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Vibratory study of harp's soundboxes

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ABSTRACT

The harps' sound-box manufacturing has evolved throughout centuries. The design of the harp sound-box is a key question still discussed by harp makers. Although harp sound-boxes look very similar, each harp maker uses his own manufacturing technique to build an instrument. The sound radiation is produced by the soundboard and the sound-box vibrations which arise when strings are excited. The relative importance of these two acoustic sources can be estimated thanks to mobility measurements. The aim of this paper is to investigate these two sources in 17 harp sound-boxes built by current manufacturers and 17 harps sound-boxes built by historical manufacturers. For each instrument, mobilities on the soundboard and on the sound-box are measured by impact testing. Mean values of these mobilities are computed and are used as an indicator to compare instruments and to evaluate their capability to vibrate under an excitation imposed by the soundboard. A statistical study shows that the tested instruments can clearly be differentiated according to this indicator. Different strategies of harp makers are identified, showing that some makers favor the mobility of the sound-box when others choose to build a more rigid sound-box.

INTRODUCTION

As defined in the reference textbook [1], "the harp is a chordophone consisting of an arched or angled neck, a resonator (sound-box) to which the neck is permanently fixed, and a series of parallel strings of unequal lengths fixed to the resonator and running at an oblique angle from it to the neck, where they are attached and tuned by mechanical means". In order to stay adapted to the music, the harp has empirically evolved throughout centuries: from the simple arched structure developed during Antiquity to the angled neck with a rigid fore-pillar between the lower end of the sound-box and the neck. The introduction of a pillar provides stability by bearing the strain of the string's increased tension. The harp, as we know it now (a single rank of 30/40 chromatic strings), appeared during the first half of the 18th century in south-eastern Germany [1] and is the subject of the present study.

The construction details of the concert harp are still evolving, especially the two main acoustical parts: the soundboard and the sound-box ([2, 3]). Among the significant evolutions on the harp manufacturing, the design of these two parts seems to be really important and could explain differences between makers. To analyze these evolutions, the study of a few isolated instruments is clearly not sufficient. It could be interesting to investigate statistics of acoustical and vibratory characteristics of a lot of instruments produced in the past or nowadays. However, collecting such characteristics on many instruments is not that easy in practice and is only possible when using an adapted experimental setup.

Therefore, the aim of the paper is to investigate some elements of the harp manufacturing thanks to the measurements of a vibratory characteristic of the instrument: the mobility. To do so, after an historical and acoustical description of the instrument, we define a criteria, the mean-value of the mobility (MVM), which is measured on the soundboard and on the sound-box of old and contemporary concert harps. Results are then discussed taking into account the instrument's manufacturing.

CONTEXT OF THE STUDY

Historical context

The pedal harp, as we know today, appeared during the first half of the 18th century in Southern Germany. In comparison with the previous harps, the novelty was the integration of a system to shorten the strings with 'hooks' activated by 7 pedals[1], in order to add superior semitones on each string to the tuning by tones and semitones (also called diatonic tuning), thus making the instrument semi-chromatic[2]. Today, this instrument is called 'hook harp'. This is how the instrument arrived in France in the 1740's, brought by the first German and Austria virtuosos. Queen Marie-Antoinette played a major role in the development of this fashionable instrument, first in Paris then in the whole country: she used to play this instrument herself and certainly helped the establishment, in Paris, of German artists and craftsmen. The first virtuosos, such as Goepfert for instance, as well as the first stringed-instrument makers who built harps, were all Germans who migrated to France during the middle of the 18th century (Naderman, Holtzman, Krupp, Hermes, etc.). These were very soon followed and competed by French manufacturers such as Cousineau, Saunier, Renault and Chatelain... all very interested by the complexity of the mechanism and the delicacy of the conception of this new instrument which was promising a beautiful future and high related economic stakes. The main structure of harps of this period was made of wood. It was made up with three major elements generally made in maple : the neck, the column, and the sound body including a soundboard in spruce and a back formed of seven ribs juxtaposed and stuck made of lime tree wood. Erard was the first to make a single

[1]There is one pedal by note of the range. As an example, when the D pedal is pushed on, all the Ds of the instrument are raised by a semitone.

[2]Chromatism is the possibility to obtain alternatively on each string the flat note, the natural note and the sharp note. It was the result of the invention of the 'double-action', created and patented by Erard in 1812.

block sound-box using plywood of maple.

The harp became very successful, despite its high price, because it appeared like an alternative to the traditional harpsichord, then to the pianoforte which arrived in France in the 1770's. This specific position helped the development of chamber music. The concerto for flute and harp (K.299) was composed by Mozart in 1778 while in Paris. The role of the harp, in this piece, is double, it is both a concert and a soloist instrument. Many of these pieces for harp were created in the 'Concert spirituel' ('Spiritual Concert'), one of the first Parisian hall dedicated to public concerts and inaugurated in 1725. Under the pressure of the increasing number of virtuosos, stringed-instrument makers tried to develop the possibilities of the instrument including its extent, its chromatic capacity, its tone and its dynamic. The competition was hard among the stringed-instrument makers and was the origin of many inventions which helped to give the instrument the characteristics it still has today.

In this context, and during the period studied here, two persons dominated the harp manufacture in Paris, considering the quality and quantity of harps they made, but also considering their inventiveness skills. They were: Georges Cousineau (1733-1800) and Jean-Henri Naderman (1734-1799). Both were in charge of prosper workshops and stores where clients could find harps and also other instruments and music scores. Georges Cousineau invented several mechanical systems for harps (rotation peg systems, system '*à béquilles*') to improve the *crochets* system. It seems that he was the first, in 1782, to create a whole chromatism harp on which each string could make three sounds (flat, natural and sharp notes), but it had a very complicated mechanism with 14 pedals!

Meanwhile, Naderman, along with the virtuosos Jean-Baptiste Krumpholtz (1747-1790), had been developing since 1787, a 'new harp' with a system called 'system with intensification' which could modify the sound dynamics, and a mute. These two systems were controlled by added pedals. The invention was very successful and was echoed by Beaumarchais in the *Journal de Paris* in February of 1786. It was presented the following year at the Royal Academy of Sciences.

A third personality who had a strong impact in this time, not only being a harp maker but also a piano manufacturer and above all a brilliant inventor: Sébastien Erard (1752-1831). He developed a mechanical system for harps known as the 'fork' system: on the neck of the instrument, the fork consists in two brass prongs mounted on a small round brass disc. When the disk rotates, controlled by the movement of the pedal, the axis turns to bring the prongs into firm contact with the string, thus sharpening it by a semitone. This innovation was very satisfactory and rapidly replaced other systems. In 1812, Erard brought the last improvement: he added a double-action which made the harps completely chromatic[3]. The modern harp was born, and to conclude with, we can observe than concert harps made today are very similar to those created by Erard two centuries ago.

Acoustical context

The concert harp, as all acoustic musical instruments, is composed of a set of strings coupled to an amplification system that produces the musical sound. The amplification system is usually composed of a flat panel called the soundboard and a cavity with sound-holes called the sound-box. The soundboard and the air cavity with sound-holes are interacting to increase the acoustical level [2]. Figure 1 shows a diagram summarizing these couplings. In order to have an instrument that efficiently radiates the sound in all its range, the classical strategy of harp makers is to design a soundboard as thin as possible, but of course able to resist to the string's tension. Following the manufacturing evolution of the instrument, not only the soundboard but also the sound-box evolved (from coopered to rounded reinforced by internal ribs sound-box). This evolution modified the global dynamic behavior of the instrument and consequently its radiation.

[3] Three positions by pedal: flat, natural and sharp notes.

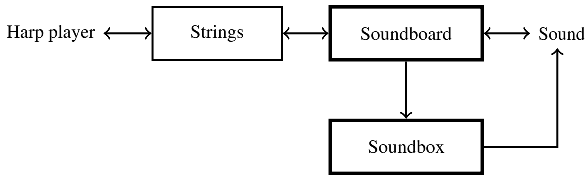

Figure 1: Schematic diagram of the harp's acoustical behavior

Mean-Value of the Mobility (MVM)

Vibratory measurements are more convenient than acoustical measurements when testing numerous instruments *in situ*, since they do not depend on the environment. We choose to measure a vibratory quantity of the instrument, which is representative, in a certain manner, of the acoustical behavior of the instrument. This quantity could be the mobility transfer function at the driving point of each string as in Waltham's studies [4]. Nevertheless, this approach is not adapted for testing a lot of instruments, because of the huge amount of data to collect.

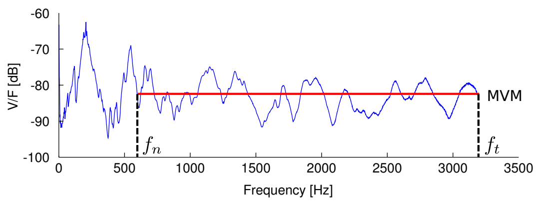

Figure 2: Mobility measured on the harp's soundboard and computed mean-value of the mobility (MVM)

The mobility contains a lot of information (modes in low-frequency, for example) as shown in Figure 2. We would like to extract an indicator that characterizes the global response of the structure to a force applied (by the strings). We choose to compute the mean-value of the mobility (MVM) as follows:

$$Y_M = \frac{1}{n-t}\sum_{i=t}^{n}|Y(f_i)|, \tag{1}$$

where $Y(f_i)$ is the mobility measured at the discrete frequency f_i. The indices t and n denote the lower and upper bounds of the frequency range $[f_n, f_t]$ which is used to estimate the MVM (shown in Figure 2). The lower bound is chosen in such a way that we consider that modes can no longer be identifiable. This value is fixed at 600 Hz in this paper, but other values were tested and we found that they do not affect results shown in the following. Note that Skudrzyk [5] developed a mean-value method that allows the description of the mean-line of the mobility of a structure from the knowledge of its mass, its density of resonances, the general form of the mode functions, information about the exciting force field and the position of the receiver. This method could be applied here, as for the piano's soundboard [6], but would clearly not affect our conclusion. From a physical point of view, the MVM evaluates the capability of the structure to vibrate under an excitation imposed by the soundboard.

Note that this MVM estimation has already been used for the comparison of classical guitars [7] and it has been shown that this indicator is useful for categorizing instruments.

INSTRUMENTS CATEGORIZATION

As explained in the precedent section, the manufacturing of the concert harp has developed throughout centuries different kinds of sound-box and soundboard constructions. These differences could explain some evolution not only for each instruments' manufacturer but also for the maker himself which creates high quality's instruments following his own criteria. The study of the vibratory behavior of instruments (by the means of the MVM) could be an indicator to compare instruments and to evaluate their capability to vibrate under an excitation imposed by the soundboard, and thus, to compare different strategies of manufacturing.

Experimental setup

Mobility measurements on the soundboard and on the sound-box of numerous harps are carried out using impact testing: a hammer applied a measured force with an appropriate force sensor near the C5 string attachment's point on the soundboard (string 31) whereas an accelerometer is successively stuck at different locations. In order to measure the vibratory behavior of the soundboard and of the sound-box, the 3 locations are defined as follows: one on the soundboard (near string 31) and two on the sound-box (each one at an equal distance between the lower hole of the harp and the soundboard), as shown in Figure 3.

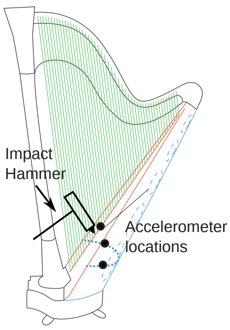

Figure 3: Experimental setup

These 3 mobility measurements are then used to compute the MVM of the soundboard and of the sound-box (mean of the two MVM measured on the sound-box), as explained in the previous section. Note that the frequency range of the measured mobility is chosen to be [0-3200Hz], adapted from the frequency range of the impact hammer defined by its cut-off frequency [8].

Results on historical harp

In Paris, the *musée de la musique* is a site within the *Cité de la musique*[4] that harbors a collection of musical instruments, works of art and scale models covering four centuries of the history of Western music and presenting an overview of the main musical cultures throughout the world. Among harps collections, those of concert harps are particularly rich covering the evolution of the instrument from the 18th century to the 20th century.

In Table 1, a short description of selected harps available (and tested) at the *musée de la musique* is presented. These instruments are made by Edmond Saunier (1730-1783), Pierre Louvet (1709-1784), Georges Cousineau (1733-1800), Jacques-Georges Cousineau (1760-1836, son of Georges Cousineau), Sébastien Erard (1752-1831) and two companies: Erard Frères and Erard & Cie. All instruments look like nowadays pedal concert harp, with single-action (1 to 9) or with double-action (10 to 17) to obtain chromatic notes on a diatonically tuned

[4]http://www.citedelamusique.fr/

Table 1: Descriptions of the 17 historical harps tested with their serial number at the museum, their harp maker, the construction's date and the number of strings. The 17 harps are ordered following the construction's date, from the oldest to the more recent.

	Serial number	Harp Maker	Date	Strings
1	E.17	Saunier	~ 1760	36
2	E.982.7.1	Louvet	~ 1765	34
3	D.AD.40297	Cousineau G	~ 1780	36
4	D.AD.2593	Cousineau G et J-G	1780	39
5	E.985.2.1	Cousineau G	1783	37
6	E.970.3.1	Cousineau G et J-G	1785	37
7	E.275	Cousineau G	~ 1790	36
8	E.981.6.1	Erard & Cie (Paris)	1799	41
9	E.2100	Erard Frères (Paris)	1802	39
10	E.991.14.1	Erard & Cie (London)	1815	43
11	E.991.11.1	Cousineau J-G	1820	40
12	E.2003.5.8	Erard & Cie (London)	1825	43
13	without	Erard Sébastien	1835	43
14	E.0998	Erard Sébastien	1835	43
15	D.0AR.240	Erard & Cie (Paris)	1874	46
16	E.998.3.1	Erard Frères (Paris)	1890	47
17	E.0997	Erard Sébastien (London)	??	43

instrument. 6 harps have a 8th pedal for closing sound-holes by mean of shutters (harp 4, 8, 13, 14, 16 and 17 in Table 1). Most of the instruments are dated but, due to a lack of information, with some uncertainties (indicated by a tilde in Table 1). The number of strings (from 34 to 47 throughout 1760 to 1900) is also indicated in Table 1 to have an idea of the load imposed by the strings on the soundboard. Note that, for conservation reason, the harps are more or less tuned a third below in order to not damage the soundboard.

The experimental procedure explained in the previous subsection is applied to these historical harps (Table 1). In Figure 4 we show, for each harp, MVM of the sound-box versus MVM of the soundboard numbered following Table 1. Each maker "family" can be identified by the marker's color and each harp maker by the shape of the marker. From a general point of view, each maker "family" is clearly identified in the figure. Cousineau's harps are located in the top right part (high mean-value both on soundboard mobility and on sound-box mobility) in Figure 4 and Erard is on the lower left part (low mean-value both on soundboard mobility and on sound-box mobility). More particularly, for different instruments, each harp maker is found to be localized in the same area as for *Erard Frères*, *Erard & Cie*, *Sébastien Erard*, *Cousineau G* and *Cousineau G and J-G*, showing the reproducibility of the manufacturing. Therefore, the criteria chosen shows us that each harp maker has a reproducible know-how and also characterizes the strategy of each harp maker concerning the dynamical behavior of each instrument's design.

Erard's harps are found to have less sound-box mobilities than the others (Cousineau, Saunier and Louvet). This result can be linked to the design of the sound-box. For Erard, the sound-box has a rounded back reinforced by internal ribs, face veneer in maple whereas, for Cousineau, Saunier and Louvet, the sound-box is coopered in maple. This evolution towards the Erard's design of the concert harp leads to the increase of the sound-box rigidity, and therefore to less mobilities. For the soundboard, the MVM's evolution is certainly due, on one hand, to the increase of the number of strings (from 34 to 47), involving more strain on the soundboard and, on the other hand, to the increase of the strings' tension. Indeed, since the force applied

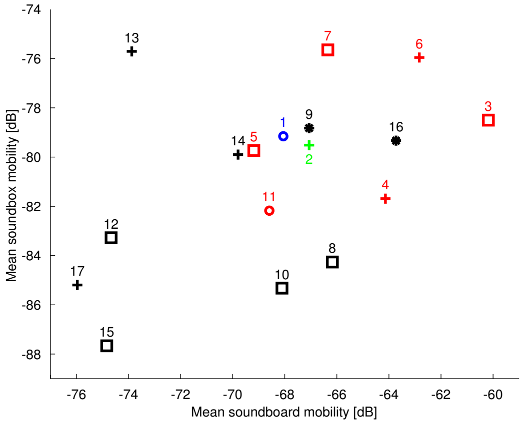

Figure 4: MVM of the sound-box versus MVM of the soundboard for the 17 historical harps described in Table 1. The number corresponds to the harps of Table 1, the color reports to each harp maker "family" and the marker to each harp maker: Saunier (○), Louvet (+), Cousineau G (□), Cousineau G et J-G (+), Cousineau J-G (○), Erard & Cie (□), Erard Frères (∗), Erard Sébastien (+).

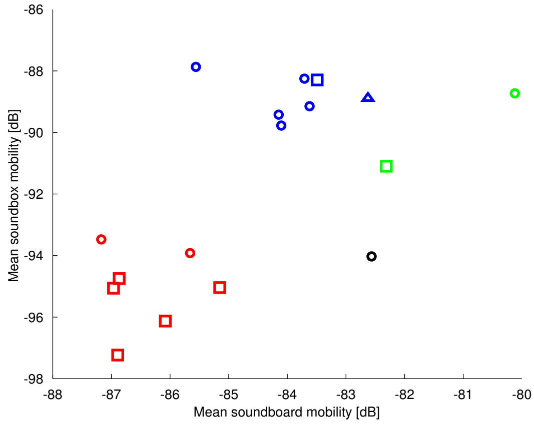

Figure 5: MVM of the sound-box versus MVM of the soundboard for 17 contemporary harps. Color corresponds to each harp maker and the marker to each harp's model: harp maker 1 - model A (○), harp maker 2 - model A (○) - model B (□), harp maker 3 - model A (○) - model B (□), harp maker 4 - model A (○) - model B (□) - model C (△).

to the soundboard by the string is proportional to its tension, the instrument's maker increases the strings' tension to make the instrument more powerful. Consequently, the maker has to increase the thickness of the soundboard and of the sound-box to resist to this strain, which leads to lower mobilities. These two phenomena are clearly visible in Figure 4.

Results on contemporary harp

In order to test the capability of the MVM indicator to categorize instruments, we estimate it on contemporary harps. We had the opportunity to perform measurements on 17 instruments at the Conservatoire National Supérieur de Musique et de Danse de Paris[5] and at the Camac Centre[6] in Paris. Harps from 4 makers (Camac harps (F), Horngacher (All), Lyon & Healy (USA) and Salvi (I)) were thus available. These harps either correspond to different models or are the replica of one model.

For the 17 instruments, we carry out mobility measurements with damped strings to prevent their vibration (including sympathetic modes [9]) while keeping the static deformation and the load imposed by them on the soundboard. Mean-values of the sound-box mobility and of the soundboard mobility are then computed and shown in Figure 5. For confidential reasons, the name of each harp maker is omitted and it is the marker's color that allows us to distinguish them. Moreover, each marker's shape corresponds to one harp's model (named A, B or C).

In figure 5, each marker's color can be clearly localized in the diagram and can be identified as follows:

- harp maker 1 (black): lower right quarter
- harp maker 2 (red): lower left quarter
- harp maker 3 (green): right
- harp maker 4 (blue): Top right quarter

Moreover, for each model of the same maker, the MVM are found to be fairly close. Note that the load imposed by the strings could slightly modify (for different tunings) the MVM of about ±0,5 dB. Therefore, this tuning influence is not significant in comparison to disparity between makers.

These results clearly show that each harp maker have its own design strategy, with less or more mobility of the soundboard or of the sound-box. These differences could clearly imply different dynamical and then acoustical behavior of each instrument, explaining that each harp maker have his own characteristics.

[5] http://www.cnsmdp.fr/
[6] http://www.camac-harps.com/

DISCUSSION

The analyzed instruments (historical or contemporary) are found to be differentiated for each harp maker according to their soundboard and sound-box mobilities. Different strategies of harp makers are thus identified, showing that some makers favor the mobility of the sound-box when others choose to build a more rigid sound-box.

For historical harps, the increase of the number of strings and of their tension has affected the harp's construction implying more rigidity of the soundboard and of the sound-box (as shown for the Cousineau "family"). Note that a quantitative comparison between mobility measured on historical and contemporary instruments is not possible because the tuning and string's tension are different.

For contemporary instruments, with close characteristics (number of strings, action-mechanism), results show that each manufacturer strategy can be identified and can probably explain acoustical differences between makers. From an acoustical point of view, the increase of the soundboard's mobility can involve a higher response to a force applied to the soundboard but, on the other hand, can lead to extra damping of the strings [10]. The harp maker has thus to adjust this compromise.

CONCLUSION

For instrumentalists, and therefore for instrument makers, the acoustical power of their instrument plays an important role in its quality. This attribute is linked to the vibratory behavior of the sound-box and of the soundboard of the harp. With our study, we show that this behavior has evolved throughout centuries and different design strategies are identified. Some makers favor the mobility of both soundboard and sound-box whereas others create a more rigid sound-box. These strategies contribute to the creation of each harp's maker's acoustical specificity.

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