ACOUSTIC PORTRAITS OF FOUR CLAVICHORDS: TANGENT VELOCITIES, LOUDNESS, AND DECAY TIMES

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1. Motivation of the work

A somewhat neglected dimension in organology and musicology is objective description of sound quality. This is an intricate task involving perception and cognition together with information processing and physics. For many instruments, including the clavichord, sound production is intimately controlled by the player, adding much valuable variability to the sound produced, and adding also much difficulty for objective sound quality analysis. Despite these difficulties, objective assessment and documentation of sound and musical qualities of the instruments would be highly desirable for many reasons:

1. **Documentation of the instruments:** in addition to other types of documentation, such as iconographical, historical, and static physical documentation (dimensions, materials, and so on), sound recordings and dynamic physical recordings under controlled conditions can serve as a basis for a more detailed documentation process.
2. **Comparative evaluation of the instruments:** acoustic documentation can help in understanding the distinctive features of specific instruments, or specific schools of instrument making.
3. **Physics and acoustics:** acoustic documentation can serve as a data basis for deeper understanding of the physics and acoustics of the clavichord.
4. **Performance analysis:** the specific control signal delivered by different performers can serve as a basis for performance studies.
5. **Virtual instruments:** databases of instrumental sound are useful for some contemporary musical practices, including construction of virtual digital instruments using sound samples and other forms of digital sound synthesis and/or sound control.

In a similar vein, acoustic portraying for the pipe organ has been described by Pollard (1999). The aim of his work was to quantify the steady state tone colour (*timbre*) of an instrument. One can hardly find a steady state in a clavichord tone; therefore Pollard's methodology cannot be straightforwardly transposed to our situation, despite its interest. Because of the rapidly time-varying nature of its sound, acoustic portraying of the clavichord involves measurement of the variation in time of a number of acoustical and mechanical parameters. Features related to the sound (loudness, duration) and to the action (dynamic range, key velocity) of the instrument are considered.

Another important question is inter and intra instrument variability. Instead of focusing on one specific clavichord model, we preferred to deal with several very different instruments, allowing for comparative studies. Four clavichords have been recorded and analysed.

For all the instruments, acoustic signals, string–tangent contact signals and tangent motion signals (acceleration, velocity, and displacement) have been simultaneously recorded for all the notes of the instruments. This large amount of data can serve as a basis for comparison of the sounds of the instruments on their whole compass.

2. Instruments studied and measurement methodology

According to the aim of this study, a comparative approach is conducted. The four different instruments studied are summarized in Table 1 and briefly described below.

	BS	**DH**	**ZK**	**BM**
Compass	C–d^3, 51 keys	C–d^3, 51 keys	C/E–c^3, 45 keys, short octave	g–g^4, 37 keys
Stringing	Double strings Brass	Double strings Brass	Double strings Brass	Double strings Brass, unison
Soundboard (mm)	316 × 346	268 × 227 (302)	268 × 227 (302)	792 × 207 × 101
Dimensions (mm)	1068 × 361 x 111	1267 × 358 × 112	994 × 295 × 101	820 × 265 × 115
Pitch and temperament	415 Hz, Kirnberger II	415 Hz, Kirnberger II	440 Hz, mean tone, in D	440 Hz, octave; Pythagorean
Fretting	Unfretted	Fretted by 2	Fretted by 2 and 3	Fretted by 3, 4 and 5
C (mm)	895	1097	820	–
c (mm)	692	926	650	–
c^1 (mm)	441	509	385	466
c^2 (mm)	229	262	210	233
c^3 (mm)	111	122	102	117

Table 1. The four instruments studied

2.1. The 'Bal-Sydey' clavichord

The first instrument, referred to here as the 'BS' clavichord, was built by Frédéric Bal in 1980, in the workshop of Antony Sidey (Paris). It was designed by A. Sidey, 'following tradition', according to a presentation booklet. Therefore, this instrument is not an exact copy of a historical model, but rather a modern design closely following eighteenth-century historic proportions and historic construction techniques. Interestingly, this design was also used for a popular kit, produced by the French early music publisher *Heugel et Compagnie* (Paris) around 1972. Such a kit-based instrument was also used in the work by Välimaki et al. (2003). This model shares a lot of features in common (although on a reduced scale: a compass of C–d^3 instead of F_1–f^3) with the 5-octave anonymous unfretted instruments attributed to Silbermann: compact unfretted design, almost square soundboard, no tool box, similar bridge shape, hitch-pin and tuning pin arrangements and so on. The present instrument is made to outstanding levels of craftsmanship and material quality. It is also a very fine and responsive musical instrument.

Figure 1. The BS clavichord.

2.2. The 'Ducornet-Hubert' clavichord

The second instrument, referred to as the 'DH' clavichord, was built at The Paris Workshop, in Montreuil, by C. d'Alessandro and C. Besnainou, and completed in 2007. It is based on a kit designed by E. Dancet and M. Ducornet after unfretted clavichords by Hubert. The instrument is not an exact copy of a historical model, but follows closely the unfretted Hubert models of the last quarter of the eighteenth century. Although not built by professional makers, construction was supervised in The Paris Workshop. The result can be considered a very usable musical instrument, even if its level of craftsmanship cannot compare with the best professionally built clavichords. This instrument was built especially for acoustic investigations.

Figure 2. The DH clavichord.

2.3. The 'Zuckerman-King of Sweden' clavichord

The fourth instrument, referred to as the 'ZK' clavichord, is a fretted instrument built around 1985 from the popular 'King of Sweden' Zuckermann kit. The kit is based on an anonymous German seventeenth-century model, with 45 notes and short octave. A similar kit was used in the study by Thwaites and Fletcher (1981). This instrument is relatively small and tuned a tone higher than standard modern pitch. Although carefully built, it can be considered as an acceptable (but not first-rate) instrument.

Figure 3. The ZK clavichord.

2.4. The 'Bavington-Medieval' clavichord

The fourth instrument, referred to as the 'BM' clavichord, was built by Peter Bavington (London) in 1988. It was a commissioned reconstruction of the clavichord depicted in stained glass (made *c*. 1439) in St Mary's Church, Warwick. As no medieval clavichord has survived, this instrument is an original design based on historical drawings and pictures of fifteenth-century clavichords. This is an octave, small-sized, instrument. All the strings are tuned in unison. The soundboard occupies the whole surface of the instrument, continuing under the keylevers. The bridge, in the form of a viol bridge, is very high. The present instrument is made with outstanding levels of craftsmanship and material quality. It is a very convincing attempt at reconstructing a medieval instrument, and a very fine and responsive musical instrument.

Figure 4. The BM clavichord.

2.5. Measurement methodology

For measurements, the instrument is installed in an acoustically treated highly damped soundproof booth. Four simultaneous signals are digitally recorded for each tone. The sampling rate is 48000 Hz for all the recordings:

- **Acoustic signal:** sound pressure is measured using a B&K 3265 measurement microphone and a B&K microphone pre-amplifier. The microphone is placed 30 cm above the centre of the soundboard (see the right-hand picture in Figure 5).
- **String/tangent contact signals:** two string-tangent contact signals are recorded, one for each string of a string pair. The tangent-string contact signal is obtained by using the tangent and string as a circuit

switch. An electrical signal is injected into the circuit on the tangent side. When the tangent is in contact with the string, the circuit is closed, and the signal is measured on the tuning pin. The contact clip on the tangent and the two alligator clips on the tuning pins are shown in Figure 5, left-hand and middle pictures.

- **Tangent motion signal:** the tangent motion is measured using a B&K 4374 miniature high sensitivity accelerometer attached to the keylever, close to the tangent, and a B&K 2692 charge amplifier. The charge amplifier is able to deliver the acceleration, velocity or displacement signals. According to a previous study by d'Alessandro et al. (2005), the logarithm of velocity is directly linked to loudness. Therefore in this study velocity is preferred to displacement and acceleration for characterizing the tangent motion. The accelerometer mass is small (≈0.75 g) compared to the key mass (≈20 g). One can therefore neglect the mass weighting effect of the accelerometer. The accelerometer and its position on the keylever are presented on the left-hand side of Figure 5.

Figure 5. Left: clip-on accelerometer and contact near the tangent; middle: contact signal on tuning pins; right: microphone. An additional contact microphone is visible on the soundboard.

An example of recording, the initial 100 ms portion of a tone, is displayed in Figure 6 (note g played on the BS clavichord). The top panel displays the acoustic signal (pressure signal recorded by the microphone); the middle panel displays the tangent velocity signal, and the bottom panel displays the string/tangent contact signals (a signal for each string in a pair). The vertical line indicates the instant of tangent string contact. Note that the sound begins before the contact: it is the finger/key motion noise. Then the string oscillation pattern begins after the contact.

The velocity signal can be broadly split into four main phases: rest, acceleration, deceleration, sustain. First, the key is at rest and the velocity is null. Then, the finger depresses the key and velocity increases. This second phase corresponds to almost constant acceleration, then to a constant velocity before contact. When the tangent hits the string, its velocity remains constant for about 1 ms. Then, in a third phase, the tangent velocity decreases towards zero, because the string is reacting on the tangent. During the fourth phase, the velocity pattern contains two superposed patterns. First, a small amplitude velocity oscillation results from the vibrating string motion reacting on the tangent. These oscillations are not very strong on this specific picture, but they can be significant, especially for low notes. Vibration of the string is transmitted to the finger, and it is usually also noticeable for the performer, at least for low notes. The second pattern varies more slowly. The velocity becomes slightly negative, and slowly returns to zero. One oscillation (with a frequency of about 50 Hz, period about 0.02 s) follows the contact, probably because of key flexion, or finger/key oscillation.

The contact signals show that both strings are excited almost simultaneously, and that the contact is maintained during the whole tone: the strings are not bouncing on the tangent. However, a closer examination of the two contact signals shows that some delay between excitation of the two strings in a pair occurs for some notes. Delays are of the order of a few (*e.g.*, 6) samples, at a sampling rate of 48000 Hz. Such a difference in timing, of about 125 µs (or 0.000125 ms), would introduce for the note a^1=415 Hz a phase difference of about 18°

between the excitation signal of the two strings. These figures will not be further interpreted here, but one can consider that the strings are excited simultaneously to a first approximation, at least for the majority of notes. For the highest notes, a quite significant difference in phase between the two strings may occur, depending on the tangent tilt. With a peak tangent velocity of about 1m/s (*i.e.*, 1 mm for 1 ms), and a tangent distance of a few mm, the travel time of the tangent between hitting the strings is a few ms (about 5 ms in the example of Figure 6).

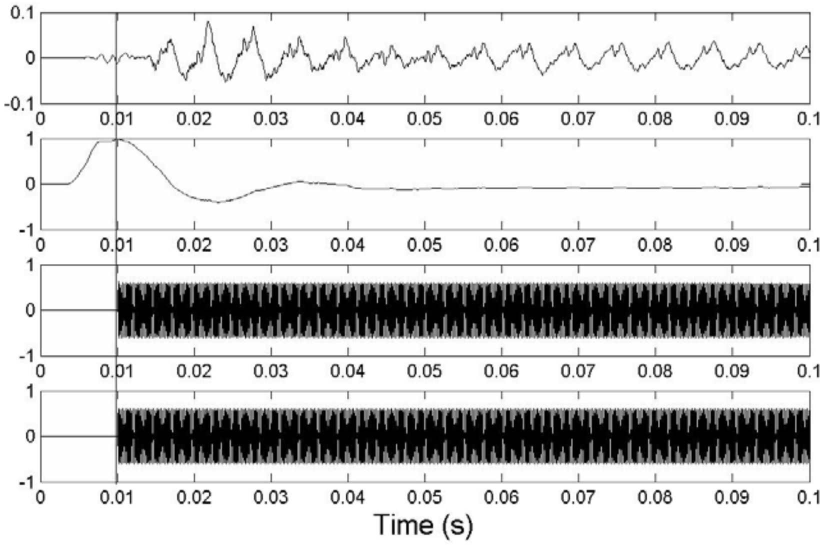

Figure 6. Acoustic signal, tangent velocity signal, and tangent/string contact signals for both strings, as a function of time (in seconds), at the beginning of a note (*g*, played on the BS clavichord).

For each instrument, all the notes were recorded with various intensities, ranging from the lowest audible sound level to the strongest possible tone that would not break or detune the strings. The same performer recorded all the notes. We believe that normal expressive playing of the instrument lies between the extremes we tried. For each note of the instrument, we recorded on average a dozen tones, *i.e.*, more than 600 tones (more than 2400 signals) for a 51-key instrument. The recordings were divided into individual tones using the string/tangent contact signals as time references.

3. Results

3.1. Tangent velocity

In a previous study, we have shown that tangent velocity is the main parameter controlling loudness for the clavichord. This is somewhat similar to the piano, replacing tangent velocity by hammer velocity.

The maximum velocity for each tone is derived from the velocity measurement exemplified above. The maximum velocity corresponds to the instant of impact between the tangent and string. In the measurement procedure, the player was asked, for each note on the keyboard, to repeat the tone from just noticeable pianissimo to the loudest possible fortissimo. All the velocities obtained for the four instruments are reported in Figure 7. The X- axis represents the key number (from 1 to 51, starting from the first key of the instrument, C for BS and DH, C/E for ZK, g for BM) and the Y-axis represents the peak tangent velocity, with a circle for each tone. Peak tangent velocities are expressed in metre/seconds.

Very soft tones give very small velocities. It is common experience that even the softest and slowest contact between string and tangent is likely to produce a (very soft) sound. On the opposite side, the maximum tangent speed seems to be around 1.5 metre/seconds.

Note that this velocity is measured at the tangent position, not at the finger position. This means that the actual finger speed depends also on the relative length of the keylever and the position of the pivot, *i.e.*, the leverage ratio. This varies a lot among instruments, and among individual keys for a given instrument. The player's gesture is directed towards the sound produced. Finger movements are always under the player's control, aiming at producing the sound, *i.e.*, the tangent velocity. Therefore, tangent velocity seems a better parameter than finger velocity for objective acoustic analysis.

A parameter influencing tangent velocity is the string/tangent distance at rest. When this distance is shorter (tangent closer to the strings) the velocity is lower than for a larger distance, just because the tangent displacement and acceleration are smaller. Other factors influencing the tangent velocity are the keylever dimensions, weights and balance. Finally, the hardness of touch will impede pitch stability, preventing players from playing too loud in such a case, as discussed in depth in Bavington (1997).

The range of tangent velocities is comparable for all the instruments. However, each instrument shows a specific 'velocity portrait'. It is difficult at this stage to interpret in detail these portraits, but one can sketch the following observations:

- **BS:** the main feature of this portrait is a bell-shaped contour for the maximal velocities. The first five notes and the last two or three notes of the instrument seem to have a markedly lower maximum velocity. On average, this instrument allows for the highest tangent velocities compared to the three other instruments.
- **DH:** one can notice a sort of gap in the middle register (centre of the keyboard). On average, the tangent velocity seems lower than for the BS. A slight increase in tangent velocity from bass to treble seems noticeable.
- **ZK:** this instrument seems relatively even in terms of tangent velocities.
- **BM:** this instrument, the smallest-sized, shows slower tangent motion compared to the other instruments in this collection. Maximum velocities are around 1.2–1.4 metre/seconds. This can be explained by the very short distance between tangents and strings, the very short keys, and the generally light and delicate construction of this clavichord, which does not invite the player to use brute force. Moreover, if the instrument is played with too much force, the sound lacks sustain and quality.

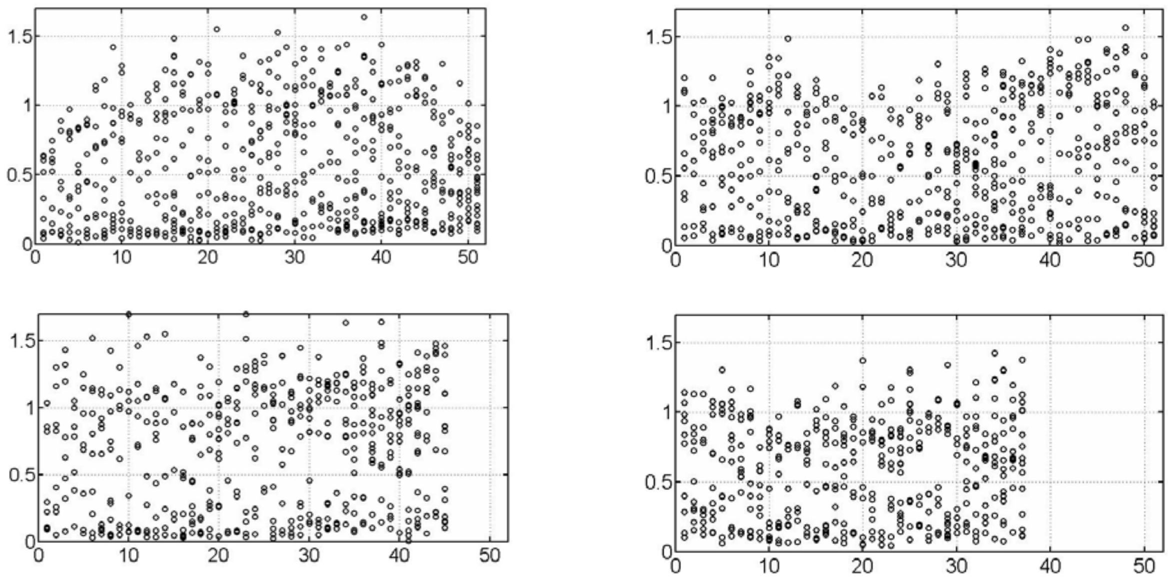

Figure 7. Peak velocities measured for all notes and various intensities. From top left to bottom right: BS, DH, ZK and BM clavichords.

An interesting by-product of these measurements is the number and distribution of velocity (*i.e.*, 'loudness') nuances. A perfect control of velocity would have resulted in evenly distributed and equally spaced circles for each note. This is apparently not the case, except for some notes. Many tones are grouped near the base line, with low velocities. Much note-to-note variation is noticeable.

3.2. Sound pressure level

A most prominent feature of the sound is its intensity, or sound pressure level (SPL). SPL features the sound 'power' of the instrument, and also the general balance or voicing between bass and trebles. The SPL is computed as the root mean square (RMS) value of a sound of a given duration. The dB (decibel) SPL is computed as 20 times the base 10 logarithm of this RMS value over a reference value of 20 μPa (micro Pascal; this value is taken as the threshold of hearing at 1000 Hz). In a previous work (2005) we have experimentally shown that SPL was a function of the logarithm of the tangent velocity. In the present work, measurements for all the tones of the four instruments studied are reported. SPL measurement is by nature an average measure, depending on some sort of time integration. We used two types of integration for measurement of SPL: 100 ms and 1 s. The shorter integration time gives an idea of SPL during the most powerful part of the tone, and the longer integration time gives SPL during the most significant duration of the tone. In addition to these two time constants, two forms of presentation are proposed. The raw data presentation shows the SPL for each tone. In order to make a smoother picture, unveiling tendencies, another presentation shows the smoothed curves.

As the tangent log velocity is the main parameter influencing SPL, different curves corresponding to velocities in a logarithmic progression are displayed. These are 'iso-velocity' contours, *i.e.* lines linking similar velocities for different notes. All the velocities are not available for some tones, because the velocity is not exactly controlled by the player. The exact velocity realized is known only after measurement. Then, velocities are grouped according to the following logarithmic categories: 0 – 0.056 m/s (dark blue, lowest contour), 0.056 – 0.1 m/s (green line), 0.1 – 0.18 m/s (red line), 0.18 – 0.32 m/s (blue line), 0.32 – 0.56 m/s (purple line), 0.56 – 1 m/s (yellow line), 1 – 1.8 m/s (grey, upper line).

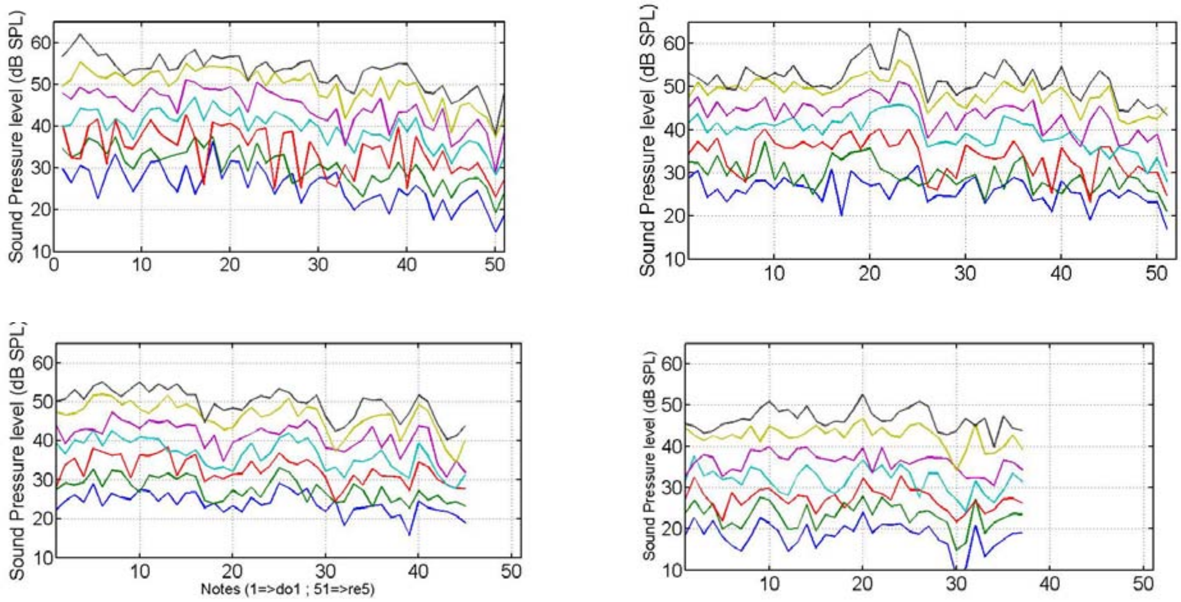

Figure 8. Sound Pressure Level (integration time, 1s) measured for all notes and velocities. From top left to bottom right: BS, DH, ZK and BM clavichords. Raw data. The different curves correspond to the same log velocities across notes.

Figure 8 shows the SPL obtained using one second integration time. The SPL portraits are different for the different instruments:

- **BS:** all the contours decrease in the treble. The SPL range is about 30 –60 dB in the bass and 15 – 45 dB in the treble. This instrument is the most powerful in terms of SPL.
- **DH:** all the contours also decrease in the treble, but the general picture is flatter than for the BS. The contours' maxima are located in the third octave of the instrument. The SPL range is on average between 20 and 55 dB, comparable to the BS above about a^1, but less powerful below a^1.
- **ZK:** contours for this instrument are very comparable to those of the DH, slightly more powerful in the bass. All the contours slowly decrease for low to high notes.
- **BM:** the contours are almost flat. This instrument is the softest in the collection, about 5 db on average lower than the DH or ZK, but remember that it is an octave instrument. It seems also to be the most equal in terms of power balance between the different registers of the instrument.

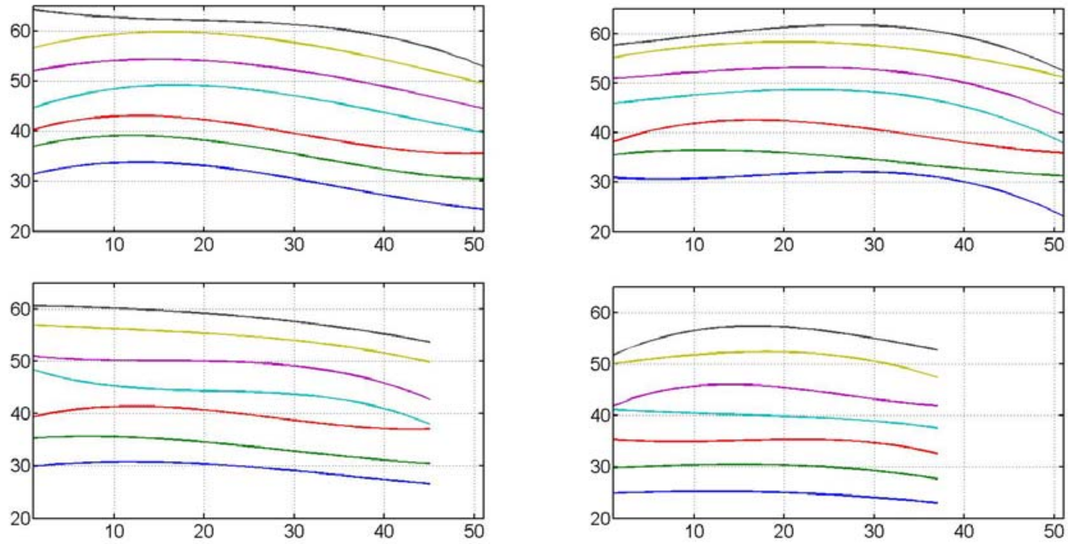

Figure 9. Sound Pressure Level (integration time, 100ms) measured for all notes and velocities. From top left to bottom right: BS, DH, ZK and BM clavichords. Raw data are smoothed. The different curves correspond to the same log velocities across notes.

Figure 9 shows the SPL obtained using one 100 ms integration time, concentrating more on the beginning of the tone. The SPL portraits are smoothed (a polynomial fit of raw data) in order to show tendencies. For all the instruments, the resulting SPL is higher than in Figure 8, because the sound of the clavichord is rapidly decreasing, so the average sound level is higher at the beginning of the tones. The contours are approximately equally spaced, with an increment of about 5 dB when the velocity doubles. Again the portraits are different for the different instruments:

- **BS:** the contours are bell-shaped, with a maximum in octaves 2 and 3 of the keyboard, in the tenor register. This instrument is the most powerful in terms of SPL.
- **DH:** all the contours are also bell-shaped, but with maxima in the centre of the keyboard, in the alto and treble registers.
- **ZK:** contours for this instrument decrease from bass to treble.
- **BM:** again the contours are almost flat, with a small decrease in the treble. This instrument is the softest in the collection, about 5 dB on average lower that the DH or ZK.

The loudness measurements obtained are in general agreement with those reported by Thwaites and Fletcher (1981). The instrument used for their study was the same model as ZK, and the microphone was at 1 m from the soundboard. They obtained a maximum of 55 dB SPL (doubling the distance would reduce the SPL by 6 dB). However, the integration time is not specified in their study. In our previous study (d'Alessandro et al. 2005) we obtained higher values, but the microphone was closer to the soundboard and maximum SPL was used instead of RMS SPL.

3.3. Decay times

An important feature of the clavichord's sound quality is decay time. Clavichord tones decay rapidly, with an exponential envelope. Decay times depend of course on the strength of initial excitation, but also on many other aspects that are difficult to quantify in detail. Decay time is therefore a global description of the instrument, another facet of its portrait. Following the methodology used for measurement of reverberation time in rooms, decay time is computed as the interval of time for a given attenuation. Decay times are reported in Figure 10.

The dark blue lines represent decay times for an attenuation of 20 dB, the green lines for an attenuation of 15 dB, the red lines for an attenuation of 10 dB and the light blue line for an attenuation of 5 dB. These decay times are almost independent of the initial velocity. The decay patterns are very comparable across different velocities. Thwaites and Fletcher (1981) measured the 'decay-time to inaudibility' (or subjective duration of the tone), reporting huge differences between notes, from 10 s (around c) to apparently less than 0.1 s (for the highest notes). This would correspond to a very badly voiced clavichord. However, the methodology used (*i.e.*, measurements by two experimenters using a stopwatch) is by nature very inaccurate. Decay time to inaudibility is in our opinion not a very significant feature, because it very much depends on the measurement conditions (distance to the instrument, acoustic environment and background noise) and because it does not reflect the actual listening situation of a musical performance. Information on the effective duration of the tones can be derived from the decay time contours. For instance, if a tone has an initial SPL of, say, 50 dB, and a decay time of 1s for 20 dB, its effective duration, or decay time to inaudibility, will be about 2.5 s.

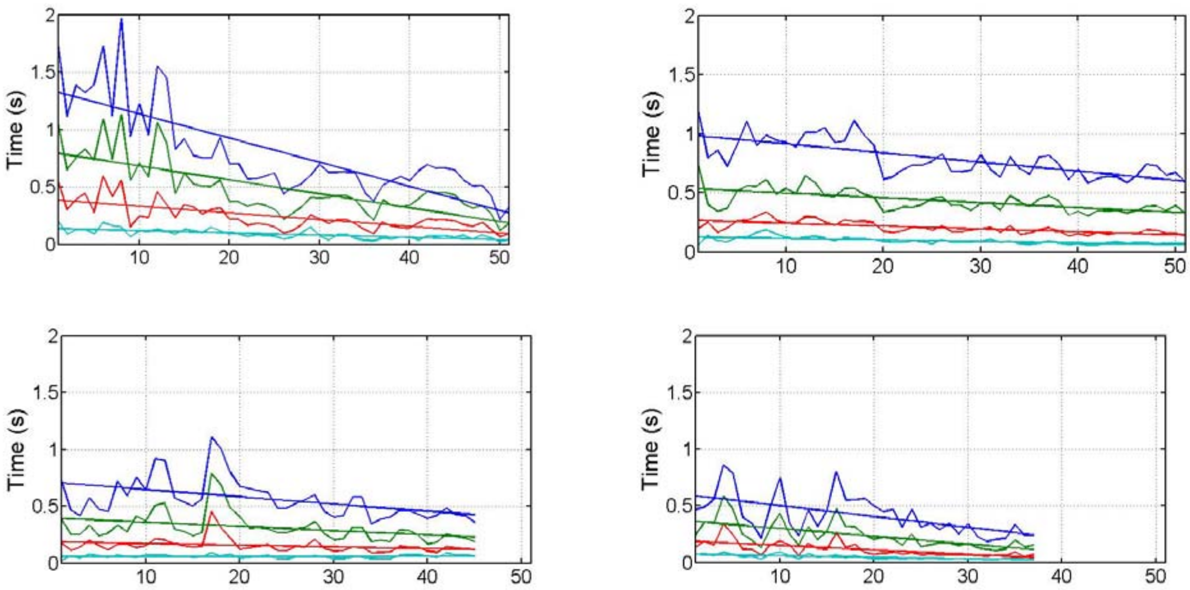

Figure 10. Decay times to 20 dB. From top left to bottom right: BS, DH, ZK and BM clavichords.

Individual features of the instruments can be summarized as:

- **BS:** the first octaves exhibit the longest decay time of all the instruments, with noticeable note to note variation. Decay time rapidly decreases for higher notes, with only modest values in the last octave.
- **DH:** this instrument is more equal on the whole range, varying from 1 to 0.6 s for the 20 dB decay time. It seems more balanced and on average longer-lasting than the BS.
- **ZK:** contours for this instrument decrease from bass to treble.
- **BM:** this instrument is well balanced in terms of decay times, with a peak in the second octave. Globally, decay times are shorter than for the first two instruments.

4. Summary of findings

A measurement methodology (including the player and the instrument) has been defined and tested on four instruments. All the notes have been measured for all the instruments, using the whole possible range of dynamic nuances. All measurements include four signals, the acoustic signal, the tangent velocity signal and the string/tangent contact signal for each string in a pair.

A first output of this study is the signal database itself, which can be used for further studies, and which is much like a photograph of each instrument. As in a photograph, the acoustic portrait fixes a given state of the instrument at a given point in time, with specific conditions (tuning, temperature and humidity, room acoustic, measuring conditions etc.). Several portraits taken under different conditions are likely to show different features on some aspects. However, one of our aims was also to propose a methodology for making 'robot portraits' of the clavichord, *i.e.*, portraits made under given fixed conditions, for the sake of instrument comparison.

Objective data have been derived from acoustic analyses. A first result is related to the action. Tangent velocity has been measured, showing rather similar values for all the instruments. This is not surprising, as, in a first approach, all the instruments are played with a similar technique. However, a more detailed observation unveils individual differences between the four instruments. These differences are certainly significant for the playability and sound of the instrument. The SPL contours confirmed that tangent velocity is directly linked to the power of the instrument, in a rather similar manner for all the instruments studied. The SPL portraits give important information on the sound of the instruments and on their voicing. The decay time portraits are objective indications of their ability to sustain sound, and then of their singing quality. We shall not discuss in detail the three types of portraits obtained for each instrument, but note that the subjective impression given by each instrument is in many cases very well reflected in their portraits, in terms of power, sustain and even mechanical feeling.

5. Future work

Apart from velocity, loudness and duration portraits, timbre portraits would be needed for descriptions of sound quality. Timbre portraits would contain descriptions of the spectral content and spectral evolution of the tones. These portraits have not been analysed in detail for the moment, and will be the subject of future work.

Another line of research concerns the player. Studies of the velocity and force patterns of different players will be conducted in order to approach the question of individual differences and expressive musical interpretation. This could also be of value for pedagogy and performance studies.

Finally, systematic comparison of a larger collection of instruments would give a better picture of the main acoustic features of the clavichord in general and of the specificities of particular instruments.

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Abstract

The aim of the present research is to measure a number of acoustical and mechanical features that are associated with the sound (dynamics, duration) and playability (dynamic range, key velocity) for four clavichords. Acoustic signals, string-tangent contact signals and tangent motion signals (acceleration, velocity, and displacement) are simultaneously recorded. Several dynamic nuances are recorded for all the notes of the four instruments. The resulting database contains about 2000 items (sets of four signals for each note). Each of the four instruments is portrayed in terms of acoustic analyses, including tangent peak velocity, Sound Pressure Level (SPL) and decay time. These portraits give a first approach to objective comparison among instruments, and objective evaluation of voicing.