Experimentally-based description of harp plucking [a]

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Abstract

This paper describes an experimental study of string plucking for the classical harp. Its goal is to characterize the playing parameters that play the most important roles in expressivity, and in the way harp players recognize each other, even on isolated notes - what we call the “acoustical signature” of each player. We have designed a specific experimental setup using a high-speed camera that tracks some markers on the fingers and on the string. This provides accurate 3D positioning of the finger and of the string throughout the plucking action, in different musical contexts. From measurements of ten harp players, combined with measurements of the soundboard vibrations, we extract a set of parameters that finely control the initial conditions of the string's free oscillations. Results indicate that these initial conditions are typically a complex mix of displacement and velocity, with additional rotation. Although remarkably reproducible by a single player - and the more so for professional players -, we observe that some of these control parameters vary significantly from one player to another.

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I. INTRODUCTION

The physics of musical instruments has been studied to a point where many instruments can now be modeled to produce realistic sound synthesis[1,2]. However, the ways to control this synthesis is currently an active field of research, focusing on the detail of the interaction between the players and her/his instrument, in real musical playing conditions. This is related to the notion of "sound quality", which both players and instrument makers try to optimize. During many years of training, a player develops his ability to control the sound quality in a highly reproducible way. The movement of the bow in the case of bowed strings, or the plucking of the string in plucked string instruments, is developed by the player in order to control the attack, the loudness and more generally the whole set of expressive qualities of each note.

In this study, we focus on the less studied case of plucked strings. During the plucking action, the player transfers energy to the string, providing the initial conditions for the free oscillation that follows. The individual morphology of the finger and the detail of the motion before the free oscillation can be described as the basic element of the individual technique of the player. The initial conditions of the free oscillation of the string reflect the past history of the plucking action, from the gesture preparation to the final launch of the string. The resulting sound is therefore affected by the history of the plucking action, marked by the player's signature. The idea of a different signature for each player was an initial motivation for this work. Some trained harp players even claim, in informal discussions, that they even can recognize each other through a single note. While the confirmation of this claim would require a large statistical study, the goal of this work is to investigate which features in the initial string excitation could potentially explain players' differences.

Throught the centuries, the harpists playing technique has evolved with changes in string tension and material. In medieval Europe, brass harp strings were plucked and even struck with long fingernails[3], a technique also used by Irish harpers who struck the brass strings of their harps with specially trimmed long fingernails[3]. During the Renaissance, horsehair strings were plucked with the fleshy part of the fingers. This technique is close to the classic one still in practice nowadays for the concert harp, as a result of continuity in teaching since the late of 18th century. From that time on, harp has been played with both hands on either sides of vertical strings[3]. In preliminary studies, the plucking action in the concert harp was briefly described in order to propose a simple interaction model[4–6]. Other studies concerning the harp focus on the instrument itself (modal studies[7–10], instrument homogeneity[11,12]), sometimes using a harpist to pluck the strings[8,12,13].

The general mechanism of plucking strings can be described as a succession of three temporal phases[14]: the string is pulled from its initial position until at a particular threshold force (sticking phase), the string slips on the plectrum or on the finger (slipping phase) until it loses contact and is free to vibrate (free oscillation phase). For the harpsichord, this plectrum-string interaction was experimentally studied in detail[15]: initial conditions during normal playing were measured and, with a particular set-up, the plectrum force during all the interaction (sticking and slipping phase) has been estimated. These results allowed the authors to validate a simple plucking model. For the guitar, a detailed description of the finger-string interaction was proposed by Pavlidou[16]. In this study, the string displacement in two transverse directions was measured at one point during the plucking action. These measurements were then used to validate a model predicting the trajectory of the plucking position during and after the interaction. With this model, a parametric study has shown that the guitar player has a great influence on the sound production, due to the frictional force between string and the fingertip, the response of the finger-muscle and the fingertip mass, and the initial direction of the finger's movement (angle of attack). The latter parameter has also been studied by Woodhouse[17]: using a frequency domain approach to synthesize the guitar pluck, he has shown the influence of the plucking angle on the spectrum of body acceleration. For the harp, a preliminary study[18] was focused on the analysis of the plucking action, but this study was done in a non musical position since the harp could not be tilted onto the harpist's shoulder, and was also restricted to two harp players.

The current paper is part of a general study that aims at relating the initial touch of the finger on the string to the sound produced by the harp. This paper focuses on the plucking of a concert harp in different musical conditions and with different fingers, rather than on the sound produced. The experimental procedure that studies the reproducibility of the plucking is described in Sec. II. Then, a set of descriptors for the plucking has been developed (in Sec. III). Finally, these descriptors are used to compare different pluckings (in Sec. IV).

II. EXPERIMENTAL PROCEDURE

A. Experimental setup

To study the plucking action, a specific experimental setup was designed (Fig. 1). It is mostly based on filming the finger / string interaction with a high-speed camera, which allowed us to estimate the finger and string trajectories. Simultaneously, the soundboard vibrations were also measured. It is important to note that the high-speed camera was fixed to the harp, musicians could therefore tilt the instrument at their convenience, as in a usual musical performance. The high-speed camera (Phantom v5.1) was set at 5167 frames per second, and gave access to the finger and string movements in the three-dimensional space, denoted (x_s,y_s,z_s) and (x_f,y_f,z_f) respectively. Indeed, as the motion was performed in the plane perpendicular to the strings[5,18] ($\vec{e}_x$,$\vec{e}_z$, defined in Fig. 1), displacements along the first axis were directly known by positioning the camera in front of the strings, and movements along the second axis were obtained through a mirror (Fig. 1). The latter was fixed to the harp by two means: it is fixed directly to the soundbox and it is also fixed to the high-speed camera. In this way, the position of the mirror was not affected by the vibrations of the instrument. Finally, an accelerometer (B&K 8001) measured the resulting vibrations. It was fixed to the bottom of the 16th string, at the back of the soundboard.

Fig. 2 shows images obtained through the high-speed camera, in direct and mirror view. One can see markers (highlighted black dots) on the fingertip and on the string on either side of the plucking position. A pinhead was also fixed to the string, as close to the plucking point as possible, to measure its angular deviation over time. These markers were then individually tracked on every video frame of the plucking action. This was detected automatically through image processing, using a block-matching algorithm combined with an active contour model[19,20]. This gives an accurate estimation of the markers' positions through time: $x_f(t)$, $z_f(t)$, $x_p(t)$, $z_p(t)$, $x_{s_1}(t)$, $x_{s_2}(t)$, $z_{s_1}(t)$ and $z_{s_2}(t)$. The string trajectory $(x_s(t), z_s(t))$ is then computed using string's markers ($x_{s_1}(t)$, $x_{s_2}(t)$, $z_{s_1}(t)$ and $z_{s_2}(t)$ in Fig. 2), assuming that the string is flexible.

As the camera was fixed to the harp, both string markers define the plucking area on the string (Fig. 2). In this way, the plucking position was imposed on the harpists, which allowed us to point out the musicians' individual and common characteristics, regardless of the plucking position.

B. Measurement protocol

Players were asked to play on a concert harp (CAMAC harps, Atlantide Prestige model) in several musical contexts to obtain a representative set of plucking actions: chord and arpeggio sequences performed *mezzo-forte* with forefinger, annular finger or thumb of the right hand.

Obviously, performing chord or arpeggio sequences involves several strings. However, the dimension of an image obtained by the high-speed camera is restricted to a small area of 480x600 pixels. Therefore, we only had access to the movement of a single string, within these chord and arpeggio sequences. This note was extracted from the whole film sequence, before its analysis.

In order to pinpoint the harp players' individual and common characteristics, ten harpists with different musical skills were asked to participate in these measurement sessions: six professionals and four amateurs, noted H_1 to H_6 and H_7 to H_{10}, respectively. In this paper, the adjective *professional* refers to harp teachers or concert performers, while *amateur* means non-professional players who occasionally practice the concert harp.

Regarding the vibratory study, harpists were asked to play only isolated notes. They repeated each note eight times by fingering (thumb, forefinger and annular), damping the vibration between each in order to facilitate the study of each signal.

The physical characteristics of the studied strings are given in the Tab. I. As the present study focuses on the right hand, which is rarely used to pluck lower notes, all the studied notes are higher than the second octave. While the trajectory study was performed only on the D♭2, the vibratory study involved the D♭ at four different octaves, to have some information about the influence of the *tessitura* on the harp plucking. Note that the *tessitura* of the concert harp used is from about 30.9 Hz (Cb0) to 2960 Hz (Gb6).

III. DESCRIPTORS OF THE HARP PLUCKING

In order to characterize the harp plucking depending on the musical context, a set of descriptors was defined, based on the string displacements (temporal phases, trajectories, initial conditions) and soundboard vibrations (plucking position and cutoff frequency).

A. Temporal phases

Following previous studies[1,4–6,16], the plucking action can be decomposed into several sequences, as shown in Fig. 3:

- The approach phase (Fig. 3(a)): the finger approaches the string which is at its rest position $\forall t < t_c$
- The sticking phase (Fig. 3(b)): the finger and the string move in parallel at the contact point $\forall t \in [t_c; t_s[$;
- The slipping phase (Fig. 3(c)): the finger and the string are still in contact, but the string slips on the finger surface with opposite direction $\forall t \in [t_s; t_r]$;
- The free oscillations phase (Fig. 3(d)): the finger and the string are no longer in contact $\forall t > t_r$.

The estimation of each instant (t_c, t_s, t_r) was made using the harp plucking film. First, the beginning of the sticking phase is automatically determined at the first instant where the finger and the string are in contact and the string does not oscillate anymore, using finger and string trajectories. Then, the slipping instant detection is defined as the instant where the finger and the string move with opposite directions. Finally, the release instant is estimated as the instant where the string acceleration suddenly jumps. Note that for these events, detection is manually performed by observing the filmed plucking. We estimate the uncertainty of this estimation at about 3 frames, i.e. about 0.58 ms.

B. Finger and string trajectories

About 15 plucking actions were filmed for each harpist. The analysis of these curves shows repeatable patterns for each harpist and musical context. In the present section, a representative example has been chosen to describe the way the finger and string trajectories are analyzed: a note extracted of a chord sequence, performed with the right annular finger by a professional harpist.

According to the frame of reference defined in Fig. 4(a), Fig. 4(b) presents the finger and string displacements during the plucking. While the left curve represents the movement of the finger during the plucking action, from the beginning of the sticking phase (t_c) to the end of the slipping phase (t_r), the right curve shows the trajectory of the string from the beginning of the sticking phase (t_c) to its first free oscillations. Note that, as expected, the movement of these free oscillations is close to elliptic.

Note that the original position at t_c of the finger and string are not superimposed because, to make the automatic movement detection easier, the finger position is measured close to the nail while the string is plucked with the pulp. The distance between the finger and the string at the initial time t_c therefore corresponds to the thickness of the finger.

C. Initial conditions shape and velocity

Using the finger and string trajectories, we can define descriptors of the initial conditions of the string vibrations: D_{t_r} and V_{t_r} are the distance between the string at t_r and its rest position, and the velocity of the string at t_r, respectively.

Experimental finger and string trajectories presented previously in Fig. 4(b) describe the movement of one point of the string during plucking. Even if the shape of the string at each instant is not directly known, the displacement of each point of the string during the sticking phase ($\vec{r}(y,t) \forall t \in [t_c; t_s[$) can be computed. Indeed, assuming that we have a flexible string of uniform linear density ρ_l, stretched to a tension T fixed at its ends, the transverse vibrations in x and z directions are[14,21,22]

$$\vec{r}(y,t) = \sum_{n=1}^{\infty} e^{-\alpha_n t} \Big(A_n \vec{\Phi}_n \cos\left(2\pi f_n t + \Psi_n\right) + B_n \vec{\Phi}_n \sin\left(2\pi f_n t + \Psi_n\right) \Big), \tag{1}$$

where t is the time, $f_n = \frac{nc}{2L}$ are the eigen-frequencies (with the assumption that they are equal for the two directions), α_n is the damping coefficient, $\Psi_n = \mathrm{atan}(\frac{\alpha}{\omega_n})$, and $\vec{\Phi}_n$ is the modal deflection. A_n and B_n are modal amplitudes that depend on the initial conditions:

$$A_n = \frac{2x(y_0,0)\sin\left(k_n y_0\right)}{k_n^2 y_0 (L-y_0)}, \tag{2}$$

and

$$B_n = \frac{2\dot{x}(y_0,0)\sin\left(k_n y_0\right)}{k_n^3 y_0 (L-y_0) c}. \tag{3}$$

The initial shape ($x(y,0)$) and velocity ($\dot{x}(y,0)$) of the string depend on the plucking. It is usually assumed[23] that the initial velocity of a string plucked with a thin plectrum is negligible ($B_n = 0$) while the initial shape is a triangle ($A_n \neq 0$):

$$\vec{r}(y,t) = \begin{cases} \frac{y}{y_0}\left(x_s(t)\vec{e}_x + z_s(t)\vec{e}_z\right) & \forall y \in [0; y_0], \\ \\ \frac{L-y}{L-y_0}\left(x_s(t)\vec{e}_x + z_s(t)\vec{e}_z\right) & \forall y \in [y_0; L], \end{cases} \tag{4}$$

where y_0 is the plucking point along the length of the string.

D. Initial angle of polarization

The initial polarization (denoted Γ in Fig. 4) has a strong influence on the produced sound[16,24,25]. Indeed, it relates to the coupling between the two vibration polarizations of the string. Using the string trajectory, the initial angle of polarization can be computed. To evaluate this angle, the trajectory of the string during its first free oscillations is fitted to an ellipse. Then, the initial angle of polarization is evaluated as the angle of the long axis from $\vec{e}_x$, that is to say from the strings plane.

E. Energy

During the sticking phase, the harpist adds energy to the string. Assuming that the finger / string system is moving slowly, as compared to the characteristic movement of the string oscillations, the kinetic and potential energies (respectively noted E_k and E_p) are computed as follows[22]:

$$E_k = \frac{\rho_l}{2}\left(\int_0^L r_x\left(\frac{\partial r_x}{\partial t}\right)^2 dx + \int_0^L r_z\left(\frac{\partial r_z}{\partial t}\right)^2 dz\right) + \frac{1}{2}I\int_{t_c}^{t_s}\dot{\theta}(t)^2 dt, \tag{5}$$

$$E_p = -\frac{T}{2}\left(\int_0^L r_x\frac{\partial^2 r_x}{\partial x^2}dx + \int_0^L r_z\frac{\partial^2 r_z}{\partial z^2}dz\right) + \int_{t_c}^{t_s} M\theta(t)dt, \tag{6}$$

where r_x and r_z are the projections along $\vec{e}_x$ and $\vec{e}_z$ of the transverse displacement of the string as described in equation 4, $\theta(t)$ is the angular deviation applied to the string, $I = \frac{\rho_l L d^2}{8}$ is the moment of inertia with d the string diameter, and M is the torque applied to the string.

These computations can be made at the end of the slipping phase, neglecting the rotational kinetic and potential energies, in other words at the beginning of the strings oscillations using the previous equations 5 and 6. In this case, the transverse displacement of the string is computed with the equation 1 and considering the general case[22]: $A_n \neq 0$ and $B_n \neq 0$.

In order to compare the potential and kinetic energy contributions to the global energy transferred by the harpist to the string during each phase, the following dimensionless descriptors are defined:

$$R_{e_k} = \frac{E_k}{E_k + E_p}; \quad R_{e_p} = \frac{E_p}{E_k + E_p}, \tag{7}$$

where R_{e_k} and R_{e_p} are the ratio of kinetic and potential energy to the total energy brought by the harpist during the studied phase, respectively.

F. Soundboard vibrations

1. Plucking position

As the musicians muffled the harp's strings in their own way, temporal signals all end differently. Therefore, we only studied the first 100 ms of the vibration signals. Furthermore, as soundboard vibrations are studied when the modal behavior is established, we assume that this phase begins when the signal energy reaches its maximum value.

Thus, the spectrum of each pluck was averaged over 100 ms of the soundboard vibration signal. This allowed the estimation of the position y_0 where each string is plucked. The origin of the string was chosen as the position at which it is attached to the soundboard. y_0 was estimated, following[26], by minimizing the difference between the ideal string magnitude spectrum and the computed spectrum. The position a string is plucked at is indeed of prime importance regarding the spectral composition[27]. To compare this descriptor regardless of the string length, a dimensionless indicator of the plucking position is defined:

$$R_{y_0} = \frac{y_0}{L}. \tag{8}$$

2. Spatial width of the excitation

The harp string is plucked by a finger of non-negligible width. The displacement of a string plucked with a plectrum of width Δ is given by[14,22]:

$$x(y,t) = 2F\Delta \sum_n \frac{\sin(k_n y)\sin(k_n y_0)}{m_n} \frac{\sin(\omega_n t)}{\omega_n} \frac{\sin k_n \Delta}{k_n \Delta}, \tag{9}$$

where F denotes the amplitude of the applied force and m_n the modal mass of the nth mode. Equation 10 means that the finite width of the excitation acts as a low-pass filter on the vibratory response of the punctual case. The cutoff frequency of this filter is[14]

$$f_c = \frac{c}{2\Delta}, \tag{10}$$

where c is the transverse wave propagation velocity along the string. In the present study, Δ is assumed to be egal to the width of the finger at the point of contact with the string.

IV. DISCUSSION

A. Characteristics of the harp string plucking

1. Finger and string movements

In this section, we focus on the finger trajectory to highlight common behaviors or particular characteristics of each performer movement. Fig. 4 represents an example of finger / string displacements while plucking the harp. Fig. 5 shows finger trajectories of notes played through an arpeggio sequence by two harpists (H_4 and H_5). These two sequences were chosen because of their relevance in relation to the entire set of measured trajectories. The most interesting result is that harp plucking movements are particularly complicated and specific to each performer. Thus, for a given musical context, every harpist performs her/his own kind of finger movement, which is repeatable. During the interaction, the finger is mostly pulling the string outwards. However, after displacing the string to its maximum position according to the plucking plane ($\vec{e}_x$,$\vec{e}_z$), a phenomenon appears in varying proportions according to the player and the technique used (chord or arpeggio): the harpist slightly relaxes his grip on the string. This phenomenon appears for instance clearly for the harpist H_5 (Fig. 5) and the two chord trajectories in the Fig. 6. When the string is relaxed by the finger, its direction is hence modified and its distance from rest position tends to decrease.

Fig. 6 shows two finger trajectories by musical context (combinations of techniques and fingering), for a single harpist (H_4). The different shapes confirm the repeatability of the movement for a given musical context. Furthermore, depending on the musical context, these trajectories may have more or less complex shapes (Fig. 6: arpeggio-annular example vs. figure 6: chord-annular example). It is commonly observed that the more complex trajectories are obtained for arpeggio performances. The reason is that the finger / string interaction lasts longer here than in the case of chord performances, and the musician has more time to adjust the action of his finger on the string before releasing it.

Finally, using the string trajectories for each plucking action, we can compute the force applied by the finger on the string, as described by classical plucked string theory[23]. Accordingly (cf. Fig. 5 or 6), the force will first rise during the sticking phase, reach its maximum at the onset of the slipping phase, and then decrease during the slipping phase. The shape of the curve representing the plucking force has a similar behavior to those measured on a harpsichord[15]. Nevertheless, the measured order of magnitude for a plectrum (1.5 N) is much lower than the force magnitude measured for the finger in the present study (up to 15 N).

2. Phase durations

The plucking action is mainly composed of two phases: the sticking and the slipping phases (defined Sec. III.A). The two phases have very disproportionate durations (about 250 ms versus 3 ms) which are described in Tabs. II and III. The presented durations are measured at a fixed dynamic level (*mezzo-forte* for chords and arpeggios) and *tempi* (60 beats per minute (bpm) for chords and 120 bpm for arpeggios). Each harpist was asked to perform chords and arpeggios with the forefinger and the annular finger.

Tables II and III report the measured phase durations. The small uncertainties, of about 10%, tend to indicate that the measurement protocol is reliable. These phase durations appear to be specific to the performer. Moreover, regarding the musical context, while the finger / string interaction duration for an arpeggio matches with the entire amount of time available before the next note (250 ms), the duration of this interaction for a chord corresponds to a quarter of the available duration before the next chord (500 ms). On the one hand, to play an arpeggio in classical harp technique, performing an arpeggio requires that the fingers are in contact with the strings whereas in a chord this is not the case. Performing an arpeggio requires therefore a longer musical preparation than a chord. Note that some boxes are empty because some experimental data are missing or because of some post-processing problems.

The durations of the sticking and the slipping phases which have been measured for the harpsichord, hence plucked with a plectrum, are respectively about 150 ms and 8 ms[15]. This slipping phase duration is about two times higher than our measurements on the concert harp. Nevertheless, the sticking phase lasts as long as those measured for a chord performance and therefore about two times lower than these measured for an arpeggio sequence. For guitars, which are plucked with the fingertip like the concert harp, the plucking duration depends on the loudness of the produced sound: the higher the loudness, the longer the plucking. This duration is estimated between 84 ms and 170 ms, with a slipping phase lasting around 0.5 ms[16]. Finally, to simulate the guitar plucking, typical values chosen to obtain a satisfying sound synthesis[1] are about 0.4 ms for the slipping phase and 15 ms for the sticking phase. These estimations show that the durations measured for harp plucking are closer to the harpsichord case for the sticking phase, while they are closer to the guitar case for the slipping phase. However, the data presented in this paper are restricted to one string on the harp. Since the diameter, the length and the tension of the strings vary along the tessitura of the instrument together with the radiation of the instrument, the players may adjust their plucking, resulting in different phase durations according to the string played.

3. Maximum angular deviation applied to the string

When the finger and the string are in contact, we observe experimentally the angular deviation of the string. To quantify this, the maximal value of the angular deviation of the string during the sticking phase was measured for each filmed plucking. Note that during the slipping phase, this angle monotonically decreases. The obtained values are presented in Tab. IV.

Tab. IV shows the maximum angular deviation applied by the finger to the string during the sticking phase. Again, some boxes are empty because of post-processing issues. In the reported values, the uncertainty of the measurements is about 19 %. The maximum angular deviation of the string produced by the finger is not negligible: the mean rotation is indeed in a range of values between 7° and 82°. Each harpist appears to have a repeatable behavior, which is specific to the individual. Once again, two groups are highlighted: chord and arpeggio sequences. Different fingering does not provide any difference (44° vs. 45° on average). The rotation applied by the finger during a chord sequence is slightly lower than during an arpeggio sequence: 39° vs. 45° on average. This phenomenon can be explained in the same way as before: performing an arpeggio implies more preparation time and thus more control of the string, unlike that of performing a chord. This seems to indicate that the control of the string during the sticking phase, and the way it is released, are important control parameters used by musicians: harp plucking appears here much more complex than the simple pulling out as described by the classical plucked string theory. Furthermore, a second tendency seems to appear with the two musicians who practice their instrument (H_8 and H_{10}) the least as compared to the others, who practice more regularly: the former provide less rotation to the string than the latter. This may mean that they have less control of the strings than the regular performers, or that the skin of their finger has different properties (eg. friction coefficient).

4. Plucking position

Fig. 7 shows dimensionless plucking position R_{y_0} which are computed for every performer plucking each of the four studied notes (Tab. I) in a isolated way, with three different fingers (right hand thumb, forefinger and annular finger). Note that markers disposed on the 30th string for the trajectory study has been removed for these vibration measurements. An interesting first result is that there is no important variability in the plucking position of each fingering. Surprisingly, the measured differences between annular finger, forefinger and thumb does indeed not exceed 1% of the string length. Therefore, to make reading easier, values computed on all three fingers are presented here without any distinction. The dimensionless plucking position values are computed over about 290 observations.

Harpists pluck the string between about one third and two fifths of the distance from the soundboard to the neck. During the measurement session, the plucking position was directly estimated based on the harpist's hand position. Values obtained in this way and measurements reported in the litterature[12] validate the computed values presented in Fig. 7. Furthermore, the plucking position rises slightly with the octave number. Even if there may be some justification to this rise from the global balance of the sound spectra over the tessitura, we expect this evolution to be mostly due to morphological reasons. Indeed, the further the string is from the performer, the more the arm is held out making hand positioning more difficult. Moreover, the variance also increases with the octave number because of the extension of the length of the string at lower frequencies. The computation of dimensionless plucking position leads to the conclusion that there is no significant difference between musicians concerning the position at which they pluck a harp string. Therefore, this parameter alone does not seem to play an important role in the acoustical signature of the player. However, these measurements validate our experimental protocol which consists of observing finger / string movement at an imposed position on the string.

5. Spatial width of the excitation

Tab. V presents the cutoff frequency values computed for each studied string, using equation 10. According to repeated plucking observations, the maximum width of the finger in contact with the string Δ is estimated at about 2 cm. The computed cutoff frequencies are high enough that we can still assume a punctual string excitation. In line with theory[14], the low-pass filter resulting from the excitation's width is therefore negligible.

B. Characteristics of the free oscillation

1. Initial shape and velocity

The classical description of a plucked string instrument assumes that the string is released without significant velocity[22,23]. In other words, the mechanical energy of the string is only composed of potential energy at the release instant t_r. Using the kinetic and potential ratio defined in equation 7, the composition of the string energy at the end of the sticking phase is computed; it is mostly composed of potential energy without any difference between fingerings or techniques. This means the sticking phase matches with the classical plucked string description. Fig. 8 presents the string initial conditions, for all the harpists. While Fig. 8(a) concerns chord sequences for all fingerings, arpeggios are presented in Fig. 8(b). The initial velocity of the string is not negligible and seems to be correlated with the initial displacement: the musician cannot provide a significant initial velocity without a significant displacement, and similarly a weak velocity cannot be associated to an important displacement. Moreover, the initial conditions of the string vibration appear to have a different behavior for chords and for arpeggio sequences. These two different playing techniques lead to different initial shape and velocity conditions of the string. Furthermore, it appears that each musician plucks the string in a characteristic area of the (D_{t_r},V_{t_r}) plane, with a higher uncertainty for arpeggio than chord sequences. The initial displacement of the string is particularly dependent on the musician regardless of whether she/he is professional or amateur, particularly in the chord sequences. As shown Fig. 8(a), $\mathrm{H}_{1\ldots10}$ are grouped in the same area for the two types of fingers. This phenomenon is mostly observable for chord sequences. The uncertainty in the initial velocity is higher than in the initial displacement. As this velocity component mostly appears during the slipping phase, this seems to indicate that, unsurprisingly, string control is more difficult in the slipping phase than during the sticking phase. Fig. 8 also illustrates the different initial conditions of the string according to the fingering used by the musician. Fig. 8(a) shows that the behavior of the string plucked by the annular finger is usually close to the values for the forefinger. This is for instance the case with harpists H_5 or H_7. Concerning arpeggio sequences, except for H_6 or H_4, the same phenomenon appears. Therefore, the initial shape and velocity of the string vibration does not seem to depend much on the fingering. The energetic composition of the string at the release, according to equations 7, can be computed using the initial conditions presented in Fig. 8. Considering average values of measured velocity and displacement ($D_{t_r} = 4mm$ and $V_{t_r} = 2m/s$), computed potential and kinetic energy are about 1 mJ and 0.4 mJ, respectively. Regardless of the chosen velocity and displacement, for instance extreme values ($D_{t_r} = 0.5mm$ et $V_{t_r} = 0.2m/s$ and $D_{t_r} = 7mm$ et $V_{t_r} = 5m/s$), the string owns about 15% and 37% of kinetic energy at the end of the slipping phase, respectively. The initial conditions of the string vibrations are therefore mainly composed of displacement but the velocity component is not negligible.

2. Initial angle of polarization

Tab. VI presents the initial angle of polarization, for each of the ten musicians, for different musical contexts, and for the forefinger and the annular finger. On the reported values, the uncertainty of the measurements is about 15 %. The estimations of the initial angle of attack are between 7° and 43°. Thanks to this large range of values and the reasonable uncertainties observed, this descriptor allows us to distinguish harp pluckings by different musicians. It means the musician controls the string precisely during the slipping phase to release it with the desired direction. These differences may also be explained by morphological differences. Regarding the musical context (arpeggio or chord), we did not observe any particular trend. However, it appears that the fingering has a non-negligible significance. The initial angle of attack is indeed slightly higher when the string is released by a forefinger than by an annular finger.

3. Vibration spectra

As explained in Sec. I, we assume each musician produces her/his own particular sound at the individual note level. In other words, this means they set their instrument into vibration in a way that is particular to them. Hence, just listening to isolated notes performed by different harpists should be sufficient to characterize the player's acoustical signature. For instance, we can hear that, while some of them seem to pluck the string with their fingertip, others seem to pluck the string close to their fingernail. Furthermore, the brightness of the produced sound varies from one musician to another.

To illustrate this phenomenon, Fig. 9 presents spectrograms computed for harpists playing an isolated D♭2 with their right forefinger.

As the spectral effects of the plucking position has not been removed, the spectrograms exhibit some differences between one musician and another which are related to the plucking position. However, this does not explain all observable differences. The spectral mode decreasing is for instance higher for harpist H_1 than H_4. Significant differences across musicians can be observed especially in the highest harmonics, as seen e.g. in the amplitudes of the 5th (major third), 9th (major tone), 11th and 12th (fifth) harmonics.

The previously discussed differences between harpists regarding initial conditions of the string vibration and plucking phases are hence related to the particular radiated sound: as the harpist does not have any mechanical action on the vibrating structure, it means that the initial shape and velocity of the string contain an important part of the musician acoustical signature.

V. CONCLUSION

This article has presented an experimental study of harp plucking. A well-controlled measurement setup allowed the estimation of the finger and string trajectories and the string deviation, during plucking. We also had access to the soundboard vibrations during the free oscillation of the string.

Measurements were performed on ten musicians in several musical contexts (techniques and fingering). They show different behavior, depending mostly on the performer and the technique used. More precisely, each musician provides specific but highly reproducible initial displacement, velocity and rotation to the string. This means that the musician adjusts her/his control of the string in order to release it at the desired position. This string control is also dependent on the technique (arpeggio vs chord): while performing an arpeggio, the string is held by the finger longer than for a chord. In this way, the former is more controlled than the latter, which leads for instance to a more significant maximum angular deviation. Furthermore, following the decomposition of the plucking into temporal phases (approach, sticking, slipping, free oscillation), the initial conditions of the string vibration does not match the classical description for plucked string instruments (significant displacement with negligible velocity) because of the slipping phase where string velocity increases. The kinetic energy component of the string at the beginning of its free oscillation reaches between about 15 to 37 % of the global energy brought to the string by the finger during the whole plucking action. Thus the control issue leads to the idea that the harpist's contribution during the sticking phase is mostly dynamic while musical skill governs the slipping phase.

The slipping phase therefore requires more attention. It is indeed the transition phase between the classical plucking description (the sticking phase here) and the free oscillation of the string. During this phase, the string slips on the finger. It behaves according to the friction between the string and the finger, which is obviously specific to each harpist. Further work is still necessary to investigate more deeply the plucking of the harp. The finger and string trajectories discussed in this paper are restricted to one string. The analysis should be broadened to the plucking of strings at different positions in the harp tessitura. Furthermore, the study can be extended using soundboard vibrations of each performance to define descriptors related to the produced sound according to the plucking action. Although the present study does not deal with the produced sound, previous study[12] has shown the impact of the harpist on the radiated sound. This study has to be extended therefore to the radiated sound and not only to the soundboard vibrations. Moreover, a mechanical model of the finger and the string interaction, combined with the measured trajectories, could be helpful in determining characteristic parameters of the plucking action. Finally, a well-controlled mechanical excitation system[28] could be useful to characterize the influence of our descriptors of harp plucking.

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	Freq (Hz)	Tension (N)	Length (cm)	Diameter (mm)	Material
9th, D♭5	1109	86	17.6	0.7	gut
16th, D♭4	554.4	129	31	1.02	gut
23th, D♭3	277.2	168	54.2	1.32	gut
30th, D♭2	**138.6**	**260**	**97.5**	**1.96**	**gut**

TABLE I. Characteristics of studied strings[4]. The trajectory study is performed on D♭2

	Sticking phase duration (ms)			
	Forefinger		Annular	
	Chord	Arpeggio	Chord	Arpeggio
H_1	161 ± 4		147 ± 18	
H_2	125 ± 26	270 ± 25	116 ± 2	286 ± 25
H_3	98 ± 14	213 ± 39	114 ± 13	233 ± 18
H_4	231 ± 12	210 ± 33	158 ± 22	248 ± 14
H_5	146 ± 13	252 ± 6	146 ± 11	241 ± 32
H_6	73 ± 10	219 ± 29	56 ± 9	230 ± 32
H_7	199 ± 6	250 ± 18	176 ± 25	322 ± 9
H_8	152 ± 36	273 ± 21	163 ± 35	253 ± 26
H_9		402 ± 32	163 ± 28	431 ± 32
H_{10}	111 ± 29	180 ± 28	106 ± 18	220 ± 21

TABLE II. Sticking phase durations for each harpist and musical context. The mean is computed on three and six plucking actions respectively for chord and arpeggio at each fingering. The reported uncertainty represents a 95% confidence interval

	Slipping phase duration (ms)			
	Forefinger		Annular	
	Chord	**Arpeggio**	**Chord**	**Arpeggio**
H_1	2.9 ± 1.1		3.0 ± 0.7	
H_2	1.4 ± 0.2	1.8 ± 1.1	1.2 ± 0.4	1.6 ± 0.5
H_3	2.5 ± 0.4	3.0 ± 0.4	3.7 ± 0.5	2.9 ± 0.5
H_4	2.6 ± 0.2	3.0 ± 0.4	3.9 ± 0.7	3.4 ± 0.7
H_5	2.0 ± 0.4	4.3 ± 2.0	3.1 ± 0.7	4.2 ± 0.9
H_6	1.9 ± 0.6	2.5 ± 0.3	2.5 ± 0.7	2.5 ± 0.6
H_7	3.2 ± 1.2	3.1 ± 1.2	1.9 ± 0.5	6.1 ± 0.8
H_8	2.6 ± 0.8	3.7 ± 0.7	2.6 ± 0.3	3.5 ± 0.7
H_9		3.7 ± 1.3	4.4 ± 1.3	5.1 ± 1.3
H_{10}	3.0 ± 1.9	3.4 ± 0.6	2.9 ± 0.8	2.8 ± 0.4

TABLE III. Slipping phase durations for each harpist and musical context. The mean is computed on three and six plucking actions respectively for chord and arpeggio at each fingering. The reported uncertainty represents a 95% confidence interval

	Maximum angular deviation (degrees)			
	Forefinger		**Annular**	
	Chord	**Arpeggio**	**Chord**	**Arpeggio**
H_1	82 ± 10		66 ± 8	
H_2	43 ± 12	70 ± 9	35 ± 6	54 ± 11
H_3	53 ± 8	45 ± 13	47 ± 8	46 ± 7
H_4	66 ± 2	39 ± 18	44 ± 11	63 ± 9
H_5	25 ± 4	53 ± 6	24 ± 4	48 ± 9
H_6		38 ± 18		34 ± 8
H_7	32 ± 6	43 ± 9	35 ± 1.6	57 ± 5
H_8	22 ± 4	48 ± 7	22 ± 5	34 ± 7
H_9				
H_{10}	20± 5	11 ± 3	15 ± 3.2	44 ± 2

TABLE IV. Maximum angular deviation applied to the string during the sticking phase. The mean is computed on five and seven plucking actions respectively for chord and arpeggio. The reported uncertainty represents a 95% confidence interval

	Freq (Hz)	f_c **(Hz)**	**Harmonic number**
9th, D♭5	1109	9760	8
16th, D♭4	554.4	8593	15
23th, D♭3	277.2	7512	27
30th, D♭2	138.6	6757	52

TABLE V. Cutoff frequencies for each string under study, implied by a finite excitation width, estimated at 2 cm

	Initial angle of attack (°)			
	Forefinger		**Annular**	
	Chord	**Arpeggio**	**Chord**	**Arpeggio**
H_1	44 ± 2		27 ± 5	
H_2	38 ± 5	25 ± 7	28 ± 11	26 ± 8
H_3	32 ± 5	7 ± 3	15 ± 0.5	18 ± 9
H_4	44 ± 0.6	37 ± 2	21 ± 6	25 ± 3
H_5		41.2 ± 2	23 ± 9	28 ± 9
H_6	42 ± 4	38 ± 5	41 ± 4	33 ± 6
H_7	41 ± 1.5	40 ± 3	33 ± 11	38 ± 2
H_8	25 ± 12	35 ± 3	17 ± 18	43 ± 1
H_9		23 ± 6	13 ± 3	14 ± 5
H_{10}	32 ± 5	22 ± 3	18 ± 7	21 ± 2

TABLE VI. Initial angle of attack for each musician. The mean is computed on five and seven plucking actions respectively for chord and arpeggio. The reported uncertainty is an uncertainty with a 95% confidence interval

List of Figures

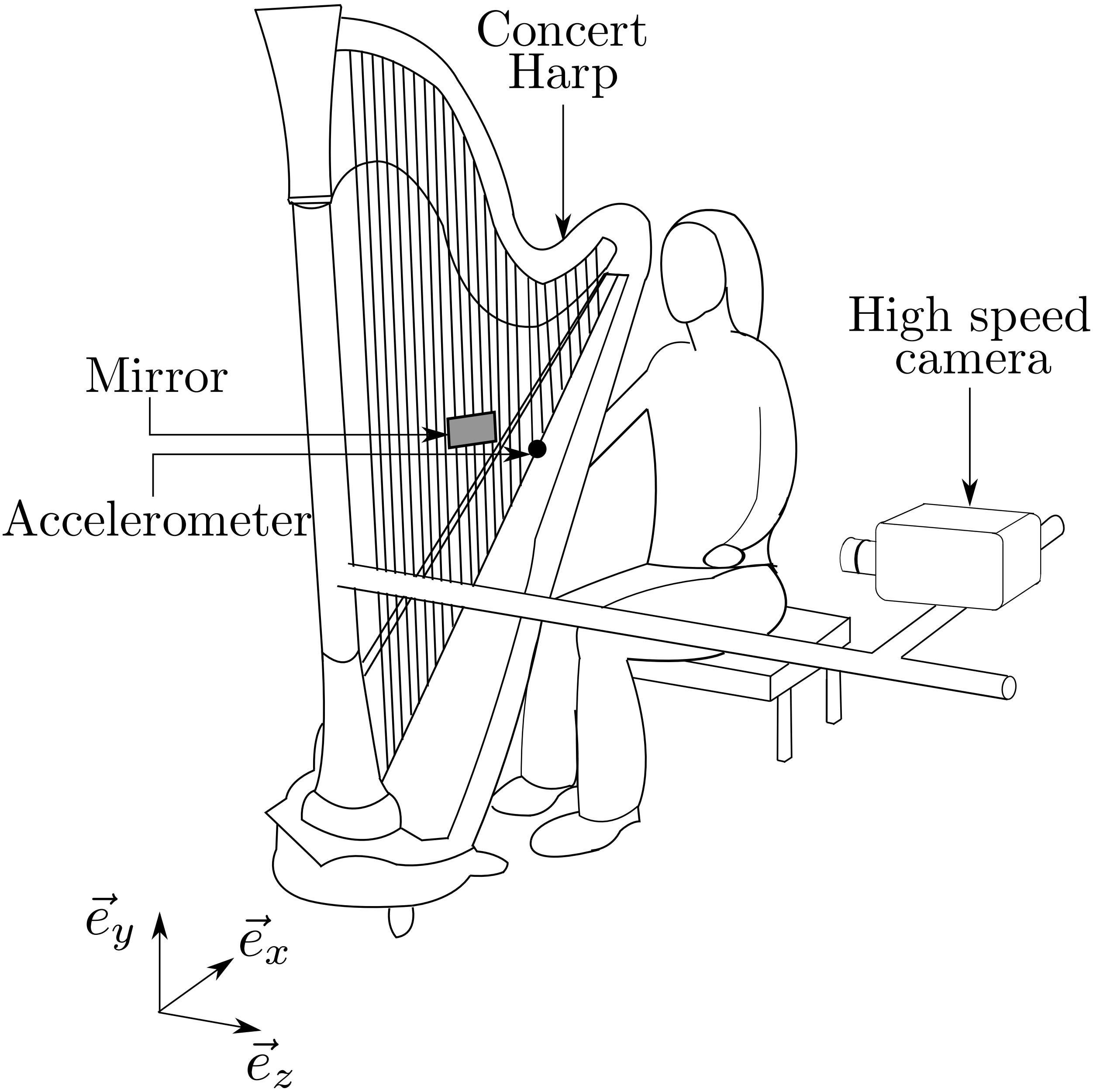
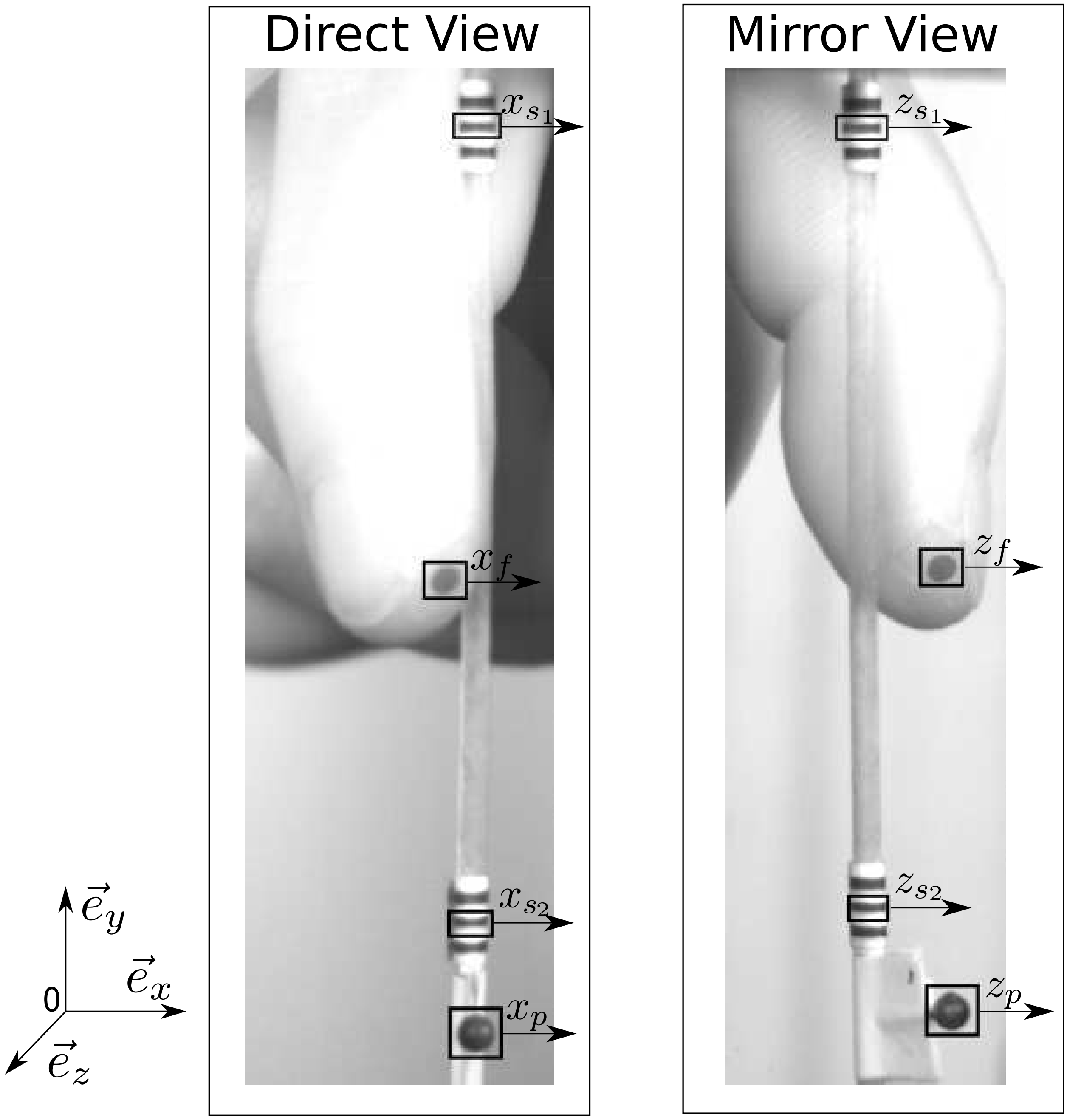

Concert
Harp
High speed
camera
Mirror
Accelerometer
$\vec{e}_y$
$\vec{e}_x$
$\vec{e}_z$

FIG. 1.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Mirror View
x_{s_1}
x_f
x_{s_2}
x_p
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z_{s_2}
z_p
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$\vec{e}_x$
$\vec{e}_z$
0

FIG. 2.

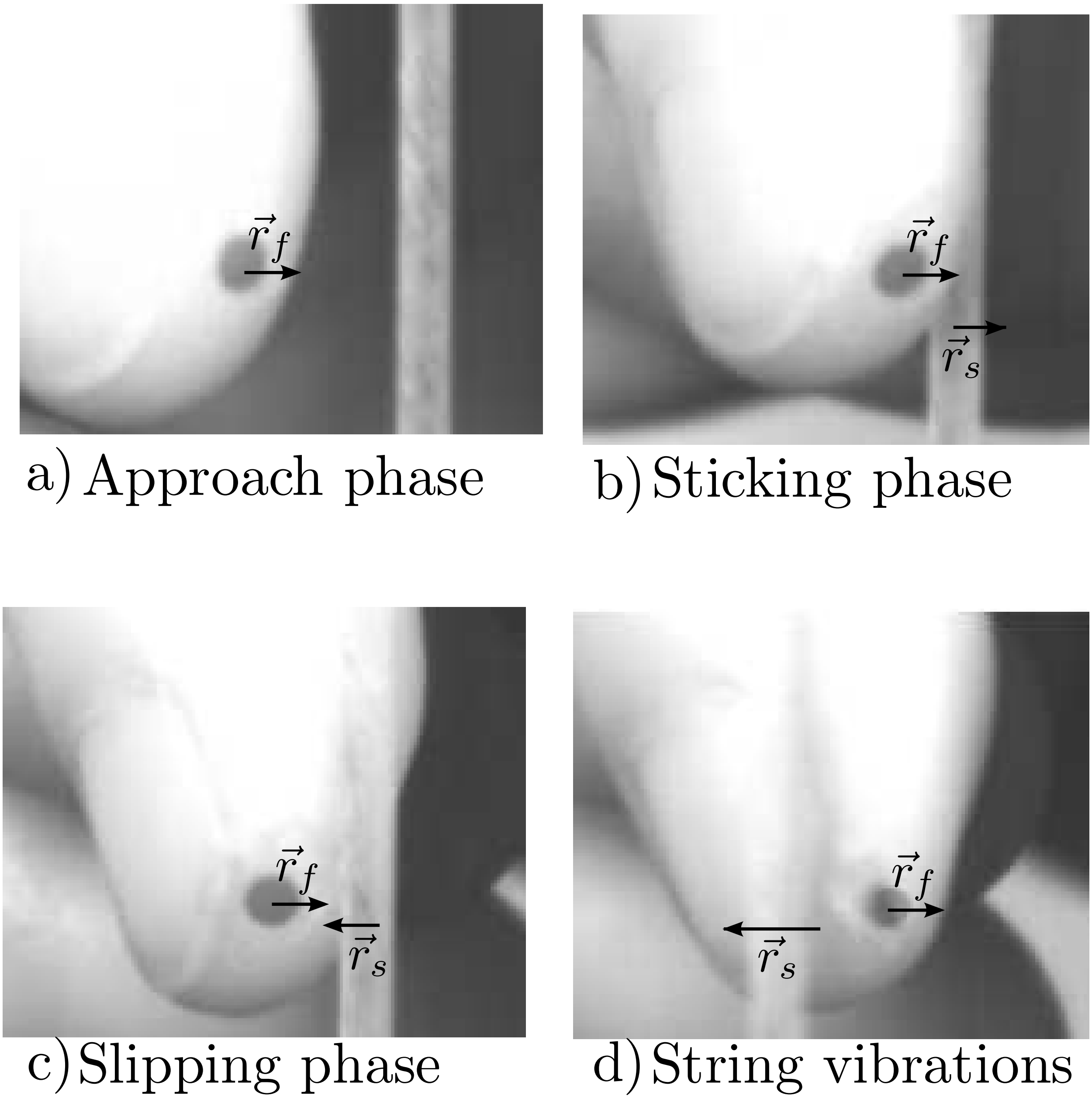
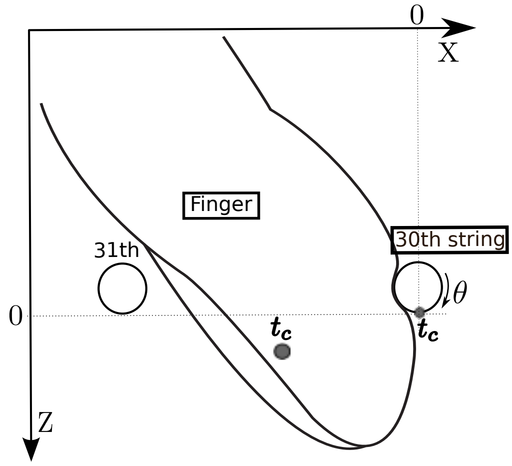
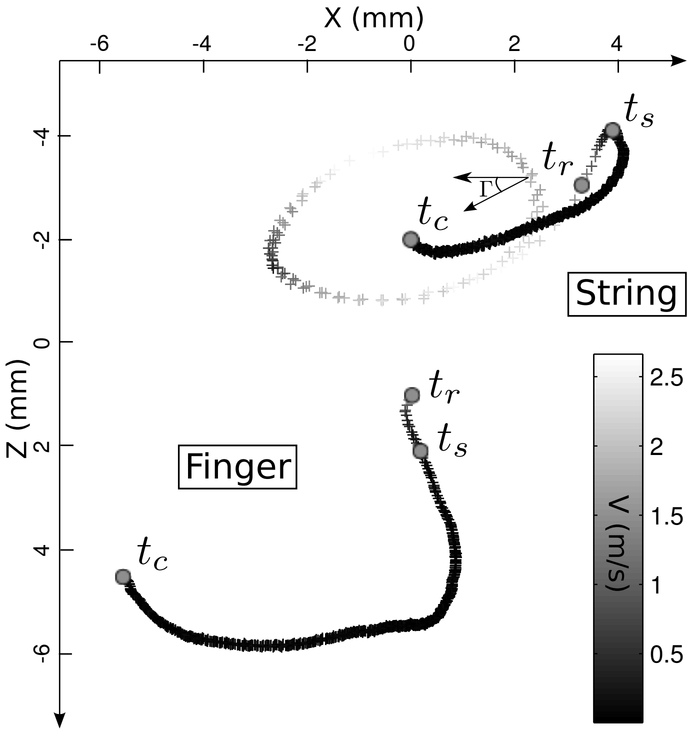

$\vec{r}_f$
a) Approach phase
$\vec{r}_f$
$\vec{r}_s$
b) Sticking phase
$\vec{r}_f$
$\vec{r}_s$
c) Slipping phase
$\vec{r}_f$
$\vec{r}_s$
d) String vibrations

FIG. 3.



a) Frame of reference definition



b) Finger and string trajectories

FIG. 4.

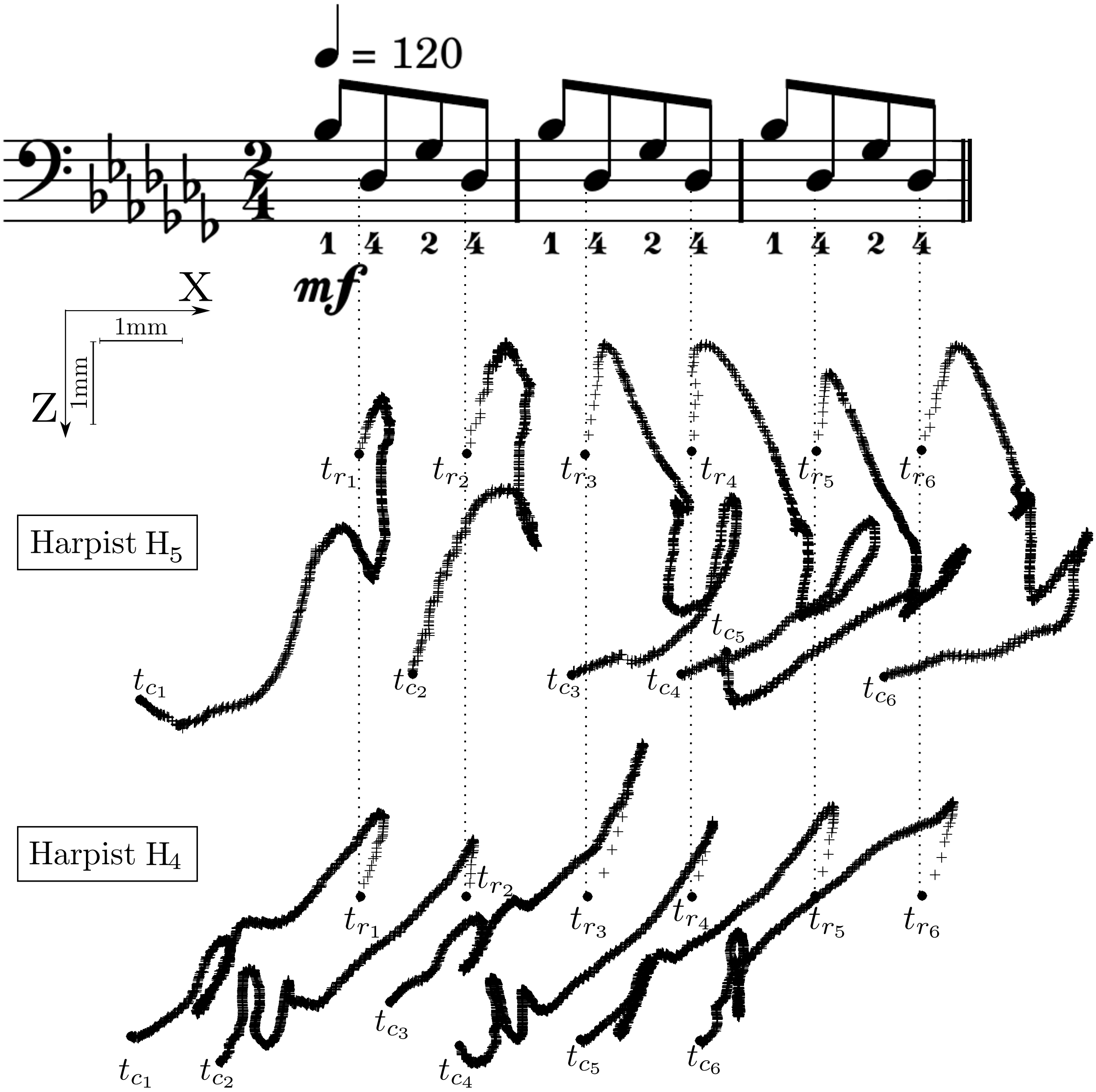


FIG. 5.

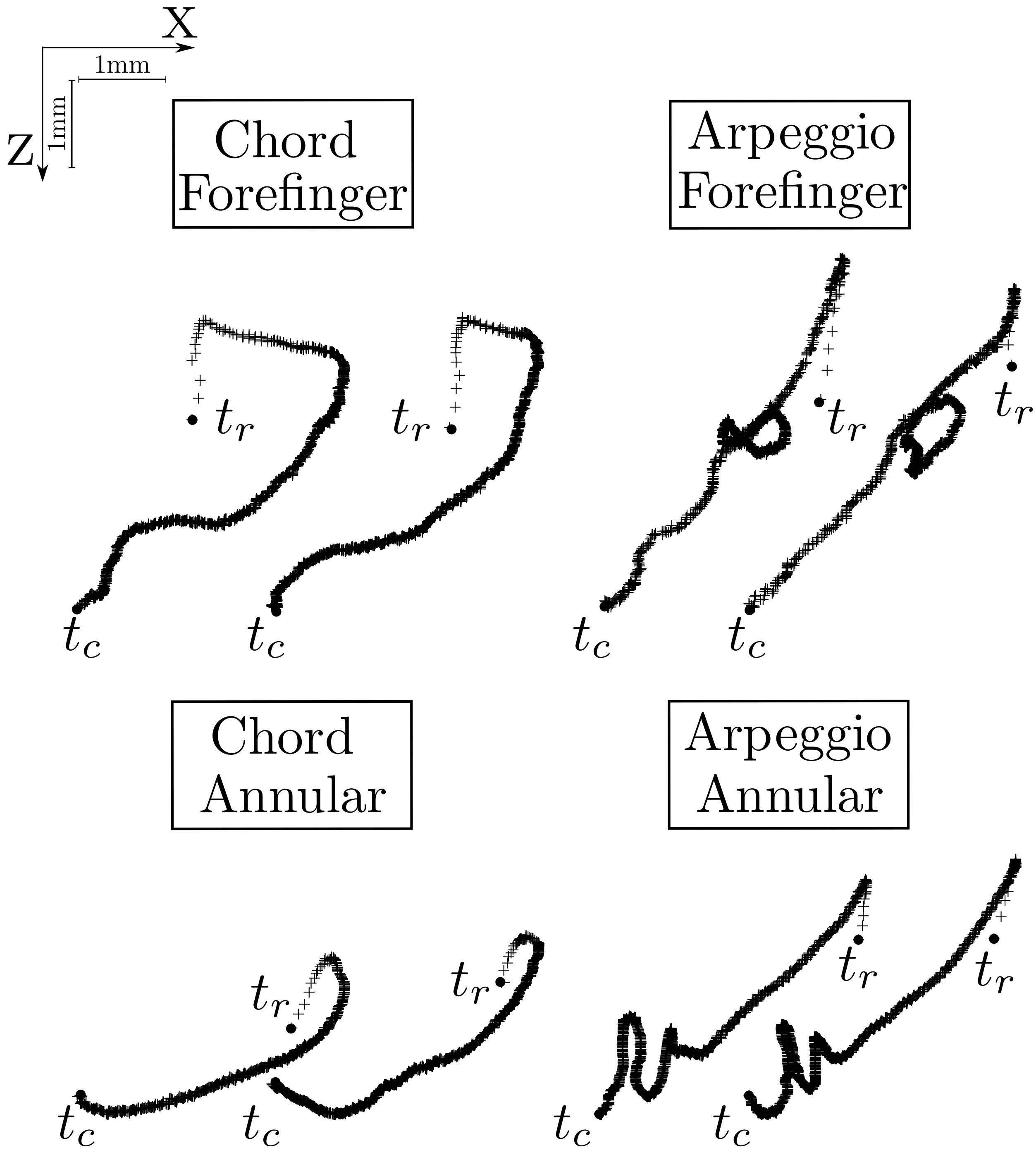

X
Z
1mm
1mm
Chord Forefinger
Arpeggio Forefinger
Chord Annular
Arpeggio Annular
t_r
t_c

FIG. 6.

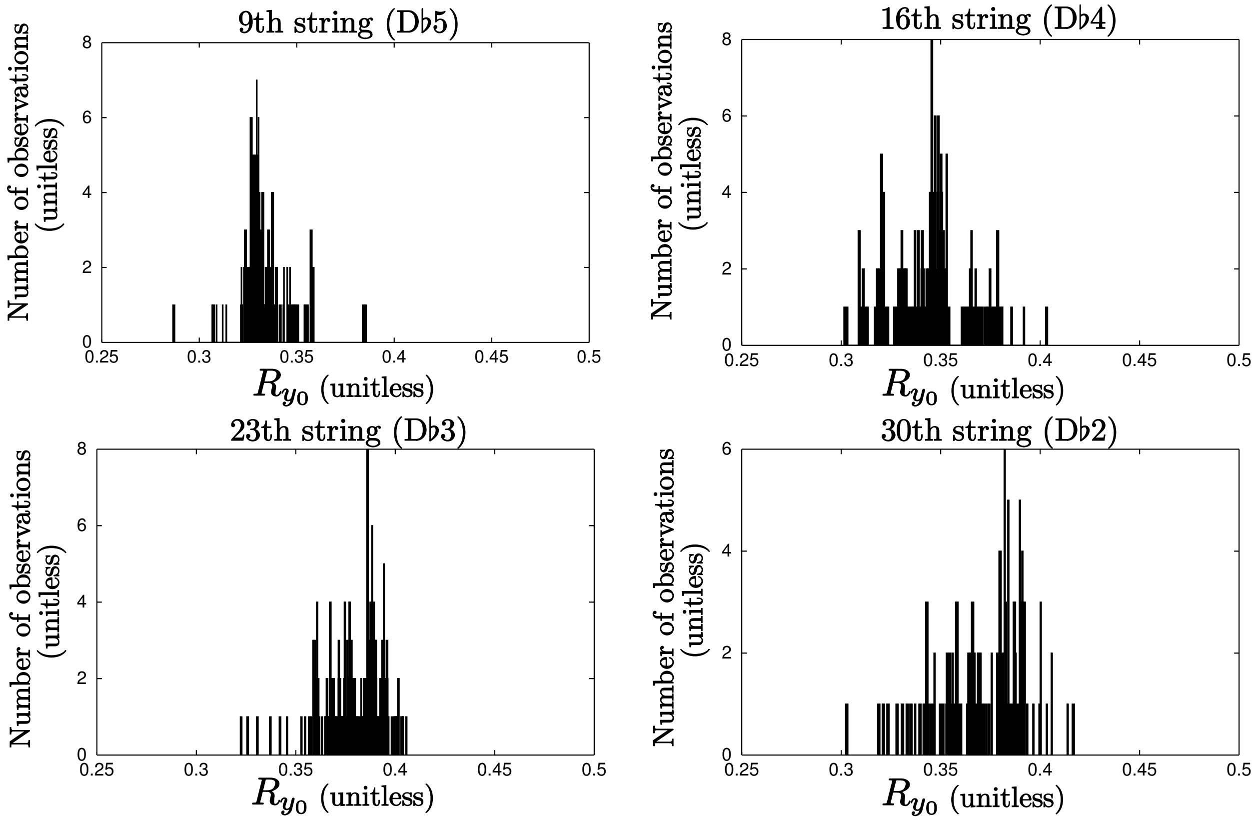
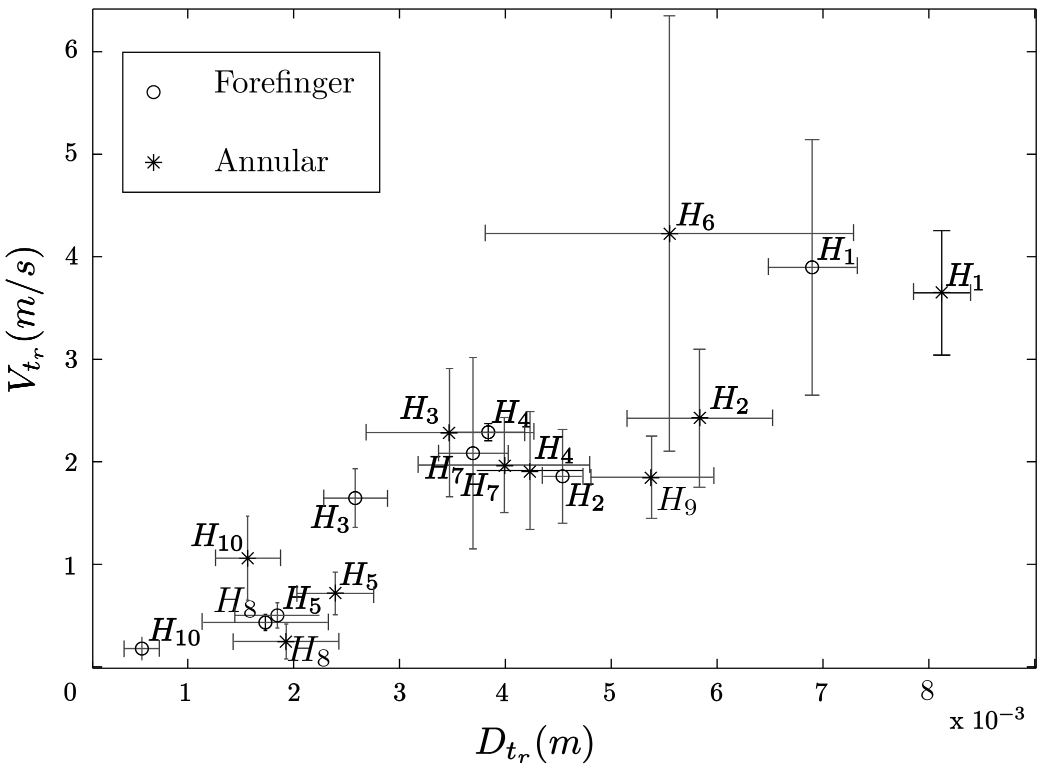
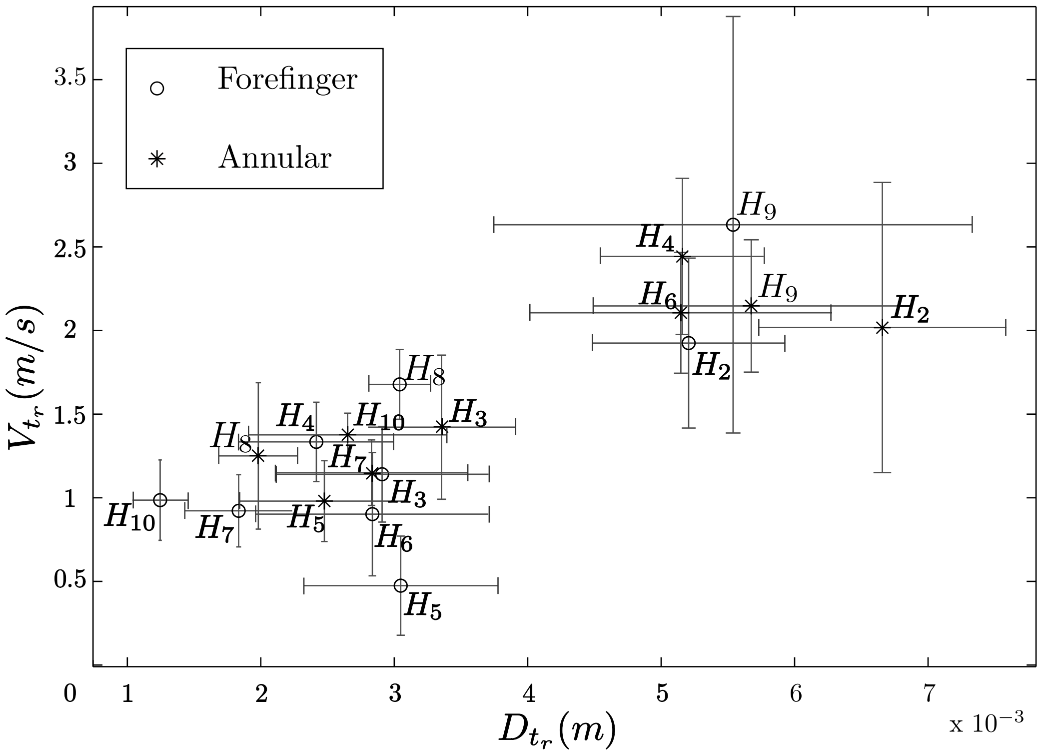

9th string (D♭5)
16th string (D♭4)
23th string (D♭3)
30th string (D♭2)
Number of observations (unitless)
R_{y0} (unitless)
0.25
0.3
0.35
0.4
0.45
0.5
0
2
4
6
8

FIG. 7.



a) Chord sequences



b) Arpeggio sequences

FIG. 8.

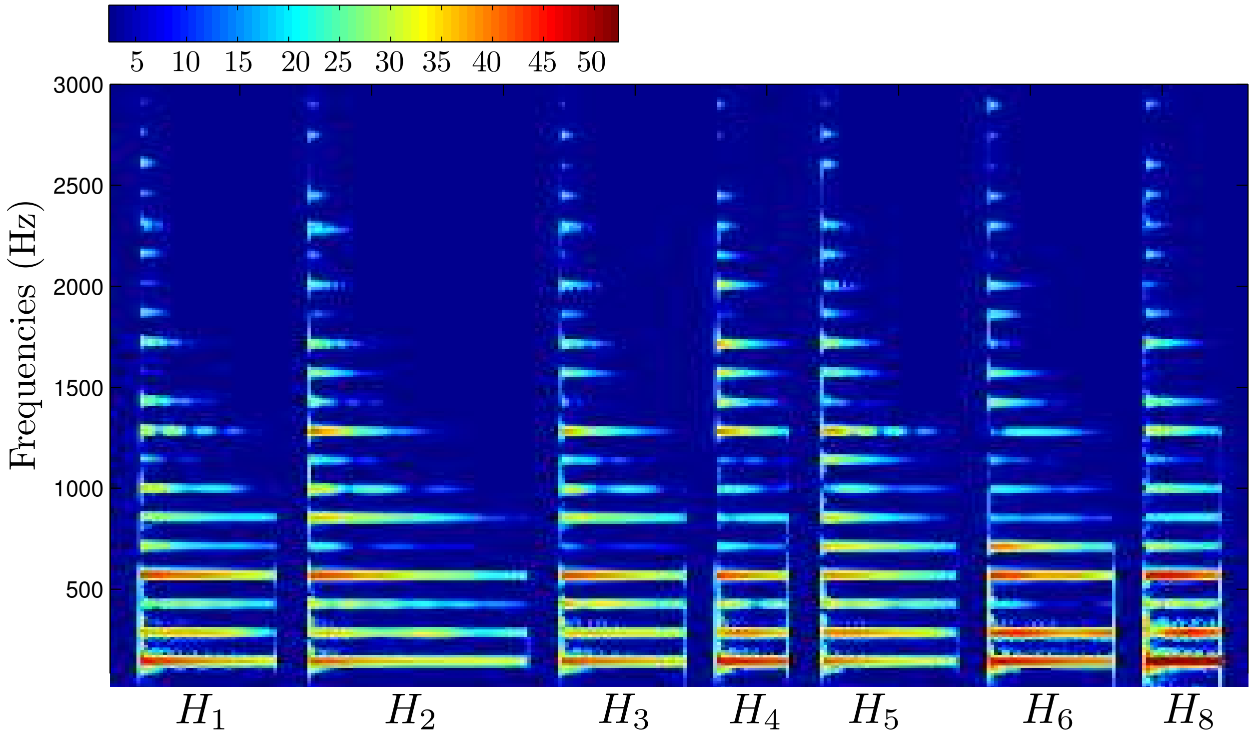

5 10 15 20 25 30 35 40 45 50
3000
2500
2000
1500
1000
500
Frequencies (Hz)
H_1
H_2
H_3
H_4
H_5
H_6
H_8

FIG. 9.