18th and 19th French harp classification using vibration analysis

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Abstract

Most heritage musical instruments are not played anymore for conservation reasons. Most of the time, each instrument is the only representation left of a style or a historical period. This is coherent with the museums' task, which is to present diversity in makers, making processes, materials, etc. It is thus interesting to study not only an instrument but also its evolution according to music history or to technical evolution. Studying the whole production of a maker allows a better understanding of his know-how and his technical evolution. Nevertheless, the museum audience has no way to evaluate the acoustical properties of these historical instruments except when a copy (or fac-simile) is ordered. This paper intends to apply a global vibrational analysis on the harp corpus of the *Musée de la musique* to understand the consequences on the potential acoustical behaviour of the different construction techniques used by two famous harp makers, Erard and Cousineau. The idea is to survey the whole corpus, using the least invasive techniques which are still effective when applied to instruments in a conservation state and to define a vibrational descriptor able to represent different making strategies from the acoustical point of view. Whereas usual descriptive measurements do not discriminate Erard and Cousineau harps' acoustical behaviours, vibrational measurements, which are strongly influenced by construction techniques, do give this possibility.

Keywords

Musical instrument – Cultural heritage – vibrational analysis – concert harp – Erard - Cousineau - Classification

1-Introduction

The study of historical musical instruments can be done from many different approaches. Wood scientists are interested in accessing to aged wood to understand the ageing of some species [1]. With this understanding, they hope to develop an accelerated ageing process to offer aged wood to makers. Some authors are studied the surface layers [2,3] of the musical instruments and their conservation within cases. Some others consider the static deformation of the mechanical structure due to hygrometric variations or string tension [4,5]. Most of these studies on historical string instruments [1,2,4] deal with the violin and very few deal with several instruments which allow comparisons. In these studies, the instrument is generally considered in its static state whereas musical instruments were designed to radiate sound and therefore to vibrate. However, one study uses real historical violins to compare their spectrum in a playing configuration [6] but this kind of study requires that instruments are kept in playable conditions, which is not always the case. The pressure of cultural heritage requires replacing the playing of the instrument with alternative measurements. How is it possible to characterise the acoustic properties of instruments, which are muted because of conservation rules? Nowadays when a musical instrument joins a museum collection, it becomes a cultural heritage object that is loaded with a new cultural value in relation to its connection to history, music and culture. However this implies changes in the criteria that attribute value and interest to the instrument: its historic role and connections, its rarity, its peculiarity of shape and material. These criteria may become more relevant than the quality and power of its sound or its usability for concert repertoire. In this context it becomes essential to think about methodology and tools of study which exclude putting those instruments under a mechanical stress such as string tension (typically more than 4500 N for a 41 strings harp) [7], and, of course, any destructive analysis. Le Conte & al. [8] applied near-field acoustical holography to track the restoration process of a famous XVIth century harpsichord by following modal frequencies. This technique allows the capturing of operating deflection shapes close to resonance frequencies. While this technique is quick in comparison to other modal analysis methods, it is still time consuming and not always easy to set-up when a whole corpus has to be studied. In this context, a comparison of historical instruments requires developping methods which have to be repeatable, reproducible, quick and independent of the acoustical environment. Mobility measurements, defined as the ratio between the velocity to a force applied on the structure at a given point [9], could be good candidates. By using criteria based on these mobility measurements, classifications linked to the structural modification of a set of musical instruments were recently successfully performed [10,11,12,13]. The aim of this study is therefore to apply such vibratory measurements to a historical harp corpus and to interpret the data in relation to the structural evolution of the harps.

The Musée de la Musique in Paris preserves 31 pedal harps built in France between the 18th and the 20th centuries (figure 1). This interesting collection allows a deep comparative study between two famous makers of this period: Erard and Cousineau.

Figure 1: Harp exhibition in Musée de la musique

In the first section, the studied corpus, i.e. harps built by Erard and Cousineau, and their role in the historical evolution of the harp is presented. In the second section, a multidisciplinary method used to compare the instruments of the corpus is described: it is based on the method usually carried out by curators added with a method based on the mobility measurement classically performed by researchers. Finally, we present results obtained from these complementary approaches in order to characterise the two makers (Erard and Cousineau) and their know-how.

2-Instrument's corpus

2.1-Cousineau and Erard, famous French harp makers: the historical context

The pedal harp such as we know it today made its appearance during the first 30 years of the 18th century in South Germany. With regard to the harps which had preceded it, the novelty of the pedal harp consisted of the integration of a system to shorten the strings with "hooks", activated by 7 pedals (each pedal corresponding to a note of the scale, for example if the D pedal is pushed then all the D notes of the instrument are raised by one semi-tone). This mechanism allowed changing the key of the diatonic tuning giving a semi-chromatic instrument. The role of Queen Marie-Antoinette was important in the process of introducing this fashionable instrument, first to Paris and then to the whole country. Not only did she play the harp (as it can be seen on the painting by Gautier Dagoty, kept in the Palace of Versailles's collection), she also encouraged the establishment of German artists and craftsmen such as J.-H. Naderman in Paris. French makers, such as Cousineau, Saunier, Renault and Chatelain etc., quickly followed in their footsteps. They were keen to compete, as they were attracted by the mechanical complexity and the delicacy of design of this new instrument, coupled with the promise of a beautiful future and corresponding economic stakes.

For the manufacturers, this complexity implied the need for a chain of different specialties: cabinetmakers, woodcarvers, mechanics, gilders and painters. Their works were coordinated by the instrument maker, who finally assembled and produced a musical instrument often brilliantly decorated.

Under the pressure of more and more virtuosos, the harp makers quickly tried to increase the possibilities of the instrument regarding its range, its chromatic capacities, its specific sound and its dynamic. The competition, which raged between makers, was also the source of numerous inventions such as the chromatic system, which contributed to the instrument the characteristics that we know today.

In this context and during the focus period (18^{th} to 19^{th}), two personalities seem to dominate harp making in Paris with regard to the quality and the quantity of constructed harps and especially with regard to their inventiveness of these makers: Georges Cousineau (1733-1800) and Sébastien Erard (1752-1831). Both were at the head of workshops and prosperous shops where the public could find harps and other instruments alongside manuscripts and printed music. For the purpose of this study, which is mainly dedicated to the acoustic potential of instruments, it is pertinent to mention the training of these men.

Thanks to his apprenticeship in Paris (with François Lejeune), Georges Cousineau comes from the Parisian environment of the stringed-instrument makers, holders of knowledge solidly anchored in a tradition of several centuries. During his career, he invented several mechanical systems for the harp. He was believed to be the first one to conceive and present to the Royal Academy of Sciences, in 1782, the first completely chromatic harp on which each string could produce three sounds (flat, natural, sharp), thanks to its complicated mechanism which used 14 pedals [14].

The second personality who had a profound impact within his own time is Sébastien Erard. He was not only a harp maker but also a maker of pianoforte and a brilliant inventor. Contrary to Cousineau, he does not come from the luthiers[1] circle but from harpsichord makers. He had been trained in drawing and geometry, which was appreciably different from the average Parisian craftsmen of the time. In 1812, Erard patented an ultimate improvement: the addition of a double movement producing fully chromatic harps (each pedal giving three positions: flat, natural, sharp).

From an organological point of view, the instruments made by Cousineau and Erard at the same time present both similarities and striking differences, bearing in mind that Cousineau was the elder by about twenty years.

The Musée de la Musique keeps in its collection 31 European harps. Among them, seven have been attributed to the Cousineau family (four to the father Georges, two to the father and his son Jacques Georges, and one to the son) and at least nine have been made by Erard (Sebastien, Company or Frères). The organological description is given in table 1. The harps are ordered by chronological order for each maker.

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[1] Luthiers refer to builders or repairers of stringed instruments such as the violin or the classical guitar.

Table 1: organologic description of the corpus

N°	Maker	Date	Diatonic tuning	String number	Soundbox	Soundbox hole	Reinforc-ment system	Sound hole	Mechanical system for tuning	Range	Museum number	Max Length (cm)	Min Length (cm)
1	Cousineau G	< 1770	simple action	34	9 ribs	-	N	6 roses made of 7 holes	*crochets*		E.275	152.9	116.4
2	Cousineau G	1770	simple action	36	7 ribs	-	N	6 roses made of 7 holes	*crochets*		E2000.26.1	154.6	120.3
3	Cousineau G	1770-80	simple action	36	9 ribs	-	N	6 roses made of 7 holes	*crochets*	E0-E5	D.A.D.40297	161.3	119.6
4	Cousineau G	1782-85	simple action	37	7 ribs	-	N	N	*bequilles*	F0-G5	E.985.2.1		
5	Cousineau G et J-G	1785-90	simple action	37	7 ribs	5 trapez	O	N	*bequilles*	A0-A5	E.970.3.1	163.6	123.5
6	Cousineau G et J-G	1790-95	simple action	39	7 ribs	5 trapez	O	N	*crochets*	F0-B5	D.A.D.2592	163	119
7	Cousineau J-G	vers 1820	simple action	40	plywood	5 trapez	N	N	rotation peg	B0-F6	E.991.11.1	167	124.8
A	Erard Frères	< 1799	simple action	39	7 ribs	4 olive	N	N	*fork*	E0-A5	E.2100	171	129.5
B	Erard & Cie	1799	simple action	41	plywood	5 trapez	O	N	*fork*	F0-D6	E.981.6.1	166.9	123.3
C	Erard Londres	1820 Patent 3006	double action	43	plywood	5 trapez	O	N	*fork*	E0-E6	E.991.14.1	169.1	132.9
D	Erard Londres	1821 Patent 3070	double action	43	plywood	5 trapez	O	N	*fork*	E0-E6	E.0997	169.5	132.2
E	Erard Londres	1826 Patent 3830	double action	43	plywood	5 ellipse	N	N	*fork*	E0-E6	E.2003.5.8		
F	Erard Sebastien	1835 N°1271	double action	43	plywood	5 trapez	O	N	*fork*	E0-E6	x	168.9	134.2
G	Erard Sebastien	1835 N°1273	double action	43	plywood	5 trapez	O	N	*fork*	E0-E6	E.0998	170	133.4
H	Erard & Cie	1873 N°1752	double action	47	plywood	5 trapez	O	N	*fork*	C1-F7	D.OAR.240	183.2	135.9
I	Erard Frères	1890 N°2099	double action	47	plywood	5 trapez	O	N	*fork*	C0-G6	E.998.3.1		

2.2-Corpus dating

The harps made by Cousineau in this corpus are difficult to date because Cousineau never put any date or reliable number on his instruments and, at the moment, we do not know if any documents such as registers or archives ever existed. Nevertheless, it is possible to evaluate the period of each harp with the help of different elements such as the mechanical system, the number of strings which tend to increase along the period, and the decorative style. By comparing all these elements, it is possible to establish a chronology in this corpus.

For Erard, even with the help of information written on the instruments as well as surviving documents such as workshop registers, dating the harps is not so easy either. The date is only certain for a few harps, when the description made in the register matches the real instrument. Nevertheless, the numbering (made by the maker) remains a reliable method to classify the instruments. Only the harp E.2100 presents a real uncertainty. No inscription has been found outside or inside the instrument except the signature and address of the firm. The making process of the body, which seems to be recycled from an older instrument (body made of ribs), the mechanical system (single action with forks) and the number of strings could correspond to an instrument built before 1798, which is the year of his first dated and numbered instruments.

3-Method

From an acoustical point of view, the concert harp is composed of a set of strings connected to a flat panel, called the soundboard. Like most plucked instruments, a cavity is added at the back of the instrument to avoid any acoustical short-circuit, allowing the soundboard to radiate the sound efficiently. When the cavity has sound-holes, the air inside the cavity interacts with the soundboard vibrations to amplify the sound radiated in low frequencies [15]. In order to build instruments that radiate sound in all its tessitura, the maker has to design a soundboard as thin as possible and that can stand the string tension. Since string tension has been increased (notably by the addition of strings, as shown in Table 1), harp makers have to adapt the manufacturing of the instrument, not only the soundboard but also the sound-box. Two complementary ways to study this evolution in the harp corpus is to measure geometrical descriptors classically used by curators as well as vibratory descriptors used by musical acoustics researchers.

3-1 Classical descriptors

In order to compare instruments, geometrical information such as the vibrating length of each string, the soundboard area and thickness a well as the weight of the instrument and the number of strings were collected. In practice, the string length was only measured for every C string (from C0 to C6) when the string colour was still present or when the tuning mechanical system worked. That is unfortunately not the case for harp 1. The shape of the soundboard was approximated as a trapezoid allowing us to obtain the area with the measurement of the length, the width at the top and at the bottom of the soundboard. The soundboard's thickness was measured by using a Hacklinger gauge when the harp had open soundbox holes to allow the magnet to be placed on the back of the soundboard. The measurements were done at the top (extreme top), in the middle and at the bottom of the soundboard along the line of string connections. Across the plane of the strings, the measurements were done between the bridge and the soundboard rib. However, for the harps with no hole in the box or with a blocked reinforcement system (harp 1, 2, 3, 5, A, C and F), the thickness measurement was impossible.

3-2 Vibratory descriptors

In addition to geometrical measurements, vibrational measurements could be done on each instrument for taking into account its dynamical behaviour.

3.2.1 Experimental setup

In order to analyse the vibrational behaviour, without playing the instrument, the mobilities of the soundboard and of the sound-box were measured. The mobility is the frequency domain ratio between the velocity of a structure and the applied force, which caused that movement. The velocity and the force can be separately measured at the same point or at two different points. The mobility characterises the capability of the soundboard or the sound-box to vibrate under an excitation imposed on the soundboard. This quantity obviously depends on the instrument and on the pair points where the velocity and the force are measured.

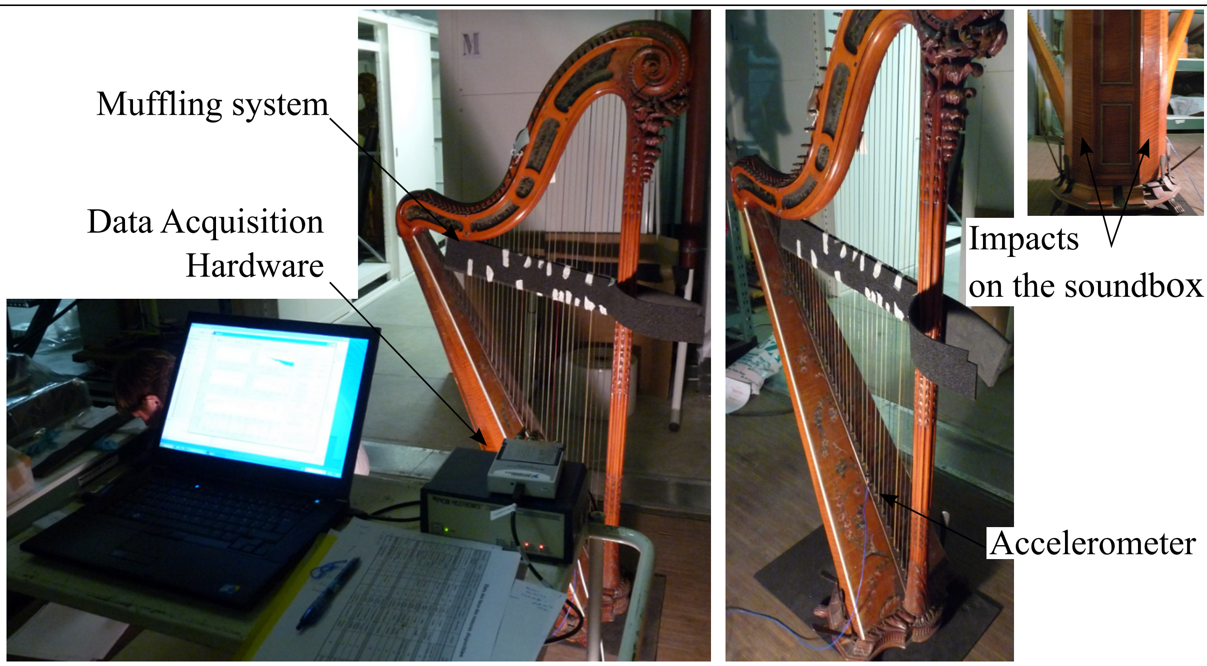

Figure 2: Experimental setup of the vibrational measurements

To measure the mobility on the 16 harps, the impact testing method was used. This method is well adapted to our corpus because it is a non-intrusive method. With this method, a hammer with an appropriate sensor was used to apply a known force by impacting the soundboard at the base of the C2-string (found by activating the appropriate pedal) and on two points at equal distance between the middle of the lower sound-box hole and the soundboard (see Figure 2). The frequency range of the measurement produced by this method depends on the hammer impact. We found that the cut-off frequency of the impact hammer [9] was about 2000Hz, which defines the high-frequency limit of the measurements. For the response, an accelerometer was glued with wax on the soundboard close to the impact point between the C2-string and the D2-string as shown on Figure 3. To avoid any parasitic vibration due to the strings, a particular muffling system consisting of two pieces of foam attached together was used as shown on Figure 2.

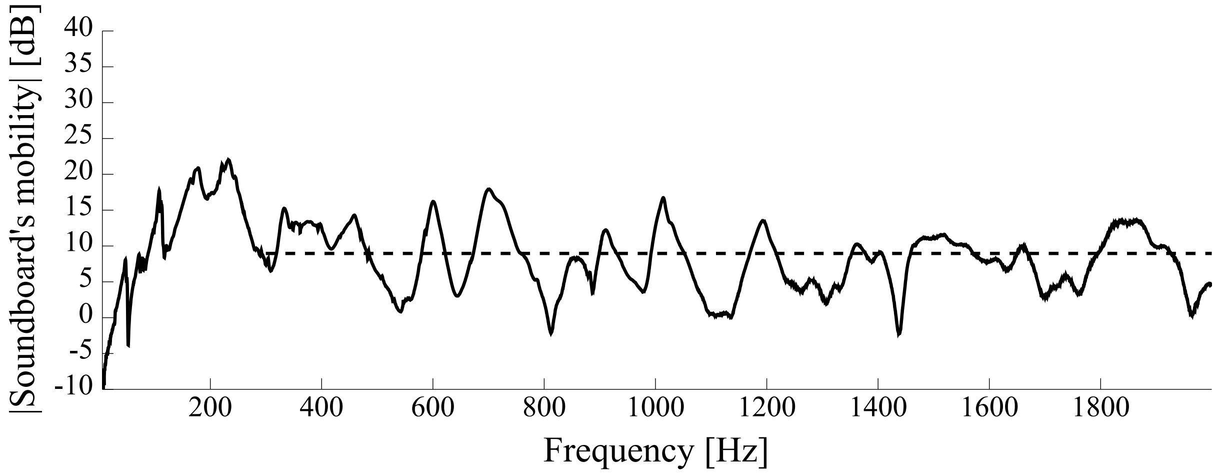

Figure 3: Soundboard mobility at the base of the C2-string with mean-value of the mobility in dashed line. Ref 1 dB: 10^{-3}m/s/N

3.2.2 The MVM descriptor

A typical mobility measurement is shown on Figure 3. In the low frequency range (before 300Hz), we can distinguish peaks, which are representative of the soundboard resonances. With other mobility measurements on the soundboard and by using a mathematical algorithm, it can be possible to identify the soundboard modes. In the middle frequency range (after 300Hz to the hammer cut-off frequency around 2000Hz), it is no longer possible to identify modes and we have to extract an indicator that can characterise the response of the soundboard (or the soundbox) and which is easy to use for the whole corpus. In a preliminary study, we used the Mean-Value of the Mobility (MVM) modulus to categorize instruments [10]. This MVM is computed from the beginning of the middle frequency range to the hammer cut-off frequency. On Figure 3, the MVM is shown for a typical mobility. This value does not represent the complexity of the mobility but extracts a global value of the capability of the soundboard (or the soundbox) to respond to an applied force (by the string for instance). Note that the MVM of the soundbox is calculated as the mean value of the two MVMs computed from mobilities measured on each side of the soundbox (see Figure 2 and explanations provided in subsection 3.2.1). For conservation reasons, no harp was tuned in the same way: some had tuned strings, some had strings at just minimum tension and some had no strings at all. Unfortunately, it was not possible to change this without running the risk of damaging the instruments. However, the influence of the string tension on the MVM descriptor should not have any significant effect. Indeed, as shown for the piano, only the first modes shapes and the frequencies are impacted by the down bearing exerted by the strings. Above these modes (in the middle frequency range), the mobility remains essentially uninfluenced [16, 17, 18].

4-Results

4-1 Analysis of classical descriptors

All classical descriptors, defined in Sec. 3.1, are gathered on Figure 4. They show some trends but do not clearly discriminate between the two makers.

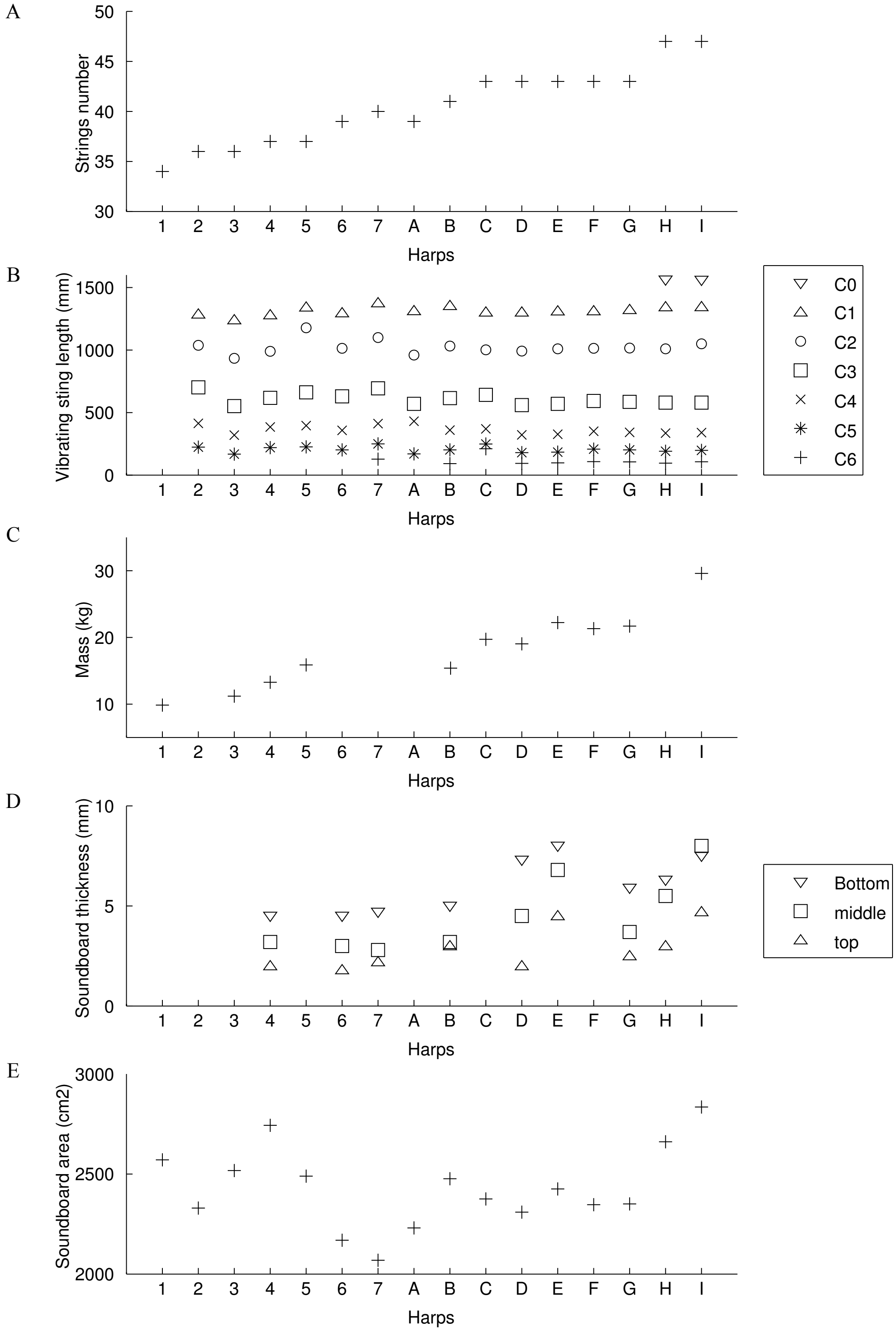

Figure 4: Number of strings (A), vibrating lengths (B), mass (C), soundboard thickness (D) and area (E) for each concert harp of the corpus. Each harp is labelled according to Table 1. The vibrating length is defined for each C from C0 to C6.

The number of strings is in average higher for Erard's harps (from 39 to 47) than for Cousineau's (from 34 to 40), showing an evolution between the two corpora (see Figure 4-A). In the same way, all harp models made by Cousineau are appreciably lighter than those made by Erard (except for harp B with 41 strings, see Figure 4-C). This observation may have two explanations: first the structure of the mechanical part situated on the console is bigger for Erard's harps, which made it stiffer and more stable for tuning, and secondly the whole forged steel pedal set is heavier than those of Cousineau. Another considerable difference is the soundbox construction: Cousineau assembled seven thin wood ribs (generally made of maple) whereas Erard introduced plywood backs with the first numbered harps (from 1799, harps B-I).

For the vibrating length (shown on Figure 2-B), only a few differences can be noticed: Cousineau's harps seem to present slightly longer strings than Erard's for the same note. At the same time, Cousineau made soundboards thinner (based on 3 harps measured) than Erard. More surprising is that Erard did -or tried- different thickness profiles (which was not the case for Cousineau) all the more that he did not change the soundboard area, as for harps C, D, E, F and G. We can believe that Erard may have used a gauge. For harps H and I, which are the latest ones in the corpus, the soundboard size is very different, larger than the other ones. At this time (late XIXth) the makers were looking for a more powerful instrument and increasing the soundboard size is a plausible strategy to achieve that. Note that for harp 2 (Cousineau E.2000.26.1), which is supposed to be a children's harp, the soundboard area is found to have a value close to the average. The soundboard area could be useful for observing a probable evolution in the acoustical power for Erard's harps but is useless for Cousineau's harps. A kind of "standardization" can be noticed for Erard's harps, independ of the workshop location (Paris or London) since every harp made at the beginning of the 19th century has the same size. These results show the need to improve the knowledge of the instruments from the acoustical point of view.

4.2 Analysis of vibrational descriptors

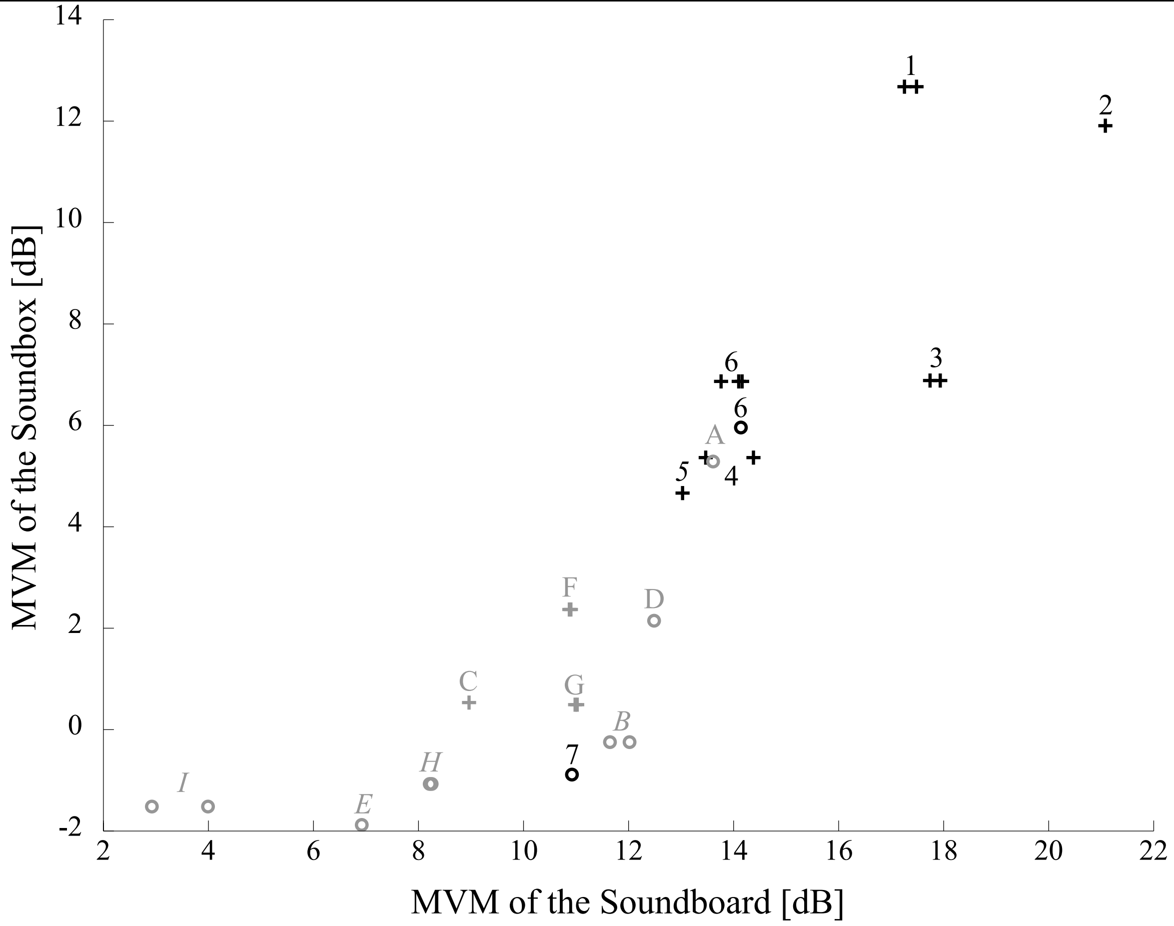

Figure 5: MVM of the soundbox versus MVM of the soundboard for the harp corpus. The number (in black) or the letter (in gray) corresponds to the Cousineau's or Erard's harps, respectively, defined in Table 1. Harps without soundbox holes or with closed soundbox holes are indicated by the marker +. Harps with open soundbox holes are indicated by the marker °. Repeatability measurements were done for harps 1, 3, 4, 6, B, G, F, H, I. For harp 6 measurements were done for two configurations: with soundbox holes open or closed. Italics numbers or letters highlight harps under tension. Ref 1 dB: 10^{-3} m/s/N.

Figure 5 shows the MVM of the soundbox versus the MVM of the soundboard. Each computed value is shown by a marker. Letters or numbers refer to the harps of the corpus (as defined in Table 1). In black are Cousineau's harps and in grey, Erard's. Mobility measurements of harps 1, 3, 4, 6, B, G, F, H, I were repeated. These results are found to be very close showing that the methodology is reproducible. This gives us confidence in our results and allows us to compare the two harp makers. Likewise, the opening or the closing of the soundbox holes, by the reinforcement system, affects very slightly the MVMs (as shown for harp 6 on Figure 5). This result was expected since the effect of the soundholes on the mobility is principally localised in the low frequency range [15]. Note that for harp 2, the conservation state may be different than a normally ageing one due to water damage before belonging to the collection. The instrument was totally disassembled and reassembled for a presentation state in the permanent exhibition in the museum [19].

On Figure 5, the two harp makers are found to be well separated except for harps 7 and A. Cousineau's harps have higher sound-box and soundboard mobilities than Erard's harps. This particular result can be linked to the design of the instrument. For Cousineau, most of the sound-boxes are coopered in various wood species whereas Erard’s soundboxes are made of rounded plywood backs reinforced by internal ribs and with face veneer in wood. Erard’s design reinforces the rigidity of the sound-box and decreases the mobility. The case of harps A and 7 confirms this link between mobilities and construction. Indeed, these two harps are built differently from other harps of the same maker. For harp 7 (of Cousineau G), the sound-box is made of a rounded plywood back reinforced by internal ribs whereas for harp A (of Erard Frères), it is coopered. Harp 7 is the most recent of Cousineau's harps in the Musée de la Musique (around 1820) and Harp A is probably one of the first harps constructed by Erard (before 1799). For the soundboard, the MVM values for Erard's or Cousineau's harps are certainly due to the increased number of strings, involving more strain on the soundboard. A complementary explanation would be that the maker increased the string tension to make the instrument more powerful. These results were found in a comparison of two harps: one built at the end of the eighteenth century with silk strings, and the other one in the twentieth century with gut strings [7]. For our corpus, this cannot be verified because we lack information about the linear mass density (diameter and material) of the original strings. Nevertheless, for both cases, the maker has to increase the thickness of the soundboard (as shown on Figure 4) and of the sound-box to stand the strain, which leads to lower mobilities [11,20].

According to Figure 5, the two harp makers are found to be reproducible in their manufacturing in terms of MVMs (both the soundboard and the soundbox) and thus on the harps vibratory behaviour. Indeed, for Cousineau, The MVMs of harps 4 to 6 are close even though their soundboard areas (see Figure 2-E) are different. For Erard, two harps built in the interval of one month with serial numbers 1271 (Harp F, September 1835) and 1273 (Harp G, October 1835) have similar vibrational characteristics: the MVM of their soundboards are equal while for the soundbox the MVM differ slightly. It could be explained by a small difference in the plywood's thickness or in the internal ribs. This seems to reveal two different approaches to achieve the same goal (i.e. keeping the vibratory response relatively constant): the Cousineau family could use very different shapes while Erard favoured geometrically similar instruments (same area of Harp F and G soundboard on Figure 2-E), confirming that the manufacturing of Erard's harps resulted in a more industrialized process.

5.Conclusion

The Musée de la Musique owns a beautiful harp collection revealing the technical evolutions of the instrument over a period of about 250 years. Studying more particularly two makers who are known to be famous allows us to have a better understanding of the harp evolution. The advantage of studying instruments preserved in the museum is that we could be sure that they are evidence of know-how. The drawback is that in most cases, it is not possible to record its sound. The present study shows that adding vibratory analysis to geometric measurements brings complementary information about the vibratory behaviour resulting from the manufacturing process choices of Erard and Cousineau. The MVM is a simple measurement but is robust enough to understand the makers' strategy. Over the years, Erard's strategy was to rigidify both the soundboard and the soundbox, which resulted in decreasing both the sounboard and soundbox mobilities. This evolution is clearly linked to the increase in the number of strings and of their tension in order to make more powerful instruments. For Cousineau, our measurements showed the same tendency but with a higher mobility. Beyond the distinction between the makers, the important result of our work is that the construction techniques used for the sound box (plywood versus ribs) significantly affects the acoustical behaviour of the instrument, which can be characterised by a straightforward experimental method presented in the paper. We also found that both Cousineau's and Erard's manufacturing have incredible reproducibility in terms of vibrational characteristics. Thanks to this study, we collected a lot of data about historical harps. Beyond the comparison between two manufacturers, a vibrational signature for each instrument is now known. This data could be used in the future to develop a monitoring method. From an acoustical point of view, the knowledge of this data would be useful to synthesise the sound of each historical instrument. Obviously, research on the material and diameter of the strings originally mounted on these harps has to be done.

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