor
● Level indicator.

Mechanical details

White Dot Indicates LED
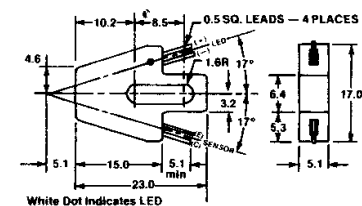
Electrical details

Reflective Surface (See Notes 1 & 2)

Electrical characteristics
at 25°C (unless stated)

Symbol	Parameter	Min.	Typ.	Max.	Units	Conditions
Input Diode						
V_F	Forward Voltage	-	-	1.8	V	$I_F = 40mA$
I_R	Reverse Current	-	-	100	μA	$V_R = 2V$
P_O	Radiant Power	0.5	1.5	-	mW	$I_F = 20mA$
Output Sensor						
BV_{CEO}	Collector-Emitter Breakdown Voltage	15	-	-	V	$I_{CE} = 100μA$
BV_{ECO}	Emitter-Collector Breakdown Voltage	5	-	-	V	$I_{BC} = 100μA$
Coupled						
I_C	Photocurrent (Note 1)	200	-	-	μA	$I_F = 40mA$, $V_{CF} = 5V$
I_{CX}	Photocurrent (Note 2)	-	-	20	μA	$d = 5mm$ (Fig.2)

232-2447

Typical characteristics

| Figure 1 Output current vs input | Figure 2 Output current vs reflective object distance | Figure 3 Nonsaturated switching time vs load resistance |
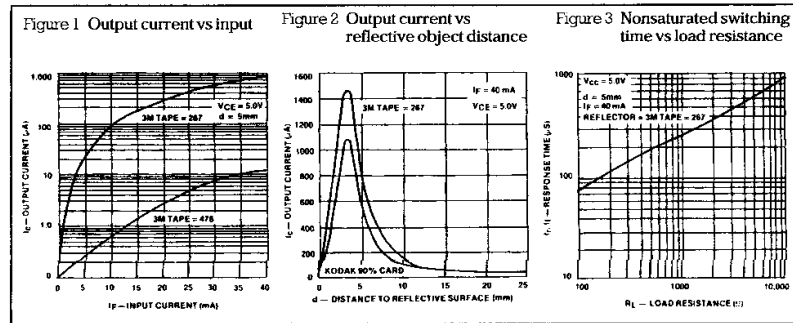
Note 1: Photocurrent (I_c) is measured using 3M tape = 267 for a reflecting surface. The reflective qualities of 3M tape = 267 are very similar to an Eastman Kodak neutral white test card having 90% diffuse reflectance.

Note 2: Photocurrent (I_{ce}) is measured using 3M tape = 476 for a reflecting surface. 3M tape = 476 has a very black dull surface with optical reflectance qualities comparable to a surface coated with carbon black printers ink.

Figure 4 Reflective object detection

Applications

Figure 5 Reflective object counter

2
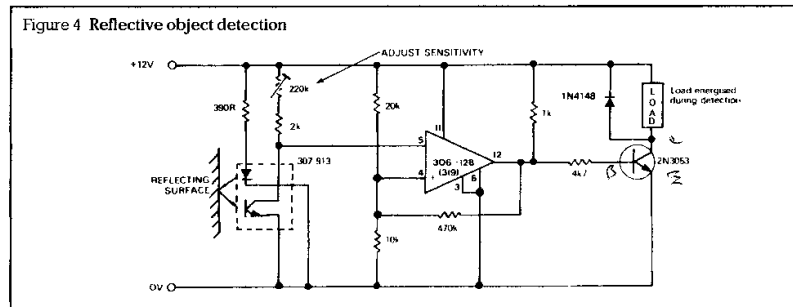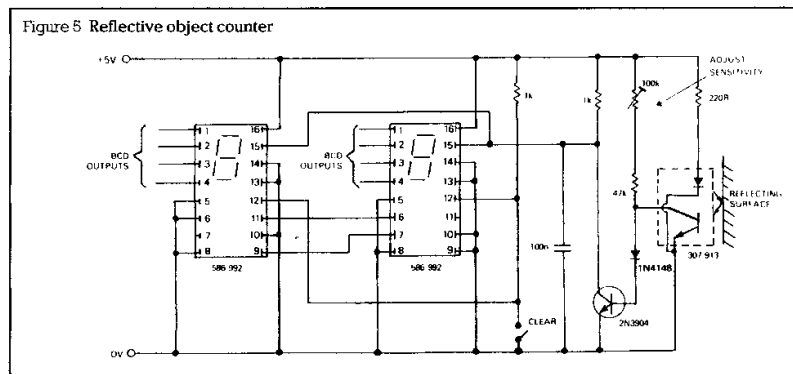
Photoelectric sensors   **Baumer** electric

Laser distance sensor

preliminary

OADM 12I6430/S35A

Art.-Code: 147121

- Compact housing
- Short measuring range with high resolution
- Teachable measuring range
- Short response time (< 900 µs)
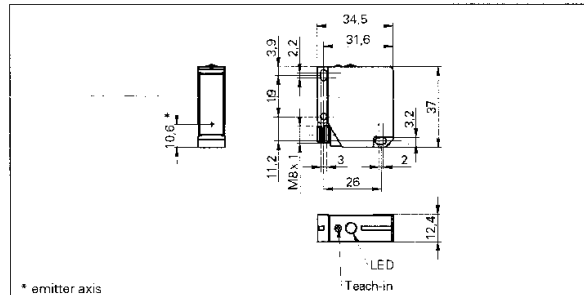
* emitter axis

technical data	
measuring range	16...26 mm
min. teach-in range	1 mm
resolution (matt white ceramic)	2 µm...5µm
linearity error (matt white ceramic)	± 6 µm...15 µm
response time	< 900 µs
sensing element	photoelectric array
analog output	4 - 20 mA
power indicator	green LED
alarm indicator/soiled lens indicator	red LED / flashing red LED
voltage supply range	12 - 28 VDC
max. supply current	< 100 mA
light source	pulsed red laser diode
laser class	2
wave length	675 nm
reverse polarity protection (voltage supply only)	yes
short circuit protection	yes
housing material	die-cast zinc
protection class	IP 67
temperature range	0...+50 °C
laser beam diameter	0,5...0,2 mm

connection diagram

Analog
BN (1) — o +Vs
WH (2) — o teach in
BK (4) — o analog 4...20 mA
BU (3) — o 0 V

pin assignment

2 teach in   4 analog 4...20 mA
1 + Vs   3 0V

Typical resolution

Typical linearity error

CAUTION
LASER RADIATION
DO NOT STARE INTO BEAM
LASERDIODE
Class 2 LASER Product
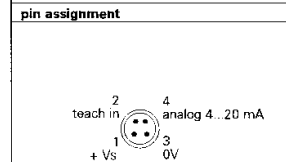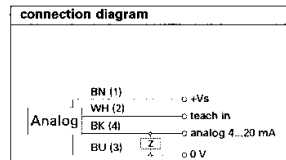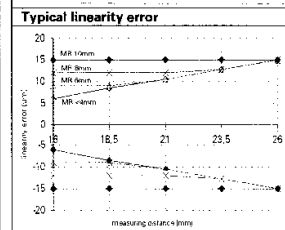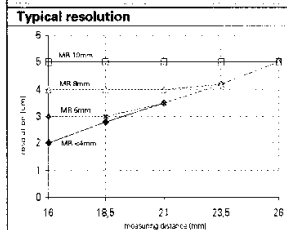
Appendix 7

Paper published in IBO Newsletter No 34 June 2004

Mechanical pipe organ actions, and their interface with the player

Alan Woolley reports on his research

Introduction

There is currently much discussion about whether it is possible for organists to influence the speech transients of pipes in organs with mechanical action, by the way in which they depress the key.

There has also been public criticism of a number of recent large mechanical-action organs that has led to the 'Action Wars' discussion in these pages. Where subsidiary electric consoles have been provided, these are reported to be used almost to the exclusion of the mechanical consoles. Some of these electric actions are themselves criticised on the grounds that they *'would be sniffed at by some organ builders'* [1].

The author became interested in this subject whilst studying for an MA at Reading University. It soon became apparent that many 'mechanical-action' organs contained a variety of devices to assist them. Some of these would affect just the lowest notes (balanciers etc). Some might extend throughout the compass (split pallets, electric sub-pallets etc). All of these will in some way affect the touch of the notes concerned and thus any control that the player may have. Perhaps the ultimate form of assisted mechanical action is that utilising Barker levers in the primary action – this is (essentially) an on/off pneumatic relay and is unlikely to allow any control over the pallet. It may however give the player the correct tactile feedback because it will 'feel' like a small mechanical action.

Fully proportional devices (Willis floating lever, Fisk servo-pneumatic lever, and possibly the various recent electric devices) do not appear to have caught on despite apparently allowing the player complete control. Ian Bell[2] suggests that this may simply be because of cost due to their complexity – there may be other reasons.

An abbreviated version of the author's MA dissertation was published in Musical Instrument Technology (and he is well aware of its many deficiencies)[3].

It should also be noted that the author is aware of very few historical references to the possibility of influencing the

nature of the pipes' speech. Stainer said in 1909 *'But the object of the player {is} to throw open the pallets in true response to his fingers as regards time, and also to throw them open so thoroughly and rapidly that the wind shall not, as it were, sneak into the pipes and spoil their tone.'* [4] He goes on to say that in general it is safest to adjust to the heaviest manual of any organ because of the risk of missing notes if moving from a lighter one.

Dom Bédos told us in 1766 that too large a pallet opening leads to a 'hard' action, and that long rollers, particularly in the pedal organ, lead to too much flexibility [5].

Equally, the eminent organists and organ builders who insist that control of the pallet is fundamental to organ playing cannot be ignored, and we need to seek to understand what is happening.

This project (the author is registered as a post graduate student at the University of Edinburgh) looks at some of the characteristics of mechanical pipe organ actions and seeks to establish how they might affect the player's control of the pallet, and thus the pipe speech, in all phases — particularly in larger organs. It is in its early stages, and there is currently no more than an indication of the direction to take.

The Bar and Slider Wind Chest

The bar and slider wind chest is used almost exclusively in mechanical-action organs and will be intimately familiar to all readers of this paper.

It has been found empirically that a comfortable action requires a force equal to a weight of 60 to 80 grams to keep the key depressed, with an additional initial pluck of 60 to 80 grams — i.e. it requires 120 to 160 grams to start the key moving. Although pluck and key force can be increased in smaller organs by increasing the strength of the pallet spring and by making the pallet opening larger than necessary, they cannot be reduced in larger organs where the inertia of the action and the required repetition rate deter-

[1] Hale, Paul 'Too Much of a Good Thing' *IBO Newsletter* No 27 September 2002.

[2] Correspondence with author.

[3] Woolley, Alan 'Actions and Reactions' *Musical Instrument Technology* September 2001.

[4] Stainer, John *Complete Organ Method* (New York 1909)

[5] Dom Bédos (Francois Bédos de Celles) L'art du facteur d'Orgue (Paris 1766-78). American translation by Ferguson, Charles *The Organ-Builder* (Raleigh NC, The Sunbury Press 1977)

mine the strength of the pallet spring, and the maximum air requirement and wind pressure determine the pallet opening and thus pluck. Any flexibility in the action due to rollers twisting, cloth bushes compressing etc. will result in the key moving until sufficient energy is stored to overcome the pluck. At this point the pallet will suddenly start opening and will catch up with the key movement. In a large organ the key can approach the end of its travel before the pallet opens.

Experimental Organ

In order to carry out this research, a small organ was built which allows for a wide range of action characteristics to be incorporated. The initial tests were carried out with a wind pressure of 75mm wg, a key force of 80g and a pluck of 120g. Two action runs have been built – an unbushed suspended action and a bushed balanced action with rollers of aluminium tube one metre long, 8mm outside diameter and 6mm inside diameter. Measurements of the movement of the key and pallet were made using an LED and photodiode.

How can the player influence the sound?

Control of the Initial Transient

The most obvious way of actually changing the sound of the pipe is by changing the initial transient. A number of laboratory experiments have shown that it is possible to influence it, but these were limited to individual keys depressed in isolation and/or restricted to small organs.[6,7,8] Indeed, it can also be demonstrated on the author's experimental organ beyond any audible doubt. However, this may not relate to how real organists actually play real pieces of music on real organs, and in particular may not take into account the characteristics of larger actions. It cannot be assumed that because mechanical actions are good in smaller organs that this automatically applies to organs of any size. In, say, a ten stop wind chest, a single rank will be fully winded with the pallet only partially open – it is this movement of the pallet that the player must be able to control.

Control of the ending transient

Some organists believe that at least as important as the initial transient is the ending one, and that players can more readily control the closing of the pallet because the

effects that may compromise control occur principally when the pallet is closest to the pallet opening.

Rhythm

Robert Noehren said *'However, if carefully observed, even in playing of a slow movement, a reasonably fast action of the finger is required to overcome the {pluck} or the key will not go down... In order for the key to be depressed, it is obviously impossible to control the speed of the descent when it is necessary to play in rhythm even in the slowest movement. However, expression is achieved rhythmically, and any subtlety of attack camouflaged by slight alterations of the rhythm, and it is this that deceives the player into believing that he is controlling the speech of the pipe'.* [9]

Factors affecting control

Tactile feedback

It may simply be that, in an essentially non-expressive instrument, the touch of a mechanical action gives the player the correct tactile feedback – it 'feels right', what my supervisor calls 'engagement' with the instrument. The organist needs to know where the keys are, and to be certain that he cannot press one inadvertently.

As stated above, it has been found empirically that a comfortable force to depress a key is equivalent to a weight of 60 to 80 grams. This does not allow the player to 'rest' his fingers on the keys. The initial resistance due to pluck allows this. As soon as it is overcome, the key will continue to move under a comfortable force. The geometry, inertia and friction may add to the feeling that 'something is happening'. If there is insufficient pluck the player may be unable to control the keys properly, because he cannot touch them without the pallet immediately starting to open.

In electric actions, where there is no natural pluck, feedback is introduced by allowing the key to move a certain distance before electrical contact is made. If this theory is correct, then when artificial pluck is introduced the contact point should occur earlier in the key's travel so as to appear to coincide with the pluck being overcome.

Pluck

In a rigid action (suspended, no rollers, no bushing) pluck is overcome in a very short distance. The player must then immediately reduce the force on the key if the pallet is to be controlled at least during its initial movement.

[6] Caddy, Roy S; Pollard, Howard F. 'An Objective Study of Organ Actions' *Organ Institute Quarterly* (Vol 7, No 2, Summer 1957) p 44.
[7] Pollard, H F. 'Time Delay Effects in the Operation of a Pipe Organ' Acustica (Vol 20, No 4, 1968) p189.

[8] Castellengo, M. 'Acoustical Analysis of Initial Transients in Flute-like Instruments.' *Acustica - Acta Acustica* (85 1999) p387-400.
[9] Noehren, Robert. 'Notes on the Design and Construction of a Modern Organ', *The Diapason* May 1993
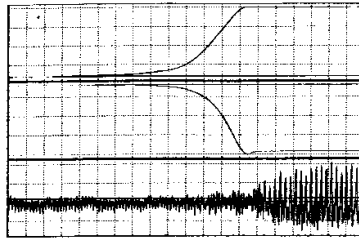
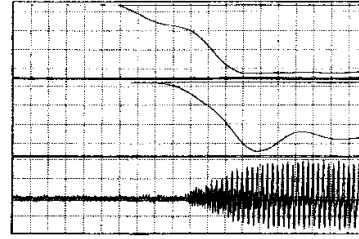Fig 1 Rigid action, 'slow' movement, 10ms divisions

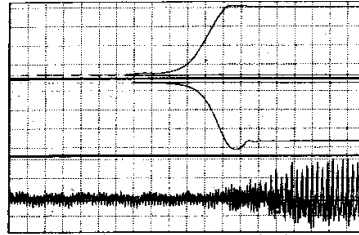Fig 3 Flexible action, "slow' movement, 10ms divisions

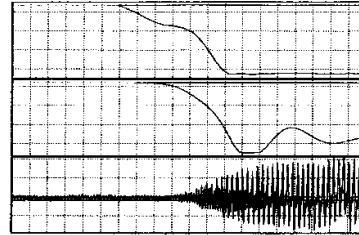Fig 2 Rigid action, 'fast' movement, 10ms divisions

Fig 4 Flexible action, 'fast' movement, 10ms divisions

Figures 1 and 2 show the movement of the key (top curve, inverted due to the geometry of the sensor), the pallet (bottom curve) and the waveform of the pipe speech with the key depressed subjectively very slowly, and quickly, respectively. The vertical movement is 10mm and the horizontal scale is 10ms per division. The movement of the key is inverted because of the geometry of the sensor.

It can be seen that although the keys were depressed subjectively in a very different way, the actual movement does not differ greatly. This may, of course, do no more than emphasise the problem of depressing keys in isolation.

Flexible Action

With the flexible action, the key moves about one third of its travel before the pallet suddenly starts to open. Figures 3 and 4 show this movement, with the characteristic shape of the key movement due to the key force increasing until the pallet starts opening, again with a slow and fast movement respectively.

These measurements were taken before felt stops were placed underneath the pallets, and the much greater overrun and the subsequent oscillations of the flexible action should be noted – this may well influence the airflow in the groove.

That the pallet movement does not exactly follow the key movement in a 'flexible' action under 'normal' playing is more clearly illustrated in Figure 5.

Real Music

Some key movements were then recorded with a concert organist playing the Hauptwerk of the 1978 Ahrend organ in the Reid Concert Hall in Edinburgh. This organ has a reputation for being difficult to play because of its very light action (100g on Hauptwerk, including pluck), but which should allow for a significant variation in touch. Figure 6 (opposite) shows the movement of the G above middle C key during the performance of a 'fast' toccata and a 'slow' chorale prelude. Again, the movement is inverted because of the geometry of the sensor.

It can clearly be seen that the key movement does not vary greatly, but it must also be very clearly understood that a great deal more data collection and analysis must be done before any conclusion can be drawn.
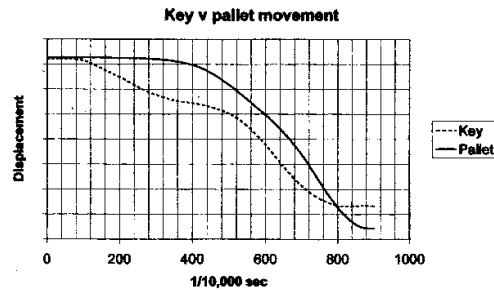
Key v pallet movement

Fig 5 Pallet movement in flexible action

Figure 7 shows key release of the same notes. Again there is little apparent difference between the two.

The Way Forward

The work so far has been done using a modified commercially available LED/phototransistor combination (OPB704), Iotech Wavebook 512 data acquisition box and Waveview version 7.14.16 software. This produces accurate, repeatable and rapid results, but the output is not quite linear and so needs very careful calibration in order to make accurate calculations of speed and acceleration, which makes it difficult to use on site. It also requires a small reflective strip attached to the moving element. It is, however, cheap, and gives valid comparative results. The author is trying to obtain some laser sensors which require no calibration and no reflective strip, but which are expensive.

The next stages of the project are:

- to obtain a better idea of how the pallet follows the key in as many conditions as possible
- to identify what elements of actions contribute to flexibility
- to identify how a variety of players actually play real music on real organs.

This requires access to organ actions and will at worst require a low tack adhesive reflective strip being temporarily attached. The laser device merely requires thin wires to be led out through the windchest seals.

The airflow through the pallet opening and in the groove can also be studied using techniques developed at Edinburgh.

Conclusion

In these preliminary results, the speed of movement of the key and pallet do not appear to reflect the player's perception of speed or relate to the speed of the music. Much further work needs to be done in order to establish how a variety of organists play real music on real organs with varying characteristics and whether this allows for the control of any of the parameters that might affect the sound. It should also be considered whether it is simply the degree of tactile feedback that a mechanical action gives to the player that is significant.

Organ building will always remain essentially an art — the more we understand the science, the more we can concentrate on the important aspects. ✣

Key depression

Fig 6 Rate of depression of key in 'fast' and 'slow' playing (Reid Concert Hall)
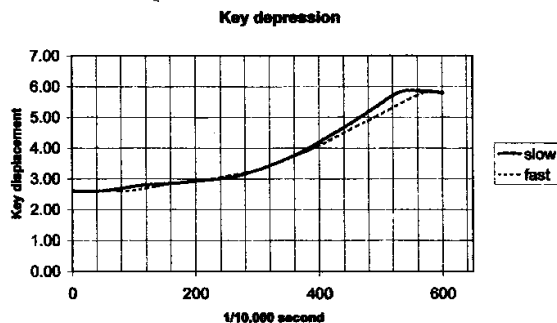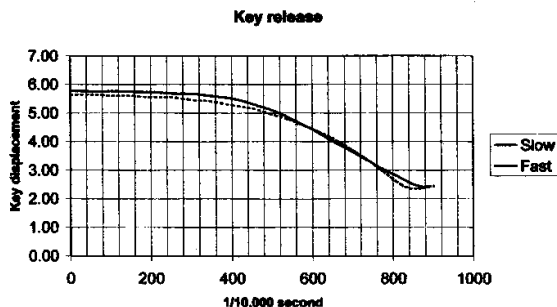

Key release

Fig 7 Rate of release of key in 'fast' and 'slow' playing (Reid Concert Hall)

Alan Woolley will be please to receive comments and data at:
Alan Woolley MA BSc CPFA
University of Edinburgh, Music,
Edinburgh EH8 9DF
email: a.g.woolley@sms.ed.ac.uk