Influence of plectrum shape and jack velocity on the sound of the harpsichord: An experimental study

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A controversial discussion in the musical community regards the ability of the harpsichord to produce sound level or timbre changes. The jack velocity (controlled in real time within a musical context) and the plectrum shape (modified by the musician or maker prior to the performance) appear to be the two control parameters at the disposal of the harpsichord makers and players for shaping the sound. This article initiates the acoustical study of the control parameters of the harpsichord, presenting a framework for the investigation of these two parameters with means of experimental mechanics measurement. A robotic finger is used for producing repeatable plucks with various jack velocities and plectrum shapes. The plectrum bending, vibrating string's initial conditions, and radiated sound are recorded and analysed. First, results are obtained from measurements carried out on one string, for four plectrum shapes and four jack velocities. The plectrum shape has been found to have an influence on its bending behavior when interacting with the string; on the string's initial conditions (position and velocity); and on the resulting sound (sound level, spectral centroid, and decay time). The jack velocity does not have an influence on any of the measured quantities.
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I. INTRODUCTION

A. State of the art

A number of acoustical studies of the harpsichord has accompanied the rediscovery of this instrument in the 20th and early 21st centuries. Most of them have focused on the radiated sound,[1,2] in particular, on the soundboard, with means of vibration modeling,[3] simulation,[4] or measurement.[5–9] Tracing back the chain of sound production, one finds studies about the harpsichord strings, investigating experimentally and theoretically their mechanical properties in relation with their vibratory behavior.[10,11]

The knowledge of the string vibration, the string/soundboard coupling, and the soundboard radiation explain a large part of the harpsichord sound. Yet it seems that the string excitation has been much less investigated, despite the fact that this process is indeed the origin of the sound. Hence the harpsichord players would be expected to control the string excitation to some extent, as, e.g., guitarists[12] or harpists do[13]… But it is actually commonly said and believed that harpsichordists have a very low level of control on the dynamics (changes in sound level) and the timbre, so that the main features of expressivity in harpsichord playing would rather be the note onset asynchrony or the phrasing,[14–16] the choice of the "register" (determining the number of plectra plucking simultaneously the string and the plucking position along the string), or the velocity at which the finger presses the key.[17] It seems that the only way for the harpsichordist to control the sound of the instrument when playing is to change the velocity of key pressing. Hall[18] showed that different key velocities (hence different jack velocities) can produce different spectral characteristics and different sound levels. That the sound level could be increased with higher jack velocities has been confirmed[19] and then refuted.[20] Acoustical as well as perceptual measurements have shown that different key velocities produce measurable ("minor but audible") differences both in sound level and spectral characteristics of harpsichord tones.[21]

Yet there is another leeway for "shaping" the sound of the harpsichord: the "voicing" process. This empirical procedure is carried out by musicians or makers and aims at modifying the shape of the plectra in order to get homogeneous sound and touch over the whole tessitura of an instrument. Only a few studies have been done about the plectrum. Qualitative reasoning has suggested[22] that the plectrum, due to its narrowness in comparison with the length of the string, should not alter the vibration of the string, whereas a simple plucked string model has shown that the string's initial shape and frequency content of vibration signal are altered by the plectrum thickness.[23] This has been confirmed experimentally in the case of the classical guitar: The frequency content and the loudness of guitar tones seem to depend on the plectrum characteristics.[24] In the case of the harpsichord, different plectrum materials have been compared, focusing on their wearing properties.[25] Using a constant-section beam model, the string motion while in contact with the plectrum and therefore its initial conditions of vibration have been

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modeled.[26–29] However, the literature lacks experimental studies about the plectrum geometry. To the knowledge of the authors of the present study, there is only one study about the influence of the harpsichord plectrum geometry. This study[30] found that audio recordings exhibited a high-frequency sound called a "pre-transient," supposedly caused by the plectrum vibration just after the string release. The frequency of this sound has been shown to depend on the material and the geometry of the plectrum. The study of the plectrum geometry also has strong rationales in the field of organology and musicology: Understanding how plectrum shape modifications can alter the sound might be interesting to players, makers, or teachers. In a more historical perspective, there is a clear need to characterize ancient instruments,[31] e.g., for restoration purposes.[4] The establishment and understanding of the link between plectrum geometry and sound can help characterize instruments so priceless, ancient, and fragile that they should no longer be played or touched.

This article presents an experimental framework for the study of the effect of plectrum shape and jack velocity (as the two control parameters over the sound of the harpsichord) on the sound. First results are presented. Section I B describes the plucking mechanism and Sec. I C details the objectives of this study.

B. The harpsichord plucking mechanism

A drawing of the plucking mechanism, reduced to the jack and the plectrum, is presented in Fig. 1. The finger presses the key (not represented here), which is a lever causing the jack to move upwards. In order to describe the plucking process, the following characteristic times are defined:

t_i: The time at which the finger starts pressing the key;
t_c: The beginning of the phase where the string and the plectrum are in contact;
t_s: The beginning of the string/plectrum slipping phase;
t_r: The time at which the string is released.

For $t_i < t < t_c$ the jack is moving toward the string but the plectrum has not yet met the string. For $t_c < t < t_s$, the plectrum lifts the string, leading it in a purely vertical motion. For $t_s < t < t_r$, the vertical motion of the string due to the jack movement goes on, yet due to the deflection of the plectrum the string starts slipping on the plectrum. At $t = t_r$ the string loses contact with the plectrum: it is released from its rest position with finite displacement and velocity and then starts vibrating.

C. Objectives

The bending behavior of the plectrum is partly (the other main factor being the plectrum material) controlled by its geometry, hence the initial conditions of the string vibration are modified by the plectrum geometry. It is therefore expected that the resulting sound is influenced by the plectrum geometry. During a musical performance, the gesture of the harpsichord player can provide the jack with different velocities. This parameter too might have an influence on the sound. This paper introduces a framework aiming at experimentally studying the influence of the plectrum geometry and the jack velocity on (a) the bending behavior of the plectrum, (b) the string's initial conditions, and (c) the sound. Section II presents the design of the experiment aimed at comparing four different plectrum shapes in terms of mechanical and audio descriptors. Section III gives the results of the measurements and Sec. IV discusses them. This paper focuses on one string and a limited set of plectra; this choice is discussed in Sec. IV.

II. EXPERIMENT

This section describes the design of the experiment. First the harpsichord (Sec. II A) and the plectra (Sec. II B) are described. Then the measurement methods for the plectrum bending, string's initial conditions, and sound are presented (Sec. II C), followed by the processing required for obtaining readable results (Sec. II D).

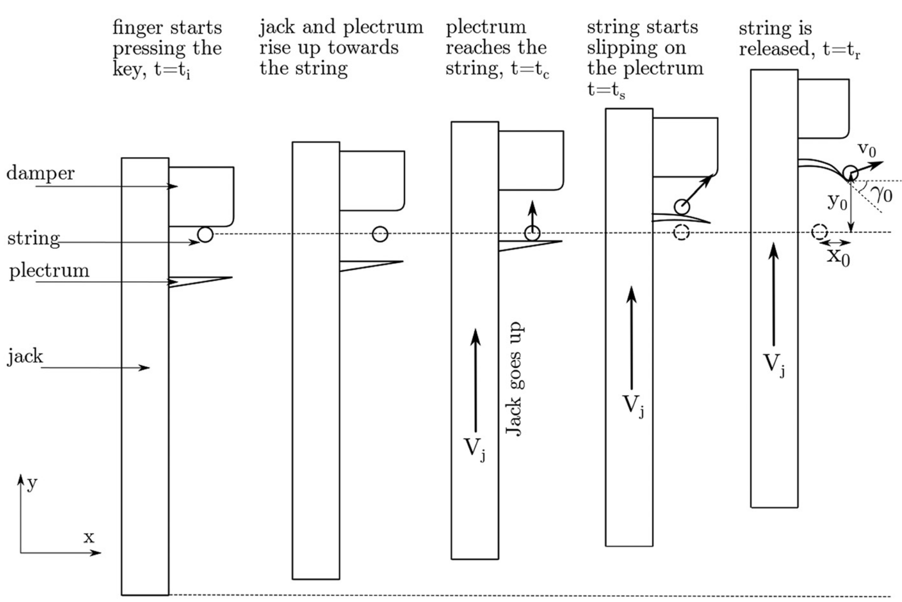

FIG. 1. Drawing of the plucking mechanism. Horizontal dashed lines represent the rest position of the jack and the axis of the string (dashed circle represent the rest position of the string). The jack moves at velocity V_j and the string is released at velocity v_0. Note that the string is in reality closer to the plectrum tip at t_i: this distance has been exaggerated for improving the readability of the drawing.

A. Harpsichord

The experiment is carried out on a harpsichord made by the French maker M. Ducornet in 1989. This instrument was made according to the specifications of Flemish harpsichords of the 17th century, but with only one keyboard and one register: For each pressed key only one plectrum plucks the string. The strings are stretched to nominal tension. This study focuses on a single key, corresponding to the G4-string (diameter $d = 0.32$ mm, cross-section $S = \pi d^2/4 = 8.04 \times 10^{-2}$ mm^2, speaking length $L = 475$ mm, plucking point at $x_p = 121.5$ mm from the pin, string made of iron with density $\rho = 7860$ kg m^{-3}, and Young's modulus $E = 169 \times 10^9$ Pa), tuned at $f_0 = 367$ Hz (the harpsichord was tuned with a meantone temperament at A4 = 415 Hz prior to the measurements). The estimated string tension is therefore $T = 4\rho S L^2 f_0^2 = 76.84$ N. The different plectra investigated in this study all correspond to this key/string. The harpsichord has a stop rail for the keys: If the finger continuously pushes the key, the lever motion is stopped by the key hitting the stop rail. For higher jack velocities, the jack can be thrown upwards and it is stopped by the jack rail. Both stop and jack rails are fitted with a small quantity of felt underneath in order to dampen the impact noise.

B. Plectrum shape

Four plectrum shapes are investigated in this study. They are carved out of a polyoxymethylene [$(CH_20)_n$ better known by harpsichord users as the commercial name "Delrin®," a registered name by DuPont™ (USA)] plate. This material has progressively gained popularity among the harpsichord community, showing a better operating life and resistance to hygrometric and temperature changes than the traditional materials such as quill and leather,[32,33] and is nowadays the most common material used for plectra in harpsichords. Each of the plectra is clamped on a jack, and all jacks are identical. Plectrum P1 is the plectrum made by the harpsichord maker himself: it is therefore adapted to the harpsichord of the study (with its current strings and mechanism setup.) An experienced harpsichord player at our laboratory shaped the plectra P2, P3, and P4 for the same key, with the aim of producing significantly different geometries than P1. These three other geometries are caricatural on purpose: They exhibit features that can be encountered in actual plectra, and are meant to sample the variety of real plectra shapes.

The dimensions of the plectra have been accurately measured using a photogrametric method. This method has been previously described in detail[35] and only a brief description is given here. For each plectrum, a picture is taken with a Nikon D800 (Japan) camera equipped with a 60 mm 1:2.8D lens, making sure the focal distance is kept constant and the light level is sufficient to insure correct contrast between the plectra and the black background. From the pictures a contour detection (Sobel method[36]) is applied in order to retrieve the plectrum profiles (respective to both thickness and width from top and side pictures of the plectra). Figures 2(a) and 2(b) show, respectively, the measured thickness and width of each of the four plectra. In terms of thickness, P1 and P4 are very close to one another: They exhibit a linearly decreasing thickness from clamping point to tip, and the major difference between P1 and P4 is the curved tip of P1 (which is typical of playable harpsichord plectra). In contrast, P2 and P3 have an almost constant thickness with a steep decrease at the tip. Compared with P1 and P4, the curvature of the tip of P2 and P3 starts however at a closer position with respect to the plectrum/jack clamping point. In terms of width profile, all plectra present an almost linearly decreasing width, with each plectrum exhibiting a different slope. P1 shows the steepest width decrease, followed by P4, P2, and P3 (the latter two being very close to one another.) P3 is significantly longer than the three other plectra.

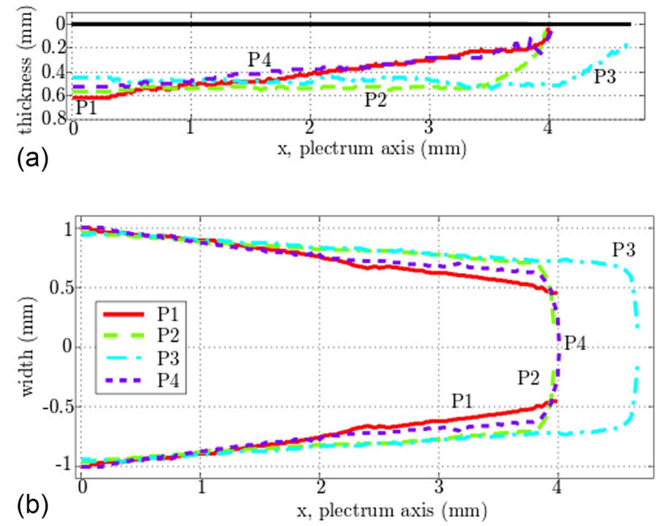

FIG. 2. (Color online) Thickness (a) and width (b) profile for each of the four plectra. Thickness and width are measured along the plectrum length/x axis whose origin is at the plectrum-to-jack clamping point.

The frequency of the first bending mode was also measured for each plectrum.[35] For this purpose, plectra were excited with a Monacor SP-60/8 (Germany) loudspeaker playing a 5 s long logarithmic sweep signal from 2000 to 8000 Hz.[37] From the measurement of the pressure excitation signal [Bruel & Kjær 4961 (Denmark) microphone] and of the plectrum vibration [Polytec PDV 100 (USA) laser vibrometer], the impulse response function of the plectra was computed and analyzed with the esprit method[38] in order to get the first bending frequency. The first bending frequency for each plectrum is listed in Table I.

C. Experimental setup

A robotic finger is used in order to provide a repeatable excitation of the string. A detailed description of the robotic finger is given in a previous article.[34] The robot has previously been used for studying the plucking process in the harp[39,40] and has then been adapted to the harpsichord.[41] The robotic finger has two degrees of freedom (rotations) and is position-driven. Instructions are given to the robot so that the fingertip presses the key with a purely vertical, constant-speed translation movement. The motion of the key is monitored using a fibre optic sensor Philtec D171-Q (USA) measuring the key depression.

TABLE I. For each plectrum of the study, measured first bending frequency, in Hz. The mean of ten measurement is given, and the uncertainty interval is two standard deviations below and above the mean.

Plectrum	P1	P2	P3	P4
First bending frequency (Hz)	6195.06 ± 1.56	5424.42 ± 1.54	4240.89 ± 1.68	5938.00 ± 2.80

The radiated sound is measured with a Bruel & Kjær 2669 microphone placed 1 m above the centre of the soundboard (similar results are obtained with a microphone located at the position of the musician's ear.) This location is consistent with the literature[21] and with the common practice of recording engineers.

A Phantom Miro M120 (USA) high-speed camera (16 000 frames per second, 320×240 pixels resolution) is used together with additional spotlights in order to measure the plectrum deflection.

The string motion is recorded with two perpendicular (for two string polarizations) optical sensors (sensor for horizontal string motion is located 6.0 mm from the nut and 115 mm from the plucking point, sensor for vertical string motion is located 13.0 mm from the nut and 108 mm from the plucking point). During its motion, the string cuts a light beam (one beam for each sensor), producing a voltage proportional to the displacement. The operating and calibration of these sensors are described in details in a recent article.[42]

The drawing in Fig. 3 summarizes the experimental setup. The data are recorded in real-time using a MATLAB (USA) interface controlling National Instruments (NI)-9234 (USA) acquisition cards mounted on a NI-9178 chassis. In order to study how the measured features depend on the jack velocity V_j, measurements are done for various jack velocities (see Sec. II D).

D. Data processing

The raw data need some pre-processing in order to be analysed. Figure 4 gives an example of the results obtained during the experiment. The key depression and the vertical and horizontal displacement of the string are plotted along with the characteristic times defined in Sec. I B. Note that the string displacement measurement has to be expressed at the plucking position. Assuming that before the release the string shape is a triangle whose top is at the plucking point, a simple proportionality rule is used considering the respective distances from the nut and bridge of each of the optical sensors and of the plectrum.

The characteristic times defined in Sec. I B are identified as follows:

t_i: identified as the first instant at which the key depression signal exceeds by 5% its rest value (mean of the first 20 samples);

t_c: identified as the first instant at which the string vertical motion signal declines by 1% from its rest value (mean of the first 20 samples);

t_s: identified as the first instant at which the string horizontal motion signal exceeds by 1% its rest value (mean of the first 20 samples);

t_r: identified as the instant at which the vertical velocity of the string reaches its maximum. Note that for $t > t_r$ the robotic finger keeps pushing the key with the same force (the same would occur with a human finger in playing conditions): at first there is no more resistance due to the string so the key moves quicker (bump on the key depression plot just after t_r), then the robot adapts its velocity to the instructions it has been given, and finally the key meets the felt of the stop rail which offers a high resistance so the key is moving slower.

The robot is checked to provide a constant jack velocity. The velocity of the jack is derived from a linear regression

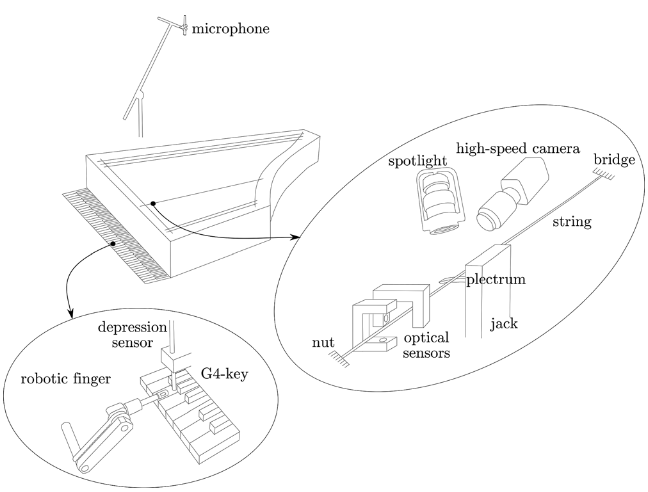

FIG. 3. Drawing of the experimental setup. A robotic finger pushes the key at constant velocity. The string displacement (two directions) is measured with optical sensors. The plectrum deflection is measured with a high-speed camera. The radiated sound is measured with a microphone located 1 m above the centre of the soundboard.

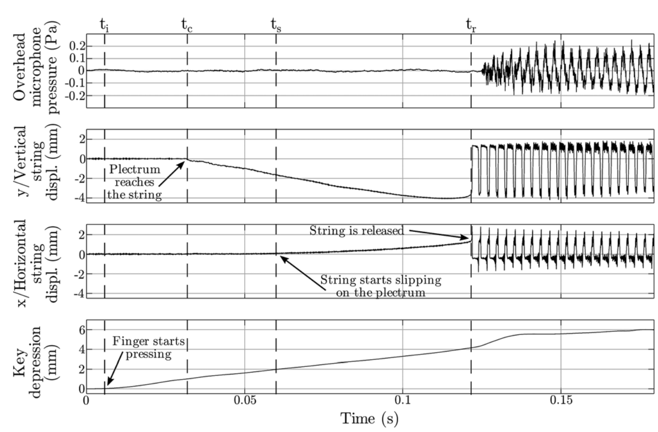

FIG. 4. Vertical and horizontal displacement of the string (at plucking point), and key depression corresponding to a single measurement at $V_j = 0.05\,\mathrm{m\,s^{-1}}$. Characteristic times are indicated with dashed lines: t_i, the time at which the finger starts pressing the key; t_c, the time at which the plectrum starts pulling the string away; t_s, the time at which the string starts slipping on the plectrum; t_r, the time at which the string is released.

of the key depression (scaled with the law of the lever) signal between t_i and t_r.

In order to study velocities that can be obtained in playing conditions,[43] the following jack velocities are investigated: $V_j = 0.05\,\mathrm{m\,s^{-1}}$, $V_j = 0.1\,\mathrm{m\,s^{-1}}$, $V_j = 0.2\,\mathrm{m\,s^{-1}}$, $V_j = 0.3\,\mathrm{m\,s^{-1}}$.

1. Plectrum deflection

Figure 5(a) shows an example plectrum deflection just before t_r the release time. In practice, the camera, and optical sensors are synchronized, so that the last picture of the bent plectrum before t_r can be automatically extracted. This picture is first deskewed using parameters from the camera calibration made prior to the measurements.[44,45] From such calibrated pictures the final shape of the bent plectrum is computed: (a) first the image is manually cropped in order to keep only the plectrum and the string visible, then (b) a contour detection algorithm is run using the Prewitt method[46] with *ad hoc* threshold, and (c) the contour detection is manually checked, discarding irrelevant points. In order to make the result easier to present and read, the identified points of the contour are fitted to a polynomial corresponding to the equation of the deflection of a bent beam. To a first approximation, the plectrum can be considered to bend according to the equation of a cantilever constant-I beam loaded at its free end, which can be found in the literature[47]

$$y(x) = \frac{PL^3}{6EI}\left(\frac{3x^2}{L^2} - \frac{x^3}{L^3}\right), \tag{1}$$

where $y(x)$ is the deflection at abscissa x, P is the force applied at $x = L$ with L the length of the beam, E is the Young's modulus, and I is the quadratic moment of the beam section. The identified points of the contour are fitted to a polynomial of order 3 consistent with Eq. (1)

$$y(x) = \alpha x^3 + \beta x^2 + \delta x + \gamma, \tag{2}$$

checking that $\delta, \gamma \ll \alpha, \beta$ in order to comply with the absence of zeroth- and first-order terms in Eq. (1). The result of the contour detection as well as the polynomial fit are given in Fig. 5(b).

2. String's initial conditions

The string's initial conditions are estimated from the signals of the optical sensors. The initial displacement x_0 and y_0 are the values given by the horizontal and vertical optical sensor, respectively, at t_r the time of string release. In order to estimate the string's initial velocities vx_0 and vy_0 (respectively, the initial velocities along the horizontal and vertical axes), the following method is used for the signals of each optical sensor:

- Collect the 100 samples preceding t_r;
- Compute a polynomial regression of order 2 (corresponding to the shape of the string trajectory observed before t_r) on this truncated signal;
- Estimate the velocity by evaluating the derivative of the polynomial at $t = t_r$.

We also define the magnitude of initial displacement as: $D_0 = \sqrt{x_0^2 + y_0^2}$, the magnitude of initial velocity as: $v_0 = \sqrt{vx_0^2 + vy_0^2}$, and the angle of release which is the angle between the plectrum tip and the horizontal axis $\gamma_0 = a\tan(y_0/x_0)$.

3. Audio features

In order not to disturb the audio analysis with noise coming from the robotic devices and the measurement apparatus, only the first 2 s (starting from t_r) of the audio signals where kept for the computation of audio features. The following audio features are computed from the signal of the microphone:

Equivalent sound level L_{eq}(A) computed from the pressure signal $p(t)$:

$$L_{eq} = 10\,\log_{10}\left(\frac{1}{T}\int_{t=0}^{T} \frac{p^2(t)}{p_{\mathrm{ref}}^2}\,dt\right), \tag{3}$$

where $p_{\mathrm{ref}} = 2\times10^{-5}\,\mathrm{Pa}$, and $T = 2\,\mathrm{s}$. The A-weighting scale[48] is then used because it is easy to compute and is a satisfactory first-order approximation of the human hearing;
Spectral centroid (SC) represents the centre of gravity of the spectrum and is defined as[49]

$$\mathrm{SC} = \frac{\sum_{k=1}^{N} f_k a_k}{\sum_{k=1}^{N} a_k}, \tag{4}$$

and is computed from the discrete spectrum of the pressure signal: f_k and a_k are, respectively, the frequency and amplitude in bin k;

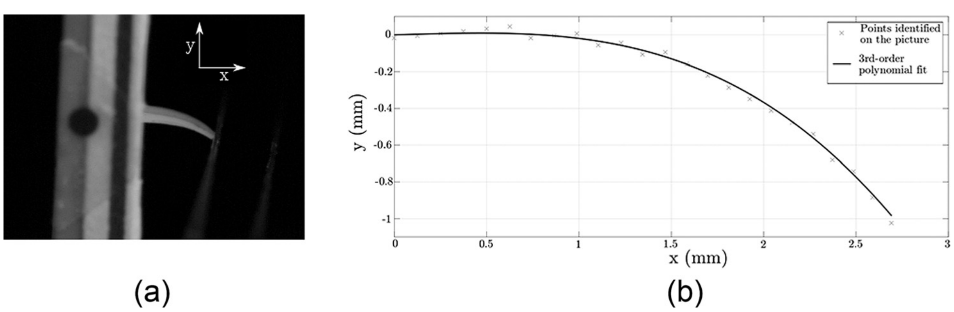

FIG. 5. Deflection of the plectrum P1 (jack velocity $V_j = 0.05\,\mathrm{m\ s^{-1}}$) just before the release of the string at t_r. (a) Photograph from the high-speed camera and (b) corresponding contour identification and third-order polynomial fit.

Decay time T10 computed from the energy decay curve (EDC). The EDC is defined as[50]

$$\mathrm{EDC}(t) = \int_0^t p^2(\tau)d\tau. \quad (5)$$

A linear regression of the EDC is then computed, from which the decay time T10 is derived.[51] The T10 is defined as the time needed to decrease by an amount of 10 dB from its maximum level. Prior to selecting a threshold of 10 dB and to computing the T10, it was checked that no signal exhibits any double-decay in the EDCs (all signals decay linearly.)

Log rise time defined in the field of psychoacoustics.[52] Here it is defined as the time needed by the energy (proportional to the squared signal) to reach its maximum, starting from a pre-defined threshold (here a tenth of the maximum energy.[53]) We then take the decimal logarithm of this time. Note that we also computed this rise time (also called "attack time") with different thresholds, with or without the logarithm, all options giving similar results.

Note that these audio features were selected because they are very simple and synthetic descriptors of traditional basic sound aspects (amplitude—L_{eq}(A), spectrum shape or repartition of spectral energy—SC, decay—T10, and attack—log rise time). They are used to attempt to categorize the sounds according to basic acoustic criteria rather than to provide an estimate of the sound quality, which we leave to perceptual studies.

III. RESULTS

This section presents the results of the experiment, and is divided as follows: First the plectrum deflection measurements are analyzed (Sec. III A), then the initial conditions of the string (Sec. III B), and eventually the audio features computed from the microphone measurements (Sec. III C.)

A. Plectrum deflection

Figure 6 shows the deflection of the plectrum at the time of string release, for each of the four geometries and jack velocities. The camera measurements and associated analysis are shown to be well repeatable. It can clearly be seen that P1 has the lowest deflection, and P3 has the highest deflection. The deflections of plectra P2 and P4 are intermediate and quite similar to one another, although P2 bends a bit less than P4. P1 exhibits a higher curvature, particularly at the tip, which is consistent with the fact that P1 has the thinner tip (see Fig. 2).

On the other hand, no influence of the jack velocity is observed.

B. Initial conditions for the vibrating string

Figure 7 shows the trajectory of the string measured at the plucking point, before string release. For each plucking, the string is vertically lifted and horizontally shifted from its

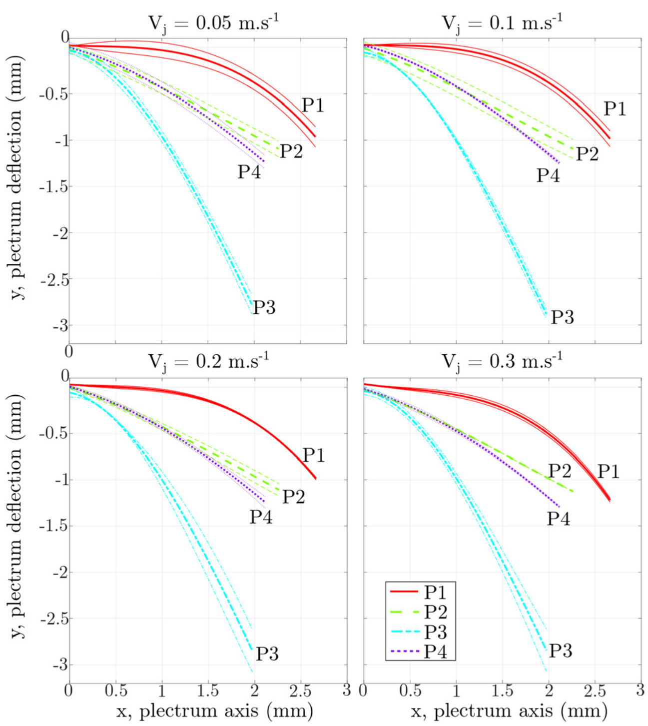

FIG. 6. (Color online) Plectrum deflection (third order-fit) at release time, for each category of jack velocity. Different colors and line styles are used for the plectrum geometries. The thick (resp., thin) lines represent the mean (resp., mean ± standard deviation) of ten measurements.

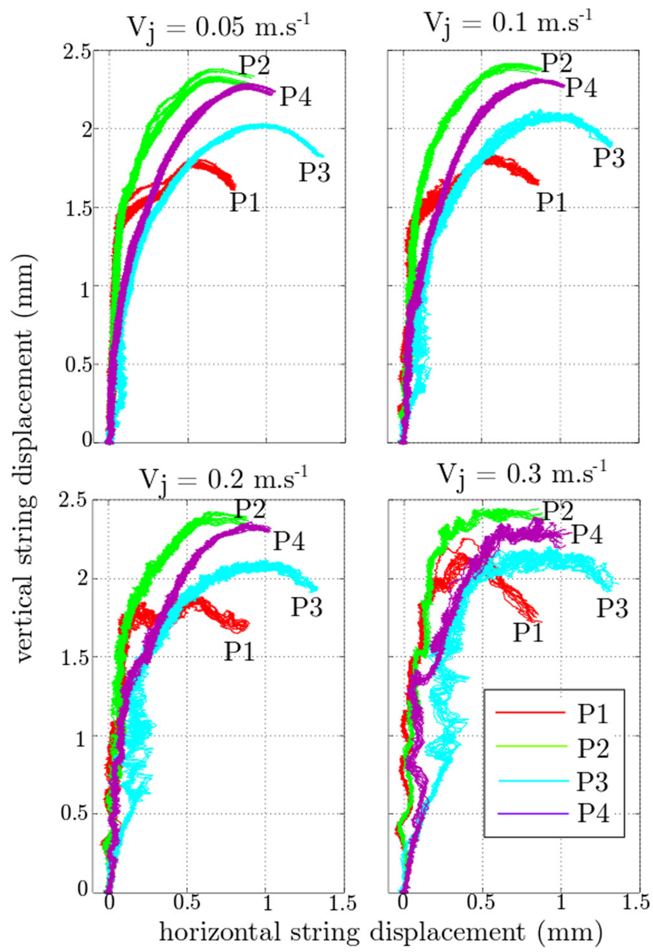

FIG. 7. (Color online) String displacement before release, for each category of jack velocity. "Horizontal" and "vertical" correspond, respectively, to the x and y axes defined in Fig. 1. For each plectrum/jack velocity combination, ten measurements are plotted. Different colors are used for the plectrum geometries.

rest position $(x, y) = (0, 0)$ to the initial position of vibration $(x, y) = (x_0, y_0)$. Different plectrum geometries clearly lead to different string trajectories and hence different initial conditions (see below for more details.) The jack velocity does not change the overall shape of the trajectory, but higher jack velocities foster horizontal (the string slips back and forth on the plectrum) and vertical (both upward jack pushing motion and string restoring force apply on the plectrum) oscillations, indicating that the string and plectrum motions are no longer quasi-static but dynamic for higher jack velocities.

The identified initial conditions of the string are plotted in Fig. 8(a) (magnitude of initial displacement and velocity), Fig. 8(b) (horizontal and vertical components of initial displacement), and Fig. 8(c) (initial angle of string release against magnitude of initial velocity.)

Figure 8(a) clearly shows that the magnitude of the initial displacement is dependent on the plectrum shape: P2, P3, and P4 move the string much further away than P1, and P3 produces smaller initial displacement than P2 and P4. It is then expected that P1 produces lower sound levels.

Figure 8(b) gives a more detailed view into the initial displacement. The plectra differ not only by the magnitude of the initial displacement, but also by the distribution of horizontal and vertical initial displacements. P2 and P4 provide much higher vertical displacements: With P2 and P4 the string is primarily excited in the direction in which the soundboard vibrates, and louder sound levels are expected. P3 provides the string with a large horizontal displacement; hence a less efficient sound radiation is expected with tones produced by P3. Figure 8(b) also shows differences in the ranges of variation: The plectra differ in the variation range of the initial (horizontal and vertical) displacements they can provide to the string. The largest horizontal variation range is achieved by plectrum P1: Different jack velocities can change the horizontal initial displacement of the string by up to 0.1 mm versus 0.05 mm for the other plectra. The vertical variation ranges of the four plectra are similar and approximately equal to 0.1 mm.

Moreover one can notice the influence of the jack velocity: For all plectra, the quicker the jack moves, the further the vertical release position of the string from its rest position. The influence of the jack velocity on the horizontal displacement is less clear: For P1, the faster the jack moves, the further the string is horizontally released from its rest position, whereas for P2, P3, and P4 the velocity of the jack has no influence on the horizontal displacement of the string.

Figure 8(c) shows that the magnitudes of initial velocity provided by each plectrum do not stand out from each other as clearly as observed for the initial displacement. For plectra P1, P3, and P4, it is clear that increasing the jack velocity increases the initial velocity of the string. For a given jack velocity, initial string velocities provided by P1 and P3 cover wider ranges than P2 and P4. Note that for higher jack velocities an increase in the variability in the initial string velocity and unexpectedly high string's initial velocities (P1 and $Vj = 0.03\,\mathrm{m{\cdot}s^{-1}}$) is observed. This may indicate a limitation of the plucking robot for higher velocities.

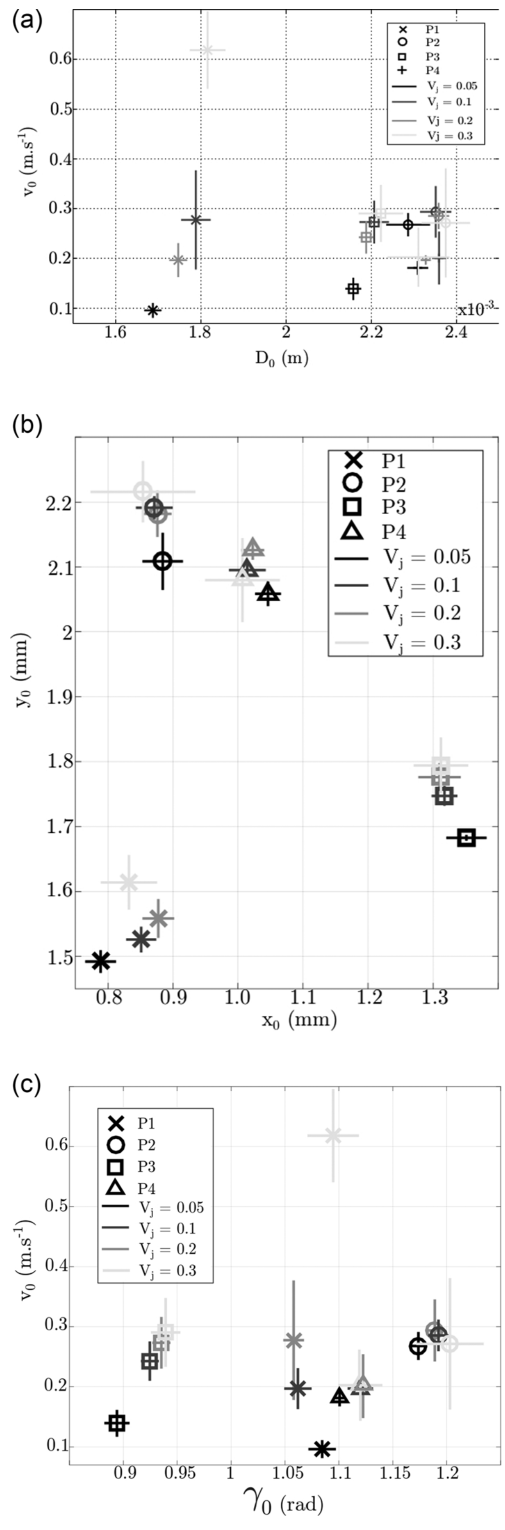

FIG. 8. Measured string's initial conditions. (a) Magnitude $D_0 = \sqrt{x_0^2 + y_0^2}$ of the displacement and magnitude $v_0 = \sqrt{vx_0^2 + vy_0^2}$ of the velocity, (b) horizontal x_0 and vertical y_0 initial displacement of the vibrating string, and (c) initial angle of string release versus magnitude v_0 of the initial string velocity, for each plectrum geometry and jack velocity. A color-code is used for the categories of jack velocity, markers are used for the plectrum geometries. Distances are counted from the string's rest position for $t < t_i$.

Figure 8(c) shows that the initial angle of string release depends on the jack velocity and on the plectrum shape. The higher the jack velocity, the higher the initial angle. Plucking with P3 results in smaller initial angles, plucking with P1 or P4 results in intermediate angles, whereas plucking with P2 results in small initial angles. P2 and P4 show a very small variation range in initial angle, in comparison with P1 and P3.

The slightly wider ranges (depending on the jack velocity) observed in the initial horizontal displacement and angle for P1 can be interpreted as a finer and more precise control given to the player: Controlling the jack velocity, the player has access to a broader range of string's initial conditions when using P1. This should not come as a surprise since P1 has been designed and adjusted by the maker himself for this very harpsichord.

C. Audio features

We present here the results from the microphone measurements.[54]

1. Spectrograms and waveforms

Figure 9 presents the waveform and spectrogram of the attack transient extracted from the audio recordings, for each plectrum, at jack velocity $V_j = 0.1$ m s^{-1} (this jack velocity has been chosen because it is an intermediate velocity, the tendencies presented in the following are similar for the other jack velocities, the only difference being higher amplitudes for higher jack velocities, see Sec. III C 2 for more details on this aspect). No influence of the plectrum geometry is observed on the waveform: this holds close to the attack transient as shown in Fig. 9, and also further away from the attack transient.

On the other hand, it can be seen in the spectrograms that each plectrum produces its own sound signature in the attack transient. Red ellipses in Fig. 9 show typical zones of spectral energy reinforcements: between 6 and 6.5 kHz for P1 and P4, around 5 kHz for P2, and between 3 and 4 kHz for P3. These frequency formants correspond roughly to the measured frequencies of the plectra as given in Table I. An explanation for this, which has been proposed by Gäumann,[30] is that the microphone picks up the acoustic emissions of the plectrum vibrating shortly after string release, presumably resulting in these observed formants.

2. Audio features

We present next the audio features (described in Sec. II D 3) computed from the audio recordings.

a. Sound level. The sound levels are plotted in Fig. 10(a). For all jack velocities, plucking the string with P1 (resp., P4) clearly leads to a softer (resp., louder) tone: Such sound level differences [1 to 2 dB(A) lower than the other plectra] might be audible (the just noticeable difference in sound level being approximately 1 dB.[55]) This is consistent with the result of Sec. III B showing that the string's initial displacement provided by P1 is smaller. The observed tendencies are supported by a 4 (plectrum) × 4 (velocity) analysis of variance (ANOVA)[56] on the L_{eq}(A) showing that the plectrum geometry has a significant influence on the sound level [F(3,144) = 219.48, $p < 0.01$**[57]]. A Tukey HSD *post hoc* test shows that, in terms of the sound level of the resulting tones, P1 is different from P2 ($p < 0.01$**), P3 ($p < 0.01$**), and P4 ($p < 0.01$**), and that P4 is different from P2 ($p < 0.01$**) and P3 ($p < 0.01$**).

The two-way ANOVA also shows a significant influence of the jack velocity [$F(3,144) = 4.48$, $p < 0.01$**] on the sound level. A Tukey *post hoc* test shows that only the extreme jack velocities ($V_j = 0.05$ m s^{-1} and $V_j = 0.3$ m s^{-1}) are significantly different ($p < 0.01$**), which is obvious for the tones produced by P1 and P2, but not for P3 and P4. This apparent inconsistency can be explained by the significance of the interaction jack velocity × plectrum geometry [$F(9,144) = 2.41$, $p = 0.014$*].

b. SC. The SC values are plotted in Fig. 10(b). No dependence on the jack velocity is observed. Tones resulting from a plucking with P1, P3, and P4 have the highest SC. Tones produced by P2 have the lowest SC. This is confirmed

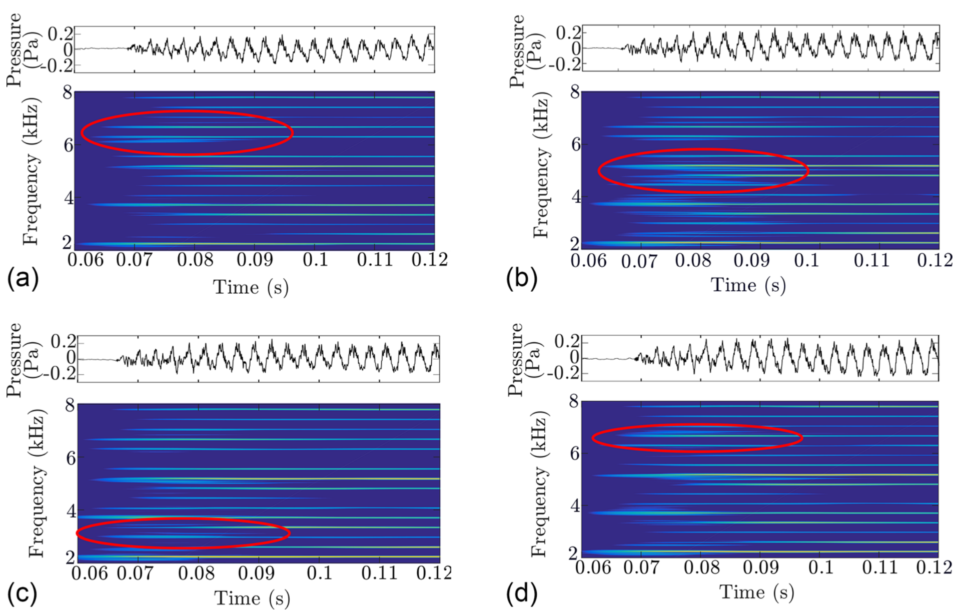

FIG. 9. (Color online) Waveform and spectrogram of the attack transient extracted from the audio recordings, for each plectrum, at jack velocity $V_j = 0.1$ m s^{-1}. (a) P1, (b) P2, (c) P3, and (d) P4. Red ellipses highlight the distinctive features in the spectrograms. The spectrograms have been trimmed to the frequency range where differences can be seen between the plectra.

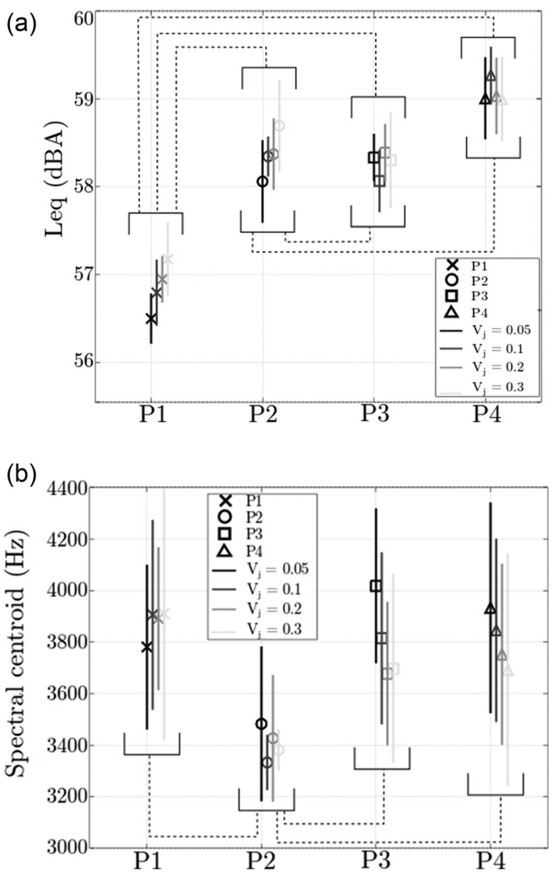

FIG. 10. (a) Equivalent A-weighted sound level and (b) SC, for each plectrum geometry. A color-code is used for the categories of jack velocity. Dashed lines highlight which plectrum geometries are significantly different one from another.

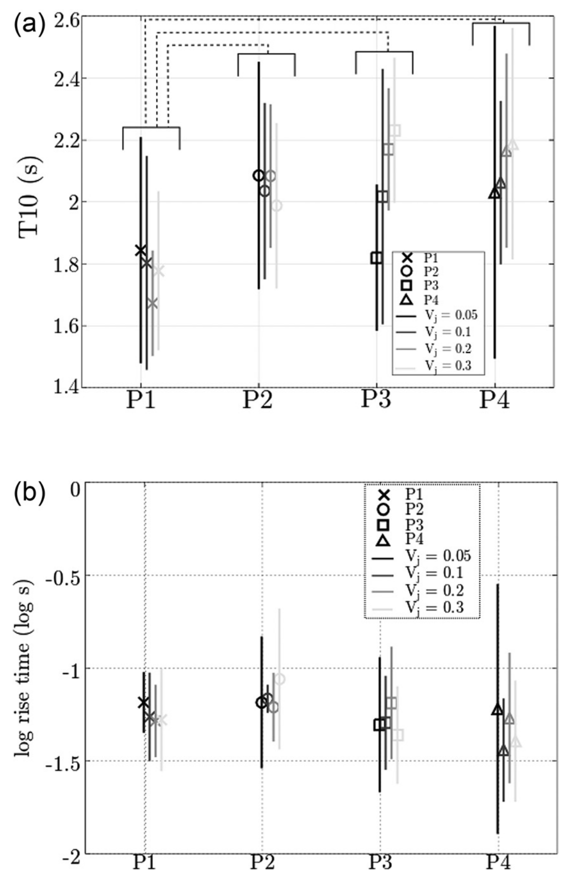

FIG. 11. (a) Decay time (T10) and (b) log rise time, for each plectrum geometry. A color-code is used for the categories of jack velocity. Dashed lines highlight which plectrum geometries are significantly different from one another.

by a 4 (plectrum geometry) $\times$ 4 (jack velocity) ANOVA on the SC values, showing that the plectrum geometry has an influence on the SC [$F(3,144) = 16.48$, $p < 0.01$**], whereas the jack velocity [$F(3,144) = 1.28$, $p = 0.28$] and the jack velocity $\times$ plectrum geometry interaction [$F(9,144) = 0.89$, $p = 0.53$] are not significant. A Tukey HSD *post hoc* test shows that P2 and P1 ($p < 0.01$**), P2 and P3 ($p < 0.01$**), and P2 and P4 ($p < 0.01$**) are significantly different from one another in terms of the SC of the tones they produced.

This suggests that P1, P3, and P4 may produce brighter[58,59] sounds than P2. This remains to be confirmed by perceptual tests that may be conducted with stimuli derived from the recordings of this study. However, it can be remarked that P2 is wider than P1 and P4, and hence may favor lower frequencies.[23]

c. T10. The T10 values are plotted in Fig. 11(a). The jack velocity does not seem to have an influence on the decay time in general, whereas plectrum P1 seems to produce faster decaying tones. This is confirmed by a 4 (plectrum geometry) $\times$ 4 (jack velocity) ANOVA on the T10 values, showing that the plectrum geometry has an influence on the T10 [F(3,144) $= 9.21$, $p < 0.01$**], whereas the jack velocity [$F(3,144) = 0.81$, $p = 0.49$] and the jack velocity $\times$ plectrum geometry interaction [$F(9,144) = 1.29$, $p = 0.25$] are not significant. A Tukey HSD *post hoc* test shows that P1 has a significantly different influence on the T10 than P2 ($p < 0.01$**), P3 ($p < 0.01$**), and P4 ($p < 0.01$**).

d. Log rise time. The log rise times are plotted in Fig. 11. Surprisingly, the attack time does not seem to depend on either the plectrum geometry or the jack velocity. This is confirmed by a 4 (plectrum geometry) $\times$ 4 (jack velocity) ANOVA on the log rise time, showing no significant influence of either the plectrum geometry [$F(3,144) = 2.21$, $p = 0.09$], the jack velocity [$F(3,144) = 0.37$, $p = 0.77$], or their interaction [$F(9,144) = 0.61$, $p = 0.78$].

IV. DISCUSSION

A. Link between the measurements

Links can be made between the different measurements [please refer to Figs. 2(a), 6, 8(a), and 10(a) throughout this paragraph]. First, the thickness profile of the plectra influences their bending shape: P1, and to a lesser extent P4, has a regularly decreasing thickness from its clamping point to its end, resulting in an increasing bending angle (from almost null angle and horizontal tangent to high angles), that is "curvier" in bending shape. In contrast, P2 and P3 are slightly thinner at the clamping point, although have almost constant thickness. This results in a high curvature which remains constant along the entire length.

Second, the plectrum thickness at its clamping point controls its maximum deflection. P1 (resp., P3), which shows the highest (resp., smallest) thickness at the jack/plectrum clamping point, has the minimum (resp., maximum) deflection. Similarly, P2 and P4 with intermediate thickness, show intermediate deflections.

Third, the maximum deflection controls the initial string displacement and the sound level. P1 has the smallest maximum deflection, leading to smaller horizontal (x_0) and vertical (y_0) initial string displacements. This causes smaller amplitude for the vibrating string and therefore a lower sound level. Accordingly, P2 and P4 have similar and higher maximum deflections leading to similar initial string displacements. These string's initial displacements (vertical, in particular) are higher than those caused by P1, this results in louder sound levels. By contrast, P3, with the highest maximum deflection, tends to increase the horizontal string displacement by a lot and only slightly increase the vertical initial string displacement (with respect to P1). An explanation is that the large and straight deflection of P3 favors the (horizontal) slipping of the string on the plectrum, making the horizontal component prevail over the vertical component in the initial string displacement. P3 also produces louder sound levels than for P1, presumably mostly because P3 plucks have a higher vertical initial string displacement than P1 plucks.

B. Further remarks

The sound level increase that is sometimes observed for higher jack velocities ($V_j = 0.3\,\mathrm{m\ s^{-1}}$) might come from the noise made by the jack hitting the jack rail or by the key hitting the stop rail.[60] The introduction of this additional percussive noise with higher velocities has been described in a recent article[17] showing that the perception of harpsichord dynamics is strongly related to the presence or absence of this percussive noise. Here the percussive noise at high jack velocities may increase the sound level, at least for tones produced by P1 and P2. However, this percussive noise does not change the SC values (no jack velocity dependence for the SC). Yet it should be emphasized that this phenomenon may depend on the instrument, whether or not equipped with a stop rail, with different quantities of felt, etc. There might be other noise sources, such as the plectrum touching the string on its way back just before the damper touches the string, but this aspect of the sound has not been studied here.

No clear difference is observed in terms of decay time (T10.) This may mean that no jack velocity or plectrum shape alters the string's initial conditions enough to change the balance between the horizontal and vertical string polarizations. Such a change would result in different couplings with the soundboard and potentially in decay time inhomogeneities (some notes with "normal" decay, some adjacent notes with much smaller decay.)

As a more general remark, it should be emphasized that the plectra of this study have been cut with different shapes on purpose, in order to provoke noticeable and measurable differences, keeping however shapes adapted to the string investigated thus playable plectra. Differences in plectrum deflection and initial conditions of the vibrating string are very clear, but computed sound descriptors show less clear differences: Even more subtle changes can be expected with "real" plectra (i.e., plectra actually mounted on harpsichords and used by musicians.)

Finally, it is observed that in comparison with the plectrum shape, the jack velocity has little to no influence on the features measured in this study. This indicates that apart from gesture and interpretation strategies (*legato* or *staccato* play, in order to favor or inhibit the overlap between notes and smooth out the note onsets), the main control parameter for the musician is the plectrum shape. This is not a real-time parameter, but it is rather part of the instrument setup prior to the performance. Unsurprisingly harpsichord players pay close attention to the voicing process. Furthermore, it is observed that changing the plectrum shape can change the variation range of the string's initial conditions: With P1, the only "real" plectrum (i.e., the only plectrum designed for musician use), the initial displacement and velocity of the string are more dependent on the jack velocity than with other plectra. This suggests that if players are able to adapt to the plectrum and finely vary the jack velocity when playing, they may be able to change the sound very subtly.

The present study investigated one string only, in the medium register of the instrument. Extending the experiment to all strings of the instrument would be very onerous (a new set of plectra would have to be designed for each string, typical jack velocities in playing conditions would have to be measured for each string before running the experiment) and would probably not change the results of this paper. The investigation of other strings will bring changes in the string tension and in the string/plectrum frictional behavior, but if plectra are designed in a way that they have features of playable plectra, then the results of this study are likely to hold (the plectrum shape is more influential than the jack velocity, the shape of the plectrum determines its bending behavior and therefore the string's initial conditions.)

V. CONCLUSION

In this article we presented an experimental framework studying the influence of different plectrum geometries and jack velocities on the string/plectrum interaction and on the sound, along with results obtained for a single string. Objective descriptors have been derived from measurements such as the initial displacement, velocity and angle of the string, sound level, SC, decay time, and log rise time of the resulting radiated sound, and the plectrum shape before string release.

As expected, plectra differing in their geometry clearly have different bending behaviors, changing the initial conditions of the vibrating string and the sound (sound level and SC.) The bending frequency of the plectrum has been shown to be part of the transient of the radiated sound. The jack velocity has been shown to have only little influence on the string's initial conditions, and no influence on the plectrum deflection. The influence of the jack velocity on the sound level may be mostly explained by the appearance at high jack velocities of a percussive noise corresponding to the key hitting the key rail or the jack hitting the jack rail. This noise is part of the harpsichord sound and is used by listeners to auditively discriminate between gestures (soft or loud touch).[17] As a consequence, controlling this noise is part of the harpsichord performance.

This paper has shown that introducing sound level and timbre variations in harpsichord playing is possible. The musician's limited freedom and subtle control over the sound is determined by the plectrum geometry more than by the jack velocity. This main result has to be generalized to other strings from other registers, as well as to other harpsichords (French, Flemish, Italian, etc.), but the hierarchy of the effects (greater influence of the plectrum geometry in comparison with the jack velocity) is likely to remain valid.

This study is a first step toward a more comprehensive study of the voicing process. Ongoing studies are investigating the perceptual aspects of playing different voicings, aiming at understanding the makers' strategies and their results on musicians' feelings and performance. The link between the features measured in this article remains to be confirmed (e.g., smaller plectrum deflection for P1 causing smaller initial string displacement hence lower sound level.) For that purpose, further work is needed to develop a model linking the geometrical and elastic properties of the plectrum to its bending behavior (deflection) and interaction with the string. There already exist models describing the string/plectrum interaction with methods from the field of mechanics,[19,20,23,26,27,29] but only a few have been considering realistic plectrum shapes with non-constant width, thickness, and length.[41,43] Further modeling efforts will be coupled to an ongoing study devoted to precisely measuring the geometrical and mechanical parameters of the plectra.[35]

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[59]J. M. Grey, "Multidimensional scaling of musical timbres," J. Acoust. Soc. Am. **61**(5), 1270–1277 (1977).
[60]There is however no noise of the finger against the key since the robotic finger rested on the key before each measurement.