

THE ACOUSTICS OF TANGENT-STRING INTERACTION IN THE CLAVICHORD COMPARED TO HAMMER-STRING INTERACTION IN THE FORTEPIANO

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1. Introduction

The clavichord and square fortepiano share many features in common: rectangular shape, similar dimensions and construction principles. The same makers or workshops often built them. However, their sounds are markedly different in volume, dynamics and quality.

The main differences between these two types of instrument do not lie in their general dimension, stringing or construction, but in their action and string excitation mechanism. For example, the two instruments pictured in Fig. 1 are almost similar in size and design, one being a copy of an eighteenth-century Hubert German clavichord, and the other an eighteenth-century anonymous German fortepiano. As for the action and sound production, the clavichord and fortepiano differ in the striking position (at the extremity of the sounding part of the string vs. at a distance from the extremity of the string), the string excitation mechanism (tangent vs. hammer), and the damping mechanism (a band of cloth vs. individual dampers). Other differences also exist, in the stringing patterns, additional effect pedals, etc. but they seem much less significant and cannot explain *per se* the difference between both instruments.

This communication is organized as follows. In the first part the main acoustic features of the clavichord, mainly due to the tangent-string interaction, are reviewed. This interaction is able to explain the main features of the clavichord's sound and dynamics (spectral richness, effect of key velocity, sound level, intonation variation with sound intensity). In the second part, the main acoustic features of the fortepiano are reviewed. Acoustic models for the hammer-string interaction in the fortepiano are quite well documented in the acoustic literature. By comparing these acoustic models, the main differences between the fortepiano and the clavichord sounds can be explained.

1.1. Preliminaries: sound production in stringed keyboard instruments

All stringed instruments (and especially keyboard stringed instruments) work according to similar principles. The sound produced, i.e., the air vibration radiated in the open space in

the vicinity of the instrument, results from the small amplitude vibration of a relatively large object.

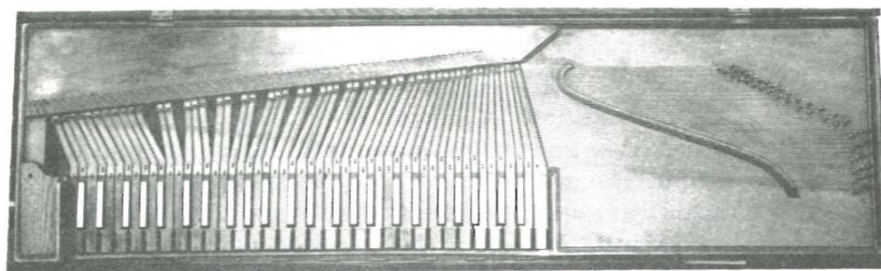


Fig. 1a. An anonymous eighteenth-century German fortepiano
(from R. Harding, *The Piano-Forte*, Plate V (a), facing p. 44)

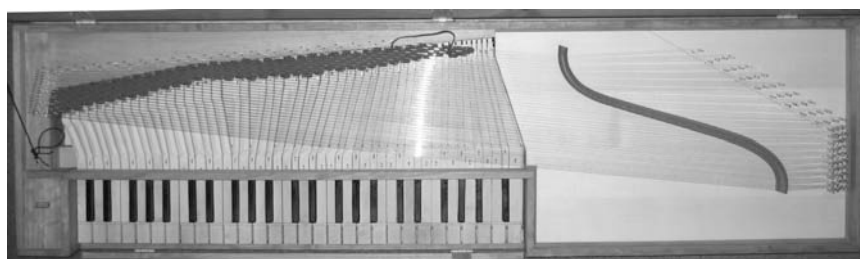


Fig. 1b. Copy of a Hubert clavichord (Germany, eighteenth century)

This vibrating object is a thin plate of wood, the soundboard. Note that the string surface is too small to produce a significantly loud sound (of the order of 0.0005 m^2 for the longest strings), compared to the surface of a small soundboard (0.1 m^2 or more for a small clavichord). The motion of the soundboard therefore produces the sound. The soundboard is moved by variation of the force applied by the string at the bridge. The string is an oscillator, i.e., a system that oscillates when set out of its equilibrium rest position. When a perturbation is applied to the string at equilibrium by the excitation mechanism, a wave, a deformation, travels along the string with the string wave velocity (about 200–300 m/s). This wave is reflected at the bridge, and comes back to the other fixed extremity, is reflected there, and the process goes on. These oscillations drive the soundboard motion.

The force on the soundboard is proportional to the string tension and the angle made by the string at the bridge; because of the string motion equation, this angle is closely related to the transverse velocity of that part of the string that is adjacent to the bridge. In other words, the force on the bridge is proportional to the excursion of the string at the bridge.

Here, differences between keyboard instruments appear, because the excursion of the string at the bridge depends on the string excitation mechanism. For plucked strings, e.g. harpsichord, spinet or virginal, the angle of the string depends on the height of the string before release. Thus it does not depend (to a first approximation) on the key velocity or force applied on the key. For struck strings, e.g. clavichord, fortepiano or hammered dulcimer, the angle of the string depends on the shape of the strike, and on its amplitude. Thus it depends on the striking velocity, but it does not depend on the force applied to the key.

1.2. Preliminaries: sound quality and sound control

Evaluation of the qualities of an instrument depends on two main aspects: sound quality, and the playability of the instrument, or sound control. The main attributes of sound quality are its pitch (musical notes and pitch inflections such as vibrato or portamento), its loudness (or sound volume or level), and its timbre (or spectral content). The timbre itself is often described in terms of spectral richness (brilliance or sharpness), linked to spectral tilt or spectral centre of gravity.

Another important aspect of an instrument's quality is the way the performer controls the sound. In keyboard instruments, the only control is the vertical motion of keys. When pressing the keys, the player is able to control the key velocity, the key displacement, and pressure or force on the key. He also controls the sound timing, attack and sustain, and the release of the key. Depending on the action, the player's gestures will have different effects of the sound produced.

The sounds and playability of the clavichord and fortepiano must be compared along these lines.

2. Acoustics of the clavichord

2.1. Tangent velocity and loudness

Loudness is controlled in the clavichord by the initial tangent velocity, i.e. the tangent velocity at the string/tangent impact. Velocities have been measured for all the notes of four instruments, played with as many dynamic nuances as possible, in d'Alessandro et al. (2008). It appeared that the maximum velocities are on average 1.2–1.4 m/s for the four instruments, with some variation between instruments, and between registers for a given instrument. Only very few measurements give more than 1.5–1.6 m/s.

One feature of the clavichord is that the key leverage (ratio of the keylever lengths on either side of the balance rail) cannot be too large (see for instance Bavington 1997). Thus the tangent velocity cannot be increased much above the finger velocity. In practice, the finger velocity when playing the keyboard is of the same order of magnitude as other muscular motions (walking is around 1.0 m/s or 3.6 km/h, jaw velocity when speaking is around 3 m/s or 10.8 km/h).

The action of a clavichord is displayed in Fig. 2. In this picture, the key leverage (velocity of the tangent/velocity of the finger key) is around 1.5.

A simple and direct relationship between tangent velocity and the sound volume has been found: loudness, expressed in terms of SPL (sound pressure level), is proportional to the logarithm of tangent velocity. Measurements of loudness for four instruments (d'Alessandro et al. 2008) showed a maximum of about 65 dB SPL at 30 cm from the centre of the soundboard (or equivalently, 55 dB SPL at 1 m from the soundboard, a typical position for the player's head).

It can be shown that the force applied by the string on the bridge is proportional to the tangent's impact velocity, and to the ratio of the string tension over the wave velocity in the string. Therefore, a way to increase loudness is to increase string tension and string diameter or weight. But this can be done only in a limited range.

In summary, playing louder on the clavichord means playing faster, not playing with more force or weight. But the maximum velocity of the string motion is that of the tangent, and close to that of the finger. This velocity is limited by the simplicity of the action, which does not allow for much multiplication of the finger velocity. This explains the relatively weak SPL of the instrument.

2.2. Tangent-string interaction: spectral richness

Another peculiar feature of the clavichord is that the tangent/string contact is always a hard contact, a shock of metal on metal. Therefore, as the metal is almost incompressible, the shape of the deformation in the string is always angular, whatever the tangent velocity. Even the softest tones induce a kink in the string. The consequence of this angular shape of the string is that the sound spectrum is always rich, with a lot of high-frequency harmonics, whatever the dynamic nuance (d'Alessandro et al. 2006).

Another instrument with an angular string pattern is the harpsichord. When the string is released in the harpsichord, an angular point propagates on both sides of the plectrum (Hall 1993). The harpsichord is also an instrument with a spectrally rich sound.

2.3. Tangent height and string tension: intonation

When the tangent touches the string, it raises the string. Thus in one and the same motion, a wave is sent to the soundboard, and the string tension is modified. In return, the player feels the 'hardness of touch' (Bavington 1997). The string acts like a spring on the tangent, with a resistance proportional to the tangent height. The string tension modification significantly affects the pitch produced.

This is a well-known paradox of clavichord playing: to make the instrument sound, the player must play with as much velocity as possible, but at the same time she/he must not raise (displace) the string too much. In other words, the player must control at the same time the velocity and position of the tangent. The clavichordist's paradox can be expressed as follows: 'moving fast without moving much'.

The finger's velocity controls the initial tangent velocity. A complex servomechanism involving the force returned by the string controls the string displacement after contact. This 'aftertouch' is maintained during the whole of the sounded notes, and it allows for a fine, almost vocal, control of intonation.

3. Acoustics of the fortepiano

The situation for the fortepiano is very different, in terms of mechanism, control, and sound. In the fortepiano, a free hammer excites the string. The key pushes the hammer, and then the hammer escapes from the mechanism (which can be reduced to a simple pilot) and strikes the string. The hammer stays in contact with the string for a short time, and rebounds. The strings vibrate between the bridge and the hitch-pin block bridge, until the damper stops the sound.

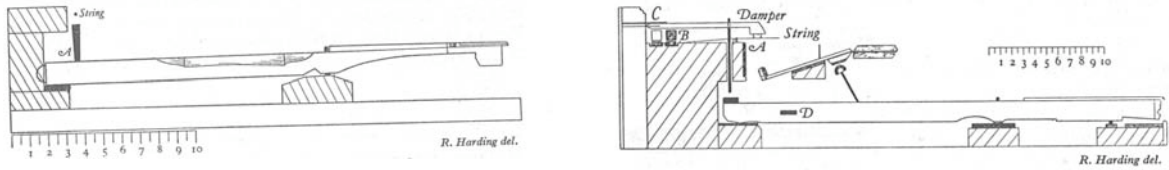


Fig. 2. Clavichord action (left, R. Harding, *The Piano-Forte*, Fig. 14, p. 24, Stuttgart, No. A 1) and fortepiano single pilot action (right, R. Harding, *The Piano-Forte*, Fig. 38, p. 54, Pohlman, 1784)

3.1. Hammer velocity and loudness

In the piano, as in the clavichord, one can show that the loudness, or SPL, is proportional to the excitation velocity, of a hammer in the case of the fortepiano (Palmer and Brown 1991). The hammer velocity is much higher than the finger velocity, because of two leverage effects:

- The key leverage effect. The leverage ratio can be higher or lower in the fortepiano than in the clavichord, depending on the key lengths on both sides of the balance-rail.
- The hammer shank leverage effect. A second lever is provided by the relative pilot, hammerhead, and pivot positions. For more complex actions (double pilot action or double escapement action) a third leverage effect can also take place in the mechanism.

The actions of a clavichord and of a single pilot square fortepiano are compared in Fig. 2. In this picture the key leverage of the clavichord (velocity of the tangent / velocity of the finger key) is around 1.5. The key leverage of the fortepiano is around 1 but the hammer shank leverage is more than 6, resulting in a hammerhead velocity at least 3 times higher than the tangent velocity.

To the best of my knowledge, no figures of hammerhead velocities for historical fortepianos are currently available. For an upright Gaveau (1930), Boutillon (1988) measured the following hammer velocities: 0.11 m/s (*ppp*), 1.48 m/s (*mf*), and 6.83 m/s (*fff*). Askenfelt and Jansson (1991) reported the following figures for a concert Steinway: 1 m/s (*p*), 2 m/s (*mf*), 5 m/s (*f*) with corresponding key velocities of 0.1, 0.4, 0.6 m/s respectively. In their experiments, a maximum key velocity of 1 m/s was reached. On a concert Bösendorfer, Palmer and Brown (1991) reported hammer velocities between 0.25 and 4 m/s. Therefore, hammer velocities can be almost 5 times higher than tangent velocities in the clavichord.

According to Palmer and Brown (1991), loudness is proportional to hammer velocity. Remember that in the clavichord, loudness is proportional to tangent velocity. So, in theory, loudness can be more than 14 dB SPL greater in the piano than in the clavichord, for the same string tension. This multiplication effect can explain the difference in loudness of the two instruments, all the other parameters being the same (string tension, soundboard dimensions etc.).

In addition, the fortepiano historically followed a tendency towards higher string tension and higher string diameters. It must be noted that the question of hardness of touch for the clavichord is meaningless for the fortepiano. As the hammer is free, the finger never feels the string tension, but is stopped by the mechanism. So tension can be increased without affecting the touch.

As in the clavichord, the force or weight on the key has no effect on the loudness produced. Only the finger velocity is significant. However, the piano mechanism is generally heavier than the clavichord mechanism (Askenfelt and Jansson 1990). Thus the minimum

force required to produce a sound is higher. This is because the hammer must be projected and must have enough energy to leave the pilot. If the key velocity is not high enough, the kinetic energy transmitted to the hammer is not sufficient for it to hit the string.

3.2. Hammer cover and compression: spectral richness

As far as string excitation is concerned, the second difference between the clavichord and the fortepiano is the very nature of the contact with the string. The hammerheads are covered with some kind of more or less compressible material: cork, leather, chamois, deerskin, and later beaver or rabbit felt (mainly after Pape's patent on felt preparation for piano hammers, in 1826).

Compression of the hammerhead cover plays an important role in sound quality. This is well documented in the acoustic literature, at least for felt covers of modern piano hammers. It seems that no specific acoustic work on leather covers has been published to date. The cover compression, and thus the acoustic effect of the cover, changes dramatically as a function of the impact velocity. The hammer/string interaction is clearly non-linear, contrary to the tangent/string interaction in the clavichord, which is mostly linear.

For low-velocity impacts, the string deformation is smoother, with a less angular shape. Moreover, the hammer/string interaction is longer: several string wave reflections react on the hammerhead during interaction. The main result on sound quality is a softer sound with fewer upper partials.

On the other hand, for high-velocity impacts, the string deformation is sharper, with a more angular shape. The cover is more compressed, and the hammerhead seen on the string side seems harder: this is closer to the clavichord situation. In consequence the sound is richer, with more high ranked harmonics.

Another aspect of piano voicing is the hammerhead weights, which also change the harmonic content of the sounded tones. Hall and Askenfelt (1988) reported that light hard hammers would produce a richer spectral content, whereas heavy soft hammers would produce tones with fewer upper partials.

In summary, key velocity in the fortepiano controls two aspects of the sound: the tone's spectral content or 'colour' and the tone's loudness. Control of the tone's colour may be as important as, or even more important than, control of the tone's loudness. This is an additional expressive means, compared to the clavichord or harpsichord.

3.3. Free hammer, free string: voicing

In the fortepiano, the hammer flies freely after leaving the pilot: the player definitely loses control of the hammer after it has left the pilot. In contrast to the clavichord, there is no aftertouch control: the only remaining control left to the player is the damper release. The string tension is not significantly altered by the string hammer interaction, except maybe under extreme playing conditions. Thus there is no intonation control in the fortepiano.

A main advantage of the free hammer (and free string) is that the impact point can be carefully chosen. This is another degree of freedom in the fortepiano design process. Depending on the impact point, the instrument can be made louder or softer, and its tone colour can be adjusted. In the clavichord, the impact point is always fixed at the extremity of the vibrating string.

As the string excitation and string vibration processes are independent in the fortepiano, it is possible to let the string sound as long as the dampers are raised (or lowered, for under dampers). This opens the way for new sound resonance effects, generally controlled by specific pedals.

4. Summary and conclusions

Playing the piano involves a different type of control from that required when playing the clavichord. The finger velocity in the fortepiano controls the tone volume and the tone colour as well, due to the cover compression effect. But the pianoforte key is stopped by the mechanism, and so aftertouch finger pressure is of no effect.

Finger velocity in the clavichord controls mainly the tone's volume, and has only a marginal effect on the spectral richness: it may play a role for lower harmonics, as discussed by Thwaites and Fletcher (1981). But the finger displacement or finger pressure is of the utmost importance, because it provides a direct control of the string tension, and thus of the pitch produced.

Clavichord tone is always spectrally rich, somewhat comparable to harpsichord tone. In contrast, the fortepiano's tone richness can vary with hammerhead velocity, depending on the compression of the hammerhead cover.

When hammerheads that are almost uncompressible (covered by, e.g., cork, metal or wood) and very light are used, the fortepiano's sound resembles that of a clavichord or a harpsichord, but with much more loudness. Many such instruments existed, such as, for example, the *Tafelklavier* by Schmahl that was played at the Magnano 2009 conference. An instrument with two hammers for every note is depicted by Harding (1933), and shown in Fig. 3: one hammer is of wood, whilst the other is capped with a pad of leather. According to Harding, the wooden hammer gives the 'cembalo' tone, whilst the leather hammer gives the usual pianoforte tone. Brauchli (1998, pp. 182, 184) gives examples of instruments equipped with a clavichord action attached to a fortepiano action.

Another example of an instrument using lightweight and hard-covered hammerheads is the tangent piano (*Tangentenflügel*). In this type of instrument, a free tangent that is projected by the key replaces the hammer. The main difference from a piano is that the tangents are not moving on an axle, like fortepiano hammers, but are projected vertically on to the strings. An example of tangent piano action is depicted in Fig. 3. The sound produced undoubtedly has a clavichord-like quality, but without the subtle intonation control allowed by the clavichord.

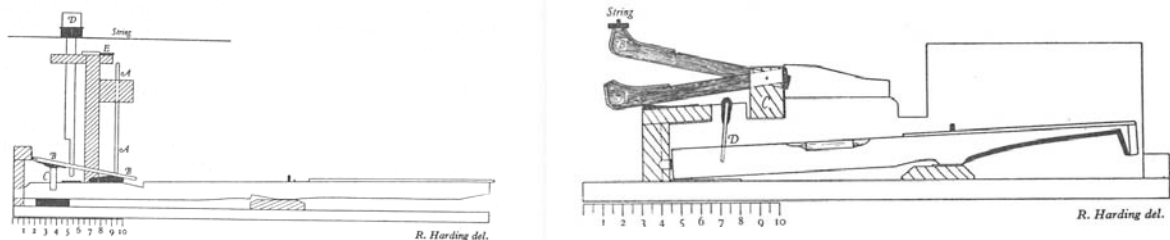


Fig. 3. (left) Tangent action, Schmahl, 1795 (R. Harding, *The Piano-Forte*, Fig. 34, p. 50) (right) Square fortepiano in the Musikhistorisches Museum Neupert, Nuremberg, with a wooden hammer and a hammer clothed with a pad of leather (R. Harding, *The Piano-Forte*, Fig. 35, p. 51)

One of the reasons for the tangent piano's short-lived history might be its relatively steady tone colour whatever the playing nuance, which could not compete with the fortepiano in the late eighteenth-century musical aesthetic.

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Abstract

The clavichord and square fortepiano share many features in common: square shape, similar dimensions and construction principles. However, their sounds are markedly different in volume, dynamics and quality. In the first part the main acoustic features of the clavichord are reviewed (spectral richness, effect of key velocity, sound level, intonation variation with sound intensity). In the second part the fortepiano's sound features are reviewed along the same lines. The main differences between fortepiano and clavichord sound and playability can be explained by the difference in hammer and tangent velocities due to the different action of both instruments, the string tension control in the clavichord (vs. the free string in the fortepiano) and the effect of hammerhead compression in the fortepiano (vs. the hard tangent in the clavichord). With hard and lightweight hammers, the pianoforte sound resembles that of the clavichord, but with more loudness, no intonation control and no tone colour control. Many such instruments existed, such as the tangent piano (Tangentenflügel).