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# MEASURING THE MOTION OF THE PIANO HAMMER DURING STRING CONTACT

Anders Askenfelt

## Abstract

The motion of the striking point on the piano hammer was measured before and during string contact by means of an optical equipment. The measurements resolved the motion in two perpendicular components; in the striking direction (vertical), and in the string direction (horizontal).

The influence of dynamic level and touch on the hammer motion was studied. Three different types of touch were evaluated; *legato*, *staccato*, and "strained" touch. In addition, two different hammer shanks were tested, normal and soft. Key questions tried to answer included changes in the initial horizontal displacement of the striking point, and the presence of a horizontal hammer motion during string contact.

## INTRODUCTION

This study deals with the motion of the piano hammer immediately before and during string contact, and a possibly connection with the pianist's "touch." In particular, the influence of hammer resonances on the free motion of the hammer, and the following interaction with the string are examined.

## HAMMER VIBRATIONS

Previous studies have shown that the shank of the piano hammer bends during the acceleration towards the string (Suzuki, 1982). It is also well known that the hammer can be set in vibrations for certain types of touch (see Fig. 1). The results have been confirmed in independent studies by Suzuki (1983) using computer simulations, as well as by measurements (Askenfelt & Jansson, 1982; 1991; Boutillon, 1988). The vibrations, which mainly consists of a mixture of the two lowest hammer modes at about 50 and 250 Hz, respectively, are excited only for a relaxed, "pianistic," type of touch. The second mode features a pronounced horizontal motion of the hammer head, i.e., in the string direction (see Fig. 2).

At string contact, the boundary conditions change, and modes of other shapes and frequencies will come into play. An example of the vertical and horizontal components of the hammer motion during string contact is shown in Fig. 3, as measured on the wooden hammer moulding. The horizontal motion involves a full period of vibration at approximately 800 Hz. The displacement amplitude at the top of the hammer head could be estimated to 0.1 mm, approximately. Also included is a higher component at about 2100 Hz, caused by repeated impulses on the hammer from reflections on the short string segment hammer-agraffe (Hall & Askenfelt, 1988; Askenfelt & Jansson, 1988).

The present study aimed at a direct measurement of the motion of the striking point at the top of the hammer, before and during string contact. The motion was measured in two perpendicular directions, vertically (in the striking direction), and horizontally (in the string direction).

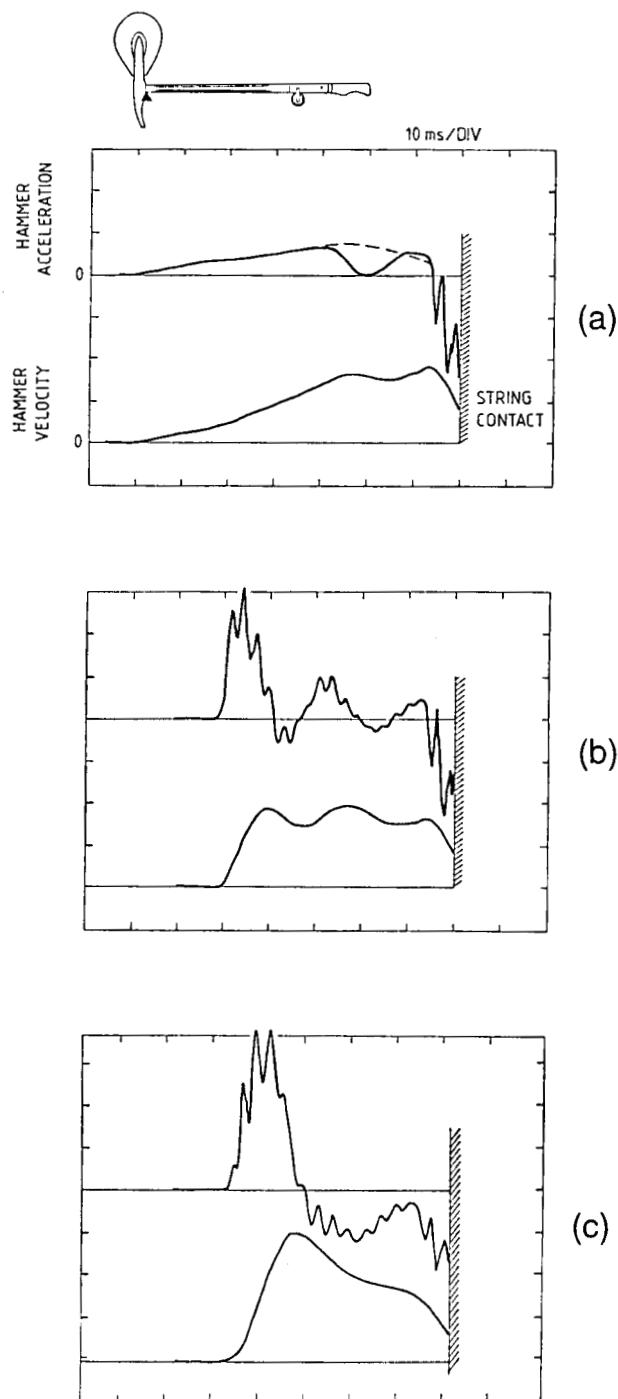


Fig. 1. Examples of the hammer motion for three different types of touch (mezzo forte,  $B_3$ ). Approximate vertical scale units are  $25 \text{ m/s}^2$  and  $1 \text{ m/s}$ , respectively. The position of the accelerometer is marked with a triangle. (a) Legato, the corresponding acceleration curve without damper is shown dashed. (b) Staccato, relaxed finger. (c) Staccato, strained finger. (From Askenfelt & Jansson, 1991. By permission of American Institute of Physics.)

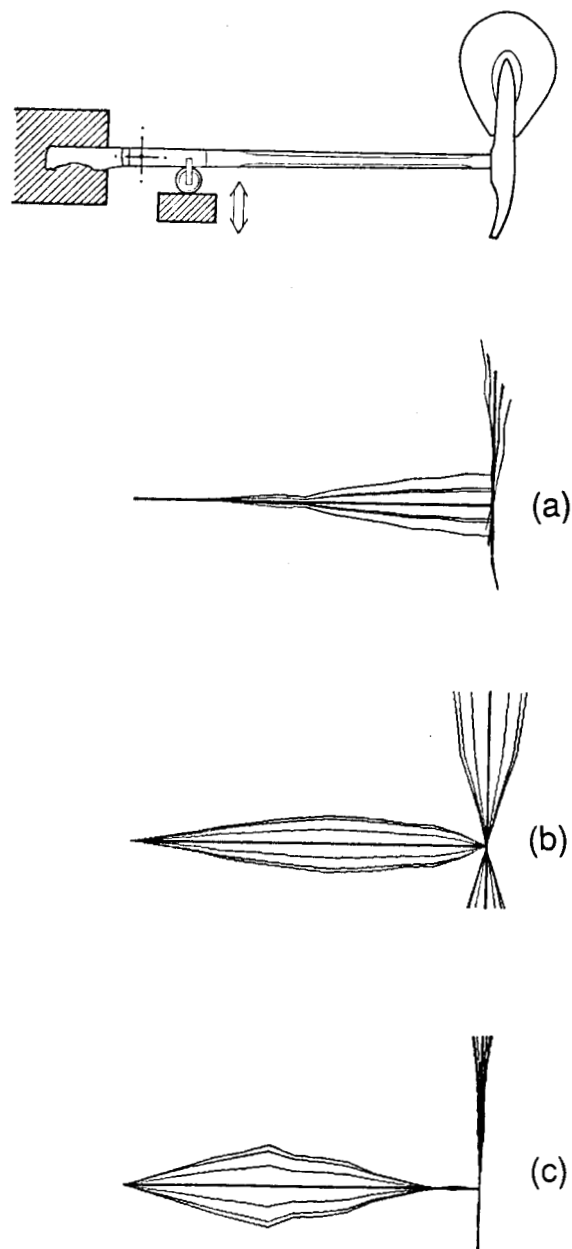


Fig. 2. Bending modes of a piano hammer at approximately (a) 50 Hz, (b) 250 Hz, and (c) 650 Hz. (From Askenfelt & Jansson, 1991. By permission of American Institute of Physics.)

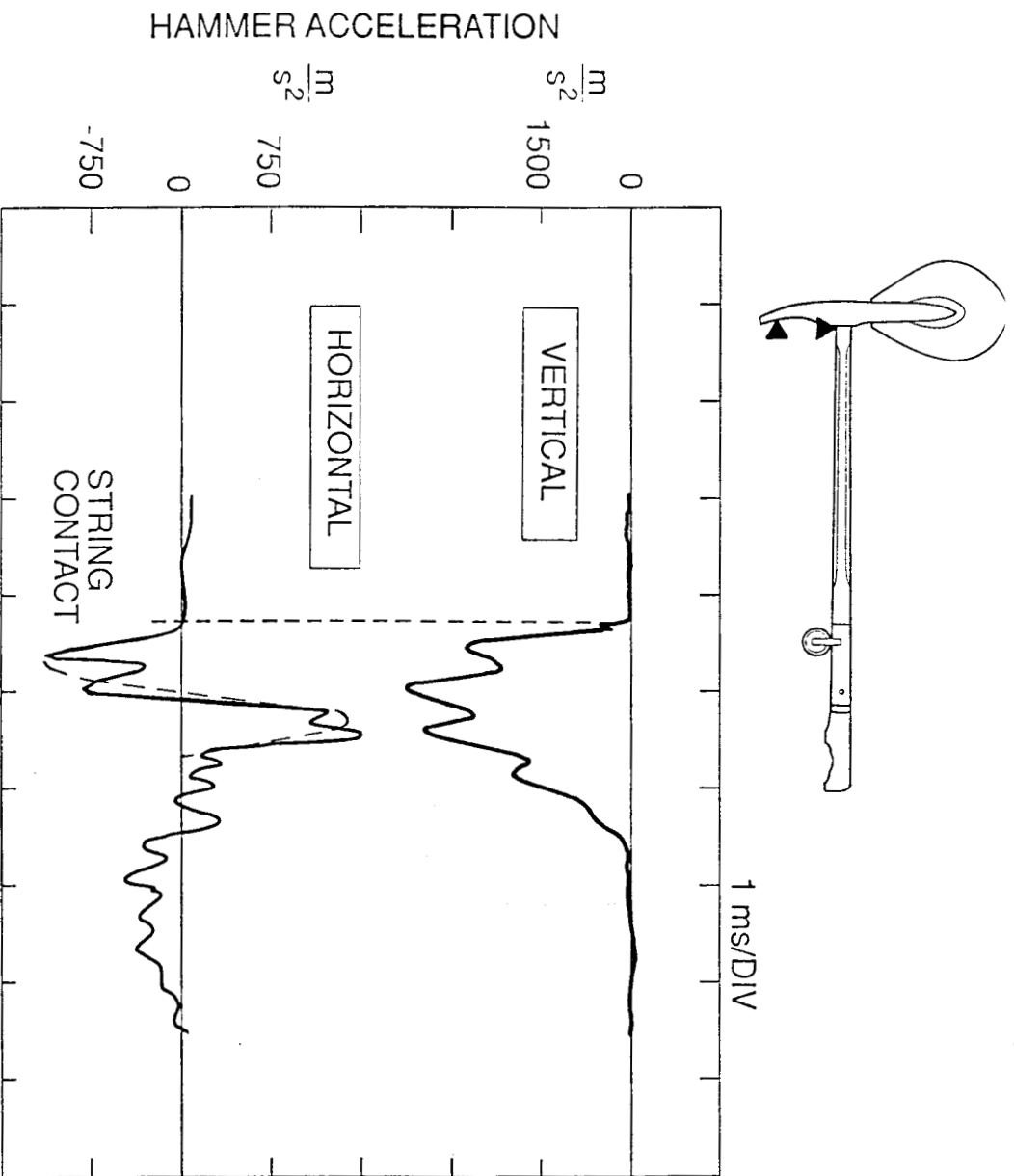


Fig. 3. Registrations of vertical and horizontal acceleration at the hammer head during string contact (staccato, forte,  $C_4$ ). The positions of the accelerometers are marked with triangles. A period of vibration at 800 Hz is included in the horizontal motion for reference (dashed). (From Askenfelt & Jansson, 1991. By permission of American Institute of Physics.)

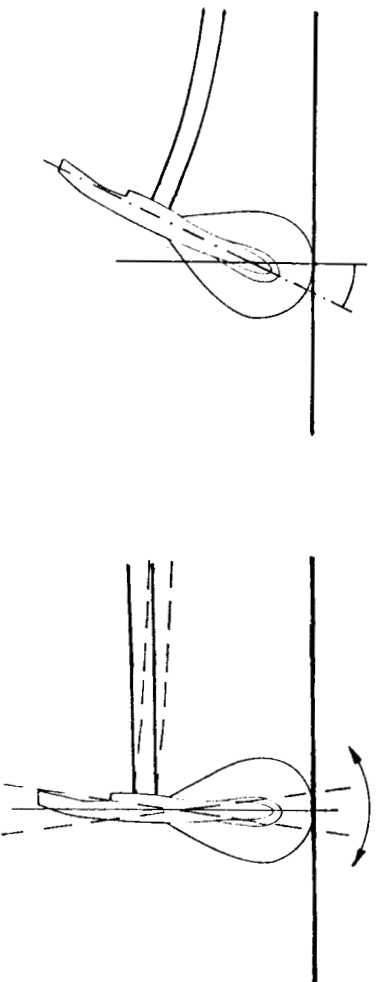


Fig. 4. Illustration of two mechanisms by which the touch could influence the hammer motion at string contact; change in initial angle (left), and a rubbing motion during string contact (right).

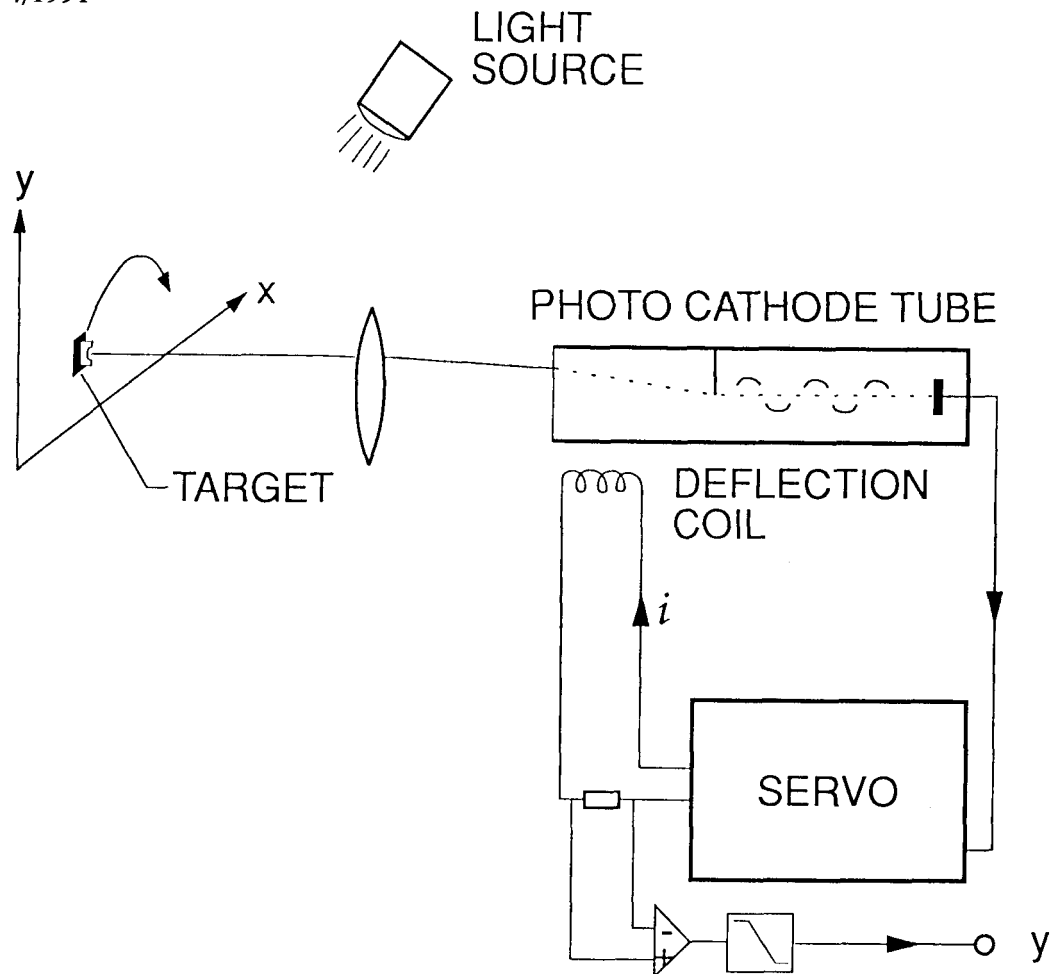


Fig. 5. Schematic view of optical measurement system (electro-optical displacement transducer). Only one measuring direction shown ( $y$ ).

### HAMMER VIBRATIONS AND TOUCH

The observed bending of the shank, and, for certain types of touch, also the vibrations of the hammer head, suggest a possible connection between the pianist's "touch" and the motion of the hammer at string contact. In extrapolation, such a motion could be hypothesised to influence the string excitation, and hence tone quality.

There are two mechanisms by which the touch could influence the motion of the hammer at string contact (see Fig. 4).

- (1) The bending of the shank could change the initial angle of the hammer head (i.e., the angle at the moment of string contact), thus moving the striking point slightly, as well as presenting a slightly different contact point on the hammer felt.<sup>1</sup>
- (2) The vibrations of the hammer during string contact occur at a frequency that is high enough to permit some rubbing or sliding motion against the string. The period of the major horizontal vibrations in the example in Fig. 3 is about 1.5 ms, compared to a string contact time of about 2–3 ms (mid-range).

In both hypotheses, the hammer could be said to serve as a memory for the main characteristics of the history of the preceding key motion.

<sup>1</sup>The rounded shape of the hammer will in principle reduce the shift in striking point somewhat, but for small displacement amplitudes as discussed here, the reduction will be small.

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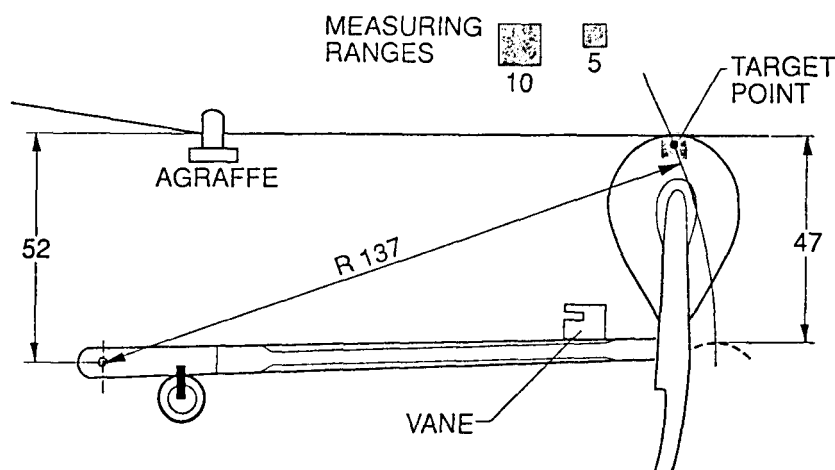


Fig. 6. Striking geometry (Steinway & Sons, model C, note G<sub>3</sub>). The two measuring ranges used are shown shaded. The slotted vane on the hammer shank was used for velocity measurements, see text. Dimensions in millimeters.

## METHOD

The motion of a target point on the side of the hammer head, close to the striking point, was measured by means of an optical equipment.<sup>2</sup> The measurement principle is in a sense similar to the inverse of an oscilloscope (see Fig. 5). The image of a target is projected via a lens on a photo cathode tube mounted in a camera. The generated electron beam in the tube is deflected by servo controlled currents in two perpendicular coils. The servo system locks the image of the target at a fixed position in the tube, the positioning error being amplified in an electron multiplier. In this way, the servo currents become proportional to the x and y-coordinates of the target, respectively.

The measurement range extends from meters to fraction of millimeters, depending on the type of lens used. The resolution in the measurement ranges used in this study (5, 10, and 55 mm) varied from 25 to 250 microns. The bandwidth of the measurement system is about 200 kHz. The target point – which must be defined as a sharp transition from black to white or vice versa – consisted of the head of a thin needle (diameter 1 mm), pressed through the hammer felt for safe fixation, 2 mm below the striking point (see Fig. 6). The insertion of the needle did not lead to any perceptual change in tone quality.

<sup>1</sup>The rounded shape of the hammer will in principle reduce the shift in striking point somewhat, but for small displacement amplitudes as discussed here, the reduction will be small.

<sup>2</sup>Zimmer OHG: "Electro-optical displacement transducer."

The velocity of the hammer at the moment of string contact (in the following referred to as initial hammer velocity,  $v_i$ ), was measured by means of a slotted vane on the hammer shank and a photogate (see Fig. 6).

The measurement equipment was mounted on top of a grand piano,<sup>1</sup> and the motion of the hammer was monitored via a mirror. In this way, the hammer motion in the vicinity of the string (the last 10 mm) could be measured. The path of the target point was illuminated by an intense light source. In a separate part of the study, the entire hammer travel was measured with the hammer mounted in a model of the action.

The striking geometry for the particular key studied in the experiments is shown in Fig. 6 (key 36,  $G\#_3 = 208$  Hz). The striking point at the top of the hammer follows a circular arc, in this case with a radius of 137 mm. The axis in the hammer flange is located 52 mm below the string. When the hammer is lifted during a blow, the striking point will move horizontally (i.e., in the string direction), first in the direction away from the player (towards the bridge), and during the latter part towards the player (towards the agraffe).

## KEY QUESTIONS

The experiments aimed at answering the following key questions:

1. How does the hammer move from position of rest to string contact for different types of touch?
2. Does the initial angle of the hammer head change depending on dynamic level and touch?
3. Does the striking point on the hammer move during string contact?
4. Are any observed differences in the hammer motion reflected in the string spectrum?

In order to answer these questions 18 cases were evaluated: three dynamic levels (*p-mf-f*), three types of touch (*legato-staccato-strained*), and two kinds of hammer shanks (normal-soft). Also, the touch of an untrained subject was compared with the performance of a professional pianist.

The terminology used for the three different types of touch used in the experiments may need an explanation. By "*legato-touch*" we mean a relaxed touch in which the finger is resting on the key initially. In a "*staccato-touch*," the key is hit from some distance above, with a relaxed finger and hand. In the "*strained touch*," the key is struck with a stiff finger, the fingers and hand held strained straight vertically – indeed a very unpianistic way of approaching the key.

The two types of hammer shanks (normal-soft) used in the experiments differed substantially in stiffness. For the normal shank, the frequencies of the two lowest bending modes were close to 50 and 250 Hz, respectively. The soft shank was obtained by removing wood from the shank of the normal hammer, thus keeping all other hammer properties unchanged between the two cases. The mode frequencies of the soft hammer were lowered by about 50% to 25 and 130 Hz, respectively. The softened shank was very easy to bend with the fingers ("spaghetti-like"), but surprisingly the feel in the key at a touch was not changed noticeably.

## RESULTS

### Overview of the hammer travel

As mentioned, the path of the hammer follows in principle a circular arc. When overlooking the entire hammer travel in a model of the action, an essentially clean circular path is seen in

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<sup>1</sup> Steinway & Sons, grand piano model C (7 ½ ft), # 516 000, Hamburg (1990).

line with expectations (see Fig. 7a). However, when zooming in the last 3–4 mm before string contact, the hammer head is seen to vibrate, both on its way up and down (see Fig 7b).

In the following we will look at the motions in the vertical and horizontal (string) direction separately, as illustrated in Fig. 8. The full travel of the hammer is shown, from rest to string contact, followed by rebound and check (cf. Fig. 7a). Also included is the predicted horizontal component, assuming a circular motion.

As discussed in the introductory passages, the vibrations of the hammer are associated with certain types of touch. A comparison of the hammer motion for a *legato*, *staccato*, and strained touch, respectively, all at a *forte*-level, is given in Fig. 9. The figure illustrates that only the *staccato*-touch, giving a strong impulse at the beginning of the key descent, excites the hammer resonances efficiently.

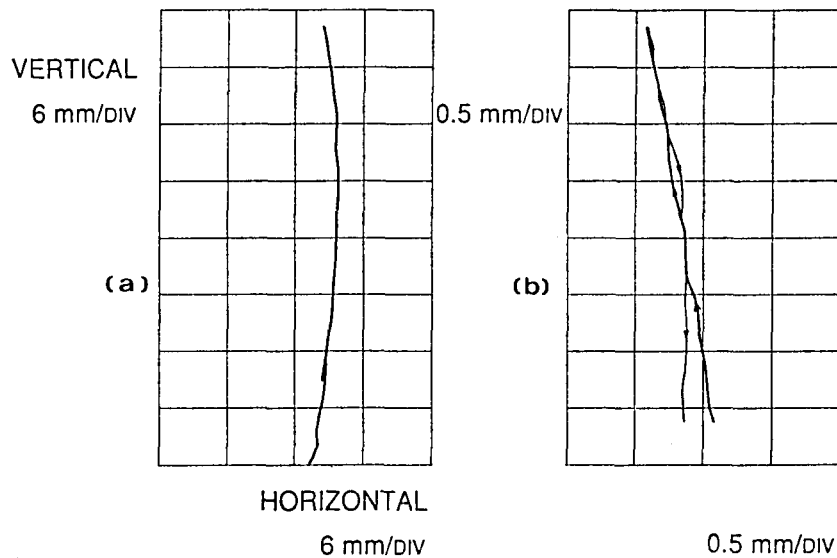


Fig. 7. Registration of hammer motion, vertical vs. horizontal components (a) Full hammer travel. (b) Close-up around string contact. Staccato, forte  $v_i=3.8$  m/s.

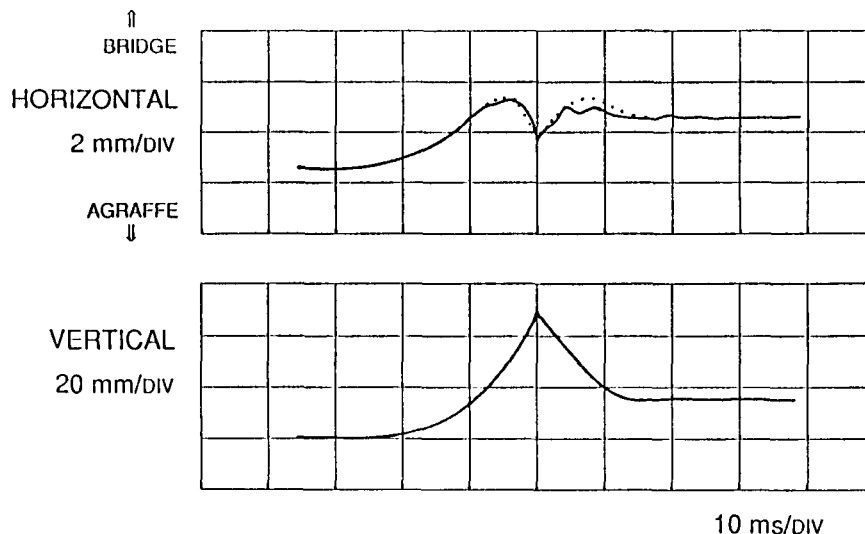


Fig. 8. Registration of hammer motion, vertical and horizontal components shown separately vs. time. Legato, forte,  $v_i=4.5$ . Also shown is the predicted horizontal motion along a circular arc.

We now approach the details in the hammer motion close to and during string contact. The next figure shows the vertical and horizontal motion around string contact with a resolution of 1 mm/div in both directions (see Fig. 10). Also shown is the hammer string contact duration

as measured electrically (Askenfelt & Jansson, 1990a), and the time window corresponding to the velocity measurement.

We could observe that the hammer makes a smoothly rising and falling motion in the vertical direction, while the striking point stays essentially fixed in the horizontal direction during string contact. Later, strong vibrations are seen in the horizontal component during hammer rebound.

After this familiarisation with the format of measurement presentations, we now examine in turn the influence of dynamic level, touch, and shank stiffness on the hammer motion. The magnification is increased even further compared to the previous figures; in the following the displacement scales are consistently 0.5 mm/div in both the vertical and horizontal components.

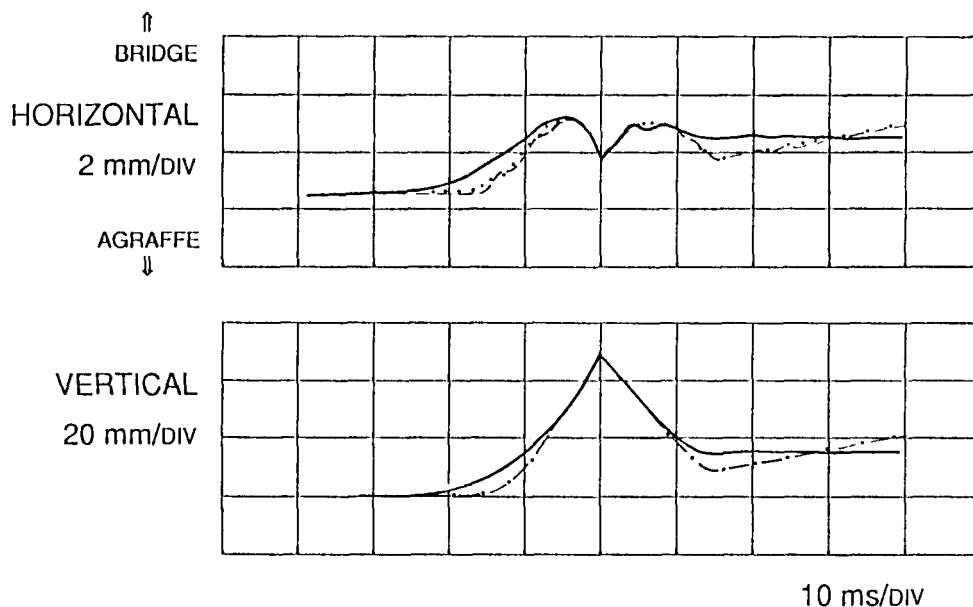


Fig. 9. Illustration of differences in hammer motion for different types of touch, full hammer travel. Legato (full line), staccato (dashed), and strained (dotted); forte,  $v_i=4.5$  m/s.

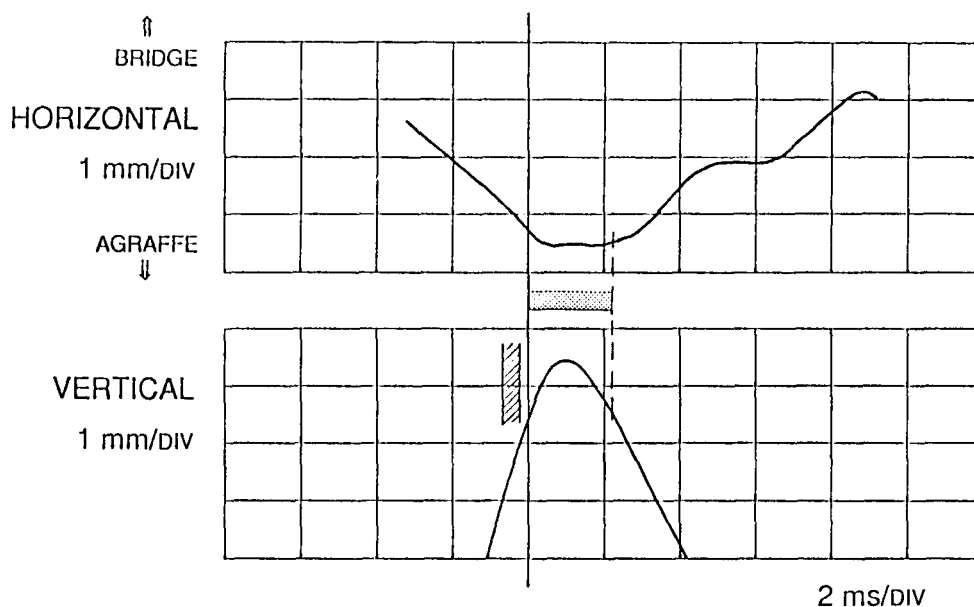


Fig. 10. Close-up around string contact, legato, mezzo forte,  $v_i=2.3$  m/s. The predicted horizontal motion along a circular arc is shown dotted. Also shown are the hammer-string contact time and the time window for the hammer velocity measurement.

### Dynamic level

The influence of dynamic level is illustrated by the differences between a *staccato*-touch in *forte* and *piano* (see Fig. 11). The initial hammer velocities were 3.7 and 1.1 m/s, respectively, corresponding to a dynamic span of 11 dB (cf. Askenfelt & Jansson, 1990a).

Naturally, the string is deflected more by a blow at a loud dynamic level so that the hammer rises higher at *forte* than at *piano*. This is illustrated in the registration of the vertical component. However, due to the compression of the hammer felt, this difference is smaller for the striking point at the top of the hammer than for a point on the wooden moulding. In this example, the striking point turned at a vertical level about 1 mm higher in *forte* compared to *piano*. The amplitude of the string pulse in *forte* is typically 2 mm (Askenfelt & Jansson, 1988).

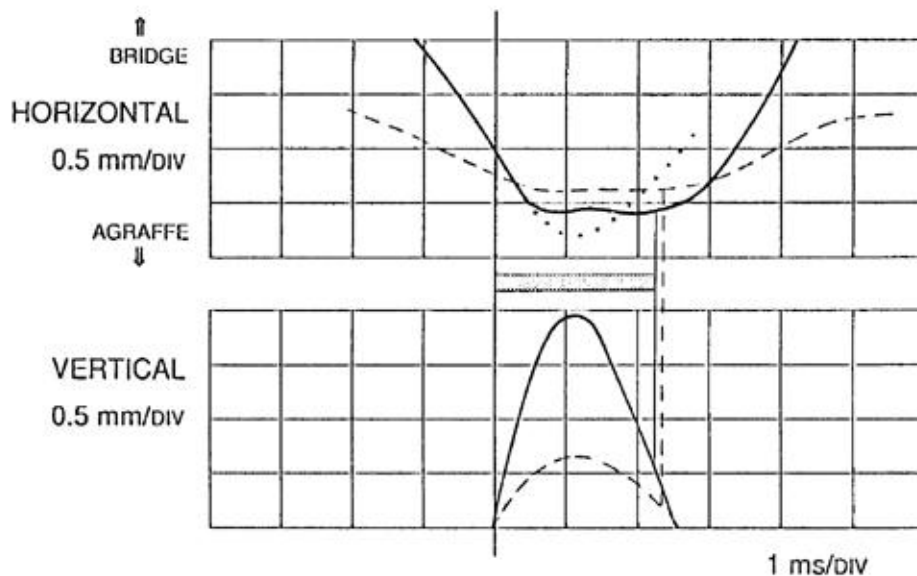


Fig. 11. Illustration of the influence of dynamic level. Staccato, *forte*,  $v_i=3.7$  m/s (full line), *piano*,  $v_i=1.1$  m/s (dashed). The predicted horizontal motion along a circular arc is shown dotted (forte only).

The difference in the horizontal motion between *forte* and *piano* was less. Again, the motion in the string direction seems to stop shortly after the hammer has made contact with the string and a certain compression of the felt has been reached (after about 0.5 ms). Compared to a predicted path along a circular arc, the maximum deviation was about 0.3 mm (*forte*). This is interpreted as that the horizontal motion at the top of the hammer is stopped at string contact, and instead the felt shears or the shank bends. Upon rebound the deviation persists until the felt has expanded or the shank straightened.

The figure also shows that the striking point was shifted a little along the string for a blow in *forte* compared to *piano*-level. In *forte*, the hammer stroke the string a little further towards the bridge, indicating that the initial angle of the hammer head was different compared to *piano*. However, the shift was small, not more than 0.3 mm.

### Touch

The influence of touch is illustrated by the differences between a *legato*, *staccato*, and strained touch, respectively, all at a *forte*-level (see Fig. 12). The influence of touch on the horizontal hammer motion was much smaller than the differences evoked by the changes in dynamic level.

Only small differences could be observed among the three types of touch. The *legato*-version deviated somewhat in that the target point was slightly more displaced towards the bridge at string contact, indicating a different initial angle, but the difference was small ( $< 0.1$  mm). Soon after contact had been established ( $< 0.5$  ms), the *legato*-version followed the course of the other two touch-examples identically. A professional pianist did not produce any deviating patterns, but performed in a manner practically identical to the untrained subject.

The small hump in the horizontal component about 1 ms after string contact was observed in all registrations, particularly pronounced at loud dynamics. This motion, which means that the hammer recoils towards the bridge temporarily, was found to be connected with the arrival of the first string reflection from the agraffe end.

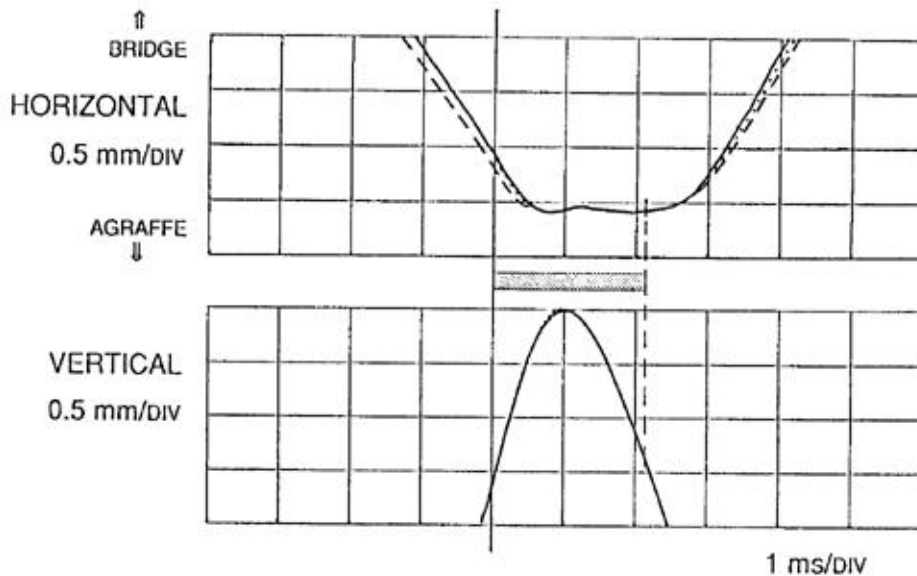


Fig. 12. Comparison of the hammer motion for different types of touch, normal shank. Legato (full line), staccato (dashed), and strained (dotted); forte,  $v_i = 3.7$  m/s. The maximum difference in  $v_i$  was 0.10 m/s.

#### Normal – soft hammer shanks

The influence of the stiffness of the hammer shank is illustrated by comparisons of the same three types of touch as above, *legato*, *staccato*, and strained touch, respectively (see Fig. 13). The difference between the different types of touch was larger with the soft shank than with the normal. This applied both to the horizontal displacement at string contact, as well as the motion during contact. The difference in horizontal displacement at striking between a *legato* and strained touch in *forte* was between 0.1 and 0.2 mm. As for the normal shank, the initial horizontal position was a little closer to the bridge in the *legato*-case. The *staccato* and strained touch performed very similarly. During string contact, the differences in horizontal displacement were of the same magnitude as at the initial moment of contact.

It could be observed that the hammer head stayed displaced horizontally for a longer time with the soft shank (cf. Figs. 12 and 13), even increasing the horizontal displacement after string contact had ended. This behavior could be interpreted as a result of bending vibrations in the shank, during and after string contact.

Also the vertical motions differed in this experiment, a fact not observed with the normal shank (cf. Fig. 10). However, the differences were only about half the magnitude of the differences in horizontal motion.

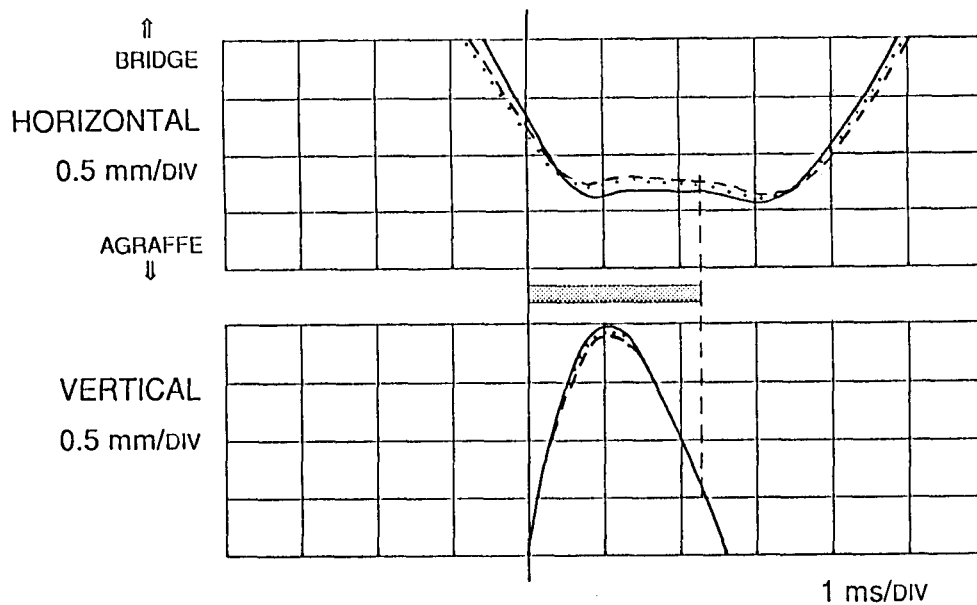


Fig. 13. Comparison of the hammer motion for different types of touch, soft shank. Legato (full line), staccato (dashed), and strained (dotted); forte,  $v_i=3.5$  m/s. The maximum difference in  $v_i$  was 0.05 m/s.

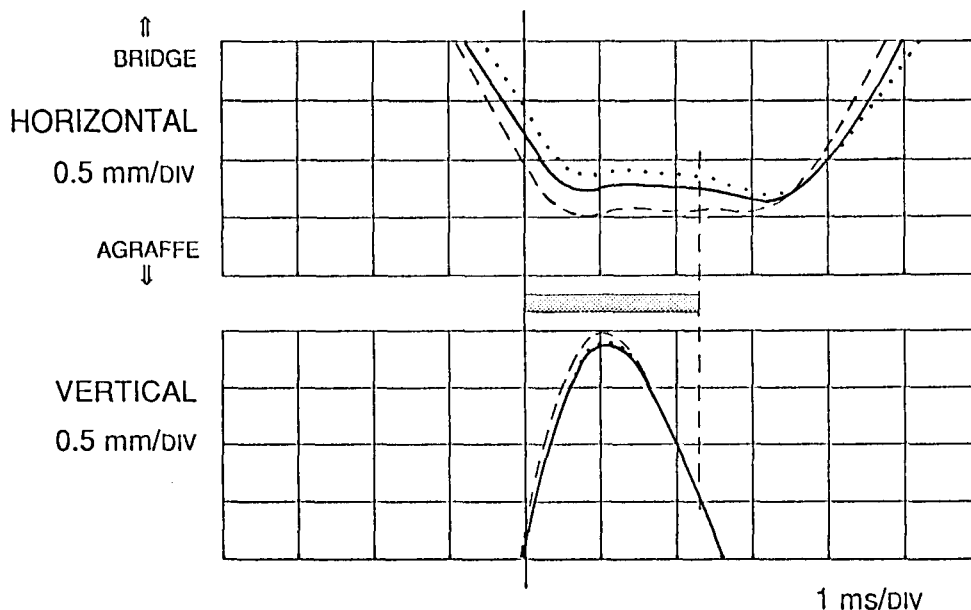


Fig. 14. Comparison of the hammer motion for three variations of staccato touch, soft shank; forte,  $v_i=3.4$  m/s. The maximum difference in  $v_i$  was 0.09 m/s.

Interestingly, the *staccato*-touch seemed to offer several possibilities. By applying touches with differing amount of "staccato-ness," easiest characterised by how long the finger stayed in contact with the key ("peaked-round" *staccato*), relatively large changes in the horizontal motion could be achieved with the soft shank (see Fig. 14). For instance, the horizontal displacement at string contact could be varied as much as 0.4 mm approximately, indicating a relatively large change in initial angle. These differences in horizontal displacement persisted throughout the duration of hammer-string contact. After release, however, the motions approached a common path. The relatively large differences in the horizontal motions were reflected also in the vertical components.

During string contact a small wiggle in the horizontal motion ( $< 0.1$  mm) could be observed, a little more pronounced for the soft shank. However, these minor undulations seemed not to be influenced by touch.

### String waveform and spectra

As illustrated in the previous figures, the differences in hammer motion associated with different types of touch are small. This applies in particular to the cases with the normal shank. It was thus no large surprise to learn that the differences between the corresponding string waveforms and spectra also are small. The waveforms and spectra for a *legato*, *staccato*, and strained touch, respectively, with the normal shank are compared in Fig. 15. The string motion was measured electro-dynamically (Askenfelt & Jansson, 1988). The spectra correspond to a time window of 40 ms, immediately after the onset of the note.

The only difference that can be seen in the spectra is a slight rise in level for the *legato*-touch in the frequency range 6–8 kHz. The difference is limited to an increase in level of 2 dB for three partials (partials 26 and 28, and a longitudinal string mode in between), and 4 dB for a single partial (partial 32). For the soft shank, the differences were larger, between 2 and 4 dB in a broader range between 2–8 kHz, again with a higher level for the *legato*-touch (see Fig. 16). These differences should be set in relation to the shift in spectral envelope between *mezzo forte* and *forte* for the same note (see Fig. 17). In that case, the differences typically start with 5 dB at the lowest partials, increasing to 12 dB at 5 kHz, beyond which frequency the *mezzo forte* spectrum does not extend.

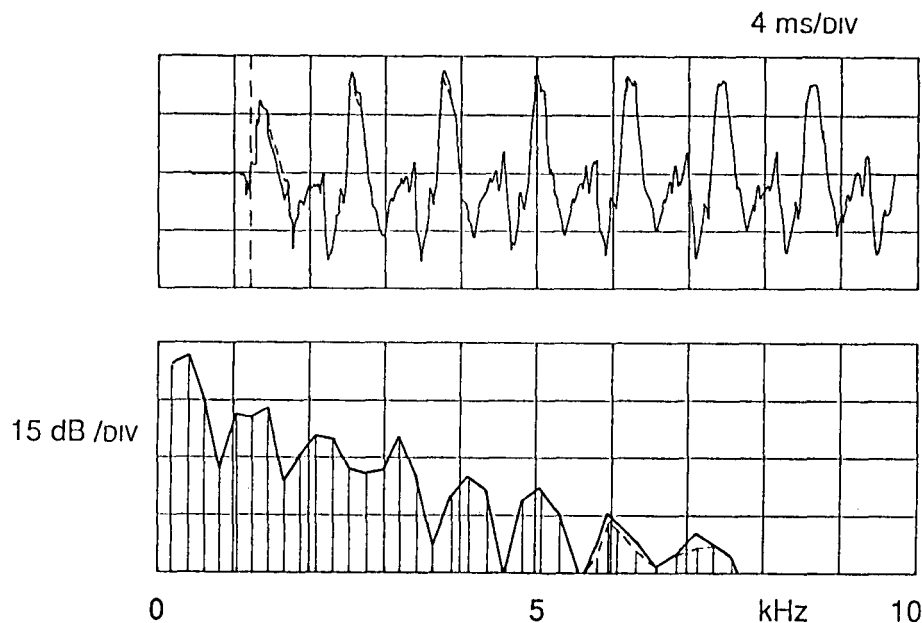


Fig. 15. String waveform and spectra for different types of touch, normal shank. Legato (full line), staccato (dashed), and strained (dotted); forte,  $v_i = 3.5$  m/s. The staccato and strained case merge completely. The maximum difference in  $v_i$  was 0.06 m/s. The spectra are not compensated for the influence of detector position. The dashed vertical line in the waveform indicates the left limit of the time window (40 ms) for the spectrum calculation.

The differences in waveform were more difficult to discern, being limited to the details in angularity and slopes (cf. Fig. 15 and 16). However, the first string pulse (but not the following) was always lower for the case with the soft shank, an observation that probably has to do with a decrease in effective hammer mass (as seen by the string) for the soft case (Suzuki, 1983).

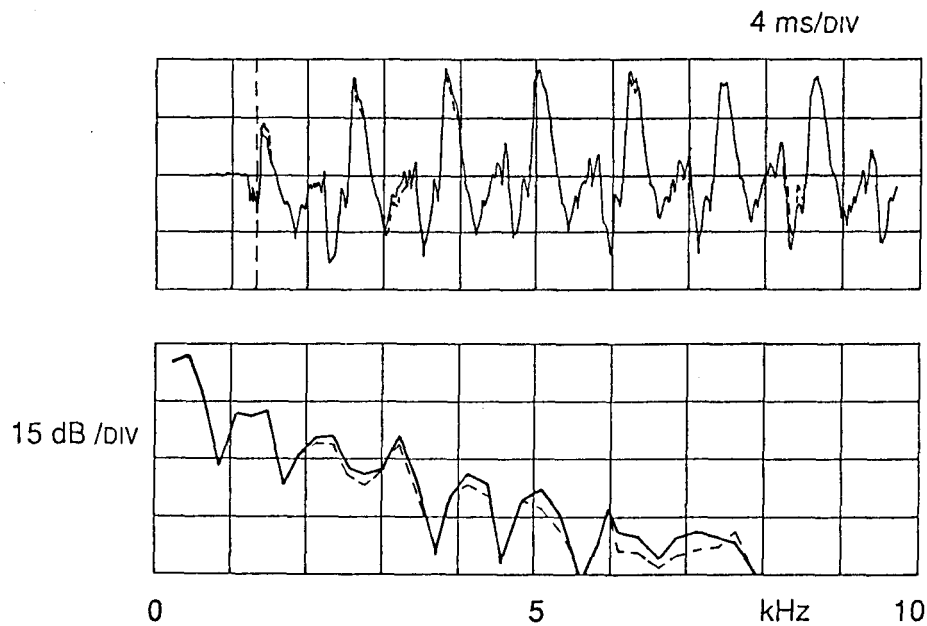


Fig. 16. String waveform and spectra for different types of touch, normal shank. Legato (full line), staccato (dashed), and strained (dotted); forte,  $v_i=3.5$  m/s. The maximum difference in  $v_i$  was 0.05 m/s.

#### Considerations on the spectrum measurements

A comparison of spectrum and waveforms is highly dependent on an accurate measurement of the initial hammer velocity. This is due to the pronounced nonlinearity of the hammer felt (see, e.g., Hall & Askenfelt, 1988). The largest spread in initial hammer velocity between the three cases in Figs. 15 and 16, respectively, did not exceed 0.06 m/s according to the optical velocity measuring device used. Whether the relatively large differences in spectra, observed between the touch-versions with the soft shank (Fig. 16), in some way are connected with an error in the velocity measurement would need to be checked in a separate experiment. Such an error could be connected with the flexing of the shank and the corresponding motion of the slotted vane.

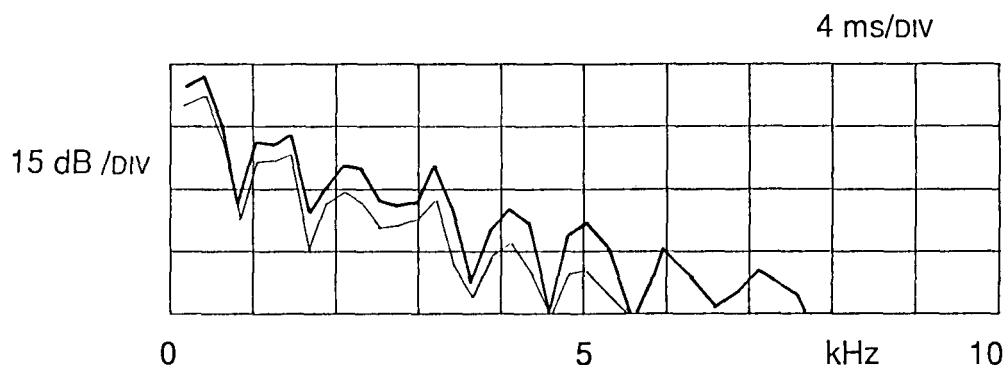


Fig. 17. Comparison of the shift in spectrum envelope between mezzo forte and forte, normal shank. Legato, forte  $v_i=3.7$  m/s (broad line), mezzo forte,  $v_i=2.3$  m/s (thin line).

In order to estimate the accepted spread in initial hammer velocity for equal sounding notes in musical performance, an informal experiment was made. A professional pianist was asked to repeat notes at a slow rate (about 1 note per 5 s) at an identical dynamic level (*mezzo forte*). The spread in initial velocity in a series of four notes was typically 0.1 m/s, corresponding to approximately 5%.

## DISCUSSION

The present results give a strong indication on that the influence on the string excitation from touch normally is very small. The observed spectral differences of a few decibels associated with different types of touch occur in the highest partials, about 50 dB below the levels of the low partials (see Fig. 15). It seems reasonable to assume that these differences are inaudible.

An exception seems to be the *staccato* variations with the soft shank (Fig. 16). The spectral differences observed in that case are so large that they ought to be possible to perceive. On this point it would be desirable to supplement the present experiments by a verification of the velocity measurement. As mentioned, a slight difference in initial hammer velocity could easily overthrow the comparison of spectra. The supplementary experiments would include:

- (a) A check of the uncertainty in the present indirect measurement of initial hammer velocity (by means of a slotted vane on the shank), by a direct measurement of the vertical velocity at the striking point. This could best be done by a doppler-laser technique.
- (b) A listening test in which the just noticeable difference (JND) in hammer velocity is determined, using a normal shank and a reproducible touch, preferably delivered by a computer controlled "striking finger."

Having excluded a major influence on the string vibrations by touch, leaves us with the rather prominent "thump sound" in the attack of the tone as a possible explanation to the different sound qualities created by different pianists. The thump is in part caused by the retardation of the key against the key stop rail, and spread to the keybed and other parts of the instrument (Boutillon, 1988).

It seems reasonable to assume that the relation between the thump and the string sound can be influenced by the way the key is depressed, in particular how the key is retarded as approaching its bottom position. This aspect is also enhanced in classical schools of piano playing (see, e.g., Leimer & Giesekeing, 1931). The significance of the thump component has been verified by simultaneous recordings of the isolated string sound, and the airborne sound in the room (Askenfelt & Jansson, 1990b), as well as in synthesis of piano sound (Reinholdt, Jansson, & Askenfelt, 1987; Chaigne, Askenfelt, & Jansson, 1990).

The great attention paid by recognized piano manufacturers in selecting the wood for the keybed also gives evidence to importance of the attack component in the piano tone (Steinway & Sons, Hamburg, personal communication, 1988). The selection is made with the purpose of arriving at the desired thump quality.

## CONCLUSIONS

The experiments have answered the key questions as follows:

1. How does the hammer move from position of rest to string contact for different types of touch?

The motion of the hammer before string contact can be very different depending on the type of touch, even when the dynamic level, i.e., the initial hammer velocity at string contact, is held constant. For a touch where a strong impulse is given at the beginning, vibrations were observed, in particular so for the *staccato*-touch. In contrast, for a *legato*-touch the hammer motion was smooth.

2. Does the initial angle of the hammer head change depending on the dynamic level and touch?

An influence of dynamic level could be observed. The striking point was moved slightly towards the bridge in *forte* compared to *piano* (up to 0.3 mm), indicating a

stronger bending of the shank, and corresponding change in initial angle at loud dynamics.

The influence of touch was much smaller. For a hammer with a normal shank, the shift in striking point was less than 0.1 mm among the three types of touch evaluated (*legato*, *staccato*, strained). For the soft shank, the corresponding shift was 0.4 mm at a maximum.

3. Does the contact point move during string contact?

The general answer appears to be no. The hammer stayed essentially fixed at a horizontal position set shortly after string contact ( $< 0.5$  ms), when a certain compression of the hammer felt had been reached. This applied to all three types of touch tested, as well as to the soft shank. This means, among other things, that the contact point does not move horizontally along the string as predicted by a circular arc. In this sense the hammer seems to be "glued" to the string during string contact. Any difference in horizontal displacement at striking thus tends to be preserved during most part of the string contact duration. A small horizontal undulation during string contact of the magnitude 0.1 mm, could be observed, a little more pronounced for the soft shank. However, this motion seemed not to be influenced by touch.

4. Are any observed differences in the hammer motion reflected in the string spectrum?

The analysis of the measurements does not give a completely clear answer to this question. For a hammer with a normal shank, the differences in spectra among the three types of touch were marginal, limited to a level difference of a few decibels around 6–8 kHz. For the soft shank, the differences were larger. Despite careful attempts of measuring the initial hammer velocity accurately, an influence from small measurement errors could not be ruled out. On this point, it would be desirable to supplement the present registrations with a verification of the velocity measurements.

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