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► **To cite this version:**

Henri Boutin, Stéphane Vaiedelich, Arthur Pathé, Givois Arthur, Benoît Fabre, et al.. FA-RE-MI (Faire parler les instruments de musique du patrimoine). *Wooden Musical Instruments Different Forms of Knowledge*, 2018. hal-02470016

HAL Id: hal-02470016

<https://hal.science/hal-02470016>

Submitted on 21 Feb 2022

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FA-RE-MI (Faire parler les instruments de musique du patrimoine): *Making Historical Musical Instruments Speak*

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Abstract

Musical instruments can be considered objects that have been empirically optimized for centuries. Depending on geography and epoch, these optimizations have followed or boosted the evolution of music itself, as instrument-making choices, playing techniques and sound aesthetics are greatly intertwined. For preservation reasons, most of the musical instruments kept in public collections (e.g., in museums) are no longer played. In order to bring these sounds from the past back to life, facsimiles are made by contemporary makers through the study of cultural heritage instruments and their documentation (archives, paintings). Nevertheless, being able to copy an instrument does not mean being able to understand the original meaning and purpose of the instrument. In particular, some material or assembly choices and instrument-maker adjustments are not really known and, using the sample instrument, we have to infer this knowledge. A mechanical and acoustical approach applied to cultural heritage objects allows us to extract objective information by non-invasive means: in situ measurements, observations, modelling. This paper is a step towards a better understanding of the choices made by instrument-makers of the past. The multidisciplinary methodology used here (mixing acoustics, history, organology and perception) allows us to go beyond limitations due to classical descriptive approaches. The paper presents studies about plucked and woodwind instruments as separate sections, as these two instrument families exhibit different technical aspects and instrument-making decisions. As an example of the methodologies used, we consider the voicing of harpsichord plectra and the wood species of woodwind instruments.

1. Introduction

Assuming that materials used to make musical instruments are deliberately chosen by makers to meet their functional needs seems to be reasonable and is often confirmed by experience. It is also clear that the instrument-maker's turn of hand and skills are guided and limited by the needs of musical performance. For these reasons, the musical instrument is deep-rooted in the culture or cultures in which it is—or was—played, so that these material preferences and practices are closely tied to a cultural context, which natural sciences or engineering cannot justify. Thus, although a solid relationship can nowadays be established between the mechanical parameters of the wood used in instrument-making and some of its measured physical properties, the criteria for the selection of the species often escape this logic alone [1-6]. The importance of some parameters whose functional influence is not directly assessed has been highlighted for a long time. As early as 1637, Father Mersenne [7], a scholar and thinker often referred to as “father of acoustics”, did not dissociate the mechanical properties from the visual qualities of the material. In his “Universal Harmony”, he said: “To make a good flute, a good wood will have to be chosen among those which will seduce the ear and delight the eye”.

The approach of physical sciences and engineering identifies and prioritizes the physical parameters involved in the functional mechanisms of the musical instrument, as well as the musical gesture itself. Mixed with historical and musical knowledge, such results make it possible to better categorize and explain the choices in the art of making musical instruments. This multidisciplinary perspective provides the musical instrument with a broader identity, in agreement with the essential place it holds within all human societies.

The FA-RE-MI research project initiated during COST action FP1302 explores relationships between material and knowledge, combining different approaches associating museum issues, analytical methods, psychology and perception, as well as musical performance. It mostly focuses on historical harpsichords on the one hand, and wooden wind instruments on the other—two sets of musical instruments associated with a time and a culture of which very little documentation and knowledge are now available. The project deals with two particular points:

- the critical parameters of the “voicing process” in the harpsichord, of all the gestures and interventions concerning functional and musical modalities, on which the string plucking depends, and of the relationships between the string vibration features and results founded on a psycho-perceptual approach;
- the influence of the microstructural properties of wood on the functionality of wind instruments in a historical perspective.

The project originated partly due to the proven lack of material elements and historical sources about the excitation system of the harpsichord string—plectrum in feather of goose, crow or other species—and about the musical voicing. François Couperin, “Organiste du Roy” (king’s organist), is one of the few known historical sources. He summarizes the problem in a few words in his famous method *The Art of Touching the Harpsichord* released in 1717, urging young students to use “lightly-feathered [harpsichords], as this point is of infinite consequence” [8, 9] (see Fig.1). He emphasizes that, in any case, it is essential for performers “to [always] play on a well-feathered instrument”. However, these remarks are not enough to be able offer to the public today historically documented musical instruments, in terms of voicing and performance.

Fig.1

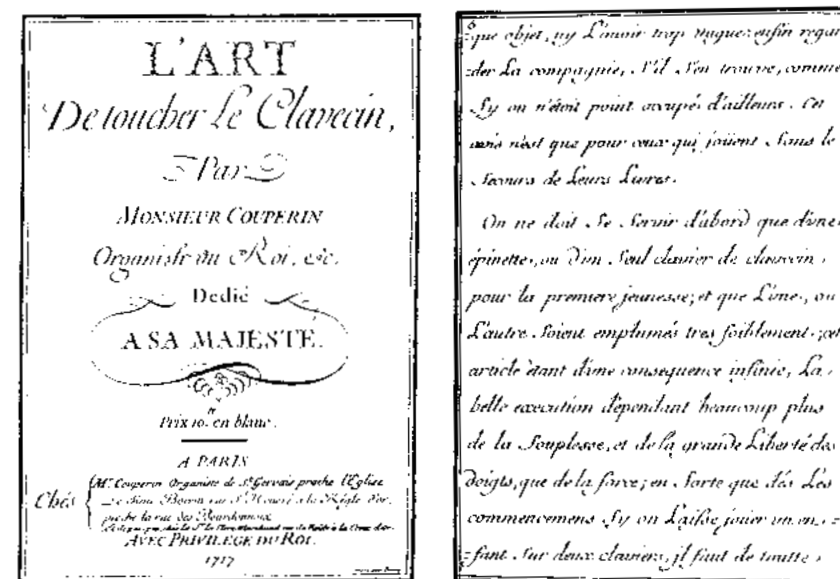


Fig.1

Cover and sample of the facsimile of François Couperin’s method. Composer, player and teacher in the court of Kings Louis XIV and Louis XV, François Couperin was one of the best harpsichord players in France during the eighteenth century. His method was first published in 1716 and then in 1717, the only change being the spelling of “Roy” changed to “Roi” on the cover. Translation of the original text by Couperin [10]: [...] When playing before a group, it is best to look at the company that has gathered, and not appear preoccupied. This advice is relevant only to those who are not playing from written scores. During the earliest years it is best to play only on a spinet or a one manual harpsichord, and that each of these be quilled only very weakly [the crow quill plectra of the harpsichord be set to produce a very light touch]. This is a very important point. Good execution depends much more on suppleness and great freedom for the fingers than it does on force. Consequently, if one starts off youngsters on a two-manual harpsichord, the small hand of the student will be strained when trying to make the keys “sound,” and from this the hands will become poorly placed and a hard touch will develop [...].

The FA-RE-MI project also started from the observation that a large diversity of wood species is traditionally used in the making procedure of various wind instruments, including oboes, flutes, serpents and basset horns. From usually long-winded written sources on this matter, physical models of wind instruments commonly used in the literature ignore the material properties in the constituting mathematical expressions. In the “Méthode raisonnée pour le hautbois” [11], published a few years later, François Joseph Garnier l’Aîné, First Professor at the National Music Conservatory of the nascent French Republic, in Paris, specifies that “boxwood, species employed to make oboes, should be dry and free of knots, and should show almost uniform porosity along its full length: [he says] almost uniform because the same piece of boxwood never shows the same porosity in all of its parts”. He adds that “makers should devote the hardest part of the piece of wood to the upper part, and the softest to the lower part.” This consideration echoes Johann Joachim Quantz’s text [12] “Versuch einer Anweisung die Flöte traversière zu spielen” published in Berlin in 1752: “Boxwood is more long-lasting, and consequently more commonly used than other species to make flutes; however, ebony provides a more beautiful and clearer tone”.

The team built up around this project is composed of researchers from the Lutheries-Acoustique-Musique team of d’Alembert Institute, Sorbonne University, Paris, and from and the Conservation-Recherche team of the Centre de Recherche sur la Conservation (CRC), Museum of Music, Paris.

2. Methods and Results

2.1. Harpsichords

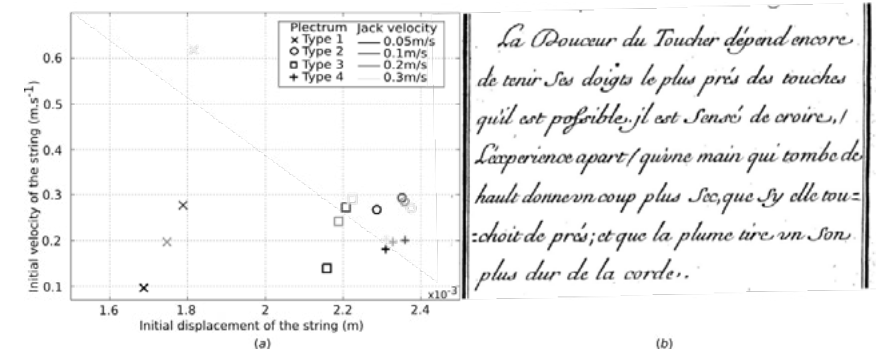
2.1.1. Context: the voicing process

Since the plectrum is the part that sets a harpsichord string into motion (it controls the string’s “initial conditions”), harpsichord connoisseurs and practitioners have always focused their attention on the voicing process. This process of carefully selecting the materials (leather or quill, and more commonly now polyoxymethylene) and meticulously shaping the plectra is unavoidable for the delivery of a harpsichord that has a homogeneous sound and touch over the whole tessitura [13].

2.1.2. Of plectrum shape and jack velocity: some acoustical measurements

To rephrase and expand on the previous paragraph, we may state that providing a harpsichord with an appropriate voicing puts the player in the ideal position to render an expressive piece of music. It follows that two parameters appear to be fundamental in the production of harpsichord sounds: plectrum shape and the movement of the key-jack-plectrum system in a performance situation.

Fig.2



A parametric study was carried out using a robotic finger (ensuring reproducibility of measurements and avoiding weariness of a human operator), depressing with different velocities a key that was pushing a jack fitted with different plectra made of the same material but with different shapes [13]. In this study, the key/jack velocity is a parameter controlled by the instrumentalist, while the plectrum geometry is determined by the maker’s gesture.

We analysed plectrum deflection at string release time (using a high-speed camera), string trajectory during the plucking phase, string’s initial position (i.e., deviation from rest position at release time), speed and angle (using optical vibration sensors), and resulting sound (recorded by a microphone), described as sound level, resonance time, attack time, and spectral centroid, the latter being a measure of the location of energy in the spectrum, i.e., the more energy content in the high/treble frequencies, the higher the spectral centroid, providing a descriptor supposed to account for sound “brightness” [14].

Results [15] show that the plectrum deflection and string trajectory before release are quite independent from the key/jack velocity. Also, different plectrum shapes allow for different initial conditions: some plectra will consistently provide the string with larger initial displacements or velocities than others. More interestingly, it was found that some plectra allow for larger ranges in the string’s initial conditions, depending on the jack/plectrum velocity: in other words, these plectra allow the player to produce a larger variety of sounds

Fig.2 (a) Amplitude of the initial displacement (D_0) and speed of the string for 4 different plectrum shapes and 4 different key/jack velocities. Markers indicate mean values. (b) Copy of the original text by François Couperin, page 7, showing that these results were already suspected in 1716 [9]. Translation from the original text by Couperin [10]: “Smoothness of touch depends additionally on holding the fingers as closely as possible to the keys. It stands to reason (entirely apart from the fact that experience shows) that a hand that falls from a height will produce a drier blow than would one falling from close by and that the quill will draw a harder [harsher] sound from the string.”

when varying the key depression movement (see **Fig.2:** with Type 1 plectrum, there is more freedom to vary the initial velocity of the string).

2.1.3. Are different plectrum shapes perceived by musicians?

The study reported in the previous paragraph showed that the interaction between the gesture of the maker (voicing the plectra) and the player (pressing the keys) leads to a certain expressivity in harpsichord playing. As the plectrum shape appears to facilitate the expressivity in the player's gesture, the question that naturally followed was: how do players perceive and describe different plectrum shapes?

Two professional harpsichord makers made each a set of plectra for a single-keyboard, 56-key harpsichord. Makers were given identical jacks and raw material (polyoxymethylene) and "voiced" the harpsichord their own way. In the following, sets of plectra are denoted "V1" and "V2" respectively.

Professional harpsichordists took part in a free playing and verbalization task: For each of the voicings, the participants were simply asked to play the harpsichord as they usually would, and to engage in a conversation with the experimenters, expressing their feelings when playing. At the end of each phase, short musical excerpts were played by the harpsichordists and recorded [14]. Between the two phases, participants took a short break outside of the room while the jacks were changed, so that they were neither aware nor told that they were playing with a different set of plectra when back in the test room.

In order to compare perceptual measurements with physical measurements, at separate occasions, the following two measurements were taken: a) "activation force", for each key, i.e., the minimum force needed to activate the note, and b) sound recording of isolated notes: all keys slowly played in a row with a medium-velocity pressing motion by an experienced harpsichord player on our team.

Our method for analysing the verbalizations is thoroughly described in [16, 17, 18] and only landmarks are given here. First, the recorded verbalizations were transcribed. Then a semantic analysis was done, identifying the meaning of the words used by the participants. Linguistic methods were applied: word search, context interpretation, search for linguistic marks in order to determine semantic proximities and distances. Words referring to similar perceptual aspects were grouped into the semantic categories listed in **Table 1:** Each category groups words of similar meaning (not shown here) under a label chosen from these words (titles in the column "Semantic category"), explanation of this meaning is given in the "Associated perceptual aspect" column as the result of the linguistic analysis of verbalizations.

Then all sentences uttered by the players, organized in semantic categories (e.g., all sentences about "attack" were grouped and analysed

Table 1

SEMANTIC CATEGORY	ASSOCIATED PERCEPTUAL ASPECT
Loud / hard / strong	Volume of the sound, hardness of the plectrum, "strength" of the voicing
Length	The way the sound lasts and evolves after note onset
Attack	Either the onset part of the sound, or the way the sound behaves in response to a finger gesture
Homogeneous	Equality / inequality of sound and touch across notes and tessituras
Evolution	Graduality over the whole tessitura (gradually lighter from bass notes to treble notes)
Sound descriptors	Sound quality, or timbre

together, then all sentences about "length", etc.), were reallocated to each voicing, using context information (who is playing, who is speaking, what voicing is being played V1 or V2), and linguistic tools (mostly grammatical and syntactic) were used to discover how each voicing was described by the players within this framework of semantic categories (i.e., what are the evaluations of V1 and V2 according to the criterion "Homogeneous"?).

A perception-based description of V1 and V2 was obtained from this linguistic analysis. The main perceptual results can be summarized:

- a. V1-sounds are louder than V2-sounds,
- b. V1-plectra are harder than V2-plectra,
- c. V2-sound are more resonant than V1-sounds.

These three perceptual results are confirmed by the acoustical and mechanical measurements:

- a. Isolated notes produced with V1 are louder than notes played with V2 (typical difference 1 dB(A)), and for a given excerpt and a given musician, V1 systematically produces louder equivalent sound levels,
- b. one needs to apply 5 to 10 g more to trigger a note with V1, for notes above C3 (no difference seen below this note),
- c. V2-notes have a slight tendency to have a longer resonance time than V1-notes.

Other perceptual results are:

- a. V2 gives more dynamics than V1,
- b. V1 achieves both a better equality and a better evolution of sound and touch over the tessitura. This latter point deserves further investigation.

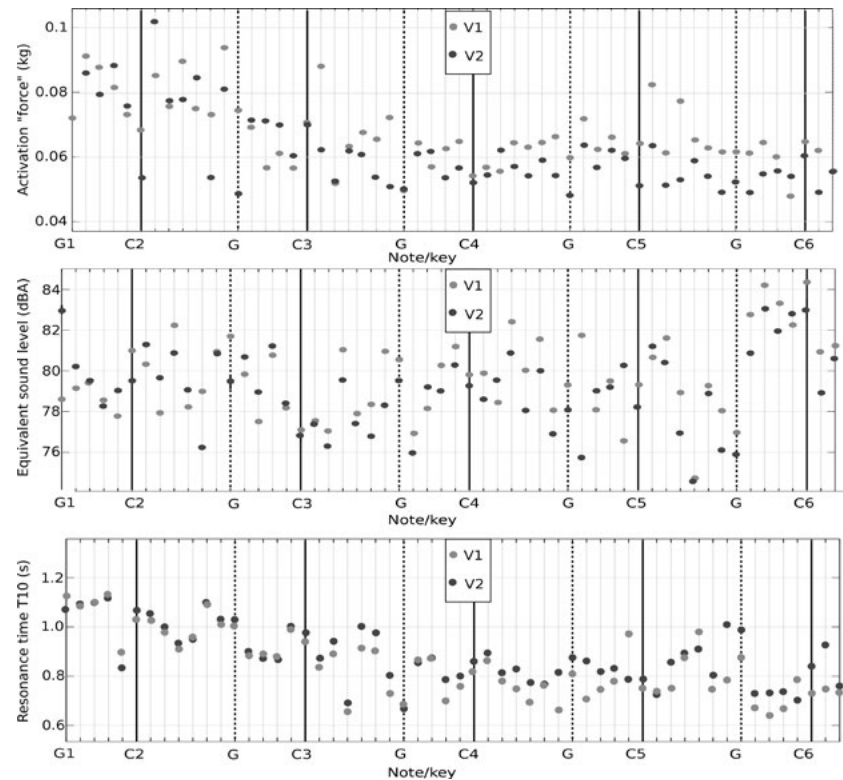
As a summary of this part that approached the voicing process with a multidisciplinary method combining psychology, musicology and experimental acoustics, we state that:

- the interaction of the maker's (voicing) and player's (pressing) gestures sets the frame for the expressivity of harpsichord playing,

Table 1 Summary of semantic categories.

- plectrum geometry is very influential: musicians can feel very tiny differences, describe them, and adapt their playing to different voicings,
- perception of voicing is multimodal, with a strong auditory-tactile integration: loudness (sound) and hardness (plectrum) evaluations are well correlated. This is not as clearly observed on the physical side: equivalent sound level and minimum triggering force measurements are poorly correlated (see Fig.3).

Fig.3



2.2. Wind Instruments

In wind instruments made of wood, the surface condition of the bore has a critical impact on the playability and hence on the radiated sound. Indeed, aging wood typically introduces cracks in the resonator leading to leaks and making the instrument hardly playable. This is the reason why makers and players attach particular importance to keep the inner surface of the bore smooth. For deontological reasons, instruments in museum collections cannot receive such treatment, and

Fig.3 From top to bottom, minimum triggering force (in kilograms), equivalent sound level (in dB(A)), resonance time T10 (in seconds) for each note of each plectrum set (pink dots for V1 and blue dots for V2).

consequently are extremely rarely played. This study aims at quantifying the impact of polishing on the acoustics of the resonator, for different wood species traditionally used in instrument-making. From a cultural heritage conservation point of view, this point is crucial in order to synthesize the sound that instruments of museum collections would produce in playing conditions. For that purpose, an experimental method has been developed to quantify the acoustic dissipation in a cylindrical pipe. It was subsequently applied to wooden pipes manufactured by a recorder maker, at different steps of the making procedure. This part of the FA-RE-MI project, relying on both researchers and craftsmen skills, is intended to provide essential information for museum curators as well as experimental results of great interest for instrument-makers.

2.2.1. Estimating acoustic dissipation in a cylindrical pipe

The first step of this study consisted in implementing a method to estimate the attenuation factor of pressure waves, equal to $\pm \text{Im} \left(\frac{2}{L} \arctan(\sqrt{1-2Z_1/Z_2}) \right)$ [19] where L is the air column length and Im stands for the imaginary part of a complex number. The \pm sign is chosen so that the attenuation factor is positive. Z is the input acoustic impedance of the pipe, defined as the ratio between acoustic pressure and acoustic flow at one end, with the other end sealed. Subscripts 1 and 2 correspond to an air column length equal to L and $L/2$ respectively.

2.2.2. Manufacturing the wooden pipes

In order to report on the acoustic dissipation in wooden resonators of wind instruments, five cylindrical pipes were manufactured by a recorder maker: one was made of African blackwood (*dalbergia melanoxylon*), one of boxwood (*buxus sempervirens*), one of pear wood (*pyrus communis L.*) and two of maple (*acer pseudoplatanus*). These species are commonly used to make numbers of wind instruments including modern clarinets and oboes, recorders, baroque oboes, serpents and cornetts. The pipes are parallel to the fibre direction, except one, made of maple, at an angle of 60 degrees. The two maple pipes are made out of the same piece of wood. All pipes have the same dimensions. The manufacture process consists first in shaping the external surface of the wood pieces with a gouge (see Fig.4), and then drilling the cylinders with a stainless-steel reamer. Eventually, the inner surface of the pipes is polished using fine sandpaper.

2.2.3. Attenuation factors in the wooden pipes

For each pipe, input impedances Z_1 and Z_2 are measured between 50 Hz and 2.5 kHz. For Z_1 , the air column length is equal to 239 +/- 1 mm. For Z_2 , the air column is twice shorter, equal to 119 +/- 1 mm. The far end is closed with an airtight sealing made of aluminum and modelling

Fig.4



Fig.5

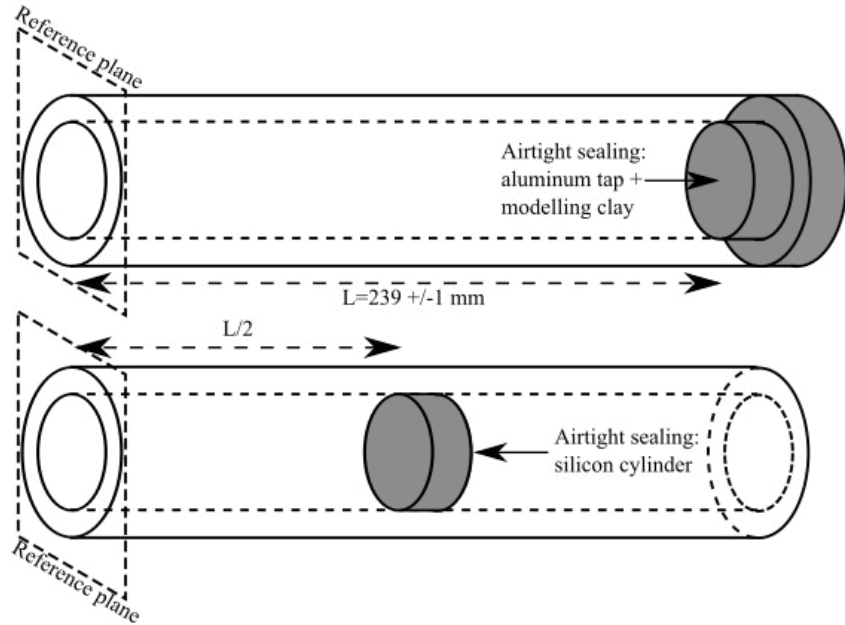


Fig.4

External shaping of the maple pipe.

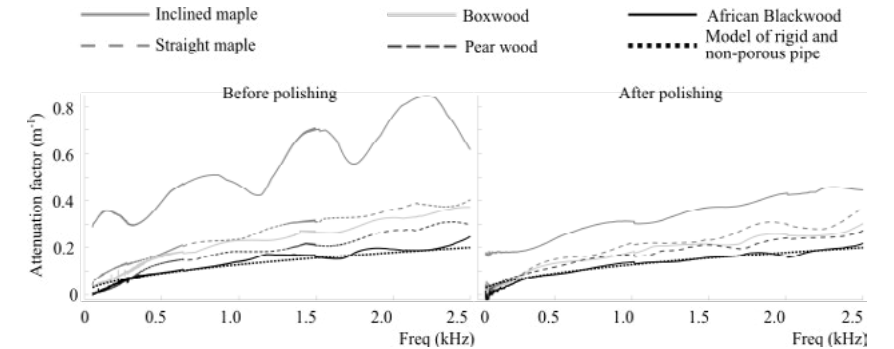
Fig.5

Experimental setup used to estimate the acoustic dissipation in a cylindrical pipe. The attenuation factor is derived from two impedance measurements: one with an air column length twice as long as the other. For each measurement, the far-end is closed with an airtight sealing.

clay, or silicone (see Fig.5). The measurement method uses a sensor from CTTM and LAUM, Le Mans, France, placed at the reference plane. Its principle is described by Le Roux *et al.* [20].

For each wooden pipe, the attenuation factor is estimated twice during the manufacture procedure: before and after polishing (see Fig.6). These curves are compared to a theoretical attenuation factor, calculated using a model of smooth and non-porous cylinder of same dimensions [21].

Fig.6



2.2.4. Results

The estimates of attenuation factors give insight into how the acoustic dissipation varies among the wood species considered. Except for the inclined maple pipe, the ratios between estimates and model show small fluctuations between 300 Hz and 2.5 kHz. Over this interval, their average values range from 1.1 to 2.0 before polishing. Such a discrepancy, shows that differences of roughness and wood porosity among the wood species strongly affect the acoustic dissipation inside the pipes. However, polishing tends to lessen the differences between wood species and theoretical model. Indeed, after polishing, the ratios between estimated attenuation factors and the theoretical value are reduced to less than 1.6. In contrast with the other curves, the attenuation factor in the African blackwood pipe is barely affected by polishing, as it is relatively close to the theoretical value, calculated in the absence of roughness and porosity, even before polishing.

This experiment allows us to rank the wooden pipes, in terms of acoustic dissipation: maple, boxwood, pearwood and African blackwood from largest to smallest attenuation factors. This order is the same before and after polishing. These results also suggest that inclining the pipe direction relative to the fibre direction considerably

Fig.6

Attenuation factors in wooden pipes of same dimensions, made of maple, boxwood, pear wood and African blackwood, before (left) and after (right) polishing. The direction of each pipe is parallel to the fibre direction, except that of the inclined maple pipe, at 60 degrees. The dotted black curve shows the theoretical attenuation factor in a model of smooth and non-porous pipe, with same dimensions.

increases the acoustic dissipation, as both the inclined and the straight maple pipes are made out of the same piece of wood. Indeed, on average between 300 Hz and 2.5 kHz, the attenuation factor of the inclined maple pipe is 2.0 times larger than that of the straight maple pipe before polishing, and 1.5 times larger after polishing. Today, in western wind instrument-making of high quality, African blackwood is extensively exploited. Also, wooden resonators are parallel to the fibre direction, except for a few instruments with a curved bore, such as serpents or cornetts. Such manufacturers choices, together with polishing, tend to reduce the acoustic dissipation inside the bore, and hence to favour oscillations of the air column at its resonance frequencies. In contrast, makers from other cultures traditionally use wood species known to be more porous, e.g., mulberry or apricot wood for zurna or duduk, bamboo for bansuri. Such instruments allow performers to reach playing frequencies relatively far from the bore resonances, compared to western instruments like clarinets or oboes. These qualities are particularly adapted to play wide glissandi, vibrato or microtones, commonly used in numbers of traditional non-Western repertoires.

3. Discussion

The results we obtained (see **Table 2** summarizing the experiments we did) show that crossing different approaches—mechanical characterization, acoustics, motion analysis of musicians, historical problematics—is an efficient methodology which offers an in-depth look on the involved phenomena. This contribution leads to a better understanding of the relationships between the materials used by makers, the expertise involved in the making process, and its implications in the musician-instrument interaction.

Instrument	Tests	Publication / Section
Harpsichord	Mechanical and acoustical characterisations of the plectrum-string interaction for several plectrum shapes and several instrumentalist controls	[13] / 2.1.2
	Perception characterisation of plectrum voicing	[14] / 2.1.3
Woodwinds	Theoretical modelling of acoustic propagation in porous pipe	[17]
	Experimental quantification of acoustic dissipation due to bore effect	[17] / 2.2.3

Table 2 Summary of tests carried out during the Faremi project, with related publications and associated sections in this article.

By finely adjusting each plectrum of the harpsichord, the maker is in a position to modify the sound produced by the instrument. Whereas this fact is well-known by makers, few studies based on an acoustical approach have considered this major aspect so far, as harpsichordists are supposed to have but little possibility for control on their instrument. By investigating the harpsichord with a multi-disciplinary approach, we show that the player is particularly sensitive to the maker's gesture and can discriminate several plectrum shapes. Further he/she can adapt his/her playing or even has different expressive possibilities at his/her disposal. For some plectrum shapes, the harpsichordist even proves to have more expressive possibilities and musical interpretation. This study shows that shaping plectrums affects the player's perception. Thus, a historical approach of this widely discussed issue is relevant. Whereas this study involves a unique material of plectra, it highlights that geometrical parameters alone—that is, the maker's gesture responsible for the “voicing process”—are significant. Consequently, the voicing process fully impacts the musical discourse. Consequently, our results confirm that the lack of precise knowledge of methods, materials and forms of harpsichord plectra makes it impossible to guarantee historical relevance during concerts on old instruments.

Similarly, in acoustical models of wind instruments, the surface specificities of the material (porosity and roughness) in the resonator are usually not taken into account. However, the estimation of acoustic dissipation in various wooden pipes shows how selecting different wood species and polishing the inner wall of the resonator affect the air column resonances. These experimental results point out some gesture in the maker's practice with considerable impact on the sound produced and the instrument playability. Further studies will aim to investigate the influence of oiling the bore, another essential step in the manufacture and the maintenance of wooden wind instruments. Among various spin-off benefits, next steps will aim at simulating wind instrument responses in playing conditions (i.e., with polished and oiled bore), from “dry” non-played historical instruments from museum collections, simply using non-invasive impedance measurements. So, just like the harpsichord study, pointing the musical and historical importance of plectrum, our work on the role of wood in the production of wind instruments addresses instrument-making issues and enhances contemporary know-how.

During the COST action WoodMusICK, the results of the FA-REMI project have met direct applications in finding information about historical instruments. Indeed, two facsimiles of oboes from Christophe Delusse—in the collection of the Museum of Music, Paris (inv. nos. E.2180 and E.2182)—known for their exceptional original condition

[22] have been made and are henceforth frequently played. Also, in 2018, all feathers plectrums of an emblematic harpsichord made by Jean-Henri Hemsch in 1761 in Paris, and nowadays part of the collection of the Museum of Music in Paris (inv. no. E.974.3.1), have been changed and their musical influence perception have been explored during and after the restoration. These interventions address the issue of timbre and musical practices in France at the beginning of the nineteenth century and will engage new research over this period involving musicians and musicologists.

Museum collections have many harpsichords which today cannot be played, since their state of conservation does not allow it, from a deontological conservation and restoration point of view. Likewise, almost all wooden wind instruments are not played because of damage that would certainly be incurred during the playing. However, the results obtained by the FA-RE-MI project make it possible to approach some of the intangible cultural values they contain, without having to play them. As we have seen, a set of non-invasive physical and mechanical measures make it possible to describe and document the functionality of these corpora. The musical instruments in museums can thus still talk about music, be witnesses of the musical taste and know-how of their time!

Beyond musical, stylistic or historical questions, the results obtained highlight the role of raw material in the sound wave creation. They allow, by comparison between old and current objects, to evaluate the development of the mechanical properties of the materials, the feather, the oils, the woods used in the manufacturing process. The acquired detailed knowledge of these phenomena acquired opens the way to finding conservation techniques that could, for example, better stabilize, for a longer time, the mechanical properties of ancient feathers which currently receive no conservation treatment. There is every reason to believe that knowledge of the influence of deposited oils within wind instruments is the required starting point for the design of temporary protection products. These coating materials should have the required acoustic quality to let the instruments express their musicality, and at the same time should provide a reversible and effective layer of protection, thus allowing music playing on historically documented instruments, in conformity with ICOM recommendations, and within appropriate acoustic performances.

As a result, bringing makers, musicians, historians, curators, restorers and acousticians together around the musical instrument allowed us to enhance our knowledge, but also and specially, to bridge the gap between the practices of the past time and of the present day.

ACKNOWLEDGEMENTS: The authors warmly thank musicians Benjamin Alard, Maria Lúcia Barros, Olivier Beaumont and his students, Florian Carré, Michèle Castellengo, Mathieu Dupouy, Jean-Luc Ho, Annie Kalifa, Françoise Lengellé, Arnaud Pumir, Lola Soulier and colleagues Brigitte Cruz-Barney, Jean-Claude Battault, as well as the instrument-makers Philippe Bolton, Gilles Thomé, Pierre Ribo, Marc Ecochard, Bruno Reinhard, Emile Jobin and Maurice Rousteau for their support, help and generosity. A special thought goes to our colleague and friend, Bruno Salenson, a wind instrument maker who recently left us.

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