Wooden music instrument vibro-acoustic fingerprint: the case of a contemporary violin

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Wooden music instrument vibro-acoustic fingerprint: the case of a contemporary violin

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***Abstract* – Violins are complex wooden musical instruments, whose quality is mainly evaluated on the basis of their aesthetics, as well as depending on the historical relevance of their makers. However their acoustic quality remains a key evaluation parameter for performers and listeners. The instrument perceived quality, in turn, depends, on one side, on the player, the environmental conditions and on the listeners' psychoacoustic factors. On the other side, the quality of a violin depends on its materials, constructive and set-up parameters, that impact on the vibro-acoustical characteristics of the instrument. This work investigates a procedure for the vibro-acoustic characterization of a violin, here called vibro-acoustic fingerprint, as an example of vibro-acoustical characterization of a wooden music instrument. The procedure was applied, as a case study, to an Italian contemporary violin, built in the year 2011 by the violin-maker Enzo Cena on a Guarneri del Gesù model.**

I. INTRODUCTION

Violins are complex wooden musical instruments, being relevant art-works for several reasons. Besides the complexity of the violin-making procedure and required skills, being recognized, in the case of the Cremonese school, as an immaterial heritage by UNESCO, they are also cultural heritage oeuvres, whose structure can be adapted due to the changes in the features of some of their replaceable components (e.g., strings materials and their tensions), depending on restoration needs (e.g., damage repair) and, in the case of ancient instruments, to the adaptation of original structure to modified performance needs (e.g., change of inclination of fingerboard in contemporary violins with respect to baroque age).

In the case of violin-making competitions, the evaluation of violins quality is mainly based on their aesthetics and features. However their acoustic quality remains a key evaluation parameter for performers and listeners, depending on the instrument specific vibro-acoustic properties, the environmental conditions of performing context, the performer actions and the perceptual reactions of listeners [1]. With this respect, it is known that the vibro-acoustic properties change over time, due to wood aging [2–4] that induces different mass and dimensional changes, being also subjected to thermo-hygrometric variations [5]. The variable characteristics of the materials used to build each violin, the violin-making process and the physical changes, depending on ageing and restoration actions, make them unique artifacts [6].

As a specific type of wooden cultural heritage, violins require to be characterized both for preserving their structure and their functionality. For such a purpose, different experimental approaches were used. In particular, a great attention is given to the structure and materials, which can change over time, determining potential variations in the acoustic performance of the instrument. For example, different tomographic techniques, ranging from conventional clinic computed tomography (CT) to micro-CT, micro-CT synchrotron beamline and optical coherence tomography were applied to detect the morphological characteristics of violins, including cracks, damages and woodworm attacks, as well as to capture details on complex coating systems [7,8]. The morphology of violins can be determined also with the aid of innovative 3D measurement and modelling techniques [9]. The use of synchrotron radiation micro-computed tomography enabled also to investigate finishing treatments in historical bowed instruments [10]. Other researchers applied Synchrotron Radiation (SR) reflection Fourier transform infrared spectroscopy, X-ray fluorescence, optical microscopy under UV light and SEM-EDX to obtain a compositional and morphological comparison, especially regarding varnishes, to increase the knowledge on violin varnish characteristics and its stratigraphic distribution [11,12]. A similar investigation was conducted, with a combined use of Optical Coherence Tomography (OCT), reflection FT-IR spectroscopy, X-Ray Fluorescence (XRF) and Nuclear Magnetic Resonance (NMR-MOUSE), along the European project IPERION CH, to characterize the stratigraphy from the innermost wood treatments to the outermost varnish layers [13].Vibratory characteristics of violins can be investigated through different data acquisition techniques, with the purpose of analysing their characteristic frequency response [14]. Acoustic characterization of strings instruments include the application of innovative approaches, such as internal cavity measurements, near-field acoustic holography, digital stroboscopic holographic interferometry and laser doppler vibrometry [15–18]. Finally, different studies in the field of psychoacoustics tried to investigate the perceptual judgement given by listeners and to relate them with the constructive characteristics of ancient and modern violins [19,20].

It is important, from one side, to remark the relevance of morphological characteristics and their variations over time [9], as well the influence of specific materials, such as varnishes [21,22], on the vibro-acoustic properties of each instrument. On the other side, structural and set-up changes, even if apparently small, can produce significant audible changes during performances. This evidence implies the need of implementing specific vibro-acoustic assessment procedures for the characterization and functional rehabilitation of wooden musical instruments, as in the case of violins. However, such an assessment procedure should not be limited to the final acoustic performance, as in the current state-of-the-art [23], but should include an assessment of the vibro-mechanical performance of the instrument.

This work investigates a procedure for the vibro-acoustic characterization of a violin, here called vibro-acoustic fingerprint, as an example of vibro-acoustical characterization of a wooden music instrument. The procedure was applied to an Italian contemporary violin, built in the year 2011 by the violinmaker Enzo Cena on a Guarneri del Gesù model. The work will give the basic details about the procedure, the obtained results, finally highlighting its potential applications in violin making and on the assessment of functional restoration outcome.

II. MATERIALS AND METHODS

The vibro-acoustic fingerprint procedure was performed through the characterization of: (1) violin vibrational behaviour; (2) violin acoustic response in relation to its vibrational behaviour. Thus, the vibro-acoustic fingerprint is focused on the source of sound production, i.e. the violin, excluding the impact of environmental, performance and listeners variables.

A. Experimental Modal Analysis

The Experimental Modal Analysis for the violin under study was performed, collecting the data under free-free conditions, suspending the violin with an elastic band (Fig. 1). The roving hammer test was performed, exciting the violin with a soft plastic tip. The mechanical response was measured using mono-axial accelerometers, being positioned above the plates lungs. Finally, a tri-axial accelerometer was placed in the neck of the violin. The violin was excited in 49 points, chosen to obtain a good compromise between geometry representation and expected violin modal behaviour. The reference geometry is represented in Fig. 2.

The identification of modes was performed on the frequency range between 0 and 1024 Hz using the PolyMAX algorithm [24]. Then, the attention was concentrated only on the "Signature" mode shapes. Further details on the experimental set-up, calculation procedures and results are available in the literature [25].

B. Acoustic characterization

Since the sound emission is related to the global motion of the violin, the localization of sound emissions and their relation with experimental mode shapes was studied through nearfield acoustic holography. The experimental acquisition are performed in the Anechoic Chamber of the Department of Energy "Galileo Ferraris" of Politecnico di Torino. The anechoic chamber has a volume of 8.0×6.4×5.2 m. The A-weighted equivalent background noise level is about 24.5 dB and the mid-frequency reverberation time (from 0.5 kHz to 2 kHz) is 0.11 s. The violin behaviour was acquired using the Simcenter Sound Camera, constituted by 81 digital microphones being distributed over nine arms, with a global diameter of measure of 60 cm. This configuration is optimal for all-around, near and far field application, with a distance between the instrument and the measured object being less than 1 m. The acquisitions were performed playing the violin in front of the Simcenter Sound Camera. A single note was excited with the bow in a manner as stationary as possible. Four different notes are played: G, D, A, E, having their fundamental frequencies at 196 Hz, 298 Hz, 440 Hz and 660 Hz. The frequencies are related to the vibration frequency of the strings that excite the violin structure. The acquisitions were performed twice, showing both the front and the back table of the violin to the Simcenter Sound Camera. The acquisitions were processed with the Simcenter Sound Camera software, which automatically uses the best sound localization methodology based on the distance measured in real time by its IR sensors. Fig. 3 reports the experimental set-up for the acoustic characterization of the violin.

III. RESULTS

The optimal configuration results as the one in which the natural frequencies of the "Signature" modes are the closest to the standard music notes frequencies; their correlation is shown in Table 1. The most interesting fact is that the frequencies related to E and F notes are the most recurring. These frequencies are close, as lower octave harmonics, to the one known as “bridge hill” (being a broad peak response of good violins in the vicinity of 2.5 kHz) [26].

Fig. 1. EMA experimental set-up.

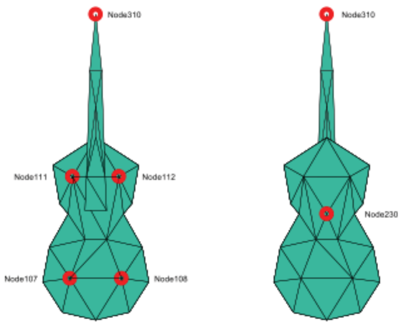

Fig. 2. Reference geometry for experimental tests: front view (left) and bottom view (right).

The previously identified global modes were well detected experimentally above ~600 Hz. Unfortunately, the sound source localization is not good at lower frequencies due to the presence of non-linear effects. However, those mode shapes can be qualitatively identified at frequencies multiple of their natural frequencies. An example of good correlation between numeric mode shape and sound source localization is related to the mode, whose vibration is concentrated on the right f-hole top part (Fig. 4), that has a frequency multiple to the corresponding E note at 660 Hz. This proved that the acoustic response at that frequency was mostly related to the f-holes vibration. Further details on the experimental results related to the acoustic characterization applied to the selected violin are reported in the literature [15].

Fig. 3. Acoustic characterization experimental set-up.

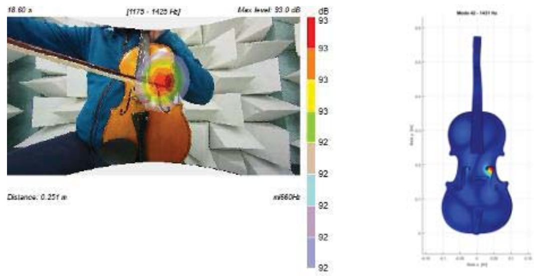

Fig. 4. Second harmonic of f-holes mode-shape sound source detection with Simcenter Sound Camera (left) and corresponding FEA mode shape at 1431 Hz (right).

Table 1. “Signature” mode shapes, measured frequency, reference music note and its related standard frequency (using A4: 400 Hz) as reference frequency.

Mode	Frequency [Hz]	Note	Standard Frequency [Hz]
17	187.03	F#3	185
27	339.55	E4 – F4	330 – 349
30	374.74	F#4	370
33	427.00	A4	440
52	690.78	F5	698
55	738.08	F#5	740

IV. DISCUSSION

Results summarized the joint application of Experimental Modal Analysis (EMA) and near-field acoustic holography to obtain the vibro-acoustic fingerprint of a wooden music instrument. The procedure was applied to a contemporary violin. The procedure summarized in this work, integrating a vibration and sound sources localization, can be applied in different contexts. First, it can support violin-makers and the craftwork of wooden musical instruments, starting from the design phase, where an ideal vibrational model based on a selected instrument design can be performed through a Finite Element Model (FEM) analysis [27]. It is known, in fact, that perceptual evaluation of violins is related to the enhancement of certain vibration frequencies emitted by the violin [28]. Then, the vibro-acoustic performance of the instrument can be assessed, constituting also the basis for future diagnostic operations on the same instrument. In particular, as proved in different industrial engineering contexts, vibration analysis can support the early detection of damages (such as micro-fractures), that could alter the vibrational properties of the instrument.

Second, the vibro-acoustic fingerprint can support the optimal set-up of new and old violins for performance purposes. In particular, a work proved that, changing the position of the sound-post, being a mobile component of a violin, variations in the modal behaviour of the instrument can be detected [25]. Moreover, the same work proved that the theoretical position for the sound-post does not correspond necessarily to the best vibrational performance of a violin.

Finally, the evaluation of the vibro-acoustic fingerprint can be useful in the case of functional restoration or set-up of historic violins. Such an experimental assessment can be integrated with a FEM analysis based on collected computed tomography scans [29]. However, the same procedure could be applied over time in order to obtain an evolutive fingerprint of the chosen musical instrument.

V. CONCLUSIONS

This work described a procedure aimed at characterizing the vibro-acoustical fingerprint of a violin, as an example of wooden music instrument. The procedure was tested in the case of a contemporary Italian violin.

The vibro-acoustic fingerprint, characterizing the performance of the instrument in a given time, can be useful for detecting the influence of instrument ageing on its vibro-acoustic properties, for diagnostic purposes, such as the early detection of potential mechanical damages, for improving the quality of set-up procedures before a performance, as well as a support to restoration of historical instrument.

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