Bio-inspired robot to study stringed instruments: application to the harp

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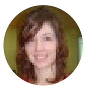
Delphine Chadefaux
Aix-Marseille Université



M.-A. Vitrani
Pierre and Marie Curie University - Paris 6

Benoit Fabre
Pierre and Marie Curie University - Paris 6

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Delphine Chadefaux
LAM / D'Alembert,
UMR CNRS 7190
UPMC Univ Paris 06

Alexandre Roy
LAM / D'Alembert, UMR CNRS 7190
ISIR, UMR CNRS 7222
UPMC Univ Paris 06

Jean-Loïc Le Carrou
LAM / D'Alembert,
UMR CNRS 7190
UPMC Univ Paris 06

Marie-Aude Vitrani
ISIR, UMR CNRS 7222
UPMC Univ Paris 06

Benoît Fabre
LAM / D'Alembert,
UMR CNRS 7190
UPMC Univ Paris 06

ABSTRACT

This paper is a review of a previous musician/harp interaction study leading to the specifications of a configurable excitatory mechanism. Such robotic tools can be valuable to investigate the musician/instrument interaction and the mechanical behavior of an instrument in a repeatable and realistic musical context. To design a robotised excitatory mechanism for the concert harp, the mechanical descriptors' typical orders of magnitude defining a musical performance have to be highlighted. For this purpose, two experimental setups have been designed. The first one focuses on the sound-producing gesture (i.e. on the plucking action). A high-speed camera has been used to accurately measure the finger and string motions in a realistic musical context. The second measurement set-up consists in capturing the whole harpist's body motion through infra-red cameras during a performance. The set of mechanical parameters extracted from these measurements is of great interest to get an insight on an ideal robotic tool to pluck harp strings. Based on these considerations, a highly-configurable and repeatable robotic finger has been designed.

1. INTRODUCTION

A configurable and repeatable excitatory mechanism may be particularly adapted for the study of musical instruments or of the musician/instrument interaction. For wind instruments, researchers designed artificial mouths to play the trumpet [1], the trombone [2] or the clarinet [3]. These systems may be automated [3,4]. For stringed instruments, classical mechanical excitatory systems used in the literature are wires rolled around the strings pulled up until they break or mechanical plectrums. They can generate repeatable initial conditions applied to the string but cannot reproduce the complexity of the plucking gesture and therefore the typical initial conditions. To do so, the idea would be to use a bio-inspired robot. This kind of robots are used to develop *virtuous* instrumentalist as Waseda flutist robot [5] but not to exactly reproduce the instrumentalist action. For plucked instruments, this action is performed by a finger or a plectrum and imposes particular initial conditions to the string. Designing bio-inspired robot needs above all an accurate description of the instrumentalist gesture. In the light of recent studies on the harp, a robot called DROPIC (Doigt RObotisé PInceur de Cordes) [6] has been designed to reproduce the musicians' expert gestures. The goal of the present paper is to suggest the development steps of a bio-inspired musical robot from formers studies presented in [7], [8] and [9] and to specify its limitations.

The paper is organized as follows: first a summary of the plucking action in the case of the harp will be presented. Then an analysis of this gesture will draw the DROPIC specifications. Eventually the final design and the choices made during the development of the robot will be presented.

2. ANALYSIS OF THE INSTRUMENTALIST GESTURE

Playing a musical instrument is a complex task, relying on a long training by the player. From the instrumentalist's point of view, the performance may be seen as series of gestures, that turn the musical intention into movements and results in sound production. The first investigation in the study of the playing is the segmentation of the gestures and movements. While the writing of the music on a score suggests a note based segmentation, the analysis of everyday practice of players suggests that scales, arpeggios, melodic and harmonic grouping of notes may be more significant.

2.1 Finger trajectory analysis

In the playing of a note or of a chord on a harp, several time periods can be identified. Starting from the postural and gestural preparation, the player brings his/her hand and fingers in contact with the strings, pulls them until the force applied by the finger reaches a threshold. This phase is called the sticking phase. Before the string is released with controlled initial oscillating conditions, it slips on the finger pulp of the musician, this is called the slipping phase.

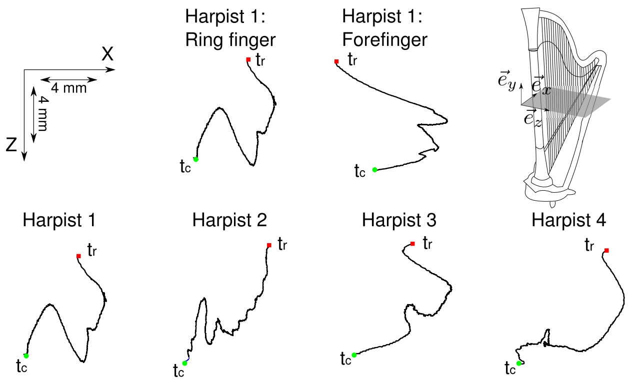

Figure 1. Example of finger trajectories. The instants denoted t_c and t_r correspond to the sticking phase beginning and the string release, respectively. The four bottom figures are trajectories extracted from an arpeggio sequence played by four harpists with the ring finger. The top-left and top-right figures presents finger trajectories extracted from an arpeggio sequence played by the first harpist with the ring finger and the forefinger, respectively.

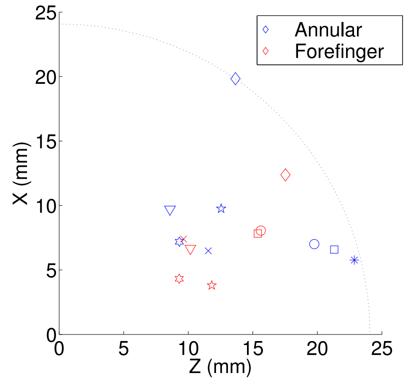

Figure 2. Maximum displacement of a harp string for the ten harpists depending on the finger used (forefinger or ring finger). Each harpist is denoted by a symbol. The blue and the red ones referred to the ring finger and the forefinger displacements, respectively. The dashed line represents the circle which radius is the maximum displacement for all harpists.

Works presented in [8], [9] and [10] focus on the movements of the finger and string during the finger-string interaction. In these papers, finger's and string's trajectories are measured in the plane perpendicular to the strings direction $(\vec{e}_x, \vec{e}_z)$ defined in figure 1. The samples given in figure 1 show harpists' finger trajectories projected in this plane. They indicate that non negligible differences occur between harpists for a given musical context. Besides, considering one harpist, the finger pattern depends on the finger and on the technique used to pluck the string [10].

The estimation of mechanical parameters needed to design the robotic finger are determined according to [6, 10]. They are summarized in Table 1. First, the peak force applied by the harpist's finger to the D♭3 string has been estimated up to 20 N, regardless of the musical context. Further, figure 2 presents the maximal D♭3 string displacement during the ten harpists' ring finger and forefinger plucking actions. Let us note that no significant influence of the musical context on this descriptor has been outlined. Although the trajectories are specific to each harpist, figure 2 tends to indicate that all the maximum displacements D_{max} given to the string are contained in a 24 mm radius quadrant.

Meanwhile the maximum fingertip velocity has been estimated to be less than 1.5 m/s [6].

Criterion	Value
maximum velocity	1.5 m/s
nominal force	20 N
area of use	4 cm^2

Table 1. Criteria the robot should match to correctly reproduce the motion of a musician finger

2.2 Arm gesture analysis

Although the description of the finger gesture is valuable to understand the plucking action itself, it is not sufficient for a thorough comprehension of a harp performance. Indeed, the "actuators" of the movement, i.e. the muscles and articulations of the arm, have to be analyzed too.

The research performed in [11] with a motion capture system presents the movement analysis of the whole harpist's body during a performance. Three harpists have been asked to perform the beginning of Debussy's *Danse Profane*. Efforts in the upper limbs (hand, arm and forearm) are deduced from kinematic measurements using a well-known human mass distribution model [12]. Figure 3 shows the computational process [11]. First, infra-red cameras accurately provide the 3D-position of reflective markers fixed on the musician in a global reference system. Then anthropometric data lead to the trajectories of each limb's center of mass. Besides, as they are not directly reachable using the experimental set-up, the more distal segment moment and force have to be estimated. The moment is neglected and the force is found to be between 2 N and 8 N (i.e. the minimal and maximal forces measured for a chord performance [10]) according to the sound level of each note. Then, a link-segment model [12] leads to the forces and moments at the first proximal joint. This process is recursively done to determine the forces $\vec{F}$ and moments $\vec{M}$ occurring at each arm joints. Each joint's mechanical power are computed from $P = \vec{M}.\vec{\omega}$ where $\vec{\omega}$ is the angular velocity of the limb's center of mass. Finally, the work done by the group of muscles related to each limb-segment is computed by time-integrating the power curve under the considered movement duration.

Results presented in figure 4 indicate that the shoulder controls the entire arm gesture while performing the octave intervals contained in the beginning of Debussy's *Danse Profane*.

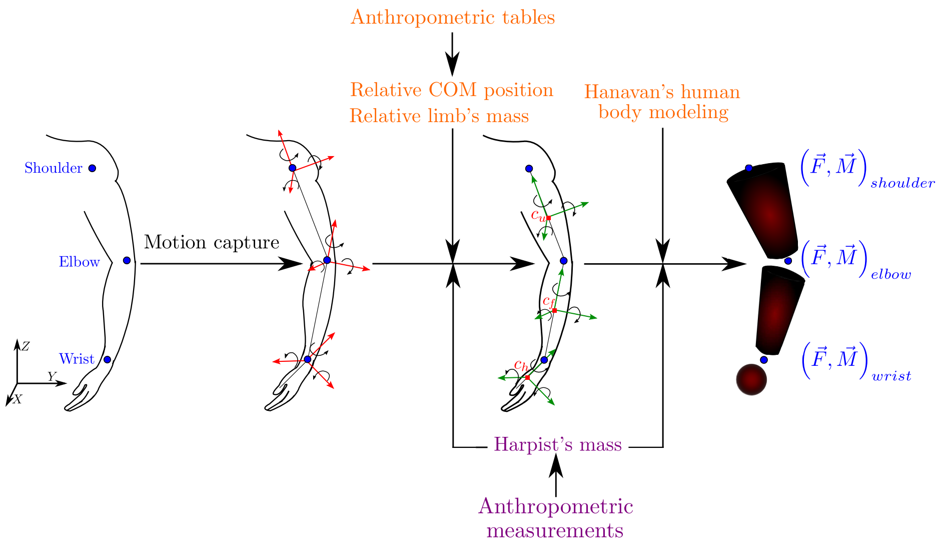

Figure 3. Retrieval process of the forces and moments occurring at a harpist's arm joints while playing octave intervals.

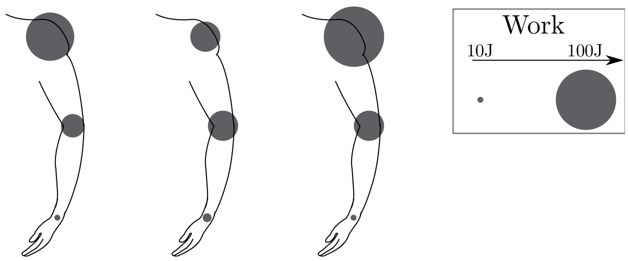

Figure 4. Average work estimated at each arm joint for the three involved harpists.

3. ANALYSIS OF THE ROBOT CAPABILITIES

In the present section, an ideal behavior of the robot is presented, according to the plucking action analysis. Then the design of the robot will be done to meet the specifications. Finally, a fingertip will be designed to reproduce the harpists finger pulp and thus the initial conditions provided to the string.

3.1 Robot specifications

Table 1 points out three parameters the robot must reproduce to provide to the string the same initial conditions as a musician. Besides, information provided in [10] about the finger's trajectories duration is required. This study indicates that the typical sticking and slipping phases durations are about 300 ms and 3 ms, respectively. Obviously, details about the forces involved in harp plucking are also required. For this, the harp strings' tension is needed. It has been computed from formulas defined in appendix A and presented in figure 5. Thus, assuming each string is plucked at the third of its length with an initial displacement corresponding to D_{max} (see Subsection2.1), the maximal efforts needed to pluck the whole set of the harp's strings are deduced and shown in figure 5. Note that the strings parameters used for this estimation are those of a concert harp (Camac, *Atlantide Prestige* model). This harp has 47 strings, and its *tessitura* extends from C♭0 (30.8 Hz) to G♭6 (2960 Hz).

Figure 5 indicates that the strings can be split into two groups. The first corresponds to the wrapped, nylon and a few gut strings (i.e. from C♭0 (30.8 Hz) to G♭1 (92.5 Hz) and from F♭4 (698.5 Hz) to G♭6 (2960 Hz)) for which the effort is comprised between 20 N and 40 N. The second group corresponds to the other gut strings (i.e. from A♭1 (104 Hz) to E♭4 (622 Hz)), for which the effort is comprised between 10 N and 20 N. For practical reasons, the first set of strings was discarded from the present study, implying that the maximum effort the robot has to apply on the strings is 20 N.

3.2 Design of the robot

Based on the previous musician/harp interaction analysis (see section 2), the shoulder has to develop important efforts to allow the finger to pull the string with a 20 N force. In the case of a bio-mimetic robot design, all the involved efforts and arm's dimensions should be taken into account. However, in the present case, considering the fingers trajectories are almost contained in a plane, we can reduce the robot to a single finger to limit its size. The basic idea is to design a planar robot with two rotational joints that mimic a human finger [16]. Its dimensions are l_1 and l_2 and it is parametrized by the angles ϑ_1 and ϑ_2, as shown in figure 6. The numerical values for l_1 and l_2 are arbitrarily inspired from a real finger, because they lead to a small robot that can deliver the desired efforts, and are:

$$\begin{cases} l_1 & = & 6.21 \text{ cm}, \\ l_2 & = & 4.75 \text{ cm}. \end{cases}$$

Using these previous parameters, a classical static analysis of the robot provides a relationship between the actuators parameters, i.e. the motor torques C_{m1} and C_{m2} for each joint, the geometrical parameters of the robot and the

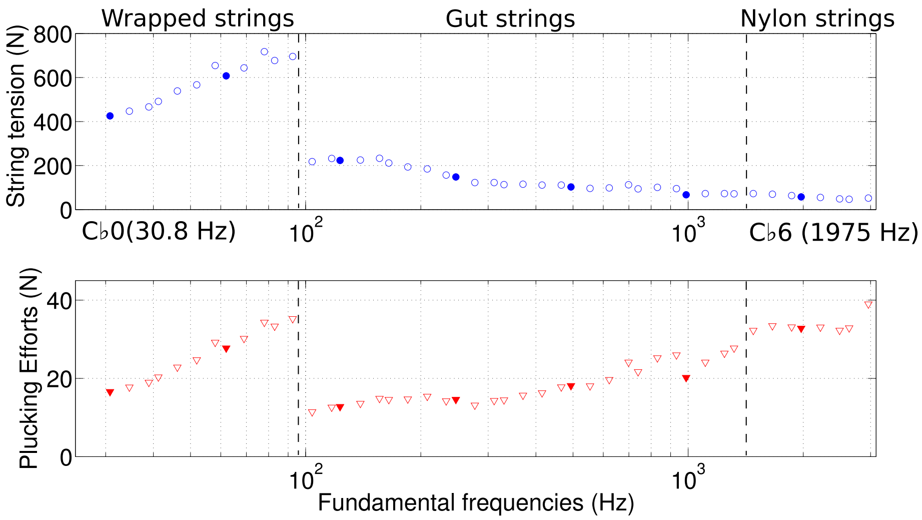

Figure 5. String tension (upper plot) over the concert harp compass. Plucking effort for each string (lower plot) in order to reach a displacement of 24 mm. String tensions are estimated from pitch and mass measurements. The plain markers on the figure show the C♭ strings.

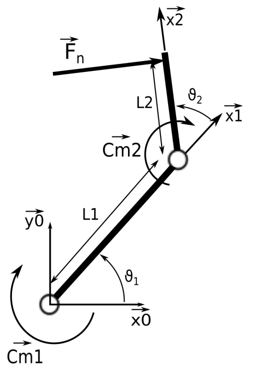

Figure 6. Parametrization of the robotic finger.

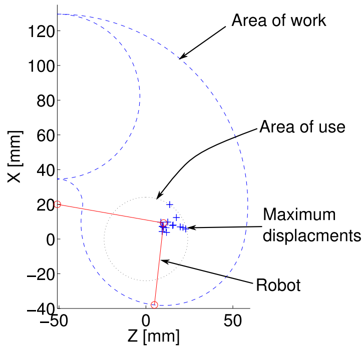

Figure 7. Area of work of the robot and area of work specified. The maximum distances are reminded on the graph with '+' symbol.

maximum force $F_{n\ max}$ as follows:

$$\begin{cases} C_{m1} & = & l_1 F_{n\ max}, \\ C_{m2} & = & l_2 F_{n\ max}. \end{cases}$$

As the maximum effort $F_{n\,\max}$ is chosen to be up to 20 N (see subsection 2.1), the motor torques numerical values are estimated to

$$\begin{cases} C_{m1} & = & 1.21 \text{ N.m}, \\ C_{m2} & = & 0.926 \text{ N.m}. \end{cases}$$

Based on these values, the motors chosen to actuate the joints are two Maxon motors, model RE35, equipped with two 12:1 Maxon GP42 reducers, which leads to a practical maximal torque for each actuator:

$$C_{m1} = C_{m2} = 1.26 \text{ N.m}.$$

The choice of the actuators and of the geometry of the robot allows the maximum speed at the end effector at $V_{max} = 1.16$ m/s. Moreover, at this maximum speed, the duration Δt takes by the robot to do a straight line with a length of D_{max} is

$$\Delta t = \frac{D_{max}}{V_{max}} \approx 20 \text{ ms}.$$

This value is lower than the duration of the trajectory. Therefore, the robot meets all the specifications.

Figure 7 shows the area of work of the robot which contains the area of use specified in subsection 3.1. The origin of the robot can be adjusted to contain its whole area of use. Thus, the robot and its actuators can reproduce the trajectories measured on the musicians. It fulfills the requirements to mimic finely the finger's trajectory during a plucking action.

3.3 Fingertip material

In a previous study [16], the shape and the material of a fingertip was investigated to reproduce human finger pulp behavior. Silicone was chosen because of its friction coefficient, which is close to the human skin [11].

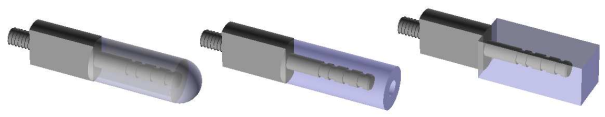

Figure 8. Fingertip shapes enhancing the aluminium end effector of the robot.

Figure 8 presents several fingertips molded with silicone. During the moulding process, a set of parameters can be controlled: the mold's shape, the quantity of filler and oil added to the mixture. Let us note that the filler increases the hardness of the material while the oil decreases it. Figure 9 shows a picture of DROPIC, enhanced by a silicone fingertip, mounted on the concert harp.

An experiment presented in [16] has been carried out to validate the robotic finger and to point out the best fingertips shape and hardness. For this purpose, a harpist has been asked to perform isolated plucking actions. Then, the extracted finger's path has been reproduced by the robotic finger enhanced with the various fingertips presented in figure 8. The resulting string's trajectories as well as the generated soundboard vibration have been compared to those produced by the harpist. Results indicate that the harder the fingertip is, the better the trajectory is followed. Moreover, better results have been obtained for fingertips with a cylindrical shape, a round extremity and a hardness close to 30 shore A. Eventually, let us remark that the silicone's drawback is the loss of its mechanical properties over time. Therefore, new materials are currently investigated to enhance the robotic finger as for instance polyurethane.

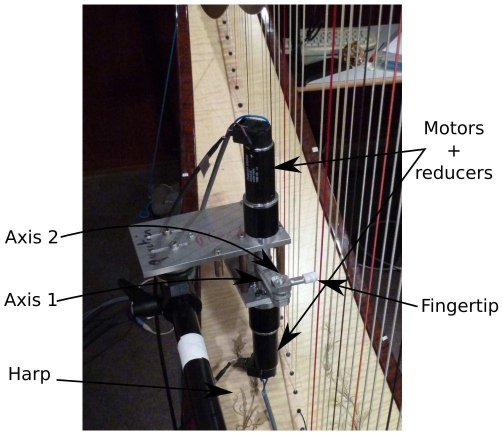

Figure 9. The robot DROPIC mounted on the harp for measurements.

4. CONCLUSION

This paper has presented the developing steps of a bio-inspired musical robot based on a review of a previous musician/interaction analysis. The proposed methodology is carried out to conceive a robot designed to pluck harp strings as harpists do. A phase of simplification of experimental results is necessary to propose specifications of the robot. Therefore, the analysis presented in [8], [9], [10] and [11] are based on simplified models of the finger-string interaction: the motion of the finger is only analyzed in the plane perpendicular to the string and the torsion of the string during the contact is ignored. Observation of actual plucking action shows that the rotation of the finger around the contact point as well as the return force due to string torsion may be decisive in the triggering of the slipping of the string on the finger. The development of a two axes robot for string plucking is therefore a first step in understanding the influence of the different elements (finger motion, finger elastic behavior or hardness, skin contact. . .) that govern the initial oscillating conditions on the string. This robot can be used to gather dynamical information on the forces, both normal and tangential to the contact surface, and therefore on the triggering of the slipping of the string on the finger. Future versions may include more complex motions such as those observed in actual human plucking. Moreover, this methodology can now be applied to others string instruments to analyse the musician/instrument interaction.

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5. REFERENCES

[1] J-F. Petiot, F. Teissier, J. Gilbert and M. Campbell. "Comparative analysis of brass wind instruments with an artificial mouth: first results", Acustica 89, pp.974-979 (2003).

[2] J. Gilbert, Sylvie Ponthus and J-F. Petiot. "Artificial buzzing lips and brass instruments: Experimental results", J. Acoust. Soc. Am. 104(3), pp.1627-1632 (1998)

[3] D. Ferrand and C. Vergez. "Blowing machine for wind musical instrument: toward a real-time control of the blowing pressure", 16th IEEE Mediterranean Conference on Control and Automation, Ajaccio, France (2008), pp.1562-1567

[4] D. Ferrand, C. Vergez,B. Fabre,F. Blanc, "High-precision regulation of a pressure controlled artificial mouth: the case of recorder-like musical instruments", Acustica united with Acta Acustica 96, pp.700-711 (2010)

[5] J. Solis, K. Chida, K. Taniguchi, S.M. Hashimoto, K. Suefuji and A. Takanishi, "The Waseda Flutist Robot WF-4RII in Comparison with a Professional Flutist", Computer Music Journal 30(4), pp.12-27 (2006)

[6] J-L. Le Carrou, D. Chadefaux, M-A. Vitrani, S. Billout and L. Quartier. “DROPIC: A tool for the study of string instruments in playing conditions”, *Proceedings of Acoustics 12*, Nantes, France (2012), pp.451-456.

[7] J-L. Le Carrou, F. Gautier, F. Kerjan and J. Gilbert. “The string-finger interaction in the concert harp”, in *Proceedings of ISMA*, Barcelone, Spain (2007)

[8] J-L. Le Carrou, E. Walhem, E. Brasseur and J. Gilbert. “Two dimensional finger-string interaction in the concert harp”, in *Proceedings of Acoustics 08*, Paris, France (2008), pp.1495-1500

[9] D. Chadefaux, J-L. Le Carrou and B. Fabre. “A model of harp plucking”, J. Acoust. Soc. Am. 133(4), pp.2444-2455 (2013)

[10] D. Chadefaux, J-L. Le Carrou, B. Fabre and L. Daudet. “Experimentally based description of harp plucking”, J. Acoust. Soc. Am. 131(1), pp.844-855 (2012)

[11] D. Chadefaux,“Interaction musicien / instrument: le cas de la harpe de concert. (Musician/Instrument Interaction: The case of the concert harp.)”, PhD Thesis, Université Pierre et Marie Curie, (2012)

[12] D.A. Winter, “Biomechanics and Motor Control of Human Movement”, 4th ed., John Wiley & Sons, Inc. Hoboken, New Jersey, 2009.

[13] C. Valette and C. Cuesta. “Mécanique de la corde vibrante”, Traité des Nouvelles Technologies série Mécanique, Hermes, Paris, France (1993), pp.27-45.

[14] I. M. Firth, C. Sykes. “Harp Strings of the Eighteenth and Twentieth Centuries: An Acoustical Comparison”, The Galpin Society Journal, Vol. 43 (1990), pp.46-59.

[15] J. Chabassier. “Modélisation et simulation numérique d’un piano par modèles physiques”, PhD Thesis (2012), pp.51-56.

[16] D. Chadefaux, J-L.Le Carrou, M-A. Vitrani, S. Billout and L. Quartier. “Harp plucking robotic finger”. in *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, Portugal (2012), pp.4886-4891.

A. FORMULAS FOR THE STRING TENSION

For a i^{th} string fixed at both ends its tension is [13]:

$$T_i = 4\rho_{li} L_i^2 f_i^2,$$

where ρ_{li} its linear density, L_i its length and f_i its fundamental frequency. For the case of the harp, strings are in gut, in nylon or wrapped. For the latter, an equivalent linear density ρ_l can be deduced as follows [14,15]:

$$\rho_l = \rho_{vw}\frac{\pi}{4}D^2 + \left[\rho_{vc}\frac{\pi}{4} - \rho_{vw}(\frac{\pi}{4})^2\right] d^2,$$

where ρ_{vw} is the density of the wrapping element, ρ_{vc} is the density of core material, D and d are the whole string’s and its core’s diameters, respectively.

In quasi-static approximation, the relationship between the string’s tension and the magnitude of the plucking effort is a straightforward geometrical relation [13]:

$$F_{ni} = h_i T_i \frac{L_i}{y_{0,i}(L_i - y_{0,i})}$$

where h_i is the displacement of the string relatively to its rest position, $y_{0,i}$ the plucking position and L_i the string’s length.