ACTA IMEKO
ISSN: 2221-870X
September 2023, Volume 12, Number 3, 1 - 6

A procedure for the characterization of a music instrument vibro-acoustic fingerprint: the case of a contemporary violin

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ABSTRACT
Violins are 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 on the basis of a Guarneri del Gesù model in the year 2011.

Section: RESEARCH PAPER

Keywords: vibro-acoustics; violin; Experimental Modal Analysis; near-field holography; characterization procedure; applied physics

Citation: Marco Casazza, Fabrizio Barone, Elvio Bonisoli, Luca Dimauro, Simone Venturini, Marco Carlo Masoero, Louena Shtrepi, A procedure for the characterization of a music instrument vibro-acoustic fingerprint: the case of a contemporary violin, Acta IMEKO, vol. 12, no. 3, article 26, September 2023, identifier: IMEKO-ACTA-12 (2023)-03-26

Section Editor: Michela Ricca, University of Calabria, Italy

Received January 9, 2023; **In final form** August 30, 2023; **Published** September 2023

Funding: Marco Casazza position was financed through the Italian Ministry of University PON fund, Azione IV.4 Asse IV "Istruzione e ricerca per il recupero – REACT-EU"

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1. INTRODUCTION

Violins are wooden musical instruments, being relevant artworks 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 the original structure to modified performance needs (e.g., change of inclination of fingerboard in contemporary violins) [1].

The evaluation of violins quality in international competitions is mainly based on their aesthetics 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 [2]. With this respect, it is known that the vibro-acoustic properties change over time, due to wood aging [3]-[5] that induces different mass and dimensional changes, being also subjected to thermal and humidity variations [6]. The materials used to build each violin, having variable characteristics, together with the violin-making process and the physical changes, depending on ageing and restoration actions, make them unique artifacts [7].

As a specific type of wooden cultural heritage, violins require to be characterized both for preserving their structure and their functionality. However, researchers prevalently concentrate on the first aspect, implementing and applying different experimental approaches for the identification and characterization of materials and shapes, that are related to specific violin-making styles. 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 [8], [9]. The morphology of violins can be determined also with the aid of innovative 3D measurement and modelling techniques [10]. The use of synchrotron radiation micro-computed tomography enabled also to analyse their finishing treatments [11]. Other researchers applied EM-based measuring techniques, to obtain a compositional and morphological comparison, especially regarding varnishes, to increase the knowledge on violin varnish characteristics and its stratigraphic distribution [12], [13]. Different techniques where, then, combined to characterize the different material outer layers, from those used for coating to those related to varnishing [14]. Vibratory characteristics of violins can be investigated through different data acquisition techniques, with the purpose of analysing their characteristic frequency response [15]. Acoustic characterization of strings instruments includes the application of innovative approaches, such as internal cavity measurements, near-field acoustic holography, digital stroboscopic holographic interferometry and laser doppler vibrometry [16]-[19]. 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 [20], [21].

It is important, from one side, to remark the relevance of morphological characteristics and their variations over time, as well the influence of specific materials, such as varnishes [22], [23] 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 is why it is necessary to implement specific vibro-acoustic characterization procedures. However, such a procedure should not be limited to the final acoustic performance, as in the current state-of-the-art [24], but should include an assessment of the vibro-mechanical performance of the instrument.

This work investigates a procedure for the vibro-acoustic characterization, here called vibro-acoustic fingerprint, of a violin, considered as a type of wooden music instrument. The procedure was applied to an Italian contemporary violin, built in the year 2011 by the violin-maker Enzo Cena and based on the design of a Guarneri del Gesù violin. The purpose of such a procedure is to define the expected and observed vibratory and acoustic emission responses, which basically depend on the violin structure, the applied input (e.g., either through the use of a bow or plucking a string or through an input vibration source) and the instrument set-up. 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.

The proposed procedure consists in the integration of different non-invasive structural vibro-acoustic characterization techniques already known in the literature. The advantage of their integration into a metrological procedure, which was neither discussed in the literature nor is systematically applied, aims at supporting violin-makers in the characterization of expected vibratory response, based on the instrument design, the evaluation of expected variability depending on the set-up configuration (in particular, with respect to the soundpost position and, eventually, with respect to the choice of string set), its comparison with the observed vibro-acoustic response, which can be experimentally determined. Besides violin-makers, the procedure can support the identification of the best soundpost position, which can be used as reference to maximize the instrument vibratory response. Such a reference set-up, depending on the instrument structure, can be used to support periodic checks and prior to performances.

In Section 2 we will introduce the method used for the characterization procedure in each of its main steps, consisting in the vibrational properties and in the sonic sources identification. The following section will outline the results of the procedure, applied to the selected case study. The fourth section will discuss the implications related to the application of the described procedure. Then, the main conclusions will be drawn based on the previous sections.

2. MATERIALS AND METHODS

2.1. Introduction

The determination of the vibro-acoustic fingerprint consists in a multi-step procedure, exemplified in Table 1.

The key procedural steps include: a morphological assessment of the music instrument, either based on the acquisition of 3D CAD files, in the case of an instrument drawing prior to its construction or based on the conversion of a CT scan or similar acquisition into a dense points cloud, later transformed in a 3D representation of the instrument; the assessment, in the form of

Table 1. Procedural steps for the metrological determination of the vibroacoustic fingerprint, their purpose and examples of applicable techniques, being already validated by the literature.

Procedural step	Purpose	Examples of applicable techniques
Morphological assessment	Design or assess the music instrument morphology	3D CAD files, in the case of an instrument planned design; 3D measurements, CT scans, tomographic measures and similar techniques, in the case of an existing instruments
Expected structural vibratory assessment	Based on the design of the instrument, define a model of expected structural vibratory behaviour (predictive simulation)	FEM model based on 3D CAD files or derived from a dense points cloud model obtained from CT scans or similar measures
Observed structural vibratory assessment	Experimental evaluation of violin body structural vibration behaviour, eventually compared with the expected structural vibratory assessment	Experimental Modal Analysis (EMA) derived from experimental measures with roving hammer and vibration sensors (either as displacement sensors, in open-loop configuration, or as accelerometers, in closed-loop configuration) or using laser vibrometry/similar optical-based measure
Sonic sources identification	Assessment of violin body acoustic emission	Near-field holography

a predictive simulation [25], of the expected violin vibratory behaviour; the experimental analysis of violin vibratory behaviour, eventually compared to the previous predictive simulation; the assessment of violin body acoustic emission, expressed in the form of sound pressure level (time history) or (selective) frequency spectra.

In particular, in this work further details are provided with respect to the structural vibration characterization and the sonic sources identification, depending, in turn, on the violin structural features. The applied characterization steps constitute the core for defining the vibro-acoustic fingerprint, which integrate different aspects of the sound production source characterization, while excluding the impact of environmental, performance and listeners variables.

2.2. Vibration characterization

The purpose of the experimental vibratory characterization, performed through an Experimental Modal Analysis (EMA), was to define the violin modal behaviour, i.e. the identification of natural frequencies and mode shapes, using experimental data, collected under free-free conditions, suspending the violin through an elastic band (Figure 1). The chinrest was kept mounted on the violin, since its use is rarely excluded from the basic instrument set-up.

A vibration test was performed, exciting the violin in 49 different points, being used as reference. We used a roving hammer test with a soft plastic tip to excite the violin structure. A set of mono-axial accelerometers, positioned along the upper and lower plates lungs, together with a tri-axial accelerometer, placed in the neck of the violin, were used for the modal identification. The accelerometer responses $\ddot{x}$ were recorded and compared with the roving hammer force signals F, through frequency response functions (FRFs).

The modal identification was performed in the 0÷1024 Hz range using the PolyMAX algorithm [26], which is an evolution of the least squares complex frequency-domain (LSCF) estimation method, embedded in Simcenter TestLab software. All the inertance FRFs $A_{j,k}(\omega) = \frac{\ddot{x}_j(\omega)}{F_k(\omega)}$, computed for each hammered point k and for all the measured point j, are used for the evaluation of the stabilisation diagram, in which the system poles are identified by the user. After that, mode shapes are found using least squares method, and also damping coefficient are estimated. Then, only "signature" mode shapes, as defined in the literature [27], were considered. Further details on the experimental set-up, calculation procedures and results are available in the literature [28].

2.3. Sonic sources identification

The sonic emission of a violin depends on its structural motion, which is modified by the surrounding environmental conditions, that influence the sound propagation. Thus, the localization of sound emissions and their relationship with experimental mode shapes was studied through near-field acoustic holography [29], [30].

Experimental data were acquired performing a set of measures in an anechoic chamber, having a volume of 8.0 × 6.4 × 5.2 m³. The chamber is located within the buildings of the Department of Energy "Galileo Ferraris" of Politecnico di Torino.

Sonic data were measured using a Simcenter Sound Camera, being configured to perform both near and far-field acoustic holography measures. The instrument, being constituted by 81 digital microphones distributed over nine arms, has a global measure diameter of 60 cm. The distance between the camera and the violin was chosen to be less than 1 m. The acquisition data were processed with the Simcenter Sound Camera software, which automatically identifies the sound source localization using an IR sensor. Measures were performed playing the violin in front of the Simcenter Sound Camera. We performed two acquisitions for each measure to record the top and bottom plate behaviour. Figure 2 shows the experimental set-up for the violin sonic sources identification.

First, the background noise level, measured as A-weighted equivalent sound pressure level, was measured. The instrument recorded a mean value of 24.5 dB(A). In parallel, the mid-frequency reverberation time, defined in the range 0.5-2 kHz, was 0.11 s.

The violin structure was excited playing a single note using the violin bow, producing a sound of perceived constant intensity, produced minimizing the differences of pressure on the

Figure 1. Set-up for the Modal Experimental Analysis.

Figure 2. Experimental set-up for the identification of sonic sources.

excited violin string. Four different notes were played, being the four open strings on which the violin tuning is based: G (fundamental frequency: 196 Hz); D (fundamental frequency: 298 Hz); A (fundamental frequency: 440 Hz); E (fundamental frequency: 660 Hz).

3. RESULTS

As known from the literature, the "signature" modes in the 196-660 Hz range are highly relevant descriptors of good- or bad-quality violins. Those modes correspond to the vibration of the violin cavity, acting a Helmholtz-type resonator, and the violin body [31].

The EMA applied to the violin made by Enzo Cena revealed the presence of 6 signature modes, corresponding to the following frequencies: 187.03 Hz; 339.55 Hz; 374.74 Hz; 427.00 Hz; 690.78 Hz; 738.08 Hz. Most measured frequencies were close to those of E and F notes, being lower-octave harmonics of "bridge hill" frequency (i.e., a broad peak response of good violins, depending on the bridge vibration, in the vicinity of 2.5 kHz) [32].

The study of the connection between global modes, previously identified through the EMA, and the violin sonic emission was performed applying a set of near-field holography measures. Results supported the identification of sonic sources connected with modes previously identified in the literature for the same violin [28]. However, the detected sources were better defined above ~600 Hz, due to the existing non-linear effects at lower frequencies.

An example of good correlation between numeric mode shape and sound source localization is related to the mode, whose sound and vibration source is concentrated on the right f-hole top part, that has a frequency multiple to the E note found at 660 Hz. This preliminary quantification 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 [16].

4. DISCUSSION

4.1. Vibroacoustic fingerprint as a procedure

The integrated vibroacoustic behaviour of a violin was analysed only once in the literature for the 'Titian' Stradivari violin [33]. However, the study consisted on the implementation of a software model, excluding further experimental investigations from the research. Other vibro-acoustic studies focused on specific parts of the violin, such as the bridge [34]. Otherwise, research works concentrated either on software models [35] or on the experimental modal analysis [36], excluding their comparison or integration within a metrological procedure. Instead, this work concentrates on the procedure, as an applied metrological method, which can be standardized.

Currently, despite the experience of instrument makers and the huge body of available works [37]-[39], there is no acoustic standard for defining the quality of tonewood for music-instrument making. Thus, the quality of the final product still depends on the ability of a violin maker to recognize a better-quality tonewood and to adapt the making process to the quality of available wood. On the other side, it is known that the biophysical and structural parameters are the key variables of such a quality determination [40]. This study integrates the know-how of experts in vibration and acoustic sensors, structural mechanical modelling, violin making and violin playing. The know-how integration enabled to define the proposed procedure and to test it in the case of a violin, starting from the design phase until the experimental verification of the expected structural behaviour. Such a procedure, as summarized in this work, can be applied in different contexts.

4.2. Potential procedure applications

First, it can support violinmakers 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 [41]. It is known, in fact, that perceived evaluation of violins is related to the enhancement of certain vibration frequencies emitted by the violin [27]. 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, depending on the soundpost position, variations in the modal behaviour of the instrument can be detected [28]. Moreover, the same work proved that the theoretical position for the soundpost 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 [42]. However, the same procedure could be applied over time in order to obtain an evolutive fingerprint of the chosen musical instrument.

5. CONCLUSIONS

This work described a procedure aimed at characterizing the vibro-acoustical fingerprint of a violin, as an example of wooden music instrument. In particular, the proposed procedural steps include a morphological assessment of the music instrument, a predictive simulation of the expected violin vibratory behaviour, the experimental analysis of violin vibratory behaviour and the assessment of violin body acoustic emission. Part of the procedure was tested in the case of a contemporary Italian violin. In particular, the experimental modal analysis and the sonic sources identification aimed at characterizing its vibro-acoustic behaviour. In the case of the Italian violin made by Enzo Cena, the experimental modal analysis allowed to identify the presence of 6 signature modes, which, according to the literature, are a sign of a good violin quality. Moreover, a good connection between the results given by the modal analysis and the sonic source experimental detection was assessed, especially considering the frequencies above 660 Hz. With this respect, measures allowed to assess the contribution of f-holes vibration in the production of sound.

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.

ACKNOWLEDGEMENT

This work is dedicated to the memory of Prof. Elvio Bonisoli, co-author of this work, who tragically passed away on February 9th, 2023. Elvio, together with Marco Casazza, started this research work in 2015, based on their friendship, first, and to their desire to cooperate in research fields of common interest. All the authors thank Elvio for involving them, with his passion, curiosity and enthusiasm, in this project, where the music and his beloved structural dynamics find their perfect combination. Marco Casazza research is financed through the Italian Ministry of University PON fund, Azione IV.4 Asse IV “Istruzione e ricerca per il recupero – REACT-EU”. The authors wish to acknowledge the support of Dr. Simone Geroso, PFD Simulation & Test Solutions, Siemens PLM Software. The Authors wish to thank also Dr. Marco Brunelli, CEO of BSim Group, for the important technical support. Finally, the Authors wish to thank the Accademia Liuteria Piemontese “S. Filippo” (Torino, Italy) and his president, the violin-maker Enzo Cena, for his suggestions and technical support in relation to violin-making know-how.

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