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Observing the 18th-century *Prellzungenmechanik* through high-speed imaging – Pianissimo and forte response compared

Stephen Birkett

Introduction

The phenomenological behaviour of two late 18th century piano action mechanisms is investigated in terms of reference that reflect the pianist. The results should also be of interest to builders and restorers who are required to construct or adjust these action mechanisms. Of primary importance is how the action responds to different kinds of touch, articulation demands, and so on. In other words what is its (musical) dynamic range? What are its capabilities for repetition? This suggests a focus on the functional interactions between components.

Piano actions are typically visualized under static conditions. That is, they are assumed to be moving so slowly that the state of the components and the relationships between them are not affected by the forces generated to produce the motion. The action response can therefore be deduced by simple geometry, considering only the configuration of the moving parts and their rigid constraints. This approach is tacitly used when regulating an action by pressing the key very slowly and observing the changes.

From a practical standpoint casual experimental investigation of dynamic response is precluded, because with even the softest of key strikes action components move at speeds that cannot be directly observed without highly specialized equipment. The practical issues are further complicated for historical pianos. While the geometric relationships in extant instruments are generally decipherable from their current state, some uncertainty will remain due to dimensional changes of wood parts from wear, accidental damage, and the cumulative effect of ambient conditions over the lifetime of the piano. Dynamic behaviour depends critically on the material properties of the components, which will have changed over time, as well as ephemera such as cloth or leather, which are often missing or has been replaced with inappropriate substitutes that behave differently from the original.

Most theoretical analyses of action design (and simulations) are also limited to a static basis,[1] due to the complexity of modelling dynamic behaviour.[2] However,

1 For example: M Cole, *The Pianoforte in the Classical Era*, Clarendon Press, Oxford, 1998; M Latcham, The check in some early pianos and the development of piano technique around the turn of the 18th century, *Early Music* 21(1993): 29–42.

2 A Izadbakhsh, J McPhee & S Birkett. Dynamic modeling and experimental testing of a piano action mechanism with a flexible hammer shank. *ASME J. Computational and Nonlinear Dynamics* 3(2008): 1–10.

under normal playing conditions action components often behave quite differently from expectation. Dynamic response is generally much more complex than implied by the static view, and extrapolation from the latter can easily lead to false conclusions.

The *Prellzungenmechanik* (PZM) was the primary action mechanism used in Germanic pianos throughout the 19th century. Its exact origin is not known, although it is generally believed to have been invented by JA Stein in the 1770s. Jurgenson[3] suggested that Stein devised the PZM by inverting Cristofori's (first) action, which he was familiar with through the pianos of JH Silbermann. In doing so, the intermediate lever became unnecessary, and the check was eliminated, leaving just three functional components: the key, the hammer, and the prell, as shown in Figure 1. The backcheck is completely absent from the implementation used by Stein and most of his followers, including, for example, David Schiedmayer, Sebastian Lengerer, or Stein's daughter Nannette Streicher, who continued to utilize a (checkless) action identical to her father's until 1805.

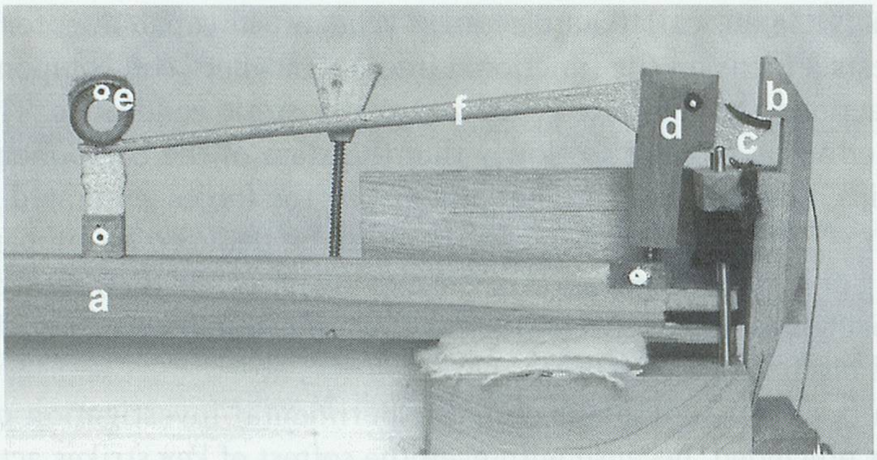

Figure 1: Stein type (German) PZM action model used for experimental observation, based on a 1794 JD Schiedmayer piano:
a) key (tracking marker above shows location of key motion reported in this paper);
b) prell; c) hammer beak; d) kapsel; e) hammer (tracking marker is visible);
f) hammer shank. Tracking marker located under the label on the prell had become detached before taking the photo. The damper lifter is also seen, however dampers were excluded from the present study.

An action of the kind used by Stein is often called a 'German action', in contrast to the 'Viennese action', the form of the PZM which first appeared in the pianos of Anton Walter (Figure 2) and typifies the PZM throughout the 19th century. The main differences between these two forms are: (i) the presence of a backcheck in the Viennese action, to catch the hammer and prevent its rebounding and re-striking the string; (ii) the use of a brass kapsel to hold the steel axle

3 WJ Jurgenson, *The structure of the classical piano*, paper read at Antverpiano, 1989.

of the hammer butt in the Viennese action, compared to a wooden kapsel with felt-lined bushings for the rotating hammer butt pin in the German PZM; and (iii) the inclination of the prells at rest, with the Walter type leaning forward and the Stein type prells approximately upright. There is also a difference in the shape of the prell, as can be seen in comparing Figures 1 and 2.

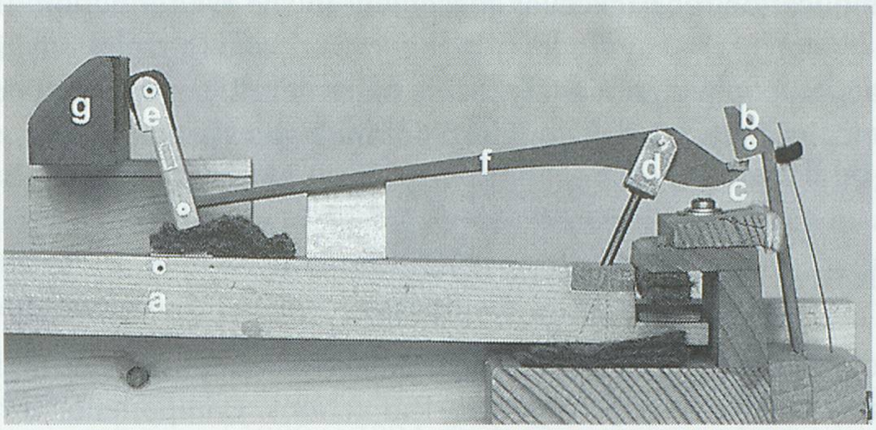

Figure 2: Viennese PZM action mechanism used for experimental observation, based on Anton Walter piano ca 1795:
a) key (tracking marker shows location of key motion reported here); b) prell; c) hammer beak; d) kapsel; e) hammer; f) hammer shank; g) backcheck rail. Tracking markers on hammer and prell are visible.

The basic static operation of the PZM may be simply described, and divided into three phases: (i) *Lost motion*, in which the hammer moves with the key until the beak comes into contact with the prell notch; (ii) *Working key travel*, as the key continues to drive the beak into the prell and the hammer is flipped upwards rotating on its axle, until the point of let off (or 'escapement') when it loses contact; and (iii) *Aftertouch*, subsequent motion of the components after let off until they come to rest with the key on the stop (rail) cloth. A final phase, the *key release*, can also be included in a complete key strike. Some lost motion – a little under a mm at the key front is typical – is generally considered desirable (necessary?) for consistent reset of the beak under the prell notch during key release, however the historically acceptable amount is not known. The extent of working key travel – 3 or 4 mm of key dip is typical of 18th century PZMs – and the events which occur during it, are dictated by both geometric and dynamic factors. Specifics vary widely between action types from different builders, and even within a particular builder's output. The amount of aftertouch is a quite variable and historically uncertain aspect of PZM regulation, with anything from almost none to a few mm of key dip being used on historical pianos in modern time. There can also be large dynamic differences in aftertouch depending on the softness of the stop rail cloth, which will be compressed more for harder key strikes, or different kinds of touch.

This paper introduces experimental methods for investigating historical piano action mechanisms using high-speed imaging techniques. Dynamic response of the 18th century Stein and Walter PZM is examined and compared for pianissimo and forte key strikes. Observations on the detailed motions of the components and their interactions are reported. The discussion and conclusions focus on the most significant difference between the behaviour of the two PZM forms, and a practical implication for backcheck placement in the Walter action. In a second paper[4] the motion of the key front is also examined, and the relationship between the other action components analyzed in more detail, considering descriptions from historical sources and the modern organological literature.

Experimental methods

Specialized experimental equipment is essential for studying piano action dynamics, especially when investigating historical actions. Components are small and flexible, and execute rapid motions with small amplitude high frequency vibrations. In order to capture important behaviour, data with both a high spatial resolution, to distinguish positions separated over very small distances, and a fast sampling rate (number of measurements per second) are required. For example, the entire working key travel of an early piano action in response to a forte key strike is typically only about 10 ms.[5] The components are also very light and easily influenced by any instrumentation that interferes with them directly. The interactions between components are complex, involving intermittent contacts through deformable felt, leather, and wood, materials which are intrinsically difficult to characterize in simple terms. In addition to these factors, the piano case and framing severely restrict access for observation and data collection while the mechanism is being operated in the piano. All these technical and practical difficulties demand a sophisticated experimental approach to obtain meaningful results.

Observation techniques

Modern digital high-speed imaging is an ideal tool for exploring piano action dynamics experimentally. It is a non-contact observation method, and therefore has no direct influence on the behaviour of the piano action being investigated.[6]

4 S Birkett, Observing the 18th century Prellzungenmechanik through high-speed imaging – Motion of the key and further analysis, in: T Steiner (Ed), *Actes des Rencontres Internationales harmoniques, Lausanne 2008*. Bern: Peter Lang. To appear.

5 A millisecond (ms) is 1/1,000th of a second.

6 The indirect influence from heat output of the lighting system is a limitation for all but the most recent, expensive high-end equipment.

The digital camera system itself is portable and requires little preparation compared to a film-based system. Aspects such as the number of frames per second (fps), image resolution (number of pixels of data captured and their aspect ratio on the sensor), and shutter speed (defining the duration for which the sensor is exposed during a frame) can be adjusted instantly. Optical factors can also be changed, for instance, the field of view by changing lenses, providing the capability for macro imaging of highly-magnified interacting small components. The video data, which is captured continuously in a buffer, can be viewed and either discarded, or any portion of it saved to a hard drive. On the downside, high-speed imaging requires a significant level of lighting, which can generate enough heat to cause damage if care is not used. Digital video also requires a large storage capability for the raw data, a typical 2 s video generating as much as a 1 GB file. It is not difficult to fill even modern high capacity hard drives very quickly this way. It should be noted, however, that this is a distinctly better approach than the kilometers of film produced by conventional high speed movies.

The author used two Photron PCI-1280 cameras for data capture with a nominal maximum resolution of 1280 × 1024 pixels and maximum frame rate of 16,000 fps. In practice, the spatial resolution drops significantly with the faster rates, and a realistic maximum frame rate is limited to 8,000 fps; a further consideration for all our experimentation was the feasibility of obtaining adequate light without compromising the experimental subjects, which can easily be affected, or even damaged, due to excessive heat from the halogen lights. This is particularly significant when working at close quarters with historical actions, for instance when using macro imaging. An important feature is the capability to synchronize the two cameras for simultaneous high-resolution observation of two different locations, for instance to study the motion of the key and hammer together.

The value of high-speed imaging for obtaining qualitative information and phenomenological insight into the detailed dynamic behaviour and functional relationships between action components is obvious enough. As well as this, and contrary to what might perhaps be assumed, it is also possible to extract highly accurate and detailed quantitative data from the videos. By analyzing the position of features frame-by-frame, the motions of components over time can be deduced. For example, the small markers seen on the action components as shown in Figure 1 were placed there for tracking purposes. The motion tracking is done by computer using automated image processing techniques to analyze the videos. The generated position data can be used to calculate the velocities and accelerations of components by numerical differentiation, a useful non-contact method for obtaining this information for piano action studies. As videos cannot be reproduced in print media, the conclusions in these papers are presented in the form of plots obtained from tracked data; in order to provide some context I have also provided a few sequences of still images obtained from the videos.

Action and string models

Videography demands an unimpeded visual access from a side view of the action mechanism. This suggests the use of a single key benchtop model, rather than a full keyboard action on its keyframe. In order to make meaningful conclusions about the behaviour of a real action, it is critical to ensure that the test action is correctly configured in all respects. Furthermore, a properly scaled string choir (bi-chord or tri-chord as appropriate) must be placed at the correct distance both vertically and horizontally with respect to the action below, so that the hammer may interact with it according to the builder's design. The dynamics of the mechanism both during and after hammer-string impact is influenced by the configuration and properties of the string model.

For this study single key models were constructed based on the two representative PZM types, as used in the following grand pianos: (i) 1794 Johann David Schiedmayer (DS) piano;[7] and (ii) ca 1795 Anton Walter (AW) piano.[8] DS is typical of Stein's second action,[9] with hollow hammer heads, wooden kapsels, notched prells leaning slightly backward, and without backcheck. With solid hammer heads, brass kapsels, 7-shaped prells leaning forward, and a continuous backcheck rail, AW exemplifies the Viennese action PZM.[10]

An adjustable single note string model was constructed and matched to each of these actions according to parameters obtained from the pianos. For DS the bichord note[11] c1 was used, with speaking length 584 mm strung with 0.46 mm iron wire (gage 2). The model was placed to strike at approximately 51 mm from the nut with a hammer throw of 34 mm.[12] For AW the bichord note b0 was used, with speaking length 590 mm strung with 0.52 mm iron wire (gage 1/0). Strike point was 51 mm and hammer throw 31 mm.[13] An adjustable slap rail was provided and put in the correct configuration with respect to each of the action models. The string model is able to accommodate dampers, which would certainly influence the action response, however for the present study they have been excluded (assume they have been raised by the knee lever). The string model with action models in place is shown in Figure 3.

Static let off was set about 2 mm below the string. This adjustment is achieved in DS by adding or removing shims from under the prell rest rail cloth for individual prells; in AW either shims or the moveable prell rest rail are used to adjust let off, but (on the full keyboard action) the latter method provides only a coarse

7 Germanisches Nationalmuseum Nürnberg, MIR 1102. Data obtained from a technical drawing and supplementary information by WJ Jurgenson, 1987.

8 Germanisches Nationalmuseum Nürnberg, MINe 109. Data obtained from a technical drawing by S Wittmayer, 1974.

9 M Latcham, Mozart and the pianos of Johann Andreas Stein, *Galpin Soc. J.* 51(1998): 114–153.

10 M Latcham, Mozart and the pianos of Gabriel Anton Walter, *Early Music* 25(1997): 383–400.

11 Pitch was determined by a1 of 430 Hz in this study.

12 Based on data from the technical drawing of WJ Jurgenson, 1987.

13 Based on data from the technical drawing by S Wittmayer, 1974.

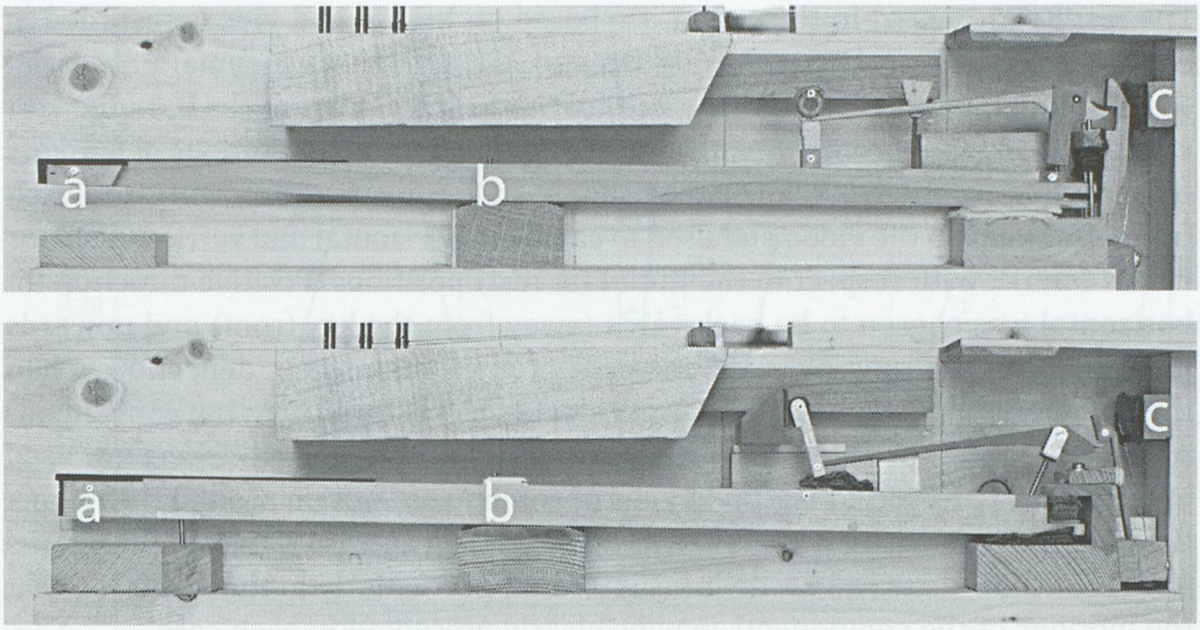

Figure 3: Bichord string model shown with DS (top) and AW (bottom) action model in correct configuration for observing experimental key strikes: a) key front; b) balance point; c) slap rail.

adjustment that affects a group of notes simultaneously.[14] Given the nature of the adjustment system, and the dependence of let off on factors which cannot be precisely controlled, such as prell spring strength, or the effects of ambient conditions on cloths, it can be concluded that precision let off was not possible to achieve and maintain, nor is it likely to have been considered important historically. In practice, let off would have been set close enough to the string to maintain control in pianissimo while avoiding being so close as to risk hitting the string before let off if conditions changed.

These experimental methods have some significant limitations. Although various parameters may be adjusted and their effects examined, as in the present study, it is difficult to do this accurately, consistently, and repeatedly, when working with these types of actions. In order to facilitate adjustment of the escapement point and to easily change the relationship between the prell and the beak, a moveable balance rail that can be fixed in position was provided for the models. The let off rail, and backcheck rail in AW, were also made adjustable. Even with these capabilities a systematic investigation, in which single parameter(s) are adjusted without affecting the others, is difficult to carry out when using historical action models. These issues are discussed in more detail in the second paper, which concludes with suggestions for systematic studies of this kind for future work.

14 Individual adjustment screws behind the prell rest rail cloth were introduced in the 19th century (the author has seen them, for instance, on an 1814 Streicher piano). However, these did not become standard. Many manufacturers, even the most prestigious such as Bösendorfer, did not provide them, relying even in the late 19th century on the same sort of system used by Walter for let off adjustment.

The results presented in this paper are based on high-speed videos recorded at 8,000 fps for various key strikes on DS and AW actions. One camera observed the motion of hammer tip and key behind the balance point at the hammer rest stool; a second synchronized camera observed the prell. The positions of markers on the three components, located as shown in Figures 1 and 2, were analyzed frame-by-frame in the video and used to calculate horizontal and vertical displacements (mm)[15] with respect to the initial (at rest) positions. Positive direction for horizontal was chosen to be backwards (away from the key front) and upwards for vertical. In all time plots the moment of maximum string deflection, when the hammer is at its highest point, was selected as the (arbitrary, but convenient) reference time zero. The rest position of the string is indicated. Insets are used in the plots to provide a magnified view of component motion around the impact time. Letters identifying specific events for discussion are also shown in the figures. Note that the axis scales used vary somewhat, particularly in the insets, so that the motions of the components may be clearly presented in each case.

Pianissimo key strikes

For pianissimo the key was played as softly as possible while still producing a sound. The strengths used for DS and AW were similar, as verified by the same string impact velocity of 0.43 m/s calculated from the tracked position data in each case. Due to the loss of energy on contact with the string, the hammer-string interaction is asymmetrical. For the pianissimo key strike duration from impact to maximum compression was 1 ms for both AW and DS; decompression lasted about 2.7 ms for DS and 2.4 ms for AW.[16]

DS pianissimo key strike

Figure 4 shows the vertical displacements (mm) of hammer and key, and the horizontal displacements of hammer and prell for a pianissimo DS key strike.

Lost Motion. The key strike begins with lost motion until point A when the beak first comes into contact with the prell. During this period both key and hammer rise together vertically and the prell is stationary. The lost motion key rise of 0.3 mm corresponds to about 0.6 mm of initial beak-prell separation at the key tail.

15 In this study typical resolutions were about 6 pixels/mm at the hammer and 16 pixels/mm at the prell camera. The tracking algorithm uses the 256 grey scale values available for each pixel to obtain sub-pixel resolution in determining the position of a marker.

16 String contact is difficult to determine precisely, particularly with slow moving hammers. Values given are approximate, determined based on the location of the string and through reconciling with the faster moving hammer contacts.

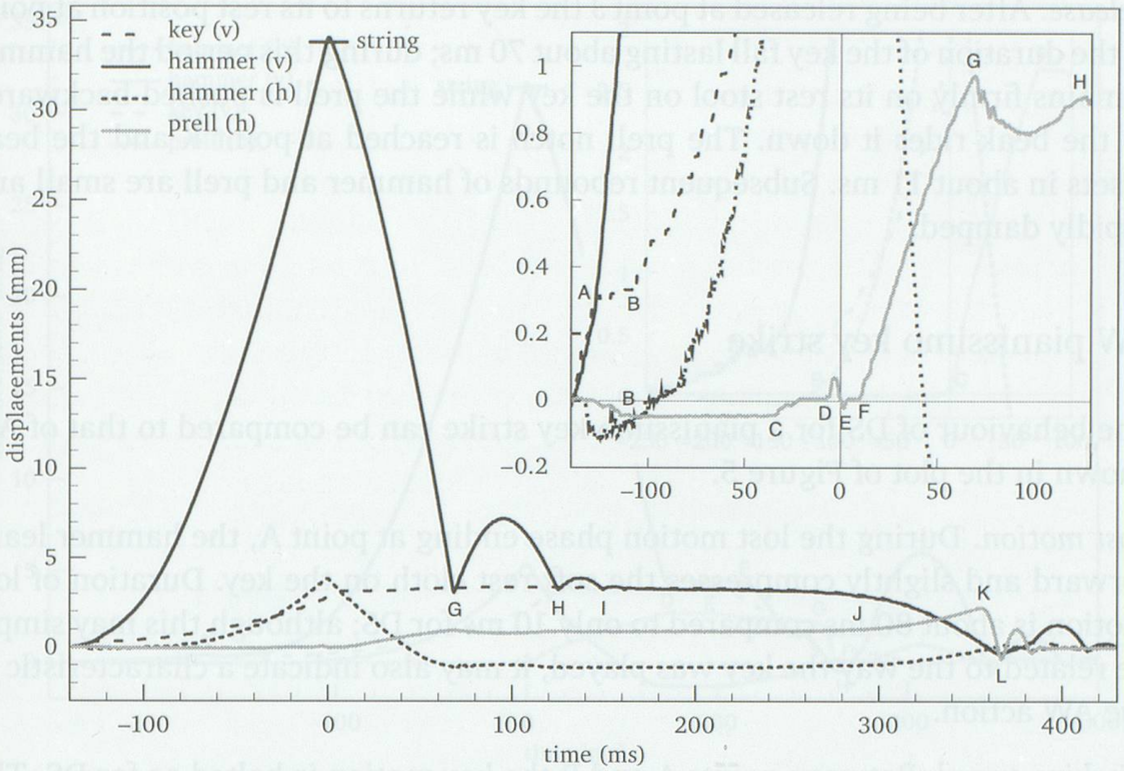

Figure 4: Vertical (v) and horizontal (h) displacements (mm) of hammer, key, and prell for DS pianissimo key strike. Time zero is maximum string deflection. Rest position of string is marked.

Working Travel. As the beak leather comes into contact with the prell notch at point A the force generated halts the key motion completely for about 20 ms until point B. During this period the impact between beak and prell causes the beak leather to compress and the hammer is flipped upward. Due to the rotation of the hammer shank on its axle the beak also moves forward, with the prell gripped by friction being pulled forward into the rest cloth where it is held. The key begins to move again at point B, continuing the upward rotation of the hammer and forward motion of the beak, which starts to slide over the surface of the prell notch. At point C the steeper angle of the beak has reduced the beak-prell contact to a small area at the forward edge of the notch, reducing sliding friction enough that the prell can return to its rest position. Let off, defined by loss of contact between beak and prell, begins at point D, while the hammer is in the vertical position which was regulated under static conditions for let off.

Aftertouch. After let off the prell executes a tiny, but well-defined, backwards motion coming to rest on the rest cloth at point E, at the same time as the hammer is still in contact with the string at the maximum point of the impact. The rising beak of the falling hammer picks up the prell at point F, after which the prell rides the beak until the end of the key strike. Friction generated between beak and prell face, and possibly also in the kapsel bushings, dissipates the energy of the hammer, which executes a small bounce between points G and H, coming to rest on the key at point I.

Release. After being released at point J the key returns to its rest position at point L, the duration of the key fall lasting about 70 ms; during this period the hammer remains firmly on its rest stool on the key while the prell is pushed backwards as the beak rides it down. The prell notch is reached at point K and the beak resets in about 11 ms. Subsequent rebounds of hammer and prell are small and rapidly damped.

AW pianissimo key strike

The behaviour of DS for a pianissimo key strike can be compared to that of AW shown in the plot of Figure 5.

Lost motion. During the lost motion phase ending at point A, the hammer leans forward and slightly compresses the soft rest cloth on the key. Duration of lost motion is about 80 ms compared to only 10 ms for DS; although this may simply be related to the way the key was played, it may also indicate a characteristic of the AW action.

Working travel. Between points A and B the key motion is halted as for DS. The force generated by the beak-prell contact pushes the hammer further into its rest cloth, shown by the brief vertical motion downward, before accelerating it upward. The tendency for the AW beak-prell contact to be more slippery than DS is already evident at pianissimo; friction is not sufficient to properly grip the prell until point B when the key begins moving again, and the amount of forward motion thereafter is less than with DS. Let off occurs at point C with the beak simply slipping forward enough to pass the leading edge of the prell notch.

Aftertouch. Between points C and D the beak rides the prell, pushing it backward almost three times as far as the DS prell. This difference can be attributed to the geometry of the AW prell, which leans forward as well as having an angled face contacting the end of the beak, as compared to the vertical DS prell with vertical contact face. At point D the key is caught on the check, where it is held until freed at point F.

Release. Key release begins at point E while the hammer is still checked. Between points E and H the key and hammer move independently. Duration of key fall lasts about 60 ms, effectively the same as that of DS (the time selected as defining the beginning of key fall is necessarily imprecise). The prell moves forward as the beak moves down the angled face, resetting under the notch between points G and H in a time of about 9 ms. Subsequent motion is noisier and less quickly damped than with DS, as the hammer is more prone to bouncing (point J) under the rebound at point H.

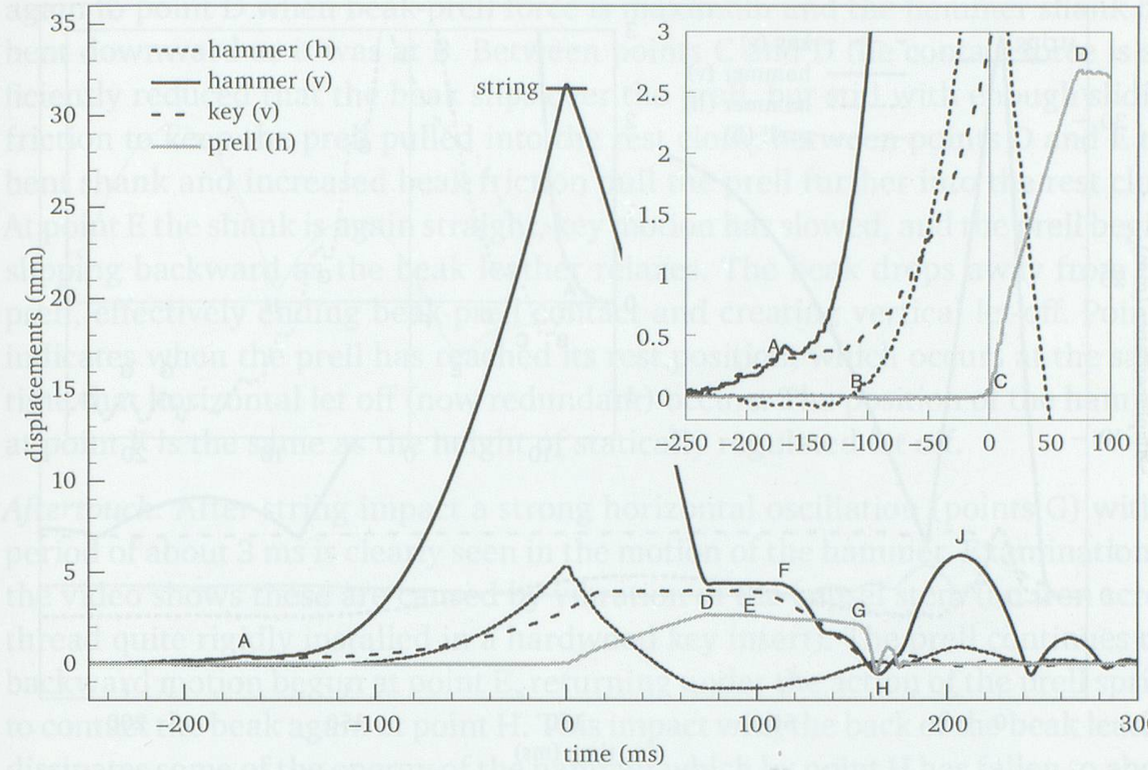

Figure 5: Vertical (v) and horizontal (h) displacements (mm) of hammer, key, and prell for AW pianissimo key strike. Time zero is maximum string deflection. Rest position of string is marked.

Forte key strikes

For investigating action response at a forte dynamic level the key was played strongly, but without aggressive overplaying and not in excess of a level that would be acceptable in a musical context. The forte key strikes were similar in strength, but not identical in terms of impact velocities. For AW this was calculated to be 3.0 m/s while the DS hammer was moving more quickly at 3.9 m/s at impact.[17] As with the pianissimo impacts the hammer-string interaction is asymmetrical. For forte key strikes on both DS and AW duration of string contact was about 2 ms and reached maximum string deflection after about 0.7 ms.

As can be expected dynamic effects evident in the pianissimo key strikes are much more obvious with the forte key strike. It is perhaps surprising how much of the dynamic behaviour is already present in the pianissimo observations. The flexibility of action components allows them to bend significantly in response to the forces generated by a forte key strike; this causes complex interactions to occur between them, particularly between beak and prell.

17 Additional experiments demonstrated that AW achieved an impact velocity of 3.9 m/s with a fortissimo key strike that was close to being abusive. As discussed in the second of these papers, for excessively strong key strike levels factors such as key flex come into play and limit the response.

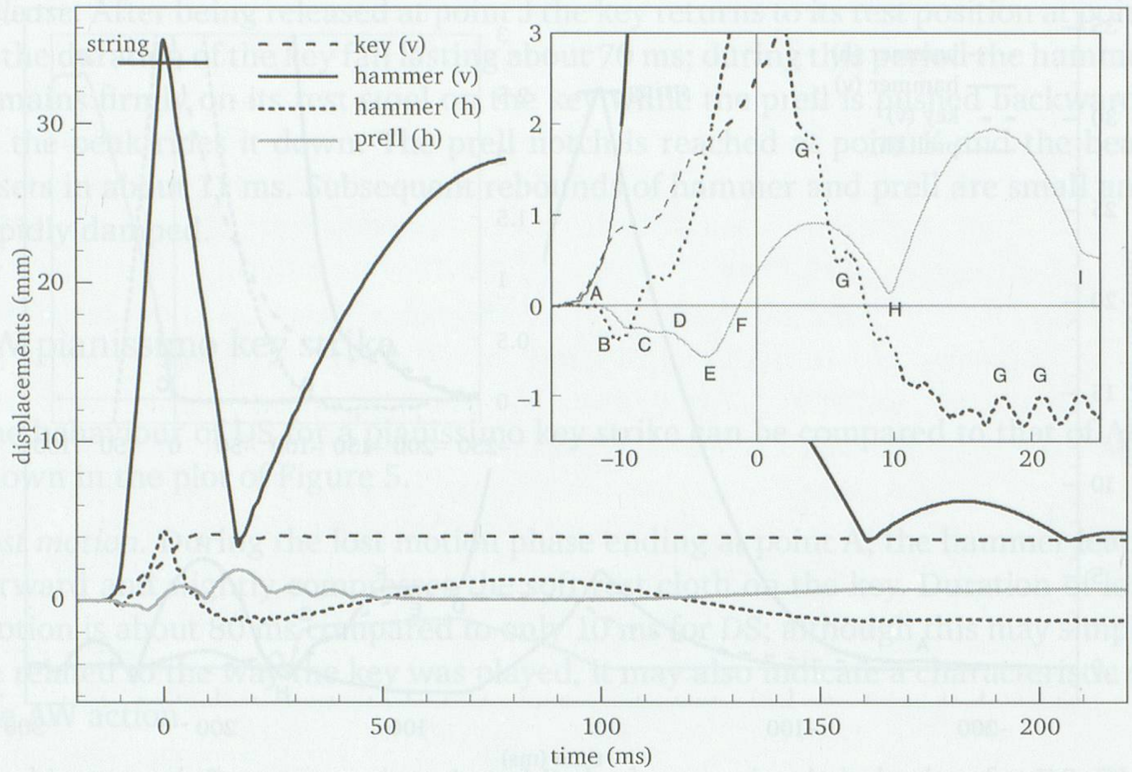

Figure 6: Vertical (v) and horizontal (h) displacements (mm) of hammer, key, and prell for DS forte key strike. Time zero is maximum string deflection. Rest position of string is marked.

It is useful to distinguish between 'horizontal let off', the state when the horizontal position of the beak geometrically precludes contact, and 'vertical let off', the state where the beak-prell vertical separation is large enough that contact force has been interrupted. As will be seen the latter may well occur before the former under dynamic conditions. The key release phase is not discussed below as it is the same as for the pianissimo key strikes.

DS forte key strike

Figure 6 shows component displacements for a DS forte key strike.

Lost motion. Hammer and key move together until the end of lost motion when the beak contacts the prell at point A.

Working travel. After point A the hammer shank bends and the hammer leans forward about 0.4 mm, keeping it and key moving together until point B when the shank is most bent. At the same time, between points A and B friction is sufficient for the beak to grip the prell and pull it forward into the rest cloth. The flexing of the shank delays the vertical motion of the hammer which begins at point B with the hammer whiplashing backwards and up. Key motion is halted between points B and C. The hammer shank has straightened and beak leather relaxed by point C and the key begins to move again. The beak leather compresses again to point D when beak-prell force is maximum and the hammer shank has bent downward as it was at B. Between points C and D the contact force is sufficiently reduced that the beak slips over the prell, but still with enough sliding friction to keep the prell pulled into the rest cloth; between points D and E the bent shank and increased beak friction pull the prell further into the rest cloth. At point E the shank is again straight, key motion has slowed, and the prell begins slipping backward as the beak leather relaxes. The beak drops away from the prell, effectively ending beak-prell contact and creating vertical let-off. Point F indicates when the prell has reached its rest position, which occurs at the same time that horizontal let off (now redundant) occurs. The position of the hammer at point F is the same as the height of statically regulated let off.

Aftertouch. After string impact a strong horizontal oscillation (points G) with a period of about 3 ms is clearly seen in the motion of the hammer. Examination of the video shows these are caused by vibration of the kapsel stem (an iron screw thread quite rigidly installed in a hardwood key insert). The prell continues the backward motion begun at point E, returning under the action of the prell spring to contact the beak again at point H. This impact with the back of the beak leather dissipates some of the energy of the hammer which by point H has fallen to about 10 mm above the key rest cloth. The hammer executes one significant bounce (duration 140 ms) during which the prell impacts the back of the beak at point I and several more times, until it comes to rest and rides the beak. This action dissipates enough of the hammer energy that it executes only two further very small bounces before coming to rest on the key.

The configuration of the DS action at various times during the forte key strike can be seen in the sequence of selected frames in Figure 7.[18]

AW forte key strike

The DS response to a forte key strike can be compared to that of AW in the plot of Figure 8.

Lost motion. During this phase ending at point A the key moves without the hammer, which remains stationary and is compressed into the soft hammer rest cloth.

Working travel. Contact between beak and prell at point A causes the hammer to lean forward about 0.6 mm, pressing further into the key rest cloth. Beak contact also forces the prell backward between points A and B. At point B the hammer

18 The frame images of Figure 7 were actually obtained from a different video taken with a wide view, which limited the capture rate to 1,000 fps. A comparable forte key strike was used. The frames shown are identified with the time of one of the events (or between them) indicated in Figure 5 and discussed in the text. This approach was necessary since the high resolution macro videos used for tracking are not visually informative for illustrative purposes.

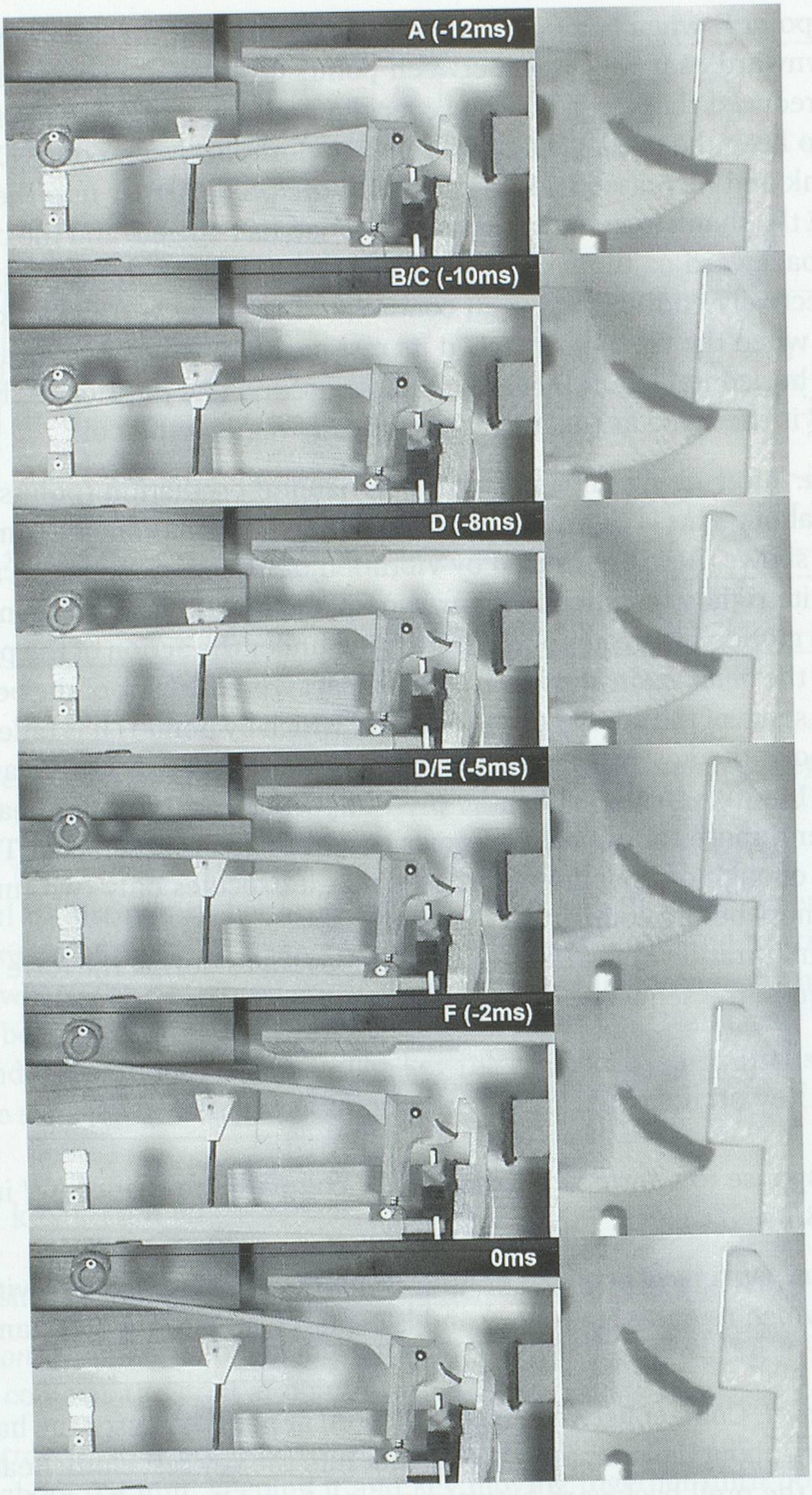

Figure 7: Selected frames from a video taken at 1,000 fps of an DS forte key strike. Letters refer to events (or between events) identified in Fig. 6 and discussed in the text; times are referenced prior to the time of maximum string deflection on impact (last frame shown). A line indicating the rest position of the prell face in each frame is provided so that the extent of prell motion may be seen clearly. Note the vertical space between beak and prell in frame F.

shank is significantly bent downward and the compression of the beak leather generates sufficient force to grip the prell. Between points B and C the key motion is halted. By point C the hammer shank has reached its most bent state and begins to straighten. The prell continues to be pulled forward, eventually pressing into the rest cloth to a small extent by point D by which time the hammer shank is straight and beak leather compression is relaxed. The reduced beak-prell friction at point D allows the prell to move backward again, and remain at its rest position from point E. Between points D and E the hammer shank bends a small amount upward, reaching the most bent at point E. The beak remains in light contact with the prell until point F, when let off occurs (with the hammer at the statically regulated let off position).

Aftertouch. As the beak slips over the edge of the prell notch at let off the prell is pushed backwards lightly. The hammer-string contact initiates very strong horizontal oscillations of the hammer and shank (points G) with period about 4 ms and amplitude a full mm. These are associated with bending of the brass kapsel stem. Driven by the prell spring (not by rebound from the slap rail) the prell impacts the back of the beak several times during the hammer fall. The hammer has sufficient momentum to impact the rest cloth on the key before riding back up the leather of the back check and coming to rest caught on it.

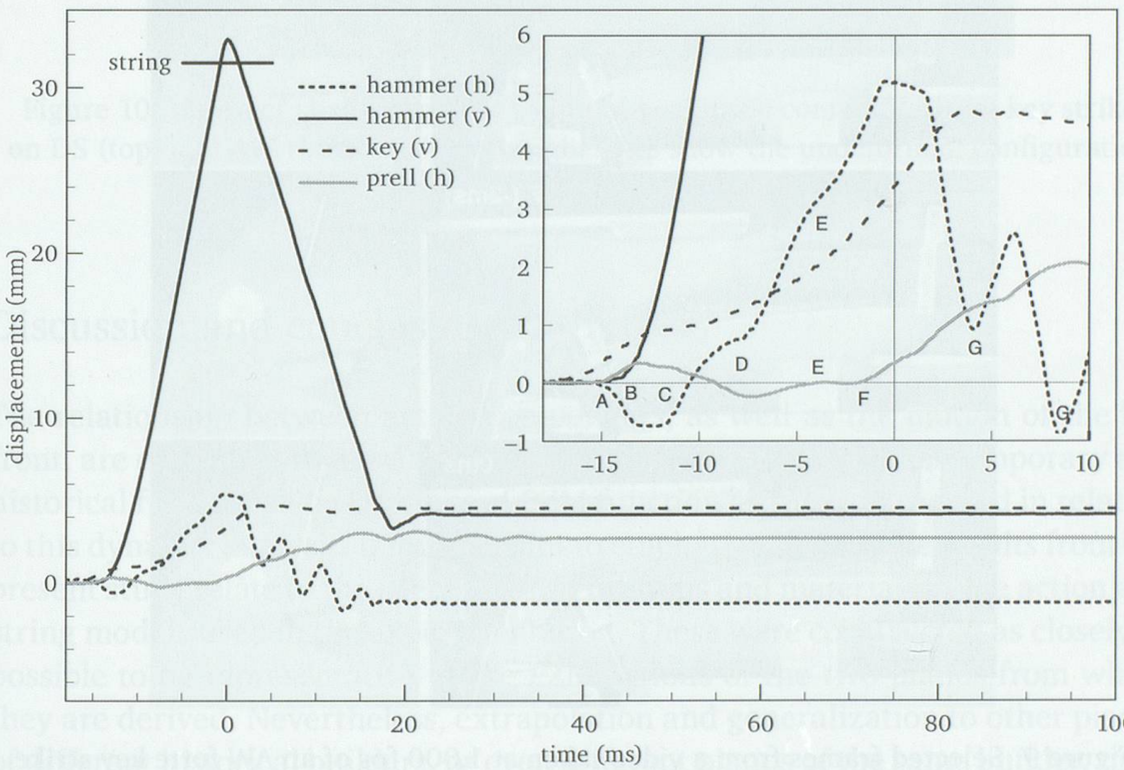

Figure 8: Vertical (v) and horizontal (h) displacements (mm) of hammer, key, and prell for AW forte key strike. Time zero is maximum string deflection. Rest position of string is marked.

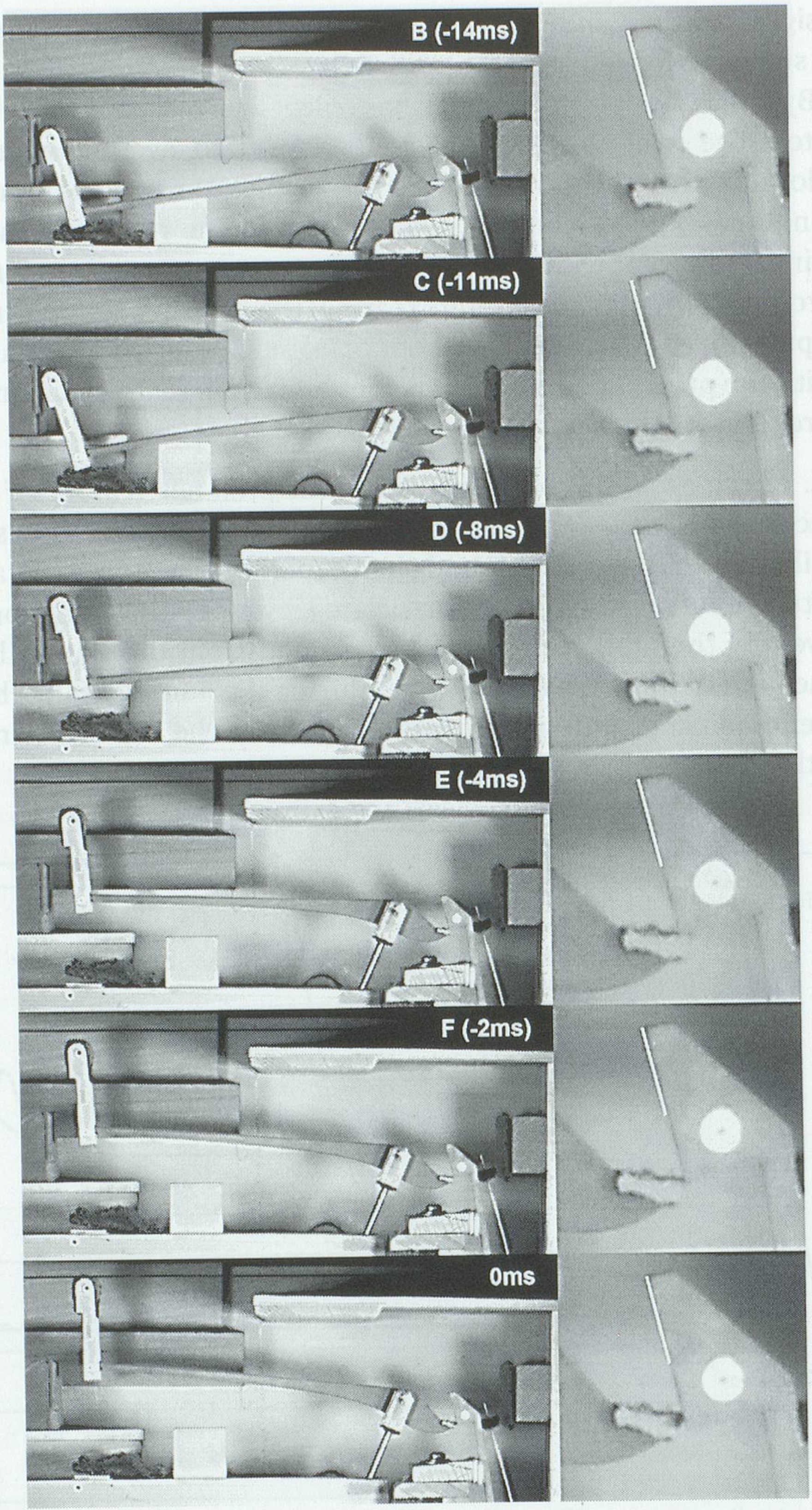

Figure 9: Selected frames from a video taken at 1,000 fps of an AW forte key strike. Letters refer to events identified in Fig. 8 and discussed in the text; times are referenced prior to the time of maximum string deflection on impact (last frame shown). A line indicating the rest position of the prell face in each frame is provided so that the extent of prell motion may be clearly assessed.

The sequence of selected frames shown in Figure 9, obtained from a video of a forte key strike, shows the configuration of the AW action at various times corresponding to events described above.

Hammer shank bending is not obvious at the image size dictated by the requirements of the frame sequences above. This is illustrated more clearly in Figure 10, which shows the state of the shank due to initial beak-prell contact for forte key strikes on AW and DS in comparison to the undeformed configuration indicated by the straight line annotation.

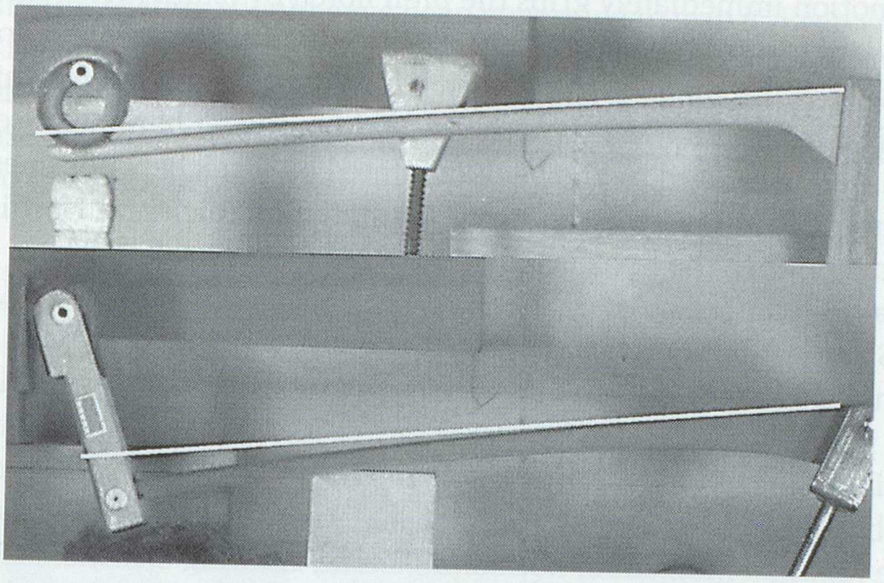

Figure 10: Hammer shank response to initial beak-prell contact for forte key strike on DS (top) and AW (bottom). The straight lines show the undeformed configuration of the hammer shanks.

Discussion and conclusions

The relationship between action components, as well as the motion of the key front, are examined in more detail in the second paper. Some contemporary and historical functional descriptions of PZM function are also considered in relation to this dynamic analysis. It is important to emphasize that all the results from the present study relate to the specific configurations and materials of the action and string models used in the experimentation. These were constructed as closely as possible to be representative of the PZM actions of the two pianos from which they are derived. Nevertheless, extrapolation and generalization to other pianos of different historical builders, or even different pianos of the same builder, must be done with caution. Apart from the limited number of samples studied, and uncertainty between the models and the historical reality, some other scientific limitations of the study must be kept in mind: key strikes were not quantitatively reproducible in repeated experiments, forces were not measured, and ambient conditions could not be controlled.

For the present the observations described above are reported without further analysis, however the dynamic response of DS and AW does suggest two important conclusions. First, the general behaviour of the beak-prell contact is compared; and second, a limitation on check function for AW is revealed.

Beak-prell contact

It is generally considered for the Walter type PZM that the initial beak-prell contact after lost motion immediately grips the prell notch by (static) friction: 'The beak moves forward toward the player … [the motion causes] the beak to drag against the underside of the tangent [prell] notch, pulling the tangent forward against its stop rail. Thus the tangent is actually held on during hammer rise, and it is neither pushed backward by the beak (as stated by Streicher) nor does it slip off the beak in order to create escapement (as stated by Rück and Harding)';[19] '[in the Walter action] … the hook is pulled forward by the beak.'[20] These assertions can be examined in terms of the dynamic responses described above.

For DS, at all dynamic levels it is certainly true that the beak grabs the prell, immediately pulling it in and holding it against the compressed rest cloth. However, it has been seen that under a forte key strike, the flexibility and consequent vibrations of the action components cause the force on the prell to vary considerably through the working key travel. Moreover, it diminishes to zero well before the nominal moment of horizontal let off, creating a vertical let off which disconnects the beak from the prell, allowing it to begin its backward motion. The prell can move backward because the force on it from decompression of the rest rail cloth exceeds the forward force from the prell spring, but the extent of backward motion past the rest position is therefore limited (which is desirable). In this sense it is quite correct to describe the prell as 'slipping off the beak to create escapement.' This occurs regardless of the apparent tendency of the DS beak to grab the prell under static conditions.

For AW, there is no immediate pull forward of the prell at any dynamic level. In fact, at all but the lowest levels for which the prell essentially remains at its rest position throughout working key travel, the prell is *always* pushed backward on contact by the beak. The prell actually remains behind its rest position for about half of the working key travel. The moment of truth, so to speak, comes with the prell in a tenuous position from which either the beak force becomes sufficient to generate enough static friction to begin pulling it forward, or else the prell is violently forced off the beak causing premature escapement and the hammer fails to reach the string. The latter event can potentially occur for a variety of

19 P Poletti, Die Tangente. Terminology, form, and function. Unpublished draft, 2001. An earlier version was read at the CIMCIM/Antverpiano conference, July 1993.

20 WJ Jurgenson, op. cit.

reasons, notably when: the prell notch angle is close to, or exceeds, perpendicular, making the mechanical connection between beak and prell more slippery;[21] the prell leans forward too much, again making it more slippery mechanically; or the beak leather is inadequate, for example too soft, too thick, overhangs too much, or is not properly glued to the beak. In short, any factor which compromises the capability of the beak leather to create static friction at the prell contact without shearing risks premature escapement in a Walter type PZM. Figure 11 shows an example of an event of this kind which occurred with AW due to improper beak leather, which can be seen to shear and release the prell at just the moment when maximum friction should have been generated to grip it. Even with correct beak-prell function the AW prell remains only tentatively in contact with the beak, slipping backward to the rest position well before the nominal moment of let off. In this sense, then, the AW prell, too, can be considered under normal dynamic response to have 'slipped off the beak to create escapement.'

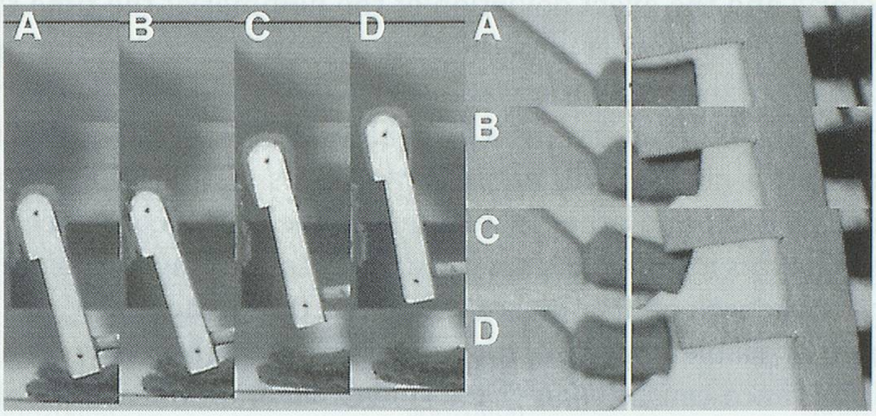

Figure 11: Selected frames from a video showing premature escapement with a forte key strike on AW, due to beak leather shearing. Hammer and prell-beak images with the same label are simultaneous events: A) during lost motion; B) beak-prell impact; C) leather shearing; D) premature escapement. The reference line marks the rest position of the prell notch edge in all frames, to show the extent of backward prell motion.

Backcheck location

In the second paper the capability of DS to function effectively without a backcheck is examined, as well as the role (if any) of the backcheck in AW repetition. The practical implications for check placement from the observations reported above are examined here.

In order to function correctly, the surface of the check must not interfere with the path of the front surface of the hammer as it travels toward the string, while

21 P Poletti, op. cit. The mechanical relationship between beak and prell is described in terms of a rachet and pawl.

the path must intersect the check on the downward motion. Static analysis suggests that the hammer will move forward during the initial key strike for two reasons: during lost motion the hammer, kapsel, and key move together following the arc defined by a pivot at the key balance point; and after lost motion the hammer rotates on the kapsel axle beginning from an inclination initially lower than horizontal, in addition to the motion of the kapsel itself which continues to follow the arc of the key. Under static conditions the overall forward motion of the hammer is tiny, less than about 0.1 mm for AW (Figure 5). This amount would increase somewhat for more lost motion.

Considering the downward path of the hammer, the timing observations discussed above show that for both pianissimo and forte key strikes on AW the hammer falls to the check level after the key has already reached the stop rail. This defines the static horizontal location of the hammer when it arrives at the height of the check surface to be caught. Dynamically, under forceful playing, the hammer will undergo large horizontal oscillations about the static downward trajectory, and the exact deviation of the hammer at the time the check is encountered will be somewhat unpredictable. Regardless of this, the check should be placed in accordance with the static downward trajectory of the hammer in order to ensure it being caught. For a forte blow on AW it can be seen in Figure 8 that the hammer is checked 1.3 mm forward of its rest position. The flexibility of the hammer shank and other factors give some latitude on check placement backwards from this ideal, but this is constrained by having to avoid the hammer scuffing the backcheck on its upward motion to the string.

The range of viable check positions lies between these two constraints. A very small tolerance can be seen in backcheck location for acceptable function in an action such as AW, with its very small working key dip, even under static conditions. This is illustrated by the pianissimo key strike of Figure 12, which shows vertical hammer displacement in relation to horizontal (with roughly equal scales on the axes). The hammer tip follows the arc on the right toward the string, with negligible forward displacement; the return trajectory on the left meets the backcheck (shown as the bold vertical line) at about 4 mm above the rest height. On key release the hammer is freed from the check, falls back to the key and bounces following the arc pivoting on the kapsel axle. Under dynamic conditions the situation looks quite different. For the forte key strike the initial forward tilt of the hammer of about 0.6 mm (much more significant than any consideration of lost motion) puts it perilously close to the backcheck on the upward motion. For the fortissimo key strike it can be seen the the hammer has tilted forward sufficiently that it scuffs the backcheck until such time as it clears the top. Moving the backcheck forward so the hammer clears it is not an option, since it would then fail to catch on the return path; lowering the check position is also not an option, since the scuffing begins before any significant upward motion of the hammer. The situation is actually worse in practice because of the compromise necessitated by the continuous check rail used by Walter, which precludes highly accurate placement of the backcheck for individual hammers.

It seems inevitable, then, that for forte playing the possibility of some degree of scuffing of the backcheck during the early key strike must be accepted, due to the tall hammers and thin, flexible shanks that characterize the AW action.

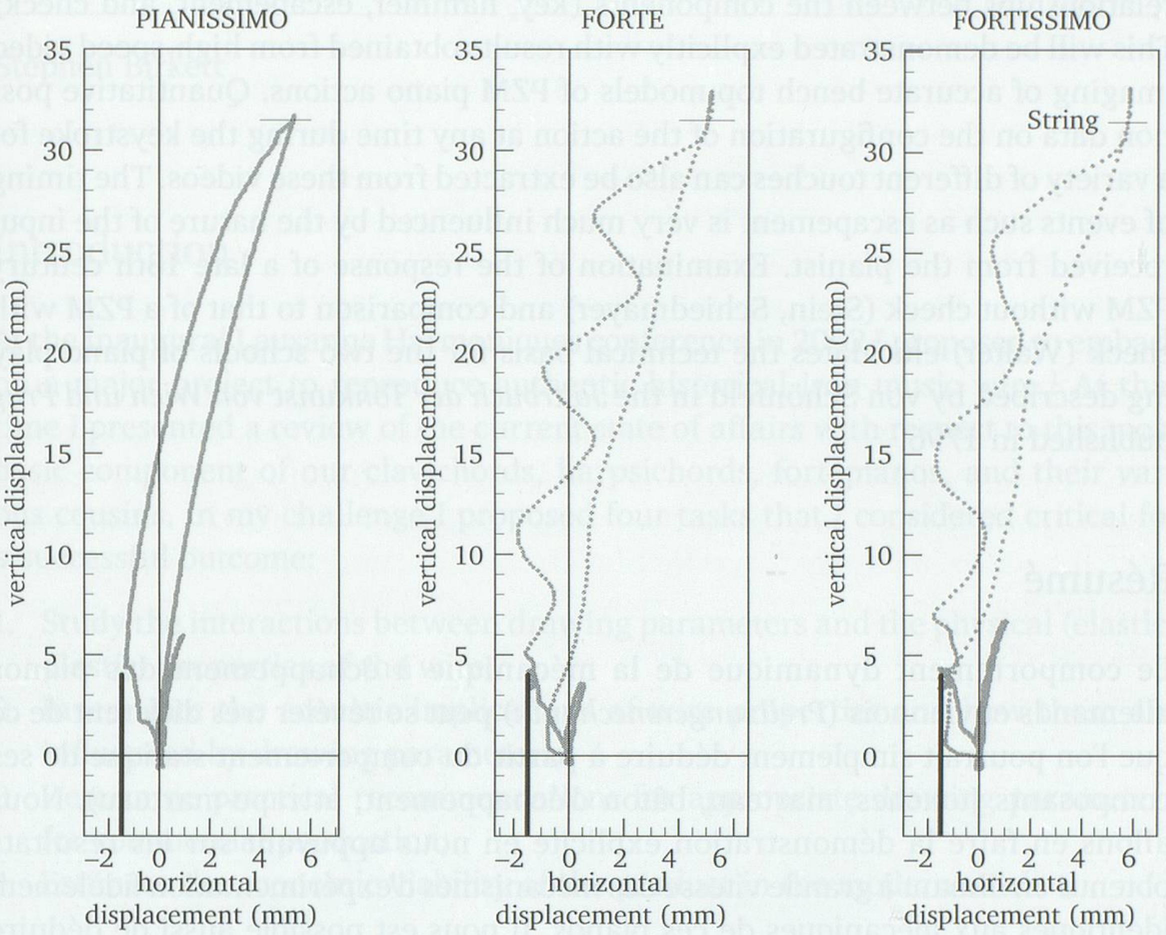

Figure 12: AW hammer trajectory for three different key strikes. The vertical bold line shows the effective location of the backcheck surface. String height is also indicated. Horizontal and vertical axes scales are approximately equal.

Acknowledgements

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Summary

The dynamic behaviour of a *Prellzungenmechanik* (PZM) hammer action mechanism can be quite different from that deduced simply by considering the static relationships between the components (key, hammer, escapement, and check). This will be demonstrated explicitly with results obtained from high-speed video imaging of accurate bench top models of PZM piano actions. Quantitative position data on the configuration of the action at any time during the keystroke for a variety of different touches can also be extracted from these videos. The timing of events such as escapement is very much influenced by the nature of the input received from the pianist. Examination of the response of a late 18th century PZM without check (Stein, Schiedmayer) and comparison to that of a PZM with check (Walter) elucidates the technical basis for the two schools of piano playing described by von Schönfeld in the *Jahrbuch der Tonkunst von Wien und Prag* published in 1796.

Résumé

Le comportement dynamique de la mécanique à échappement des pianos allemands et viennois (*Prellzungenmechanik*) peut se révéler très différent de ce que l'on pourrait simplement déduire à partir du comportement statique de ses composants (touches, marteau, bâton d'échappement, attrape-marteau). Nous allons en faire la démonstration explicite en nous appuyant sur les résultats obtenus en filmant à grande vitesse des mécanismes d'expérimentation fidèlement identiques aux mécaniques de ces pianos. Il nous est possible aussi de déduire de ces vidéos des données quantitatives de la configuration de la mécanique à chaque étape du déroulement de sa mise en mouvement. Cela nous permet de pouvoir observer et comparer aussi les effets produits par différents touchers. Le déroulement dans le temps d'événement tel que l'échappement est fortement influencé par l'énergie induite par le pianiste et qui est absorbée par l'ensemble du système. L'examen des réactions et la comparaison des *Prellzungenmechanik* de la fin du 18e siècle, soit sans attrape-marteau (Stein, Schiedmayer), soit avec attrape-marteau (Walter), nous permet d'élucider les bases techniques des deux écoles du jeu du pianoforte, telles qu'elles sont décrites par von Schönfeld dans le *Jahrbuch der Tonkunst von Wien und Prag* publié en 1796.