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Experimental study of the plucking of the concert harp

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ABSTRACT

Each musician produces his own particular sound, not only through expressive patterns between successive notes (e.g. tempo and amplitude variations), but also at the individual note level, by the precise way the instrument is set into vibration. In the case of instruments for which the player has a direct mechanical action on the vibrating structure, this action represents an important part of the player's acoustical signature. Until recently, studies on musician's identity in individual tones mostly dealt with sustained instruments (violin, clarinet,...), where the player can modify the sound throughout its duration. However, according to musicians, this notion of acoustical signature also seems relevant for plucked string instruments. It means that, during the plucking action, the player gives initial shape and velocity to the string, which are characteristic of his musical skills or the technique he uses. The aim of the present study is to highlight characteristic parameters of playing techniques, dynamics, or musician skills, in the case of the concert harp. In order to analyse the finger-string interaction, a well-controlled experiment is performed with a panel of harp players playing in several musical contexts. The plucking action is filmed with a high-speed camera. Then, finger / string rotation and displacements are extracted using image processing techniques. These parameters will be used in order to define a set of musically-relevant descriptors of the musical gesture that can parametrize the initial conditions of the string vibrations depending on the skills of the player.

INTRODUCTION

The way a harp is set into vibration is of great importance for the sound produced. Indeed, the way the string is plucked appears to be an important cue for the recognition of the musician or the technique he uses. Finger / string interaction models have been developed, in order to understand the plucking action technique, by computing the finger's mechanical parameters for both the classical guitar [1] and the concert harp [2, 3]. However, these theoretical approaches hardly focus on the musical gesture and on the initial conditions of the string vibrations while the latter may have important consequences on the vibratory spectrum. Preliminary studies [4] have experimentally observed that, in certain cases, the initial string velocity is significant, whereas the initial displacement is negligible. This apparently contradicts the classical description for plucked string instruments (significant displacement with negligible velocity).

In this paper, we investigate in detail, within the plucking of the concert harp, the relative importance of these two components (displacement vs. velocity). A well-controlled experiment, which consists in filming the finger / string interaction, is carried out with subjects of various musicianship. Our primary goal is to provide a set of musically-relevant descriptors of the plucking action that parametrize the initial conditions of the string vibrations. Then, we investigate how these parameters depend on the skills of the player (professionals vs. amateurs).

EXPERIMENTAL PROCEDURE

To study the plucking action, a specific experiment is carried out, which is based on filming the finger / string interaction. A previous study related to the concert harp [5] describes the classical plucking action. It can be decomposed into three phases:

- The sticking phase: finger and string (at contact point) move in parallel: $\forall t \in [t_c; t_s[$,
- The slipping phase: the strings slips on the finger surface (they are still in contact): $\forall t \in [t_s; t_r[$,
- The vibration phase: no more contact between string and finger: $\forall t \geq t_r$.

Because of the short duration of the movement (about 200ms), especially the slipping phase (about 3ms), measurements have to be performed with a high-speed camera (Phantom v5.1) (figure 1).

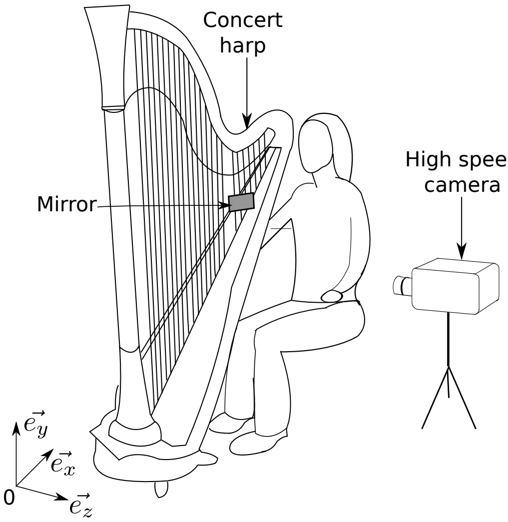


Figure 1: Description of the experimental setup

Here the camera's frame rate is set at 5037 frames per second for a 480x640 pixels image (figure 2), which allows an accurate knowledge of the finger / string movement during each phase. We assume that this motion is mainly performed in the plane

$(\vec{e}_x,\vec{e}_z)$ perpendicular to the strings. Experimentally, the first axis of displacement ($\vec{e}_x$) is directly known by positioning the camera in front of the strings, and the movement along the second axis ($\vec{e}_z$) is obtained through a mirror positioned at about 45° in relation to the strings plane (figures 1 and 2). Note that $\vec{e}_x$ and $\vec{e}_z$ are two vectors defined in figure 1.

Figure 2 shows a picture obtained with this protocol. Markers are installed on the fingertip and on the string on either side of the plucking position (black points in figure 2). Displacements of the finger and of the string are extracted from the pictures, using these markers [4]. Concerning the string, both trajectory and rotation are measured. The former is measured as close to the plucking point as possible, the latter is deduced from the displacement of a pinhead, which is fixed to the string, again as close to the plucking point as possible (figure 2). Markers' positions are tracked from frame to frame by a block-matching algorithm [6], combined with a model of active contours for object detection [7, 8].

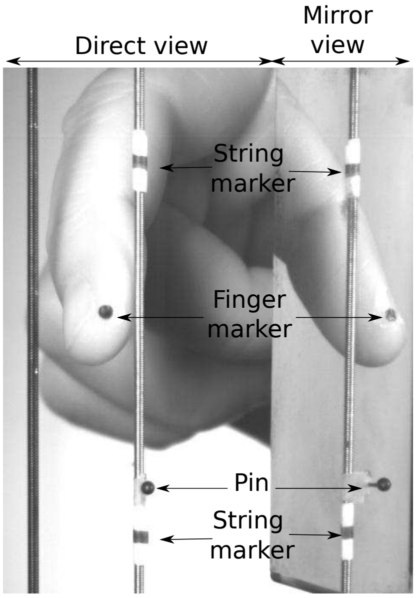


Figure 2: Image obtained with the high speed camera

During the measurement sessions, players are asked to play one or more strings of a concert harp (CAMAC harps, Atlantide Prestige model). As the high-speed camera is not fixed to the harp, harpists have to pluck the string without tilting it as usually done. Harpists play in several musical contexts to obtain a representative panel of plucking actions. Combinations of strings (Table 1), musical techniques and dynamics are proposed:

- **Techniques**: chord sequences, arpeggio sequences, isolated note.
- **Dynamics**: *forte*, *mezzo-forte*, *piano*.

Besides, in order to pinpoint individual or common characteristics to harp players, Four harp players with differents musical skills (two professionals and two amateurs) have performed the experiment. Out of these four players, two have been selected to highlight individual or common characteristics to harp players: one harp teacher, referred to as "professional" subject A, in the rest of this paper; and one occasional player, "amateur" subject B.

	Freq (Hz)	**Tension (N)**	**Diameter (mm)**	**Material**
29th, Gb2	155	267	1.9	gut
34th, Eb2	92	729	1.6	steel

Table 1: Characteristics of studied strings

FINGER / STRING TRAJECTORIES

About 15 plucking actions were filmed for each harpist. The analysis of these trajectories shows repeatable patterns for each harpist and musical context. In the following, we only present examples of plucking actions performed by both harpists with a single musical instructions: an arpeggio on the 29th string, *mezzo-forte*.

The finger / string trajectories in the $(\vec{e}_x,\vec{e}_z)$ plane for the professional and the amateur harpists are represented figure 3a and 3b, respectively. Let us describe the different curves on these figures.

- Red curves represent the finger displacement ($\forall t \in [t_c;t_r]$),
- Blue curves represent the string displacement ($\forall t \in [t_c;t_r]$),
- Gray curves represent the string oscillations ($\forall t > t_r$).

Note that the original position at t_c of 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.

The sticking phase ($\forall t \in [t_c;t_s[$) is the period where the finger and the string move in parallel. The similarity of the two curve profiles on each figure (3a and 3b) is generally well verified for both the amateur and the professional. The observable differences are explained by movements of the fingertip on the string. Figure 3a shows that the sticking phase can be divided into two parts: after displacing the string to its maximum position according to the $(\vec{e}_x,\vec{e}_z)$ plane, the harpist slightly untightens his grip according to $\vec{e}_x$. This phenomenon does not exist for the amateur harpist (figure 3b) who displaces the string continuously during this first plucking phase.

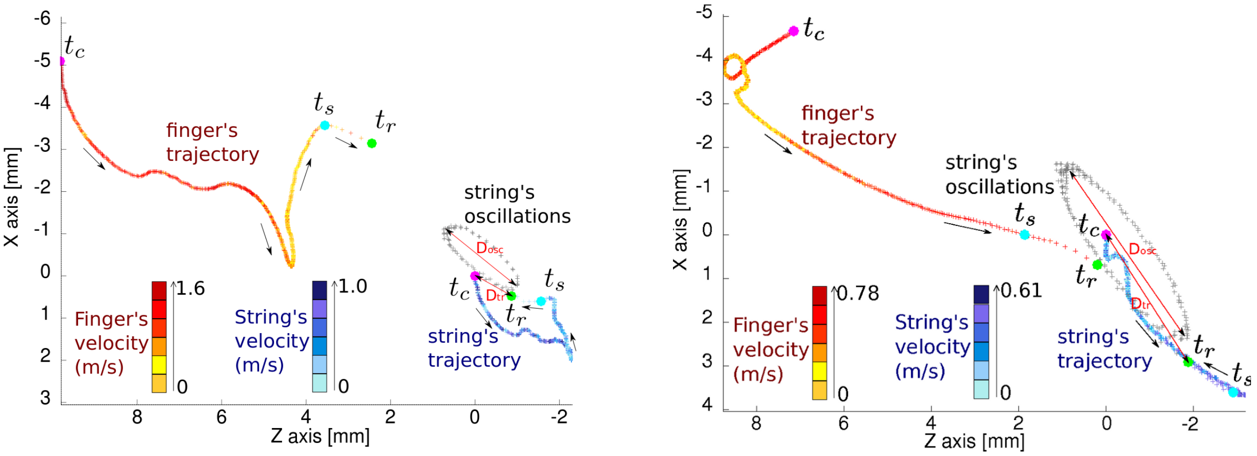
During the slipping phase ($\forall t \in [t_c;t_s[$), the finger and the string are still in contact, but the string slips over the finger surface. This phase, characterized by the opposite movements of the finger and the string, is shorter than the sticking phase (2ms vs. 200ms). During this slipping phase, both harpists have similar behaviors.

From t_r, there is no more contact between the finger and the string. The string movement is close to elliptic, as expected during this free oscillations phase. Table 2 compares displacement and velocity parameters for both players. Here, D_{t_r} and D_{osc} refer to the euclidean distance of the string at t_r and its maximal euclidean distance during free oscillations, respectively. Similarly, V_{t_r} and V_{osc} are the velocities of the string at t_r and its maximal value during free oscillations, respectively.

	Harpist A	**Harpist B**
D_{t_r}(mm)	0.9	5.1
V_{t_r} (m.s^{-1})	1.4	1.1
D_{osc} (mm)	2	5.6
V_{osc} (m.s^{-1})	1.9	5.5

Table 2: Initial conditions of the string at the release time for both harpist A (professional) and harpist B (amateur), for one typical realisation of the same musical instructions

According to table 2, the harpist B releases the string with an initial displacement (D_{tr}) about five times higher than the harpist A (5.1mm vs. 0.9mm), while the initial velocity V_{tr} appears to be equivalent in both cases (1.1m.s^{-1} vs. 1.4m.s^{-1}).



(a) Harpist A (professional player) (b) Harpist B (amateur player)

Figure 3: Finger / String displacements

Therefore, it seems that, contrary to the classical plucked string description [9], the string is released with both velocity and displacement. Besides, during the free oscillations, the string plucked by the professional has less maximal displacement and velocity than the string plucked by the amateur (2mm vs. 5.6mm and 1.9mm vs. 5.5mm): the former seems to have a better control on the string.

DEFINITION OF DESCRIPTORS

In order to parametrize the initial conditions of the string vibrations, depending on the skills of the player, a set of musically-relevant descriptors of the musical gesture is defined, based on the measured finger / string displacements. These descriptors are explained at the end of this section, after describing hypothesis and notations.

Hypothesis and notations

First of all, the string, of length L, is assumed to be flexible, of uniform linear density ρ_l, stretched to a tension T, and fixed at its ends. As the finger / string system moves slowly compared to the free oscillations of the string, inertial terms can be neglected during the sticking phase. In order to simplify the following calculations, this hypothesis is generalized to the slipping phase. We considere this ideal string as initially at rest with initial transverse displacements $(x_0;z_0)$, and we denote as $k_n = \frac{n\pi}{L}\ \forall n \in \mathbb{N}$ the wavenumber, and as $\omega_n = k_n c$ the dispersion relation. Decay being neglected, the string displacement, for instance along the x-axis, during the free oscillations can be written as a modal superposition [10]:

$$x(y,t) = \sum_{n\in\mathbb{N}} \sin(k_n y)(A_n \cos(\omega_n t) + B_n \sin(\omega_n t)), \qquad (1)$$

where A_n and B_n depend on initial shape and velocity projections on the string's modal shapes (Φ_n):

$$A_n = \sqrt{\frac{2}{L}}\frac{x_0 L}{y_0(L-y_0)k_n^2}\sin(k_n y), \qquad (2)$$

$$B_n = \sqrt{\frac{2}{L}}\frac{v_0 L}{y_0(L-y_0)k_n^3 c_l}\sin(k_n y), \qquad (3)$$

with c_l the celerity of the longitudinal waves of the string. Since the string rotation appears to be much smaller during the plucking than during the free oscillations, the associated velocity is neglected. Hence, the kinetic energy of the string is only computed with two velocity components: $\vec{v}_x = v_x\vec{e}_x$ and $\vec{v}_z = v_z\vec{e}_z$.

Dimensionless initial conditions

In order to compare displacement and velocity of the string at the initial time of the free oscillations, descriptors must be defined independently of the tension of the string or the harpist. The initial conditions of the string (D_{t_r}, V_{t_r}) are thus chosen to be adimensionalized with maximal displacement and velocity during the string vibrations (D_{osc}, V_{osc}):

$$\text{Initial displacement ratio: } D = \frac{D_{t_r}}{D_{osc}}, \qquad (4)$$

$$\text{Initial velocity ratio: } V = \frac{V_{t_r}}{V_{osc}}. \qquad (5)$$

Finger / String force

During the plucking action, the string is subject to a force $\vec{F}_{f/s}(t)$ applied by the finger. Using the description of an ideal plucked string (figure 4), the equilibrium of the plucking force $\vec{F}_{f/s}(t)$ and the reaction on both sides of the plucking point can thus be written at any time $t \in [t_c;tr[$:

$$\begin{aligned}\vec{F}_{f/s}(t) &= T\left(\left.\frac{\partial x(t,y)}{\partial y}\right|_{[0;y_0]} + \left.\frac{\partial x(t,y)}{\partial y}\right|_{[y_0;L]}\right)\vec{e}_x \\ &\quad + T\left(\left.\frac{\partial z(t,y)}{\partial y}\right|_{[0;y_0]} + \left.\frac{\partial z(t,y)}{\partial y}\right|_{[y_0;L]}\right)\vec{e}_z \qquad (6) \\ &= \frac{TL}{y_0(L-y_0)}\left(x(t)\,\vec{e}_x + z(t)\,\vec{e}_z\right) \qquad (7)\end{aligned}$$

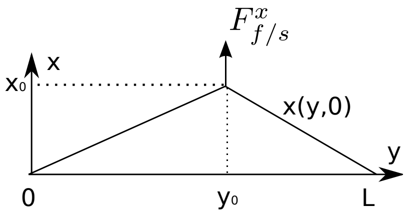


Figure 4: Initial shape of an ideal plucked string

The first finger / string interaction descriptor is the ratio of maximum finger / string force to its value at the beginning of the slipping phase:

$$R_f(t) = \frac{max(\|\vec{F}_{f/s}(t)\|)}{\|\vec{F}_{f/s}(t_s)\|} = \frac{\|\vec{F}^{max}_{f/s}\|}{\|\vec{F}_{f/s}(t_s)\|}. \qquad (8)$$

Energy descriptors

Kinetic energy

During both the sticking and the slipping phase, the harpist gives kinetic energy (E_k) to the string. Neglecting the rotational kinetic energy, E_k is calculated by the integral of the kinetic energy of each element of length.

Potential energy

The potential energy (E_p) of the string corresponds to the amount of work necessary to pluck it, which is transferred by the plucking force $\vec{F}_{f/s}(t)$ defined in equation (7).

Energy Ratio definition

In order to compare potential and kinetic energy contributions to the global energy transferred by the harpist to the string before its release, the following descriptors are defined:

$$R_{e_k} = \frac{E_k}{E_{tot}} = \frac{E_k}{E_k + E_p}, \qquad (9)$$

$$R_{e_p} = \frac{E_p}{E_{tot}} = \frac{E_p}{E_k + E_p}, \qquad (10)$$

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

RESULTS

In the following, the previously defined descriptors are computed for all measurements done with the professional harpist A and the amateur harpist B.

Energetic contributions

Figure 5 shows the logarithmic initial velocity ratio versus the logarithmic initial displacement ratio (equations (4) and (5)), at t_r.

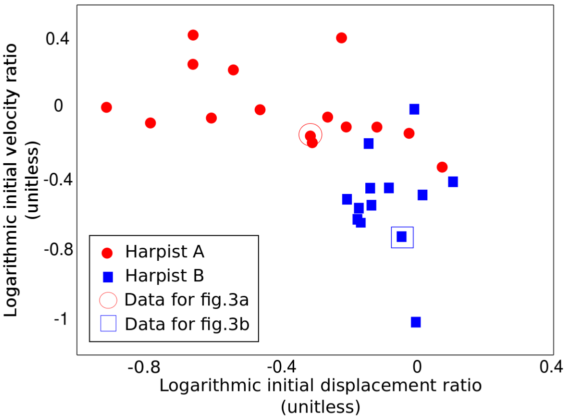


Figure 5: Initial conditions of the string depending on harpist skills

Two areas corresponding to the plucking actions of the professional harpist (red circles) and the amateur (blue squares) are highlighted on figure 5. Furthermore, both plucking actions previously studied, figures 3a and 3b, are shown. The professional harpist seems to impose about four times higher initial velocity ratio than the amateur, whereas the initial displacement ratio imposed by the former is twice lower than the one imposed by the latter.

In addition, it is relevant to study the composition of the global energy transferred to the string during the plucking action: the kinetic energy contribution is linked to the initial velocity of the string and the potential energy to its initial displacement.

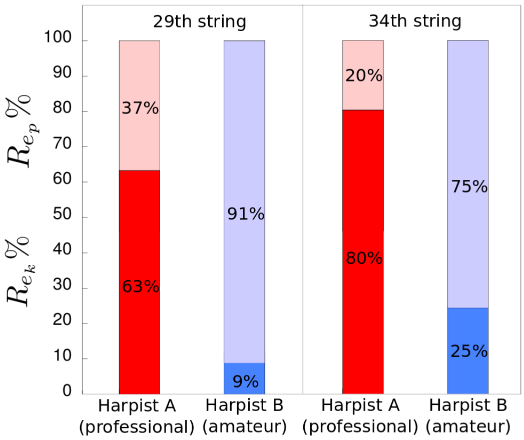


Figure 6: Kinetic and potential energy contribution in the global energy transferred to the string ($Dark: E_k; Light: E_p$)

Figure 6 shows the kinetic and potential contributions in the total energy given by each harpist. Each percent of energy is computated with 8 plucking actions. This figure, concerning both the 29th and the 34th string in several musical contexts, suggests that the professional harpist brings more kinetic energy to the string than potential energy, while the opposite is true for the amateur. This seems to confirm the tendency observed in the trajectories figure 3.

Musical gesture

The origin of the difference of the two previously observed energetic contributions between an amateur and a professional can be found using energetic descriptors; indeed, the comparison of E_p and E_k, computed during the sticking and the slipping phase, allows to pinpoint the phase in which this difference appears. For instance, concerning arpeggios on the 29th string, the contribution of potential energy seems to distinguish amateur and professional plucking actions, while de kinetic energy does not show significant differences:

	Harpist A	**Harpist B**
$E_p(t_c;t_s)$(J, 10^{-4})	9.5	110
$E_p(t_s;t_r)$ (J,10^{-4})	-7.2	-33
$E_k(t_c;t_s)$ (J,10^{-4})	2.0	1.7
$E_k(t_s;t_r)$ (J,10^{-4})	2.2	5.1

Table 3: Potential and kinetic energy bring to the string for harpist A (professional) and harpist B (amateur): arpeggios on the 29th string

The mean values proposed in the table 3 are computed from 6 plucking actions for each harp player. The potential energy given by the professional harpist to the string during the sticking phase appears to be about ten times lower than an amateur (0.011J vs. 0.00095J). Furthermore, potential energy shrinks by 76% during the slipping phase in the harpist A case, while there is only a decrease of 30% in the harpist B case. At last, the kinetic energy contributions do not show significant differences. Therefore, the difference mainly lies in the potential energy, and more precisely, in the one supplied by the harpist during the sticking phase.

In the following, the explanation of these last results is sought in the musical gesture. The correlation between the observed phenomenon of string untightening during the sticking phase in the professional case and potential / kinetic rates of the string's energy is therefore studied. The former observation means that the force applied by this harpist on the string reaches a maximum value ($F_{f/s}^{max}$) and then, decreases to the slipping value ($F_{f/s}(t_s)$). This is why the ratio (R_f defined equation (8)) of maximum finger / string force to its value at the beginning of the slipping phase is studied versus the rate of potential energy for the entire plucking action R_{e_p}.

Results highlight that an important rate of potential energy match the relation $F_{f/s}(t_s) \simeq F_{f/s}^{max}$ (harpist B case), while an important rate of kinetic energy corresponds to $F_{f/s}(t_s) < F_{f/s}^{max}$ (harpist A case). Therefore, during the sticking phase, the string untightening implies a loss of potential energy and thus, a predominance of kinetic energy over potential energy in the whole energy given to the string. From the musical performer aspect, it seems that the professional harpist can control the exact position where the string is released.

CONCLUSION

In this paper, the initial shape and velocity of the string at the release instant have been experimentally studied. The experimental setup allows the analysis of the finger / string movement according to the three dimensions of space. Only two are sufficient to describe the finger / string interaction because the plucking action is performed mostly in the plane ($\vec{e}_x$,$\vec{e}_z$) perpendicular to the strings.

Measurements show differents behaviors depending on the musical skills of the harpists. Indeed, if amateur harpists seem to give initial conditions to the string which are matching the classical description for plucked string instruments (significant displacement with negligible velocity), the professional plucking action is closer to the classical description for strucked string instruments (significant velocity with negligible displacement). Moreover, the origin of this trend is a phase where the harpist slightly untightens his grip on the string during the sticking phase. In other words, the professional harpist adjusts the action of his finger on the string before releasing it at the desired position.

Further work is necessary to confirm these trends with a larger panel of harpists and musical contexts. Thus, not only harpist skills, but also the different playing conditions, string material, and dynamics could be characterized. Besides, the experimental setup has to be improved in order to allow harpists to play more naturally, such as tilting the harp on the shoulder, or not having to pluck the string between two predetermined points.

The study can be extended using soundboard vibrations of each performance to define more relevant descriptors of the plucking gesture. Furthermore, a mechanical model of the finger / string interaction combined with experimental data collected for the present study, could be helpful to determine parameters characterizing the plucking action.

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