

On the dynamics of the clavichord: From tangent motion to sound^{a)}

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An experimental study of variations in the sound of clavichord notes at different dynamic levels is described. Radiated acoustic signal, tangent velocity and two tangent-string contact signals are synchronously measured for all 51 notes of an unfretted instrument. More than ten repeated measures are recorded in order to obtain as much variation in dynamic level as possible. The tangent motion, expressed in terms of velocity, is studied in the time and frequency domains. A model of the tangent-string contact point velocity is proposed. Then, three aspects of the sounded tones are analyzed: SPL and its relationship to tangent velocity, spectral slope, and pitch variations. These results indicate a linear relationship between sound pressure level and tangent peak log velocity. Spectral slope seems almost constant independent of tangent velocity and dynamic level. Both tangent velocity and finger pressure are shown to influence the fundamental frequency. In conclusion, controlling both finger velocity and finger pressure may prove challenging for the player, and this may explain why the sound quality of the clavichord depends so much on the players ability. © 2010 Acoustical Society of America. [DOI: 10.1121/1.3478783]

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I. INTRODUCTION

The clavichord is a unique combination of simplicity of action and subtlety of building, voicing and playing.¹ A peculiar feature of the clavichord is the intimate contact between the finger and string, mediated by the key. This results in a direct and continuous control of the string by the player, allowing the most refined modulation of dynamic level. Only a few acoustic studies have addressed the question of sound production and sound control of the clavichord, and further research on the dynamics of the clavichord is needed. In the present experimental study, characteristic properties of the sound of clavichord notes at different dynamic levels is investigated.

The most significant paper on the acoustics of the clavichord to date is that of Thwaites and Fletcher.² Their study described a simple model of the string excitation, which was used to predict the force exerted by the string on the bridge. Measurements and models of the soundboard vibration modes and soundbox cavity modes were provided, as well as measurements of SPL and decay times.

Välimäki *et al.*³ proposed a digital model for clavichord sound synthesis. This model was 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 was introduced as an impulse response in the digital waveguide model. The sound of the digital instrument resembled the clavichord sound. However the digital instrument was missing one of the most interest-

ing features of the acoustic instrument from a musician's point of view: direct and continuous control of the string using the finger.

Bavington⁴ performed a study on clavichord touch and action. The main findings concerned hardness of touch and pitch stability, i.e., how much the action yielded once contact was made with the key and the effort required to alter pitch while the note was sounding. d'Alessandro *et al.*⁵ studied the reverberation provided by sympathetic strings in the clavichord, and presented the acoustic "portrait" of four clavichords, in terms of SPL, decay time and tangent velocities.⁶

The present work addresses the question of tangent motion and variation in sound at different dynamic levels. An experimental approach is taken, based on measurements of key motion, SPL and spectra of radiated sound for all notes of an instrument, repeated with as much dynamic variation as possible. After a presentation of the instrument and recording procedure, four main aspects of the influence of dynamic level are studied. The tangent motion, expressed in terms of velocity, is studied in the time and frequency domains. A model for predicting the tangent-string contact point velocity is proposed. Then, three aspects of the sounded tones are analyzed: SPL and its relationship to peak tangent velocity, spectral slope, and pitch variations. A discussion of the measured effects and the players control of dynamic levels concludes the work.

II. EQUIPMENT AND MEASUREMENTS

A. Instrument and measurement procedure

The instrument used in this study, see Fig. 1, is an unfretted instrument professionally built in 1983 by F. Bal at A. Sidey's workshop, Paris. The compass of the instrument is 51 notes (C1-D5), each note comprising a pair of strings

^{a)} Portions of this work were presented in "On the acoustics of the clavichord" in Proceedings of the 7th International Clavichord Symposium (2005), and at Acoustic 2008.

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FIG. 1. (Color online) The Bal-Sidey clavichord studied in this article (51 keys, C1-D5, unfretted), dimensions $110 \times 36.5 \times 11$ cm.

(102 strings in total). All the strings are yellow brass. The speaking length varies from 95 to 895 mm (C1: 895 mm, C2: 692 mm, C3: 441 mm, C4: 229 mm, C5: 111 mm) with diameters from 0.25 to 0.55 mm, tuned at reference pitch corresponding to A4=415 Hz.

Measurements were made with the instrument in an acoustically isolated and damped recording booth. The player was instructed to repeat each note on the keyboard from just noticeable *pianissimo* to the loudest possible *fortissimo* that would not set the strings too much out of tune or damage the instrument. An experienced clavichord player performed the recordings. About 8 to 15 repetitions were recorded for each note, resulting in about 500 recordings for the 51-key instrument. The recordings were segmented into individual tones using the tangent-string contact signals as time references (see below).

B. Acoustic and tangent motion recordings

For each tone, four simultaneous signals were recorded at sampling rate of 48 kHz and a bit depth of 16.

Radiated sound was recorded using a B&K 3265 measurement microphone, placed 30 cm over the center of the soundboard. Two tangent-string contact signals were recorded, one for each string of a string pair. The contact signal was obtained by using the tangent and string as a circuit switch. A 5 kHz sine wave was injected in the circuit on the tangent side, using a contact clip. When the tangent was in contact with the string, the circuit was closed, and the electrical signal on each of the two tuning pins was recorded.

Recording of the vertical tangent motion were made using a B&K 4374 miniature high-sensitivity accelerometer attached to the key lever, close to the tangent, and a conditioning amplifier B&K 2635. The accelerometer mass was ≈ 0.75 g and the key mass ≈ 20 g. The additional mass of the accelerometer could thus be neglected.

Tangent velocity is obtained using the built-in integration of the acceleration in the conditioning amplifier. Numerical integration of the acceleration signal gives similar results, but is more sensitive to measurement noise. In the present study, only the vertical tangent motion is considered.

An example of data recording is given in Figs. 2 and 3 showing the initial 80 and 8 ms of tone A4, respectively. The figures show acoustic pressure recorded by the microphone, tangent velocity, and the tangent-string contact signals, with one signal for each string in the pair. All recordings are aligned, setting tangent contact at time 0.1 s.

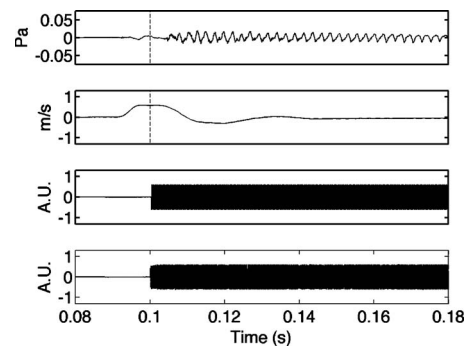


FIG. 2. Examples of data recording for note A4. From top: sound pressure in Pa, tangent velocity in m/s, and two tangent-string contact signals in arbitrary units (A.U.). The SPL is about 60 dB. The time scale corresponds to 20 ms/division. The vertical dashed line indicates the first moment of contact between the tangent and one of the two strings.

Some interesting observations on the components included in the clavichord sound can be made in Fig. 2. It is clearly seen that the radiated sound begins slightly before the tangent-string contact. This is the noise of the finger on the key and the noise of the key motion (touch noise). At tangent impact, the initial shock of the tangent on the string also excites the instrument body and adds some transient noise to the sound generated by the strings.³ A delay between tangent contact with the two strings is clearly visible (enlarged view in Fig. 3). Tangent velocity is almost constant at the tangent-string impact indicating that the tangent velocity is transmitted almost instantly to the string at rest. The radiated string sound, with a well established string oscillation pattern, begins about 4 ms after the tangent contact, due to the vibration propagation time in the instrument and the sound propagation time in the air.

C. Contact signals

The contact signals show that both strings are excited almost simultaneously, and that the contact is maintained during the whole tone. Benade⁷ erroneously predicted bounces of the contact between tangent and string in the initial part of the sound, an effect that is never observed under normal playing condition.

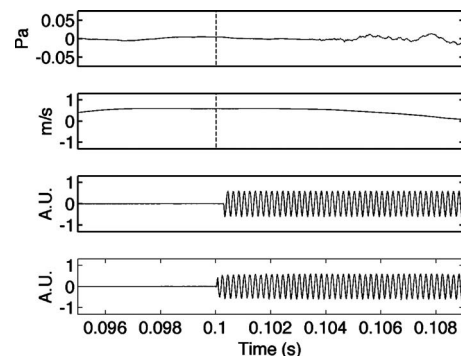


FIG. 3. The same recordings as in Fig. 2, zoomed around the moment of tangent-string contact. The time scale is expanded 10 times compared to Fig. 2. From top: sound pressure in Pa, tangent velocity in m/s, and two tangent-string contact signals in arbitrary units (A.U.). The time scale corresponds to 2 ms/division. The vertical dashed line indicates the first moment of contact between the tangent and one of the two strings.

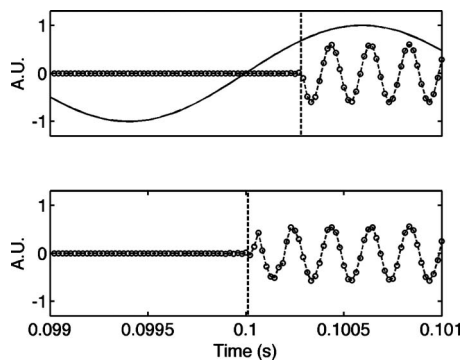


FIG. 4. Contact signals at note onset for the two strings in a pair. Each dot represents a sample point (0.02 ms=1/48 kHz). A sine wave with frequency corresponding to the note played (A4=415 Hz) is plotted in the top panel, showing the phase shift between the onsets of the two strings (about $\pi/5$ rad). The vertical dashed line indicates the first moment of contact between the tangent and one of the two strings. The time scale corresponds to 0.5 ms/division.

A closer examination of the two contact signals, as displayed in Fig. 4, allows for an estimation of the delay between the excitation of the two strings in a pair. The delay in this example (A4=415 Hz) is about 0.25 ms, which would introduce a phase difference of about $\pi/5$ rad between the fundamentals of the two strings (a 415 Hz sine wave is plotted in the same figure for reference). Since the tangent velocity is 0.6 m/s, this corresponds to an offset between the two tangents of 0.15 mm. An additional difficulty in the tangent top angle adjustment is that the time delay between the excitation of the two strings depends not only on the angle of the tangent, but also on tangent velocity.

This difference in impact timing seems to be implicitly known and carefully controlled by clavichord makers. A difference in impact timing for the string in a pair is controlled by adjusting the angle of the tangent top. Bavington⁸ (p 96–97) explains that:

“If both strings are struck *precisely* at the same moment, the sound may be loud but coarse and lacking in sustain; but too wide a separation is a more common cause of a disappointing sound.”

It seems that the main effect of delaying the two impacts when voicing the instrument is to avoid too strong a coupling. The effect of simultaneous string excitation and string coupling at the bridge has been studied by Weinreich in the case of the piano.⁹ The main results of this coupling is a double attenuation pattern in the amplitude of the radiated sound. The same type of coupling seems also significant in the case of the clavichord, as discussed by Thwaites and Fletcher.² If both strings are struck precisely at the same moment, the first wave-fronts reaching the bridge for both strings are in phase, and then induce a stronger (and rapidly decaying) soundboard motion. On the contrary an out of phase excitation of the string would result in a weaker (and longer lasting) sound.

III. TANGENT MOTION

A. Tangent velocity signal

Tangent velocity can be considered as the most relevant string excitation parameter in the clavichord,^{2,10} correspond-

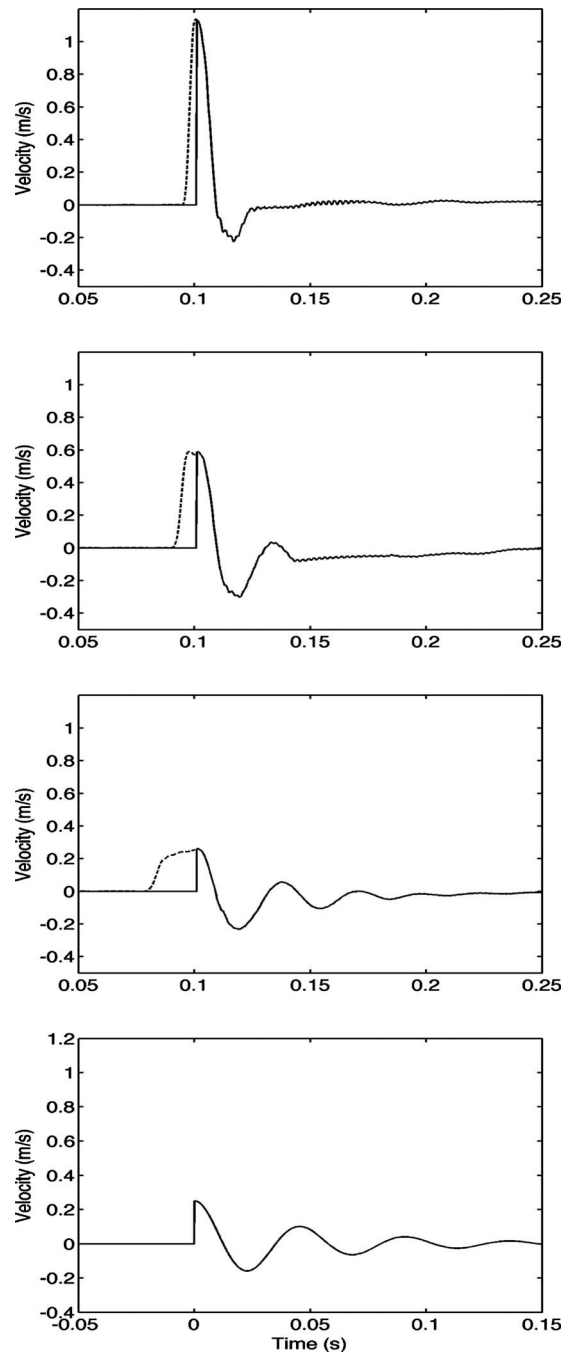


FIG. 5. Tangent velocity (m/s) for note A4 played (from top) *f*, *mf* and *p*. The tangent-string impact takes place at time 0.1 s. The dotted parts of the curves represent tangent velocity before impact. Simulation of the tangent velocity played *p* is shown in the bottom panel. The tangent-string impact takes place at time 0. The time scale corresponds to 50 ms/div in all panels.

ing to hammer velocity in the piano.¹¹ The tangent velocity during a note can be broadly divided into four main phases: rest, acceleration, deceleration with tangent-string generated oscillations, and finally almost null velocity with small amplitude string oscillations superimposed.

Examples of tangent velocity signals for the same note played with three dynamic levels: piano (*p*), mezzoforte (*mf*), and forte (*f*) are shown in Fig. 5, corresponding to peak tangent velocities of 0.261, 0.590, 1.136 m/s respectively. In the a first phase the key is at rest and the velocity is

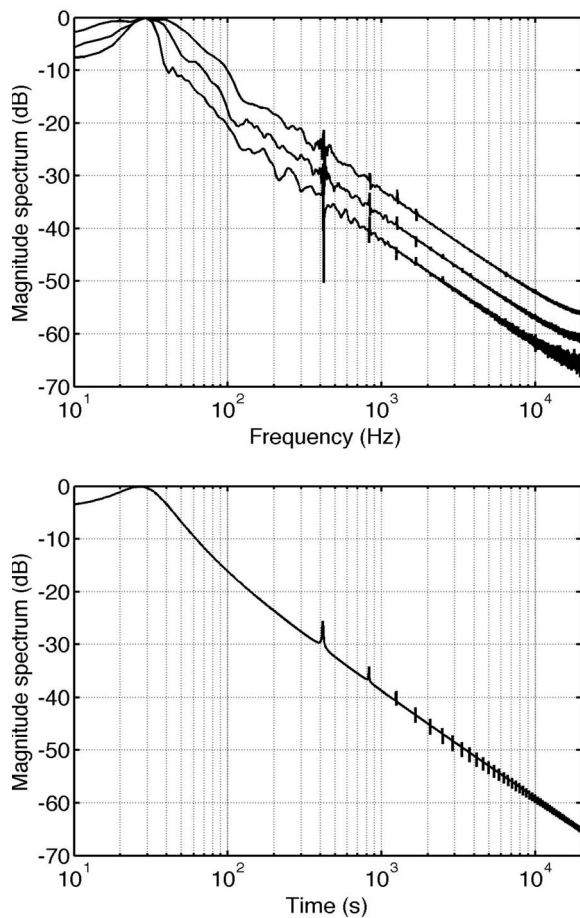


FIG. 6. Comparison of measured log magnitude spectra of the tangent velocity for note A4, played *p*, *mf*, and *f* (lower, middle and upper curve in top panel). Simulation of the log magnitude spectrum of the tangent velocity for note A4 at *mf* level (bottom panel).

null. The finger then depresses the key and tangent velocity increases to its maximum.

The travel time of the tangent before hitting the string is between 4 and 20 ms depending on the peak velocity. The tangent-string interaction begins when the tangent hits the string, and the tangent-string system starts to oscillate. These oscillations are damped out in about 1 to 3 periods. Then, the velocity is almost null for the remaining duration of the tone. Low-amplitude oscillations, due to the waves reflecting back and forth on the string and reacting on the tangent, are apparent, particularly at *f* level. The performer is able to some extent to feel these string vibrations, at least in the bass range.

B. Tangent velocity spectra

The spectra of the tangent velocity signals in Fig. 5 are compared in Fig. 6. The spectra are characterized by three main features: spectral tilt, low frequency resonance and traces of partials of the string motion.

An important observation is that spectral tilt is similar for the three dynamic conditions. This can be explained by the fact that spectral tilt is mainly a result of the step-like shape of the tangent velocity. As the tangent is made of hard material, the initial tangent-string contact is a shock with a step in velocity at impact. A step-like excitation corresponds

to a spectral slope of -6 dB/oct. This spectral slope is independent of the initial tangent velocity; even at low velocities for *p* tones the impact always corresponds to a step in velocity.

In a review paper, Hall¹² addressed the problem of string excitation for the clavichord and predicted a spectrum slope of about -6 dB/octave for the string motion, in agreement with the spectral tilt observed in the present data.

The low frequency resonances, seen as spectral peaks in Fig. 6, correspond to the oscillations of the tangent-string system. The string reacts like a spring to the force exerted by the tangent, and the system can be described by a forced damped oscillator, as discussed in the next section. The oscillation frequency and damping of these oscillations depend on the initial velocity, as can be seen in Fig. 6. A higher initial velocity results in a higher oscillation frequency and more damping (a larger bandwidth of the corresponding spectral maximum). The oscillation frequencies of the tangent-string system are rather low, about 20 Hz in this example. This is consistent with a simple oscillator model of the tangent-string system.

As the tangent serves as one termination of the vibrating string, the string motion superimposes low-amplitude components on the slow tangent oscillations. These traces of the string oscillations, hardly visible in the time domain at low impact velocities, are more apparent in the tangent velocity spectra where they are seen as vertical lines at harmonic frequencies ($F_0=415$ Hz) in Fig. 6.

C. Oscillation of the tangent/string contact point

Oscillation of the tangent/string contact point is one of the main features of the tangent velocity signal. The string reacts like a spring when raised by the tangent, and the oscillations can be explained by a simple damped mass-spring system. For a tangent raising the string of a height h , the vertical force F_t exerted by the string on the tangent is given by:

$$F_t \approx \left(T \left(\frac{L}{L_r L_l} \right) \right) h = kh, \quad (1)$$

where, L is the string length, L_r is the right part of the string (vibrating side), L_l is the left side of the string (damped side) and T the string tension. The increase in string tension and string length due to the tangent height is neglected. This force can be represented as a simple Hooke's law, with spring stiffness k .

At equilibrium, the strings are raised by the height h , and the finger force F_m and the string force F_t are equal. In its simplest form, the aftertouch action of the finger, i.e., the static force applied by the finger to maintain the key depressed after attack, can be considered as a weight on the key (assuming a leverage ratio of 1) with equivalent mass (g being the acceleration due to gravity):

$$m_{eq} = \frac{F_t}{g} \approx \frac{kh}{g}. \quad (2)$$

In addition to the string spring force and the finger weight, it is reasonable to introduce a damping force F_f ,

corresponding to viscosity or friction in the system, with viscosity constant b . Then, the string/tangent system can be considered as a forced damped oscillator. Solutions of the equation of motion for this system are:

$$y(t) = h + Ae^{j\alpha t} = h + re^{j\phi}e^{j(\sqrt{\omega_0^2 - \delta^2})t}e^{-\delta t}, \quad (3)$$

$$\dot{y}(t) = Ajae^{j\alpha t} = re^{j\phi}(j(\sqrt{\omega_0^2 - \delta^2}) - \delta)e^{j\alpha t}. \quad (4)$$

In their analysis of the tangent motion, Thwaites and Fletcher assumed a step in velocity with exponential decay,² that is a particular case of Eq. (4). The frequency $\omega_0 = \sqrt{k/m_{eq}}$ depends on the string geometry, string tension, and on the finger pressure (or weight). The oscillation amplitude A defines the maximum extra height over the static tangent height h . The damping mechanism, that defines the damping parameter $\delta = b/2m_{eq}$, involves finger flesh stiffness and a complex control of the key motion by the player. The oscillation amplitude A , assuming that $y(0)=0$ depends on all the preceding parameters and the initial tangent velocity (velocity at time 0):

$$r = \frac{-h}{\cos \phi}, \quad (5)$$

$$\phi = \arctan\left(\frac{\frac{\dot{y}(0)}{h} - \delta}{\sqrt{\omega_0^2 - \delta^2}}\right). \quad (6)$$

A simulation of the tangent velocity for note A4 and p level using this model is shown in Fig. 5 (bottom) for the following conditions: initial velocity $\dot{y}(0)=0.25$ m/s, tangent height of 0.5 mm, $L_t=232$ mm, $L_r=287$ mm, string tension 41.7 N, elastic modulus of the string $=3.52 \times 10^4$ N (Young's modulus of brass 1.03×10^{11} Pa, string diameter 0.33 mm, 2 brass strings). The agreement with the measurements in the panel above is convincing.

Note that the keylever could also introduce some flexing and then oscillations, in the finger-key-string system. The keylever could be considered as an additional damped oscillator coupled to the main oscillator. However, the keylever elasticity modulus (keyboard wood Young's modulus of about 1.2×10^{10} Pa, and keylever section of about 10^{-4} m²) is around 1.2×10^6 N, which is two orders of magnitude higher than for the string. Consequently, keylever oscillations can be neglected in a first approximation.

D. String oscillation reaction on the tangent

Small amplitude oscillations in the tangent velocity due to the string motion reacting on the tangent are visible in Fig. 5, mainly at loud dynamic level (top panel). The reason is that the tangent acts as one of the terminations of the string, and the transverse string waves are periodically reflected at the tangent. The analysis of the reaction force on the tangent can be made both in the time or frequency domains.

In the time domain, the string can be considered as a delay line,¹³ excited by the tangent motion, with reflections at both ends. This approach has previously been applied in synthesis of the clavichord.³ When the wave generated at

tangent impact reaches the bridge, it is partly reflected and partly transmitted to the soundboard. As the mechanical impedance of the bridge is high compared to that of the string, most of the energy is reflected. The same process takes place at the tangent termination. These repeated partial reflections at the bridge and at the tangent result in a rapidly damped oscillatory motion of the string.

The reacting force F_s exerted by the vibrating string on the tangent is proportional to the angles on each side of the contact point (spatial derivative of the string displacement), and to the string tension T :

$$F_s = T \left[\frac{\partial y(0_+, t)}{\partial x} - \frac{\partial y(0_-, t)}{\partial x} \right] \quad (7)$$

with striking point at $x=0$. The reacting force is conveniently expressed using the characteristic impedance of the string $Z_0 = T/c$ where c is the wave velocity on the string

$$F_s = 2Z_0\dot{y}(t), \quad (8)$$

where $\dot{y}(t)$ includes summation of the outgoing velocity wave at impact and all reflected waves from the bridge (and the damped end) up to time t .

For the present purpose the effect of the tangent-string oscillation on the tangent velocity is easier studied in the spectral domain. The tangent velocity spectrum is the Fourier transform of Eq. (4):

$$\dot{Y}(f) = \frac{re^{j\phi}(j(\sqrt{\omega_0^2 - \delta^2}) - \delta)}{\delta - j(\sqrt{\omega_0^2 - \delta^2} - 2\pi f)}, \quad (9)$$

with modulus:

$$\|\dot{Y}(f)\| = \frac{r\omega_0}{\sqrt{\omega_0^2 - 4\pi f\sqrt{\omega_0^2 - \delta^2} + 4\pi^2 f^2}}. \quad (10)$$

This equation is able to explain the main features of the spectra in Fig. 6. The low-frequency maximum corresponds to the tangent-string resonance (depending on ω_0 and δ). For high frequencies, the spectra falls off as $1/f$, giving a spectral tilt of about -6 dB/octave.

The reactions on the tangent from the reflected waves on the string are taken into account using a delay line model. In the spectral domain, a string considered as a delay line corresponds to a recirculating comb filter, with teeth placed at multiples of the fundamental frequency $F_0=1/\tau$. A comb filter, with delay τ and reflection coefficient α is given by (e is the input signal and s the output):

$$s(t) = e(t) + \alpha s(t - \tau), \quad (11)$$

with the following frequency response:

$$S(f) = \frac{1}{1 - \alpha e^{-2j\pi f\tau}}. \quad (12)$$

The effect of the comb filter is to introduce strong attenuation between the harmonics of the fundamental frequency. The spectral envelope of the comb filter is flat (all the harmonics have the same magnitude). The effect of the reflection coefficient $\alpha < 1$ is to widen or sharpen the comb filter teeth.

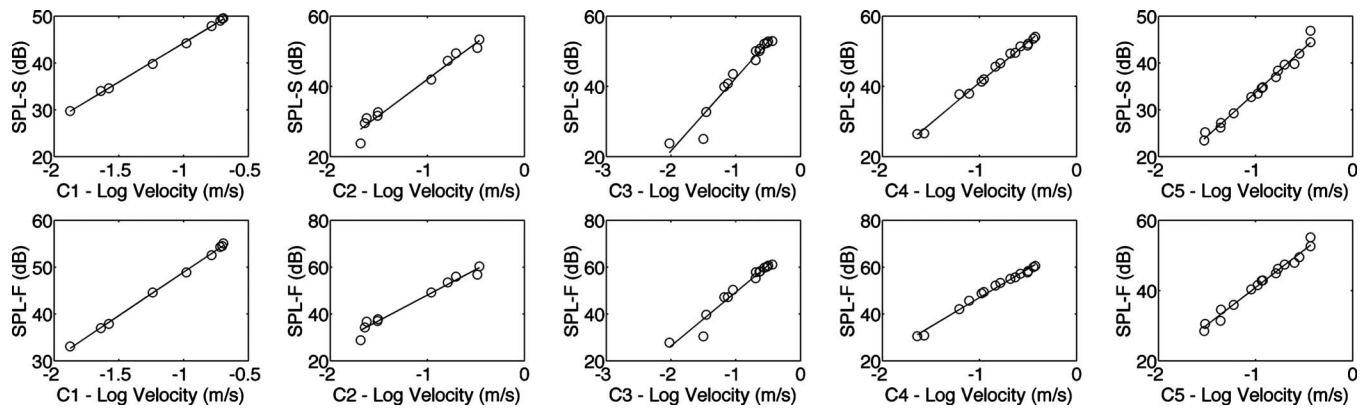


FIG. 7. Unweighted SPL as a function of the logarithm of the tangent peak velocities for notes C1, C2, C3, C4, and C5 at various dynamic levels. Top panels show SPL-S (slow, time constant 1 s), and bottom panels SPL-F (fast, time constant 0.125 s).

Losses in the string delay line can be accounted for by a low-pass filter with a complex gain constant B attenuation coefficient β , with the following frequency response:

$$L(f) = \frac{B}{1 - \beta e^{-2j\pi f}}. \quad (13)$$

In a first approximation, one can consider a linear interaction between the vibrating string and tangent, because the vibrating string motion is small. The spectrum of the reaction of the vibrating string on the tangent is thus the product of the frequency responses of the string comb filter and the string losses filter and the tangent velocity spectrum.

For a more realistic model, two strings must be considered. Some amplitude phase and frequency differences must be introduced to account for the difference in impact timing and tuning between the two strings. The tangent velocity spectrum including two vibrating string components is then:

$$B(f) = \dot{Y}(f) (1 + S_1(f)L_1(f) + S_2(f)L_2(f)). \quad (14)$$

The magnitude spectrum obtained with such a model is displayed in the bottom panel of Fig. 6, using the following values: detuning between the two strings = 0.5 Hz, $\alpha = 0.97$, $\beta = 0.95$, $B_1 = 0.0032$ and $B_2 = -0.004$, the other parameters being the same as in the simulated case included in Fig. 5. The result obtained by this simulation is closely similar to the velocity spectra displayed in the upper panels in Fig. 6.

IV. SOUND PRESSURE LEVEL PROPORTIONAL TO PEAK LOG-VELOCITY

A. Tangent peak velocity

The peak velocity of the tangent for each note is derived from velocity measurements exemplified above. It corresponds to the instant of impact between the tangent and string. In the set of about 500 measurements, the peak velocity varies from 0.05 m/s for the softest possible sounds, up to more than 1.5 m/s for the loudest notes. On average, loud note velocities are around 1.3 m/s for this instrument. In contrast to the piano, it is possible to play the clavichord with very slow finger motion and still make the instrument sound. In the piano, the hammer needs to have a certain minimum final velocity in order to swing freely the last millimeters toward the string.¹⁴

The peak velocity for each note is derived from the velocity measurement exemplified above. It corresponds to the instant of impact between the tangent and string. Figure 7 displays the measurements for all the “C” notes of the instrument (this represents 63 out of the set of about 500 measurements performed).

B. Sound pressure level

An important feature of musical instruments is the perceived power, which can be measured in terms of sound pressure level (SPL). SPL variations between notes are in principle carefully equalized when voicing the instrument, and contribute to its general balance. The unweighted, or flat SPL, is computed as the root mean square value of the acoustic pressure. SPL is by nature an average measure depending on a time integration. Two time constants are used in the measurement: 1 s (slow, SPL S) and 0.125 s (fast, SPL F). The shorter integration time gives an estimation of the SPL during the attack, while the longer integration time reflects the SPL for a whole note. SPL F turned out to be on average 5 dB higher than SPL S, because of exponential damping of the string vibrations. Most of the energy is concentrated after the attack.

The maximum SPL F is about 65 dB, with a maximum dynamic range of about 40 dB (25–65 dB) in the second octave of the instrument. Both the SPL S and SPL F contours are decreasing for the two first bass notes, and, more significantly, for the 7–9 last notes in the treble.

SPL measurements for clavichord notes were reported by Thwaites and Fletcher² but the integration time was not specified in their study. The instrument used was a smaller model based on a kit, and the microphone was at 1 m from the sound board. They obtained a maximum of 55 dB SPL. This is comparable with the present results, if one compensates for the distance difference between experiments. The distance difference gives a SPL difference of $20 \log_{10}(3) = 9.5$ dB. Our data can then be interpolated to a maximum of about 55.4 dB. Using the same clavichord model as Thwaites and Fletcher, d’Alessandro *et al.*¹⁰ reported similar values, again compensating for the microphone distance.

C. Relation between tangent velocities and sound pressure level

The players' main control parameter of dynamic level is the tangent velocity. It is interesting to relate this parameter to the measured SPL (see Fig. 7). Both SPL F and S are plotted in the figure as a function of the logarithm of the tangent peak velocity.

The five horizontal panels correspond to the five C notes on the keyboard, C1-C5. The figure indicates a linear relationship between the SPL and the logarithm of the peak tangent velocity.

In a study on the amplitude of sounded piano tones, it was found that "maximum amplitudes over the duration of the sounded tones were linearly proportional to piano hammer velocities for a range of frequencies and hammer velocities."¹¹ It seems that a similar relation holds for the clavichord. However, as SPL is preferred in this study rather than the maximum linear sound amplitude, log velocity of the tangent is used.

For all notes, a least square fit of the data is computed using linear regression. The correlation coefficients obtained for the five "C" notes varied between 0.999 and 0.971 with SPL F, and between 0.999 and 0.968 with SPL S. Consequently it is safe to conclude that the log tangent velocity-SPL relationship is essentially linear. The tangent velocity-SPL conversion factors corresponding to Fig. 7 vary from approximately 16 to 24, expressed in dB SPL/ $\log^{10}(\text{m/s})$, depending on the note and integration time.

The SPL depends on the force exerted by the string on the bridge. Applying Eq. (8) at the bridge position shows that the force on the bridge depends only on the characteristic impedance of the string and the tangent velocity. This indicates that the players main technique for controlling the sound volume or SPL is to control the tangent (i.e., key) peak velocity. The observation is consistent with players common experience: playing louder is not a matter of force or pressure, but rather a matter of velocity of the finger motion.

V. DYNAMIC LEVELS AND SPECTRAL SLOPE

In addition to the SPL it is important to study the timbre changes due to changes in dynamic level. Magnitude spectra for note A4 played at different dynamic levels are shown in Fig. 8 (Blackman-Harris window, 16 384 points FFT, corresponding to the first 340 ms of the sound). Three dynamic levels, *p*, *mf*, and *f*, corresponding to tangent peak velocities of 0.26, 0.59, and 1.14 m/s are displayed. The spectra are normalized to the fundamental.

In contrast to the tangent velocity spectra which fit well to a -6 dB/octave spectral tilt, the radiated sound show a much better fit to a -12 dB/octave slope. The soundboard modes also influence the resulting spectra much, as can be seen in the figure. The tangent-string oscillations are too low in frequency to influence the partials of the sounded tones: they are significant in the tangent velocity spectrum but not in the radiated sound spectrum.

As mentioned earlier, the step-like excitation of the string corresponds to a constant spectral slope of -6 dB/octave, independent of dynamic level. This excitation force

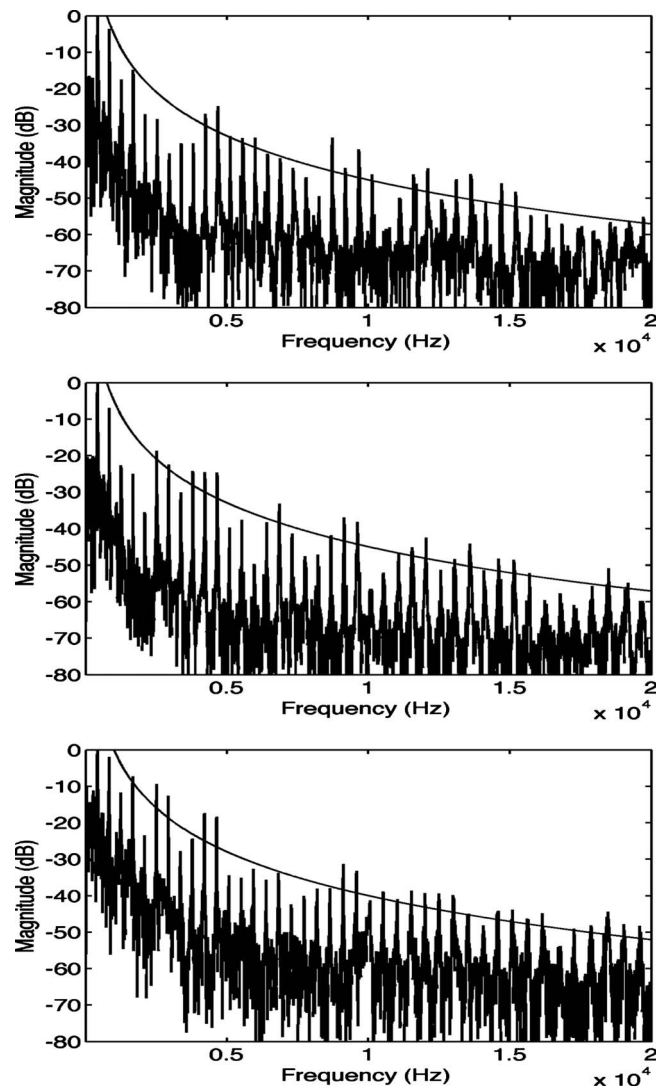


FIG. 8. Log magnitude spectra of the radiated sound for note A4, played *p* (bottom), *mf* (middle), and *f* (top), corresponding to the first 340 ms of the notes. A -12 dB/octave curve is inserted for comparison of spectral slope. The spectra are normalized to the fundamental.

spectrum is modified by the resonance and radiation properties of the soundboard.² Assuming that the transduction from the string force on the bridge to the radiated sound is essentially linear, the sound spectra recorded at a distance to the instrument should also exhibit a constant slope, independent of dynamic levels. A constant slope is found in the measurements, but with a different constant for the string excitation (-6 dB/octave) and radiated sound spectra (-12 dB/octave). In terms of signals processing, this difference corresponds to a first order low-pass filter, i.e., an integrator. But a physical model explaining this effect is lacking.

The influence of dynamic level on timbre (spectral richness) was investigated using analysis of the spectral slope. Amplitudes of the first 23 partials harmonics (up to approximately 10 kHz) for the three dynamic levels are plotted in Fig. 9. Spectra are normalized for compensating the difference in SPL between the three conditions. The figure shows that spectral tilt is comparable at all three dynamic levels. This indicates that the timbre is similar between *f* and *p* tones.

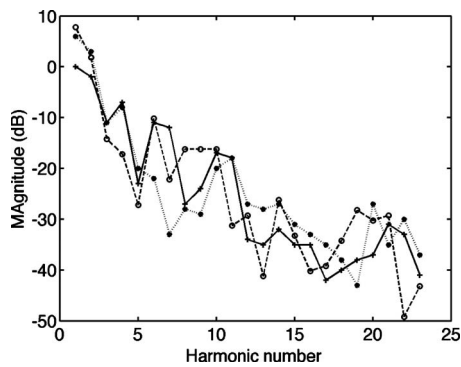


FIG. 9. Comparison of magnitudes of the first 23 partials of the spectra in Fig. 8. Note A4 played *p* (solid line), *mf* (dashed line), and *f* (dotted line). The spectra are normalized to the fundamental.

However, the rather large differences between partial magnitudes between *p*, *mf* and *f*, (up to almost 25 dB) are hard to understand in terms of the proposed differences in excitation if the clavichord is essentially a linear system. Several sources of non linearity can be identified: 1. as discussed by Thwaites and Fletcher, a change in initial velocity may affect the relative amplitude of the firsts harmonics (see Fig. 3 in their article²); 2. the soundboard modes do influence the radiation, and the pitch variation between *p* and *f* (discussed in the next section) may shift the partials in and out of modes; 3. a significant component of the radiated sound is made of structural noise,³ i.e., the shock noise generated when the strings are struck. This noise component is highly level-dependent; 4. sympathetic vibration also affects the tone quality of the clavichord.⁵

For plucked strings, spectral richness seems enhanced by the “precursor” effect due to compression wave in the string motion.¹⁵ This effect may also play a role in the clavichord sound.

VI. DYNAMIC LEVELS AND PITCH VARIATIONS

A very specific feature of the clavichord is the sustained contact between the string and tangent during the sounding tone. A consequence of this contact is that playing a tone changes the string tension and pitch. Increasing finger pressure results in an increase of string height and string tension. This control is in principle independent of tangent velocity.

Figure 10 shows an example (again for the same A4 note) of F0 variation for three dynamic levels. The fundamental frequency was obtained using an autocorrelation method (YIN) (see Ref. 16). The figures show two main phenomena. First, the average F0 rises with increasing dy-

namic level (i.e., final tangent velocity) from 418 to 420 Hz approximately (+8 cent). The differences are small, but above the just noticeable difference in F0 at this frequency which is about 1 Hz (4 cent¹⁷). Second, F0 is higher at the beginning of the tones, in particular for the louder dynamic levels. At *f* level the pitch temporarily rises 30 cent during the attack. This type of F0 pattern at the attack is a feature of the clavichord sound: such pitch accents can be used for musical purposes.

A peculiar feature of the clavichord, not shared by other keyboard instruments, is that a given note is always played with some F0 variation (like for instance, in singing and violin playing). The standard deviation of the pitch variation computed across the entire range of tangent velocities are for C1–C5: 0.46, 0.32, 0.18, 0.23, 0.27 semitones. For this instrument, more variation is possible in the bass range, with a standard deviation close to a quarter tone.

An estimation of the change in fundamental frequency can easily be computed. Let λ be the elasticity modulus of the string. When the string is raised a height h by the tangent it is extended, resulting in an increase in tension ΔT_h :

$$\Delta T_h = \frac{\lambda(\sqrt{L_r^2 + h^2} + \sqrt{L_l^2 + h^2} - L)}{L}. \quad (15)$$

This change in tension significantly alters the fundamental frequency, according to Mersenne’s laws:

$$F0 = \frac{c}{2L_r} = \frac{1}{dL_r} \sqrt{\frac{T + \Delta T_h}{\pi \rho}}, \quad (16)$$

where T is the string tension, ρ the density and d the string diameter.

For a note played at *mf* level, the typical tangent height is 1 mm ($\Delta T_h = 0.264$ N) and the predicted increase in F0 is 1.31 Hz, in agreement with the measured results in Fig. 10.

The relationship between F0 and tangent velocity/dynamic level shown in Fig. 10 suggests that finger velocity and finger pressure are not actually independent in a playing situation. The link between velocity and pressure depends both on player ability and on instrument construction. Quoting Bavington,⁴ “Finally, the hardness of touch will impede pitch stability, preventing players from playing too loud in such a case.”

VII. DISCUSSION AND CONCLUSION

A characteristic feature of the clavichord is direct control of the string by the finger, with the action being a simple lever. The player is able to control not only the key velocity

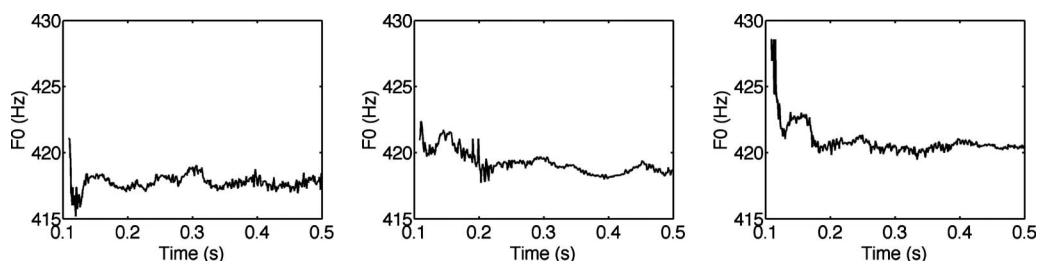


FIG. 10. Fundamental frequency (in Hz) at the beginning of note A4, played *p*, *mf*, and *f*.

(like in the piano) but also the key displacement and the force on the string (unlike in the piano, where the key is stopped by the action before it hits the string¹⁴).

The presented results show that final tangent velocity is the main control parameter of dynamic level. A linear relationship between the amplitude of sounded piano tones and maximum hammer velocity has been reported by Palmer and Brown.¹¹ The present result indicate a similar relationship for the clavichord, but with markedly lower velocities: a maximum of about 1.5 m/s for the clavichord tangent, compared to a maximum of about 4 m/s reported for the piano hammer.^{11,18}

Static force on the tangent, or finger pressure, has a dramatic effect on the string tension, and therefore on the F0 produced. This effect is well known to clavichord players, the clavichord being the only keyboard instrument allowing for finger-controlled vibrato and pitch accents. For inexperienced players, a lack of control in the tangent height, i.e., the force applied to the key, results in an increased string tension, and hence a raised pitch and an out-of-tune tone.

Spectral slope ("richness") seems very similar whatever the dynamic level played. The attack always produces a hard impact, resulting in an angular point in string displacement and a corresponding discontinuity in string velocity. This results in a low and constant spectral tilt (−6 dB/octave), independent of the impact velocity.

Attack and release noises, i.e., key motion noises and shocks transmitted to the body of the instrument, were not considered in the present study. They are certainly an important consequence of dynamic variations and an important feature of the clavichord sound.

The truly unique feature of the clavichord is the complex velocity-force compromise the player is faced with. Although they are independent in theory, in practice, finger velocity and force are often linked. Playing with a high velocity but without putting weight on the key is difficult, and is part of learning to play the clavichord. Mastering this challenge allows for subtle nuances in performance, both in dynamic level and in terms of fundamental frequency patterns like pitch accents and vibrato.

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