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## Tonal quality of the clavichord: the effect of sympathetic strings

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### Abstract

In the clavichord, unlike the piano, the slanting strings between the bridge and the hitch pins are not damped with felt. The effect of these “sympathetic strings” on the tonal quality of the clavichord has been studied. The instrument studied is based on an unfretted XVIII<sup>th</sup> century south German clavichord. Impulse responses of the soundboard have been recorded under all the combinations of damping of the strings between bridge and hitch-pins, damping of the played strings, and damping of the soundboard cavity. Individual tones and music have also been recorded under the various conditions. Impulses responses have been analyzed using the rate of amplitude decay in octave bands. Individual tones and music segments have been analyzed in time and frequency domains. The results show a significant effect of the sympathetic strings on the tonal quality of the instrument: sound duration is significantly increased and the spectrum is enhanced. This is well known by clavichord makers, and sympathetic strings have always been meticulously adjusted by makers of the finest instruments. The effect of the sympathetic strings is comparable to artificial reverberation. However, the type of reverberation introduced by sympathetic strings shows a specific decay pattern that does not correspond to a simple room acoustic.

### 1. Introduction

The clavichord is probably the most ancient extant keyboard instrument. Its tone is relatively weak, but as the fingers are directly in contact with the strings, the clavichord is renowned as the most expressive of all keyboards. Clavichord building is in principle simple, but details should be particularly refined, and thus it is probably the most challenging instrument to build for a keyboard instrument maker. Comprehensive information on the history, aesthetics, repertory, and performance practice of the clavichord can be found in the authoritative book by B. Brauchli [1].

Unlike in the piano, the slanting strings between the bridge and the hitch-pins are not damped with felt in the clavichord. Adlung (cited in [1]) noted in 1768 that this portion of the strings “will vibrate *cum Sympathia*” and that “the agreeable singing of the clavichord will be markedly enhanced”. These parts of the strings will be coined herein the “sympathetic strings”, and the other

part of the strings the “played strings”. Only few works have included efforts specifically devoted to the acoustics of the clavichord [2][3][4]. Experiments with physical modeling synthesis of the clavichord are described in [5]. In these acoustic studies, it appears that the role played by the sympathetic strings has been neglected, even if it is mentioned in [3][4]. A model for the synthesis of sympathetic strings is proposed in [7], but surprisingly is not used in the clavichord simulation [5]. However, both the acoustic and the musical effects of the sympathetic strings seem significant. Therefore, the aim of this study is to investigate the effect of the sympathetic strings on the tonal quality of the clavichord.

In Section 2, the instrument studied and the measurements performed are described. In Section 3, the waveforms and spectra of individual tones and music segments are analyzed. In Section 4, impulse responses at the soundboard are analyzed, using room acoustics techniques for measurement of reverberation features. Section 5 concludes.

### 2. Instrument and measurements

The instrument used in this study has been built in 1983 by Frédéric Bal (Anthony Sidey workshop, Paris) a highly reputed maker of ancient keyboard instruments. It is a free copy of a south German XVIII<sup>th</sup> century unfretted instrument (see figure 1 left). Anthony Sidey also designed a popular clavichord kit similar to the instrument under study (the model-based synthesis of the clavichord described in [5] is based on such a kit).



Figure 1: The instrument studied (left) View of the sympathetic strings (right) in damped test condition.

The compass of the instrument is 51 notes (C2-D6), each comprising a pair of strings (102 strings in total). The dimensions of the instrument are 110×36.5×11 cm. The soundboard is approximately square with dimensions 32×34.5 cm. It forms a ported acoustic enclosure with dimensions 32×34.5×6 cm and an opening of 3×12 cm (commonly termed the “mouse hole”) on the side of the keyboard. 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 the experiments, the instrument has been equally tempered, using standard pitch (A4=440 Hz). Note that the cover was removed during the measurements to avoid reflection effects (see Figure 1 right).

### 2.1. Sympathetic strings

For the studied instrument, the lengths of the sympathetic strings varies between 8 (C2) and 23 (G4) cm. This corresponds to the lengths of the played strings for the 4<sup>th</sup> octave of the instrument (D6 = 9.5 cm → C5 = 23 cm). As the string tension is equal on both sides of the bridge-pin, the pitch of sympathetic strings should correspond to this higher octave. The pitch of these strings has been measured and is shown in Figure 2. The pitches of the 102 strings are distributed within an octave between C5 and H5. The ensemble of sympathetic strings is excited through coupling of the bridge when any specific 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. 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 (as shown in Figure 1 right panel) determine the pitch. Then the pattern of pitch distribution resembles the shape of the bridge (compare Figure 1 right and the trend curve in Figure 2).

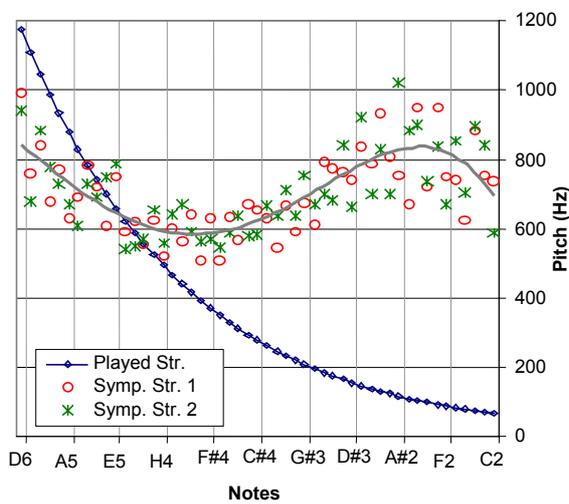


Figure 2: measured pitch of the sympathetic strings (2 strings per note) and the played strings (2 strings played in unison).

As no fundamental is below C5 (~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.

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 studied instrument, the first two notes (C2-C#2) 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.

### 2.2. Acoustic measurements

In the sound production process, one must consider 4 elements: the played strings, the sympathetic strings, the soundboard, and the soundboard cavity. Acoustic measurements were performed under the following 8 possible conditions: all free (natural state), left side (played strings) damped using a felt damper, right side (sympathetic strings) damped, cavity damped using a foam damper inside the box and mouse hole, right side and cavity damped, left side and cavity damped, both sides damped, and finally both sides of strings and cavity damped.

**Impulses responses** of the system under the 8 conditions have been measured by excitation of the bridge of the instrument with an impulse hammer at the points corresponding to all C and F#, and in front of and behind the bridge. The corresponding acoustic signal was recorded (32bit, 96kHz sampling rate) using an omni-directional microphone centered 40cm above the plane of the strings (note that this is in contrast to that shown in Figure 1).

**Pieces of music and sustained tones** have been recorded for all the C and F# of the instruments using two microphones. The tones have been recorded until their extinction under 4 conditions: all free, cavity damped, sympathetic strings damped, sympathetic strings and cavity damped. The second microphone was placed at the same height and centered over the played strings.

## 3. Waveform and spectral analyses

The reverberation effect of sympathetic strings when playing the instrument is demonstrated in Figure 3. In the bottom panel, some echo 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 top panel (sympathetic strings damped), 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 notes.

For all the individual notes, the spectra are rich, with energy up to 16 – 18 kHz, at least in the 0.2 – 0.6 sec. However, clavichord tones decay rather quickly, and the rate of decay depends on the note and on the frequency bands. An example of individual note is shown in Figure 4 (F#4, pitch = 370 Hz). Note that all the higher harmonics decay rapidly. For well tuned notes, the two stage decay pattern described by [4] is clearly visible.

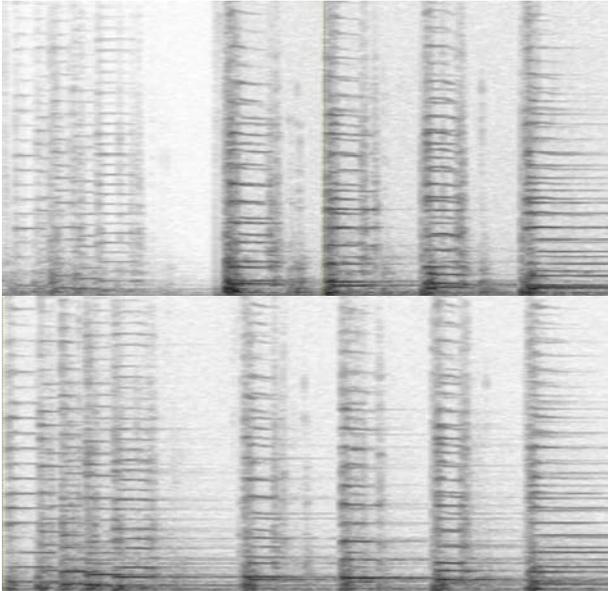


Figure 3: Spectrograms (1.8 s; 12 kHz) of music segments. Top panel: sympathetic strings damped Bottom panel: normal condition.



Figure 4: Spectrogram (7,26s; 11 kHz) of F#4.

#### 4. Impulse responses analysis

Decay rates have been calculated using the procedures developed for room acoustics, using the reverse integration of the impulse response, as described in Room acoustic measurement standard ISO 3382 [8].

An example of the decay response in octave bands of the instrument (without damping) is shown in Figure 5. Peak levels have been normalized and the curves terminate 10 dB above the noise floor.

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 msec after the initial excitation);  $RT_{late}$  corresponds to the last 10 dB of clean decay, before the background noise compromises the measurement (results are shown in Figure 6). This procedure has previously been applied to coupled volume room acoustic problems [9]. Results are calculated averages over the nine excitation points on the bridge and the two on the sounding board.

Figure 6 can be interpreted as follows:  $RT_{early}$  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 broad-band reverberation. It appears that damping the acoustic cavity response results in no effect for  $RT_{early}$ . The late response of the decay curve, quantified using  $RT_{late}$ , 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. Previous works have commented slightly on similar behavior, noting a decay to inaudibility (normally considered a decay of 60 dB) of 4 sec for notes C2 to C5, falling to 1 sec in the top octave, though this behavior was attributed to the anti-phase motion of the double string design of the played strings [4].

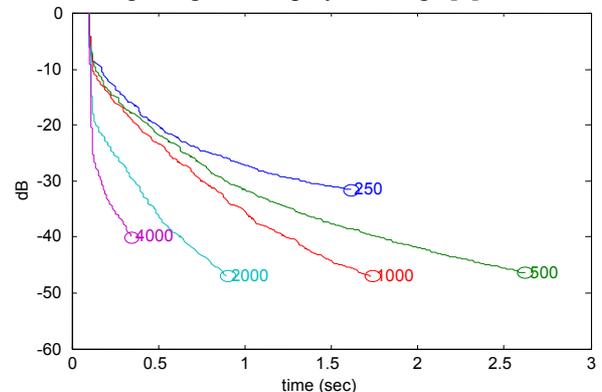


Figure 5: Normalized octave band decay curve response for the un-damped instrument.

The profile of the decay curves (see Figure 5) is similar to those observed in concert halls designed using coupled volumes (also known as reverberation chambers) and some artificial reverberation systems, while the actual length of the decays is in excess of typical design values in the lower bands. Although, the perception of this long response is determined by the radiation effectiveness and overall level of the instrument, especially at lower frequencies. A similar profile can be created using coupled volume equations with a corresponding room volume of 10 000 m<sup>3</sup>, chamber

volume of 10 000 m<sup>3</sup>, coupling area of 280 m<sup>2</sup>, and audience area of 1400 m<sup>2</sup> [9][10]. In this way, the clavichord can be seen as employing an artificial reverberation unit, creating a sound resembling that provided by great performance spaces. The balance of short *RTearly* and long *RTlate* is typical of the coupled volume approach where one is able to maintain high clarity and also provide a full, blended, and voluminous sound.

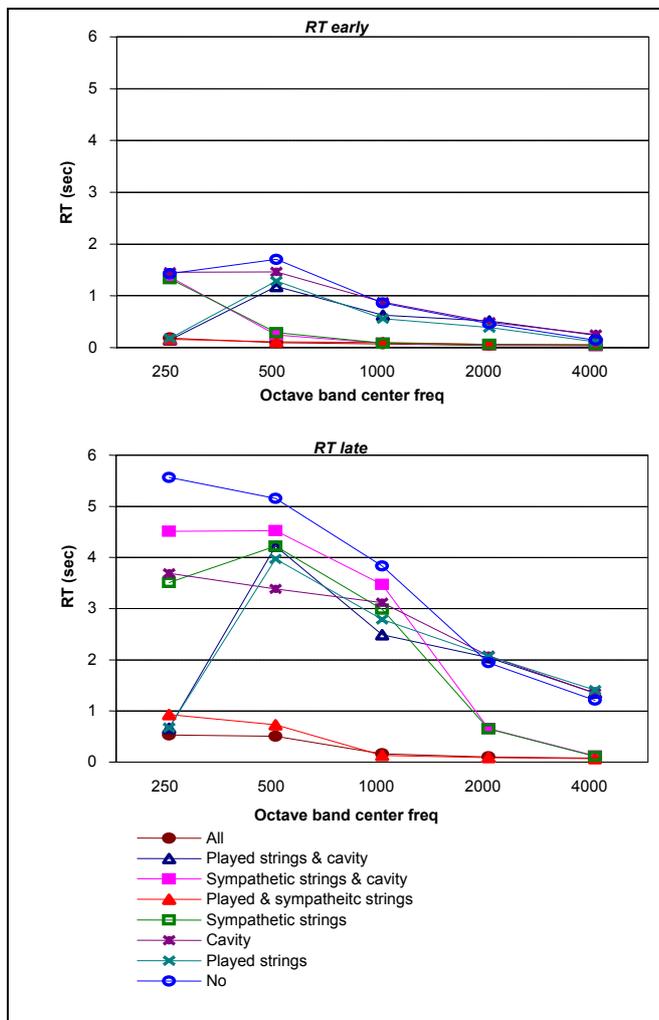


Figure 6: *RTearly* and *RTlate* for various configurations of the instrument.

## 5. Conclusions

In summary this study provides numerical data on the reverberation effect of the sympathetic strings of the clavichord. These strings 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 notes that are not well damped (the amount of felt damper is less for the low notes). Resonances of the cavity seems 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 audience is very concentrated and close by 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 with a less pronounced acoustic.

Several different types of clavichords have been designed during the long history of the instrument, from the XV<sup>th</sup> century to the present era. The instrument studied here (a copy of a south German XVIII<sup>th</sup> century unfretted model) is one possible design, and it is expected that large variations may occur between different designs. One can suspect a more pronounced presence of sympathetic resonances in the “giant” XVIII<sup>th</sup> century north German or Swedish clavichords. Future work will be devoted to systematic comparisons of the acoustic characteristics of historic instruments from different schools. More investigations on the physics of sympathetic string excitation and behavior are needed.

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