ON THE ACOUSTICS OF THE CLAVICHORD

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1. Historical review

The earliest paper on the acoustics of the clavichord found to date by the authors was published by Trendelenburg *et al.* in 1940. It presents a comparative analysis of clavichord, piano, and harpsichord sounds using octave band oscillograms. Octave band oscillogram analysis is one of the earlier techniques of time-frequency analysis by which the sound signal is filtered using octave band analogue filters, and the resulting filtered signals are observed on an oscilloscope. Through this frequency separation technique it is possible to observe octave band energy distribution differences between the different instruments. In the time domain it appears that different types of articulation (staccato, legato, and phrasing) result in different oscillogram 'patterns'. This analysis technique is outperformed by modern time-frequency representation theories, making this paper of little more than historical interest.

A subsequent and notable work is by Hands (1967), who presents the results of a series of experiments in building a clavichord model, varying many construction parameters (key weight, string tension, soundboard thickness, varnish, etc.). The main conclusions are the following:

- The strings should be as massive as possible so that their tension will be as high as possible. This should minimize stretching of the strings after the initial excitation, which should then provide maximal loudness because the greatest proportion of tangent energy is used for the acoustic excitation of the instrument, and not for static stretching of the strings.
- Trials on the soundboard material and varnish (including a glass soundboard!) are rather inconclusive. The paper does mention the fact that the requirements of loudness and duration are mutually conflicting: 'the energy originally imparted to a string may be rapidly disseminated into the air by a very flexible surface, producing great initial volume which rapidly decreases (as in the banjo), or more slowly disseminated by a stiffer surface (as in the modern piano, which produces at the same time its great volume only by using a great deal of energy initially).'
- Considering that a significant proportion of energy is dissipated at the tangent extremity, it is suggested that massive keys would result in longer note duration. Heavy keys (90 g) produced a longer duration except for the first octave of the instrument, below about *d*. Key weight is typically on the order of 20 g.

In summary, Hands' work raises several inspiring questions for instrument makers: What are the advantages of using thick strings? What is the influence of key weight? What would be the optimal string/soundboard coupling? Practical answers to these questions are also provided, but evaluation of the results is only *qualitative*, using informal listening.

Burhans (1973) addressed the problem of clavichord amplification, using a contact microphone. The clavichord model used was designed by the author, and has little in common with historical models. The main goal was to amplify the clavichord in order to make it available for large concert audiences and ensemble music. The results obtained seem outdated nowadays and outperformed by more recent audio technology. The actual acoustics of the instrument are only alluded to in the course of the paper.

The work of Benade (1976) is included in this historical summary for reference, as it cites the clavichord, though it deals only marginally with it. Sound production in the clavichord is briefly discussed in chapter 18 of the book. Benade predicts bounces in the contact between tangent and string in the initial part of the sound. However such bouncing has not been observed in our own or others' experiments, at least under normal playing condition.

The most significant paper on the acoustics of the clavichord to date is that of Thwaites and Fletcher (1981). It first describes a simple model of string excitation, which is then used to predict the force exerted by the string on the bridge. However, no measurements of this force are provided to validate the model. Following the observation of the decay patterns of the string waveform, it is suggested that the theory of Weinreich (1977) for the interaction of two piano strings at the bridge would also hold for the clavichord (this is discussed further in section 2.1 below). The majority of the paper concerns the soundboard. Measurements and models of the soundboard vibration modes and soundbox cavity modes are provided. The roles played by the acoustic resonance of the soundbox and by the soundboard plate modes are demonstrated and described by acoustic models. Electrical analogue networks representing the coupling between air cavity and the soundboard plate modes show good agreement with the measured soundboard admittance curve. The final results presented give measurements for the average sound pressure level (SPL) and the decay time to inaudibility of the instrument. The mean SPL is 48 dB at a distance of one metre from the soundboard. The decay time to inaudibility decreases from bass to treble. Three regions were observed. In the bass, considerable variations were found, between about four and ten seconds. The decay time is almost constant (about 4 sec) in most of the midrange of the instrument, followed by a sharp decline in the treble, with times of less than one second. A summary of this work can also be found in the book on musical acoustics by Fletcher and Rossing (1991).

Hall conducted in-depth investigations on piano string excitation and published a series of papers on this topic. In a review paper, Hall (1993) also addressed the problem of string excitation for the clavichord. However, after several attempts to construct a model, it was acknowledged that no satisfactory results had been obtained. Thus, the paper is somewhat inconclusive, though a spectrum slope of about −6dB/octave is predicted for the string motion.

Building on the acoustic description of the clavichord by Thwaites and Fletcher, Välimaki *et al.* (2003) proposed a digital model for clavichord sound synthesis. This model is based on a sound database for the attack and release noises, and on a digital waveguide model for the sustained part of the string vibration. The effect of the soundboard is introduced as an impulse response in the digital waveguide model. The sound of the digital instrument resembles the clavichord sound. However the digital instrument lacks one of the most interesting features of the acoustic instrument from the musician's point of view: direct and continuous control of the string by the finger.

Finally, sympathetic resonance in the clavichord has recently been studied by d'Alessandro and Katz (2004). That work is summarized below in section 3.

This paper presents two recent studies involving the acoustic of the clavichord. Section 2 describes experiments on the acoustic effect of dynamic nuances. Section 3 concerns the effect of sympathetic strings. This work concludes with a discussion of possible paths for future work on the acoustics of the clavichord.

2. Dynamics of the clavichord

2.1. Instrument and measurements

The instrument used for this study was a Zuckermann kit 'king of Sweden model', built by E. Brottier and M. Ducornet. This model is based on an anonymous seventeenth-century north German instrument (compass C/E_1–c^3, short octave, fretted by 2 and 3). For these experiments the instrument has been equally tempered, a whole tone higher than standard modern pitch (g^1 = 440 Hz). Note that this instrument is the same model that was built and used in the study by Thwaites and Fletcher (1981). The instrument was installed in an acoustically treated highly damped sound-proof booth. Acoustic measurements were made with a measurement microphone 30 cm above the soundboard. Simultaneous recordings of sound, tangent acceleration, and tangent/string contact signals were made. The tangent velocity and displacement were then later derived from the acceleration signal. The tangent-string contact signal was obtained by using the tangent and string as a circuit switch: when the tangent was in contact with the string, the circuit was closed. By constantly monitoring the tangent-string contact, it was possible to verify that contact was always maintained while depressing the key. The acceleration signal was obtained using an accelerometer attached to the key, just below the tangent. The mass of the accelerometer was small (mass ≈ 2.2 g) in comparison to that of the keys (mass ≈ 20 g) by a factor of ten.

Table 1 gives an example of the acceleration, velocity, displacement, and sound pressure levels obtained when playing nuances from *pianissimo* to *fortissimo* for the note g^1 (g^1 = 440 Hz).

Acceleration (m/s²)	Velocity (m/s)	Displacement (mm)	SPL(dB)
0.46	0.003	0.14	48.8
1.48	0.007	0.35	60.2
48.97	0.208	2.83	72.3
56.78	0.225	2.92	73.0
137.65	0.400	3.46	76.6
195.56	0.522	3.80	76.8
304.41	0.736	4.50	79.9
529.96	1.077	5.74	83.6
621.94	1.172	6.51	85.2

Table 1. Peak acceleration, velocity, displacement, and SPL for various dynamic conditions, note g^1 = 440 Hz

2.1. Waveform, time decay pattern, and sustain time

A typical clavichord note is represented in Figure 1, in which the sound pressure level as a function of time is shown with the corresponding spectrogram. The spectrogram is a time-frequency representation of the evolution over time of the spectral magnitude. The harmonic structure of the clavichord sound is identified by the presence of the parallel lines at frequencies which are integer multiples of the fundamental frequency.

In this figure the string is struck by the tangent at approximate time reference of 0.2 sec and the key is released at approximately 3.5 sec (tangent and string no longer in contact). The tone can be decomposed into four successive acoustic phases. The first phase is the attack, with duration of only about 0.01 sec. This initial phase produces a transient noise, before the establishment of periodic string vibration, including mechanic noise resulting from the tangent/string shock. After the attack, the curve transitions into two components with quite different decay rates. The initial portion, termed 'prompt sound', decays rapidly, lasting 0.30 – 0.40 sec. The second portion, termed 'aftersound', decays at a much slower rate. The final phase, the key release, is identified by the production of a short transient noise, at time 3.5 sec, and the subsequent damping of the string by the felt.

The two-part decay process (or double slope decay) is typical of a double-strung instrument. A physical explanation of this phenomenon is found in Weinreich (1977) in the case of piano strings. It results from the coupling of string movement through the bridge. The same analysis appears to hold valid for clavichord strings. To summarize, in the first phase both strings are moving the bridge in a coherent manner (in-phase), resulting in high amplitude and rapid damping of the bridge movement. Then, because of imperfect tuning the string movements become out of phase, and they exert less coherent force on the bridge, resulting in lower amplitude and slower damping.

In the frequency domain (see Figure 1), the attack is seen as a vertical line and corresponds to a broadband excitation. Following the attack, the prompt sound appears as a rich spectrum rapidly decaying in time. The aftersound continues, containing few harmonics (about five). Release of the key produces again a broadband noise, though less energetic than the attack, after which the remaining harmonics decay rapidly.

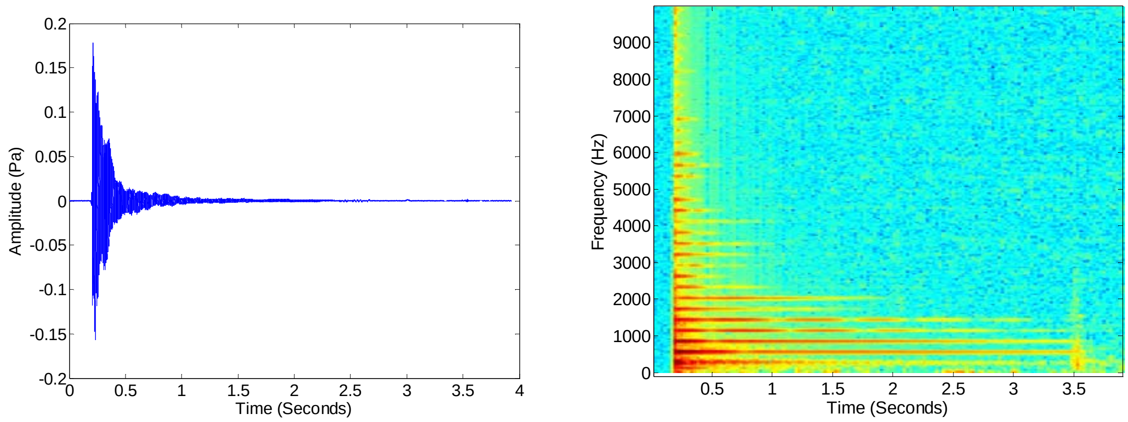

Figure 1: Oscillogram (left) and spectrogram (right) for a d^1

Prompt sound is mainly responsible for the loudness of tone. It is also mainly responsible for the tone 'colour', because during the prompt sound spectral richness is maximum. This effect corresponds to a strong coupling of the string and soundboard, with high vibrating amplitudes and a rapid decay rate. The aftersound is mainly responsible for sustain of the sound, its 'singing' quality, in which the higher harmonics decay rapidly. This sustain can be sufficiently long for rendering slowly moving polyphonic voices. In the authors' measurements the 'prompt sound' had durations of 0.3 – 1 sec, depending on the note. It is shorter in the treble tones and longer in the bass.

2.2. Sound pressure level

An important parameter of clavichord loudness is the maximum sound pressure level for a given note. Figure 2 shows the measured maximum sound pressure level of the instrument for extremely soft and loud notes. There is a great deal of variability for the soft condition, as it is highly dependent on the ability of the experimenter to control the key.

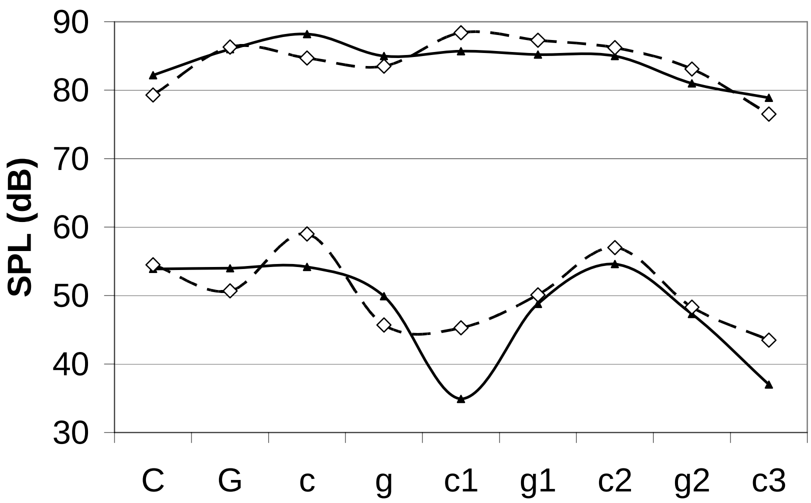

Figure 2. Maximum (top) and minimum (bottom) sound pressure levels measured 30 cm above the soundboard. Normal curves: normal condition. Dashed curves: sympathetic strings damped

The measured dynamics of the instrument (the difference between the softest and loudest tones) cover a range of 28 – 50 dB. The maximum SPL of the instrument is relatively constant over the whole compass, with loudness decreasing at the extreme bass and treble. The background noise level in the recording booth was about 30 dB SPL.

These results cannot be directly compared to those of Thwaites and Fletcher (1981), who also reported SPL measurements. Their study employed 'deaf' players, players who wore headphones with masking noise in order to prevent them from compensating automatically for the perceived intensity. The aim was to strike the notes exactly evenly, with an average level, contrary to the present study, which uses *fortissimo* and *pianissimo* tones. The data obtained by Thwaites and Fletcher are on average 30 dB lower. This can be explained by the greater distance between the soundboard and microphone they used (about one metre instead of the thirty centimetres we used: an attenuation of about 10 dB results from the distance difference). A second difference is that their subjects played on average more softly than our *fortissimo* condition. A third difference is that they reported mean sound pressure levels whereas we reported peak sound pressure levels.

Maximum sound pressure level was studied as a function of tangent velocity (*i.e.* key control by the player). The results show a linear relationship between the SPL (in decibels) and the logarithm of the tangent velocity. Figure 3 displays the results obtained for the note d^1. The slope of the curve is about 18 dB per decade of velocity. This result shows that the player's main technique for controlling loudness is to control the tangent velocity, *i.e.* the key velocity. This is accords with the common experience of the musician: playing louder is not a matter of force or pressure, but more a matter of the velocity of the finger movement.

The linear relationship between the logarithm of the tangent velocity and maximum SPL can be observed for all the tones. However, the slope of this relationship is steeper in the treble: it is 25 dB/decade of velocity for d^3. This means that, for the bass, to achieve the same difference in dynamics requires a larger difference in key velocity compared to the treble.

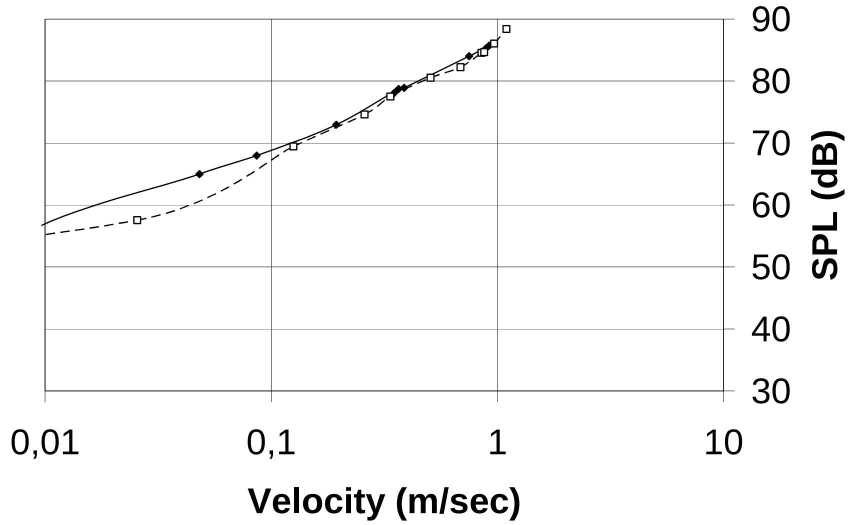

Figure 3. Sound pressure level as a function of tangent velocity: note d^1 played from *pianissimo* to *fortissimo.* Normal curves: normal condition. Dashed curves: sympathetic strings damped

2.3. Spectral richness and spectral slope

An important acoustic feature of loudness is spectral richness. This feature can be investigated using analysis of the spectral slope or spectral tilt. The spectral tilt is the reduction in amplitude of the harmonics relative to the fundamental, measured in dB/octave. For the clavichord, as for most musical instruments, the amplitudes of higher harmonics decrease as a function of the harmonic number. If the spectral slope is shallow or small, the sound will be spectrally rich (many audible harmonics), while a steep spectral slope corresponds to a poorer sound (comparatively less harmonics remain audible). Spectral slope is measured on the prompt sound, where the higher harmonics are present.

In most musical instruments, the piano for instance, the main difference between a note played *piano* and a note played *forte* is spectral richness. In *piano* playing, only the fundamental frequency and a few harmonics are produced because the hammer head appears soft to the string as it is relatively weakly compressed. On the contrary, in *forte* playing the hammer head is more compressed and therefore it behaves in a more rigid manner. This effect produces higher harmonics in the resulting sound, and hence a smaller spectral slope (Hall, 1993).

In the case of the clavichord, the tangent is made of hard material, a situation similar to the hard hammer condition of the piano. Due to this fact, the sound should be spectrally rich, with a small spectral slope. This corresponds to the results observed in the spectrogram of Figure 1 for the prompt sound (for further information see the discussion on piano, harpsichord and clavichord excitation mechanism in Hall, 1993).

An important question which can be raised is the variation of spectral richness as a function of the dynamics (*piano* vs. *forte* conditions). Measurements of spectral slope have been performed for a variety of tones and dynamic nuances. The acceleration signals assist in controlling the tangent dynamics. Results for a note d^1 are shown in Figure 4, which presents the harmonic amplitude as a function of frequency, measured at the beginning of the tones. One can observe that the tendencies of the curves corresponding to the *forte* and *piano* conditions are very similar. This indicates that there is almost no change in spectral slope, *i.e.* in spectral richness, between the *forte* and *piano* tones. In contrast to the piano and other musical instruments (including the human voice), dynamic nuances in the clavichord do not result in changes in spectral richness: even very weak sounds are spectrally rich.

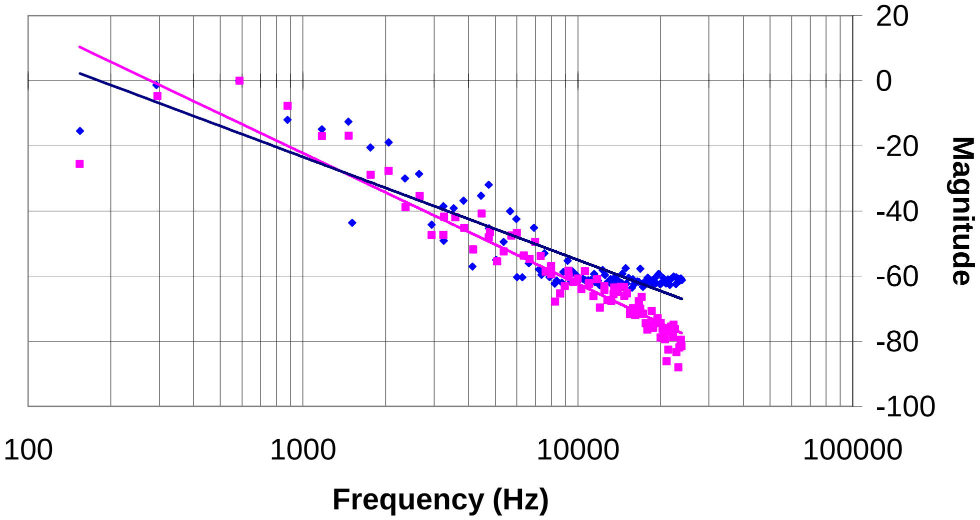

Figure 4. Spectral slope: spectral magnitude as a function of frequency, note d[1]. Blue curve: note played *pianissimo*, red curve: note played *fortissimo*.

A special feature of the clavichord is the direct control of the string by the finger through the action and tangent. The player must control both the key velocity (as in the piano) and also the key displacement (unlike the piano, where the key is stopped by the mechanism). If the key displacement is not kept under control, the tone is detuned.

2.4. Summary: acoustic correlates of dynamic nuances

The findings of the current measurement and analysis study of the clavichord have shown the following regarding the acoustic effect of dynamic nuances:

- The main acoustic correlate of dynamic variations is the sound pressure level.
- Spectral slope variations and decay rate of the prompt sound do not vary significantly between different dynamic conditions.
- The maximum SPL of the instrument at 30cm is 85 dB. The maximum sound pressure level difference between *pianissimo* and *fortissimo* conditions for a given tone is about 50dB.

In addition, fundamental frequency variations and attack and release noises are also an indication of dynamics, but are generally considered undesirable. Measurements of these effects are outside the scope of the present study.

The clavichord shows a specific behaviour in terms of dynamics, compared to other stringed instruments. In the harpsichord, the SPL is almost constant, whatever the velocity of the action. Spectral richness is also almost invariable, but the sound is spectrally rich. In the piano, both SPL and spectral richness vary as a function of action velocity, but the spectral richness is always limited. The clavichord situation lies in between. When the action velocity increases, the SPL also increases, but the spectral richness does not change much.

3. Reverberation and the sympathetic strings

3.1. Instrument and measurements

In the clavichord the slanted strings between the bridge and the tuning pins are not damped with felt, unlike in the piano. Adlung, cited in Brauchli (1998), noted in 1768 that these portions of the strings 'vibrate *cum Sympathia*' and that 'the agreeable singing of the clavichord will be markedly enhanced'. These parts of the strings will here be called the 'sympathetic strings', and the other part of the strings the 'played strings'.

The instrument used in this study was designed by A. Sidey and built in 1983 by F. Bal. This model follows a south German eighteenth-century unfretted instrument (a kit based on the same design by A. Sidey was used by Välimaki *et al*. (2003)). The compass of the instrument is 51 notes (C–d^3), each comprising a pair of strings (102 strings in total). All the strings are in yellow brass, the vibrating length of the strings varies between 9.5 and 89 cm, and their diameter is between 0.25 and 0.55 mm. For this experiment, the instrument has been equally tempered, using standard pitch ($a^1 = 440$ Hz). The length of the sympathetic strings varies between 8 (note C) and 23 cm (note g). This corresponds to the lengths of the played strings for the fourth octave of the instrument (d^3 = 9.5 cm → c^2 = 23 cm). As the string tension is equal on both sides of the bridge-pin, the pitch of the sympathetic strings should correspond to this higher octave. The pitch of these strings has been measured and is shown in Figure 5. The pitches of the 102 strings are distributed within an octave between c^2 and b^2.

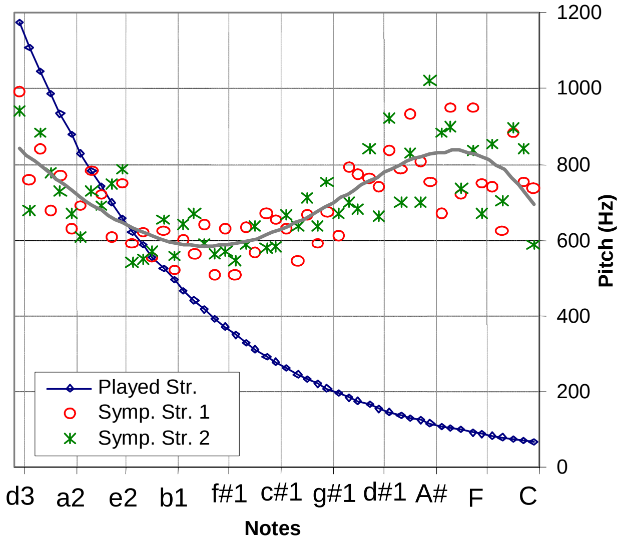

Figure 5. Tuning of the sympathetic strings: green crosses: first string of a pair; red circles: second string of a pair; blue circle: played strings

As expected, this distribution follows the geometric pattern of the bridge itself as the string tension is almost constant for all the strings and the material is the same, whereby the vibrating lengths determine the pitch. As no fundamental is below c^2 (~500 Hz), and as the string spectra are rich in harmonics, the overall response of the sympathetic strings is likely to be high-pass, with little energy under 500 Hz. The ensemble of sympathetic strings is excited through coupling of the bridge when any key is pressed. In this manner, these strings can be considered as a passive reverberation filter, with a base bandwidth of an octave and with a high-pass gain.

In addition to the sympathetic strings, the played strings are not perfectly damped by the felt damper, particularly in the case of the lower notes. In the instrument studied, the first two notes (C–CT) produce a significant sound when plucked, despite the felt damper. The next six to seven notes produce a somewhat precise and loud tone as well. This means that even if the sympathetic strings are damped, some sympathetic resonances can be produced by the lower played strings. In the sound production process, one must consider three possible sources of reverberation: the bass played strings, the sympathetic strings, and the soundboard cavity. Acoustic measurements were performed under the following eight possible conditions: all free (natural state), played strings damped using a felt damper, sympathetic strings damped, cavity damped using a foam damper inside the box and mouse-hole, sympathetic strings and cavity damped, played strings and cavity damped, both played and sympathetic strings damped, and finally both played and sympathetic strings and cavity damped.

Impulse responses of the system under the eight conditions have been measured by excitation of the bridge of the instrument with an impulse hammer at the points corresponding to C, c, c^1, c^2, c^3 and FT, fT, fT^1, fT^2 and in front of and behind the bridge. The corresponding acoustic signal was recorded (32bit, 96 kHz sampling rate) using an omni-directional microphone centred 40cm above the plane of the strings.

The reverberation effect of sympathetic strings when playing the instrument is demonstrated in Figure 6.

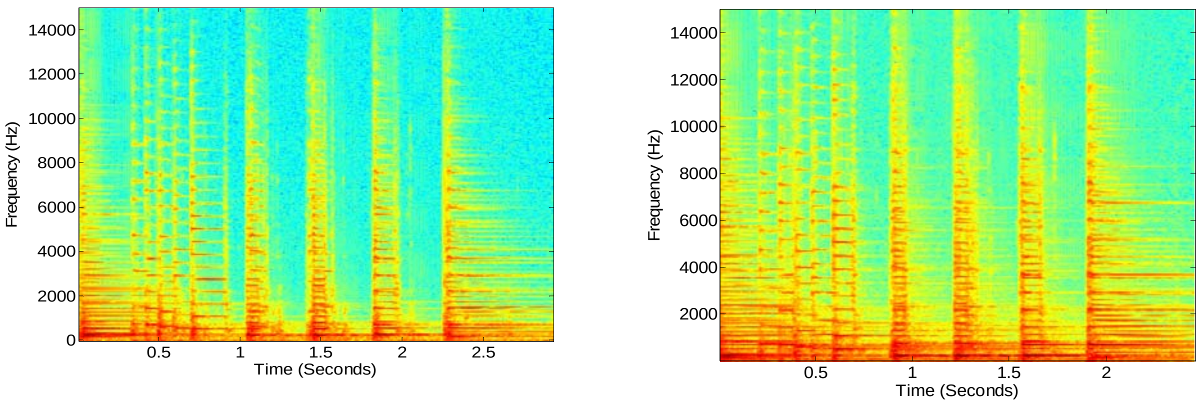

Figure 6. Spectrograms of a short music excerpt.
Left-hand panel : sympathetic strings damped. Right-hand panel : normal condition

In the normal playing condition (right-hand panel) some prolongations of the tones and chords played are visible in the articulation silence between tones. On the contrary, there is almost no energy between tones in the condition with sympathetic strings damped (left-hand panel); the sound is ‘dry’. However, some resonance appears in the 0 – 800 Hz band. This effect might be due to resonances of the first played strings, which are poorly damped.

3.2. Impulse response analysis

Decay rates have been calculated according to the procedures developed for room acoustics, using the reverse integration of the impulse response, as described in Room acoustic measurement standard ISO 3382 (2000). An example of the decay response in octave bands of the instrument (without damping) is shown in Figure 7. Peak levels have been normalized and the curves terminate 10 dB above the noise floor.

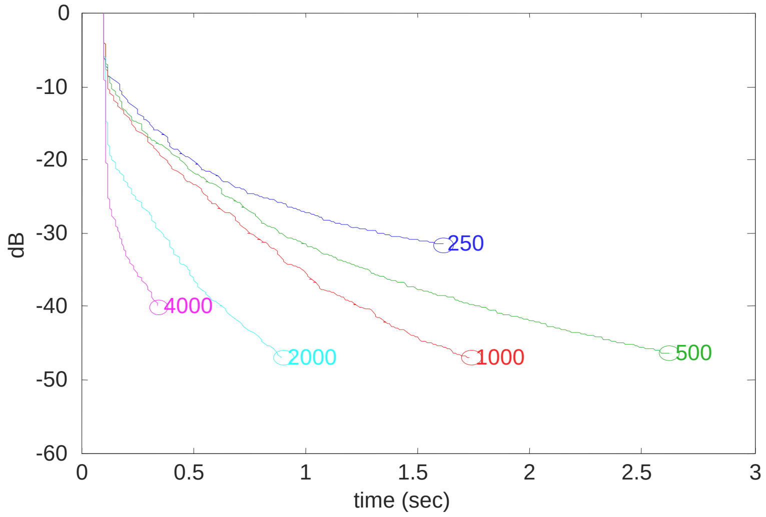

Figure 7. Normalized octave band decay curve response for the undamped instrument

The early and late parts of the decay have been estimated separately, following methods for reverberation time calculations using a linear fit to estimate the decay rate and extrapolation to the time necessary for a 60 dB reduction in level (RT60). *RT early* corresponds to a linear fit of the first 10 dB of decay (starting 5 milliseconds after the initial excitation attack); *RT late* corresponds to the last 10 dB of clean decay, before the background noise compromises the measurement (results are shown in Figure 8).

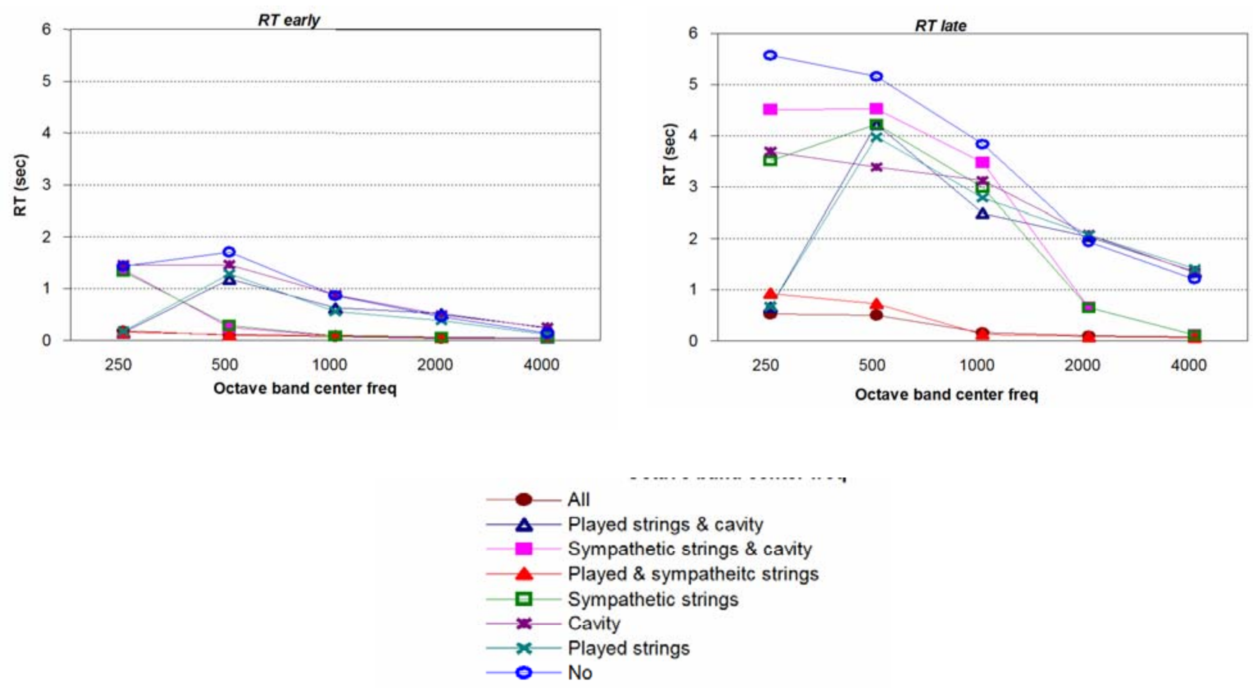

Figure 8. Decay times of the clavichord

Results are calculated averages over the nine excitation points on the bridge and the two excitation points on the soundboard. Figure 8 can be interpreted as follows: *R Tearly* shows that the played strings provide some reverberation in the 250 Hz band. This is in accordance with the sympathetic resonance of the first bass strings. The sympathetic strings provide reverberation in the 500 Hz – 4 kHz bands. This is also in accordance with the high-pass tuning of the sympathetic strings. The combined effect is a broadband reverberation. It appears that damping the acoustic cavity response results in no effect for *R Tearly*. The late response of the decay curve, quantified using *R Tlate*, is rather different. The playing strings still provide reverberation in the lower bands, up to 1 kHz in some conditions. The cavity has some effect in the 250 Hz – 1 kHz band. Finally, the sympathetic strings provide reverberation in the 2 – 4 kHz band.

3.3. Summary: the effect of sympathetic strings

The sympathetic strings of the clavichord appear to provide high-pass reverberation, being mainly effective above 500 Hz. After the first 0.2 – 0.6 sec of the tones, and for low notes, there is also a noticeable effect of the low played strings that are not well damped (the amount of felt damper is less for the low notes). Resonances of the cavity seem to play little role in the early part of the note, but have some effect later, for lower rank harmonics.

Sympathetic strings are significant for the clavichord for many reasons. Its sound is generally quiet, thus the auditory experience is very concentrated and close, allowing relatively small effects to be perceived as significant. The clavichord is a rather percussive instrument: reverberation is a useful means to enhance tone duration, especially as the clavichord is often played in smaller rooms which typically have a less pronounced acoustic.

4. Conclusion and future work

To date, very few studies have been devoted to investigating the acoustic of the clavichord. This is probably because, in contrast to the piano, violin, or guitar, clavichord building never reached an industrial stage. Acoustic studies, through the use of calibrated measurements, are desirable to accurately assess the influence of specific design aspects such as variations in shape and material. Several open questions remain concerning the physics of sound production in the clavichord. The point that requires the most investigation, in our opinion, concerns string excitation and string motion, including the influence of the moving tangent extremity. Other important questions regard soundboard vibration patterns and string/soundboard coupling.

Acoustic documentation of historical instruments would be highly desirable. Ideally this documentation would include the recording of radiated sounds, soundboard impulse responses, impedance and modal analyses, soundboard resonance frequencies, radiation patterns, action acceleration, sympathetic string tuning, string tension etc. These measurements could be used for understanding the subtle differences between different designs, and possibly for designing new instruments.

Another challenging domain for acoustic studies is the player/instrument loop. Analysis of player control movement would help for musical analysis, musical interpretation, and keyboard pedagogy. It would also be inspiring for the design of new interfaces for musical expression.

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ABSTRACT

Among keyboard instruments, the clavichord is a unique combination of simplicity of action and subtlety of building and playing. To date only a few studies have been devoted to investigating the acoustic of this quiet instrument. The aim of this paper is to report two experiments recently conducted by the authors. The first experiment addresses the effect of dynamic nuances on the clavichord tones. Measurements of tangent acceleration, velocity and motion are provided. The main findings are: the amplitude of the instrument covers a dynamic range of about 50 dB; the presence of a linear relationship between sound pressure level and the velocity of the tangent; and the absence of increased spectral richness with loudness, contrary to the piano. The second experiment deals with the effect of sympathetic resonance in the clavichord sound. The sympathetic strings of the clavichord respond as a type of reverberation, being mainly effective above 500 Hz. There is also a noticeable reverberant effect from the lowest played notes, which are not well damped.

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