Violins characterization through vibro-acoustic experiments

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An approach of integrated vibratory and acoustic experiments oriented to identify the specific characteristics and peculiarities of violins is presented in the paper. Today the up-level luthery handicraft needs a scientific and methodical supports specifically oriented to underline the acoustic peculiarities of each musical instrument, able to define the ”signature” of a specific instrument. The proposed approach integrates vibration and acoustic non destructive analyses of the musical instrument considered as only copy extant: the approach has been actually developed with regard to the violins family but can be, more in general, proposed. A three-dimensional parametric model of a violin is integrated with a FE model. The theoretical model is validated through experimental analyses of single parts of the violin during the construction or on the complete instrument. Experimental modal analyses based on the use of micro-hammer and micro-accelerometers are applied not only to the finished violin but also during previous significant construction phases like varnishing. Mechanical and thermo-graphic detections in contact areas of relative motion (e.g. string on the bridge) allow acquiring peculiar information. Finally acoustic experiments finalized to the three-dimensional mapping of the sound produced by the played instrument allow defining the vibro-acoustic signature of the violin.

1 Introduction

Characterization and performances identification are significant goals of the modern high-level art of making stringed instruments. The definition of the “signature” of a violin is interesting both for the construction of new instruments and for true copies of historical violins. In restoration and re-configuration processes these aspects are fundamental to respect the correct philological approach. Music must be proposed as similar as possible to the origins, studying the execution practice, the sound aesthetics, and, of course, using instruments correctly designed and assembled. Often lute makers and, more in general, craftsmen working in the field of musical instruments, base their activity only on own experience: today it should be strongly supported by modern techniques of dynamic and acoustic identification and analysis.

Some preliminary considerations concerning the evolution of the violin construction and of the restoration of value instruments seem to be proper to justify the development of methodological vibro-acoustic approaches applied to the violins family.

In the history of the musical instruments the term “evolution” is not always synonymous of “improvement”. The modern violin is an evolution of the baroque violin but its sound is not necessarily improved. Really each historical period generates its own culture, its fashions, and its artistic tastes, related to the state-of-art of the technical tools available in that period. The instrumental music born at the beginning of 1500, as product of the Renaissance. The violins family born in this tumultuous period and the consequent implemented model will be substantially unaltered for 250 years, showing the validity of its project. Together with the instrumental music the professional features among musicians are more and more raised, distinguishing between musicians for delight and musicians for reward. As known, the instrumental music requires different parts for different voices and the violin family is designed for this requirement: many references [1, 2, and 3] proof the presence of different sizes of instruments, devoted to different tones: bass, bassetto, tenor, contralto, soprano, falsetto. This classification corresponds to the choir of human voices, but it is also a consequence of the difficulties to make string instruments with large amplitude of register, like piano, organ or harpsichord. In return, the elements of this family can be easily moved. I the middle of 16^{th} century the violin shows all the features of a mature model: some structural elements (strings, neck, bridge, tailpiece, sound post and bass bar) are modified during the years, to adequate the sound to the aesthetic taste of the historical period.

In 15^{th} century strings were derived from sheep bowels. Baroque neck was flat, not backwards sloped and usually mounted using one or more nails: its geometrical shape doesn’t allow to reach high notes and its simple but rough mounting influences the vibration modes at different frequencies, with significant fallout on the acoustic performances. Baroque bridge is rather rigid because the strings are thicker: the vibration transmission is increased, but the acoustic quickness is reduced. The dynamic force exchanged at the base of the bridge is a fundamental parameter to evaluate the mechanical excitation on the vibrating plate. Baroque fingerboard is thick, flat and wedge-made: the tilt angle between bridge and strings is consequently reduced, allowing lower bridges but decreasing the duration of the generated sound. Finally, baroque bass bar is shorter and slimmer, producing a lower damping effect but contributing to generate a silvery sound. At the end of 17^{th} century bowels strings are reinforced with metallic ropes. In order to satisfy requirements of more virtuosity and more sound power new technical solutions oriented to easily reach high registers have been implemented. First of all backwards-sloping neck is applied: as consequence the bridge is taller, string angle and actual pressure on the soundboard increase. But increasing the string angle the bow attack position is modified and the violin becomes to be noisy. Attempting to solve these problems many lute makers propose new bridge geometries. The evolution of the violins shows geometrical and mechanical modifications until 19^{th} century: the neck is lengthened and embedded on the violin body and, consequently, the relative position between neck and soundboard is modified. The accession of steel strings allows the reduction of the string diameter, taking advantages on costs, tonality safety and mechanical stability.

Restoration of musical instruments is a very complicated and exciting activity involving a wide spectrum of technical, historical, cultural and philological aspects and problems. Today restoration processes are often considered in order to maintain structural and aesthetical peculiarities and features of musical instruments. The acoustic performances are less considered, also because, of course, an ancient instrument cannot be reported to its original, and unknown, vibratory and acoustical characteristics. In fact, the senescence of the materials is an irreversible process and stiffness and damping properties, fundamental parameters for the dynamic and acoustic response, change in the course of time.

The restoration interventions are characterized by very different levels of complexity and intrusion, depending on the initial status of the instrument and on the finalities of the intervention. They can be essentially classified in two categories: conservative restorations ("light" restorations) finalized to preserve the characteristics of a sound instrument and functional restorations ("strong" restorations) finalized to rebuilding and to structural reconstruction. First case is similar to periodic maintenance while second case occurs in presence of broken or severe failed instruments. In any case the original sound generated by an ancient instrument is unknown: but the possibility of a failed instrument recovery is the mere process able to make to possibility to play the instrument and to formulate hypotheses about its original sound. This is particularly important for instruments build with ancient technique of construction (e.g. baroque instruments) and in the stringed instruments family assumes particular relevance in the violins family. Another significant aspect concerns the exact copies of ancient and famous instruments: a correct restoration is the base for the construction of new instruments able to attempt an emulation of the originals. But a correct process of construction of new instruments can be strongly facilitated if, in addition to dimensional and structural information, dynamic, vibratory and acoustical data concerning the reference instrument are made available.

These preliminary considerations show the opportunity to develop methods and techniques able to collect vibratory and acoustic information, attempting to give a contribution on the identification of specific characteristics and peculiarities of violins. Hereafter an integrated approach of vibration an acoustic theoretical and experimental analyses is proposed and discussed.

2 Acoustical ad vibration setup

Correlation between type of mounting and generated sound is very difficult to be performed [4, 5, and 6]: each instrument has own mechanical, structural and dynamic features and the way to compare the acoustic performance is related to the mounting. Comparison between baroque and modern mounting means to make available a baroque violin, identify its acoustic features, disassembly the instrument, modify the mounting and the geometry of the different component, re-assembly and, finally, detect the acoustic features of the "new" violin. Another possible (but approximated) approach consists on the comparison of two different but very similar instruments, realised by the same violin maker, differently mounted. These procedures require good instruments, time, and synergy with expert violin makers, and oriented experimental acquisition and elaboration units. An original setup conceived and assembled by MUSICOS Research Centre is proposed for the acoustic acquisitions (Figure 1).

Figure 1: Views of the acoustic experimental setup.

An array of ten microphones covers a semicircle of 3m of diameter: an additional microphone, used as environmental reference, allows the compensation of signals acquired in consecutive phases and detects also the ambient noise. This aspect is particular important in order to develop this kind of test not only into anechoic chamber but also in music rooms. The musician is seated in such a way the violin is positioned at the centre of the arc: he can modify him relative position rotating on twelve angular positions. An infrared sensor detects the correct achieving of each angular position. On each position the musician plays the same note or the same sequence of notes: differences related to not exactly repeated sound levels can be automatically compensated by means the reference signal. Ten simultaneous acquisitions detected on twelve angular positions allow the generation of spherical maps, defined by 120 values of acoustic pressure. A portable multi-channel unit acquires all the acoustic signals (Road Runner, by LMS International) and the corresponding files are analysed and elaborated by means signal processing software (Test Lab, by LMS International).

In parallel to acoustic tests violins or parts of violin are dynamically tested following an experimental modal analysis approach: Figure 2 shows a violin and a back under test, with excitation by micro-hammer and acquisition by micro-accelerometers.

Figure 2: Vibratory setup.

3 Examples of acoustical an vibration results

Hereafter results allowing the performance comparison of baroque and modern mounting are discussed [7].

With specific reference to the comparison analysis of different mounted violins the best way is, of course, refers the study to the same instrument. Initially the violin under test, modern mounted, has been characterized. Then it has been disassembled and rebuilt following the baroque geometry. A second vibratory and acoustical investigation has been implemented. A comparison between vibration frequency response functions (FRFs) is shown in Figure 3.

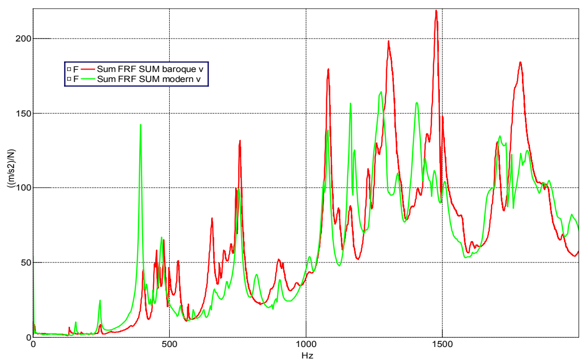
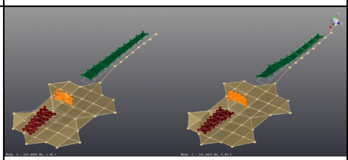
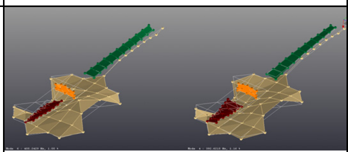
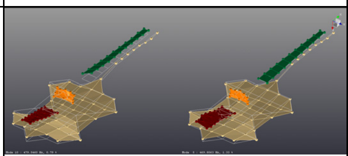
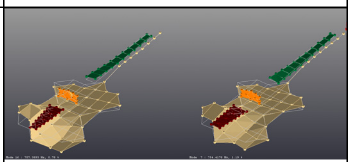
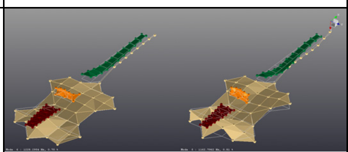


Figure 3: FRFs comparison (red: modern; green: baroque).

0÷2000 Hz frequencies range is explored. Some differences have been detected, both on the characteristic frequencies values and on the energetic contents to the single frequency: particular interesting are 0 ÷ 400 Hz and 1000 ÷ 1500 Hz ranges. The previous result concerns the whole violin, but variations are related to a different behaviour of single components: body, bridge, tailpiece, neck, and fingerboard. A comparison between mode shapes in collected in Table 1.

Table 1: Compared mode shapes.

Frequency [Hz] **B baroque** **M modern**	**Mode shape** **(Left: Baroque ; Right: Modern)**	**Notes**
B 293.4 *M 232.8*		Baroque tailpiece and bridge more excited. Greater mobility of modern fingerboard.
B 405.2 *M 392.6*		Very similar modes: Mobility of fingerboard is grater in modern mounting.
B 479.5 *M 469.8*		Fingerboard displacements are greater in the baroque mounting.
B 757.3 *M 754.4*		Some differences detected on fingerboard and neck motion.
B 1220.2 *M 1162.7*		Frequencies and mode shapes are not exactly coincident.

Acoustic experiments have been implemented using the described setup. In order to show some significant performance differences continuous notes have been played and acoustic spectra and spherical maps are obtained.

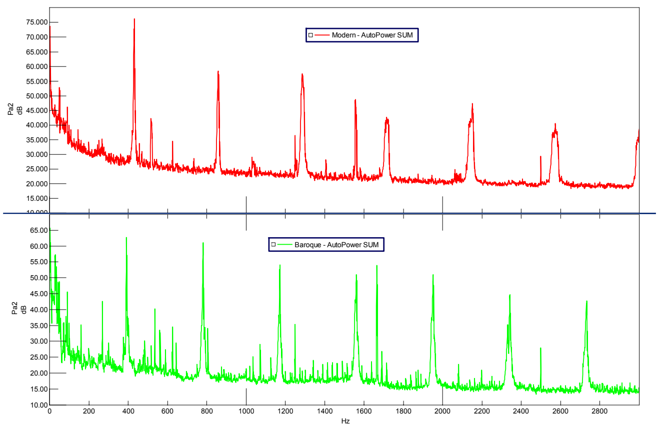


Figure 4: dB Average spectra (red modern; green baroque).

Figure 4 reports the comparison between modern (red) and baroque (green) mounting of the same instrument, playing A4 continuous note: spectra vs. frequency in the range 0÷3000 Hz are shown. Corresponding results in the field 0 ÷ 5000 Hz are respectively reported in Fig. 5.

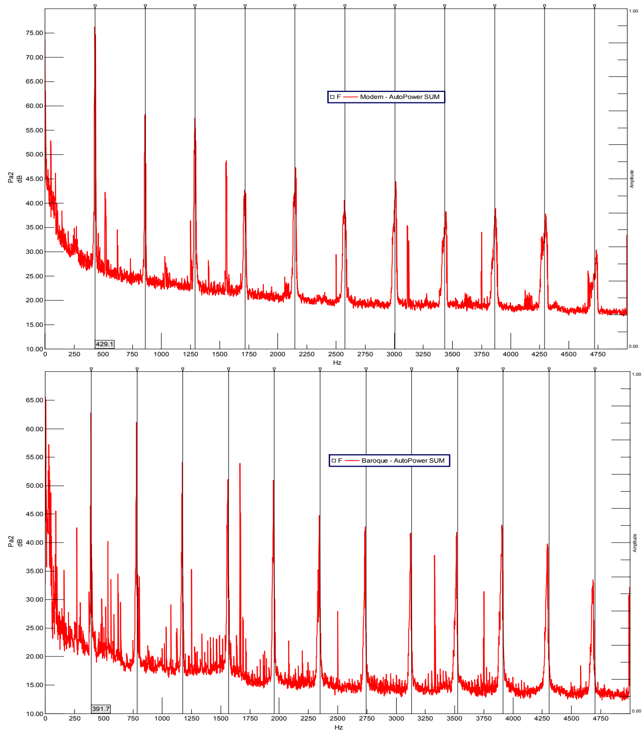


Figure 5: Spectrum vs. frequency (harmonic cursor). Up: modern mounting; down: baroque mounting.

Spherical chromatic maps corresponding to baroque and modern mounting, deduced by means the previously mentioned acquisition and elaboration unit are reported in Figure 6, taking into account all the frequency acoustic contributions. The acoustic performances of the same violin assembled following modern or baroque geometries are significantly different. This result is achieved also changing the played note or playing sequences of notes. Spherical maps can be animated, in order to easily show the local effect of the acoustic pressure variation.

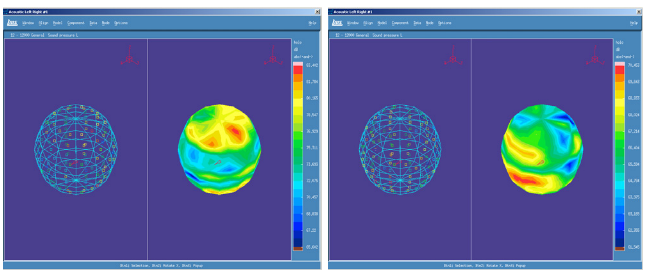


Figure 6: Modern (left) and baroque (right) mounting: overall response.

Differences concerning the sound directivity are particularly evident. The compared evaluation of these results explains the different role played by the violin within musical ensembles and orchestras in different ages and the evolution of this stringed instrument from chamber music to theatre music. In addition, the approximated approach based on comparison of very similar violins differently mounted is investigated. Three very similar violins (baroque, classic and modern mounted) are tested: the same musician, using two different types of bow, with screw-driven frog and clip-in frog, plays each violin. G3, D4, A4, E5 notes are played, without interruption, for 15 s and acquired by means a high-fidelity microphone interfaced to the acquisition unit. The microphone is located to 1 m from the wall and to 1 m from the musician.

Examples of frequency responses are reported in Figure 7. Over 3000 Hz negligible energetic contributions are detected.

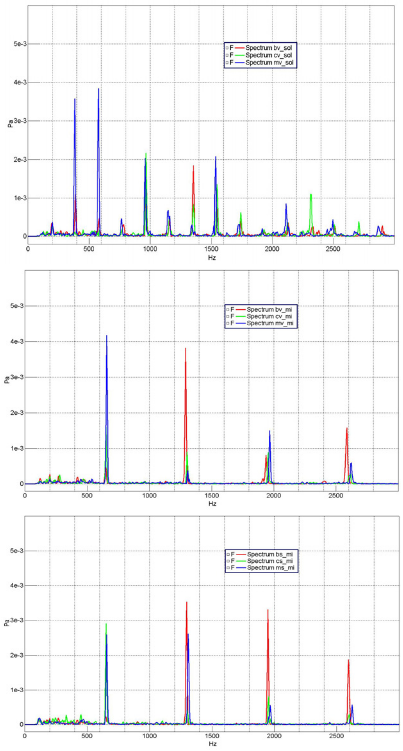


Figure 7: Spectrum excided playing G3 and E5 on baroque (B), classic (C) and modern (M) violins with clip-in frog (S) and screw-driven frog (V).

Theoretical and experimental approaches as support to vibratory and acoustical investigation of parts of instruments or of complete instruments can be proposed: standard procedures can be applied, customizing general techniques taking into account the peculiarities of the component under analysis.

Theoretical approaches are typically based on numerical procedures: FEMs are the main reference [8, 9, 10, and 11]. This approach allows a very detailed three-dimensional mapping of the body under study, meshing the surfaces with a very high numbers of elements. But, like any simulated method, it requires the definition of reliable parameters (Young's modulus, Poisson coefficients…) and must be validated through practical tests.

4 3D dynamic models

The mail goal of the dynamic identification of a harmonic plate concerns the detection of vibration performances and mode shapes. A preliminary analysis allows detecting geometrical data: starting from these information 3D numerical models can be implemented. An original three-dimensional and parametric model for sound board and back is developed: expected natural frequencies and modal shapes of the plates, associated to each vibration mode, can be deduced. Figure 8 collects an example of result.

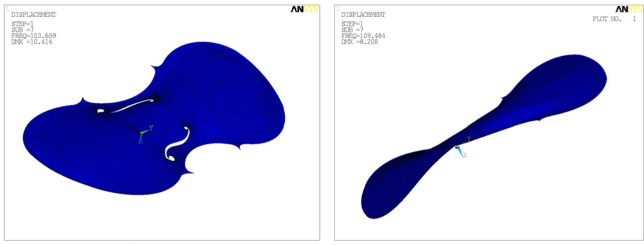


Figure 8: Examples of numerical mode shapes of soundboard and back.

After the selection of mechanical features, numerical modal analyses of the sound board (equipped with bass bar) and of the back, based on Lanczos method, are performed. This eigenvalues and eigenvectors extraction procedure is suggested by the code (ANSYS, by Swanson, Inc.), also in presence of models having a large number of elements, for its accuracy in deflected shapes. At the back a meshing of 1718 elements is applied; on the contrary the sound board requires more detailed schematizations for a better comprehension of its structural behaviour [12, 13, 14, and 15].

A more detailed meshing involves 3941 elements: the increasing of the number of elements is due to the f holes, having a complicated geometry and located in a sound board area characterized by a significant curvature variation.

In order to test the performances of the proposed numerical package a specific test has been implemented: reference is made to a specific sound board built by a violin maker (Montanari, 1999). Material for sound board and for bass bar is spruce: the experiments concern, from one side, the modification of the material used for the bass bar (maple instead spruce) and, from another side, the model geometry without bas bar. Maple is more rigid wood than spruce: consequently frequencies increase. Without bass bar the sound board is, of course, more flexible and the corresponding frequencies decrease. Similar analyses can be implemented with reference to other structural parts of the instrument (ribs, corner blocks and neck).

In order to validate theoretical results the instrument is submitted to non-invasive experimental analysis, using micro-transducers. The excitation is by impact, generated by an instrumented micro-hammer and the dynamic response is deduced by two micro-accelerometers embedded on the harmonic plates by means bee-wax. The corresponding results can be compared to simulated models (Figure 9).

Comparison of frequencies concerning thirteen mode shapes are collected in Figure 10: some modes apparently corresponding show different shapes (flexional or torsional).

Vibratory and acoustic approach is integrated with unconventional tests. Thermo-graphic responses of specific areas of the instrument (e.g. strings) and experimental detections of the forces in the contact between bridge and soundboard define other significant elements of comparison between different instruments.

Some references of these tests are shown in Figure 11: temperature variations occur not only in the bow-string contact but also in string-bridge contacts, modifying the string tuning.

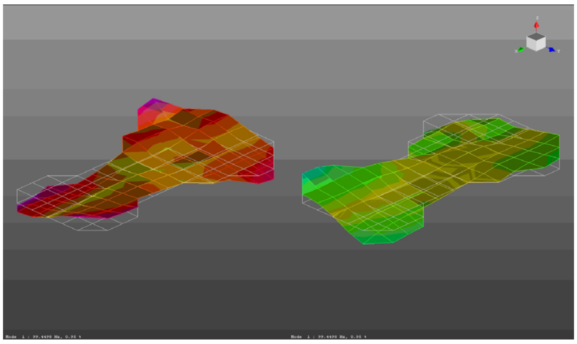


Figure 9: Example of experimental mode shape of soundboard and back.

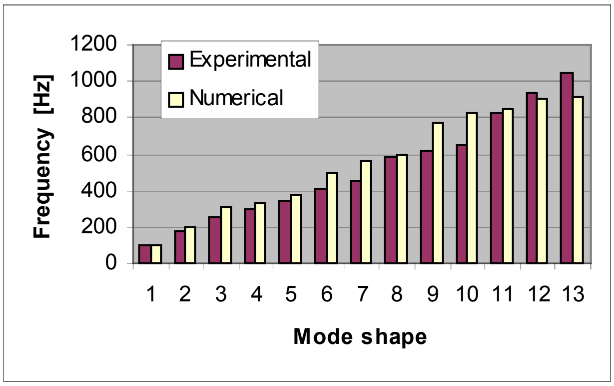


Figure 10: Numerical end experimental selected frequencies: comparison.

Another phenomenon influencing the dynamic and the acoustic performances of the instrument is the force transmission in the bridge-soundboard contact. Experiments oriented to detect force time histories under different bow attacks are still under development. Figure 11 shows an example of result corresponding to plucked notes: force is detected by means of two pressure micro-sensors (0.1 mm of thickness) inserted under the bridge feet.

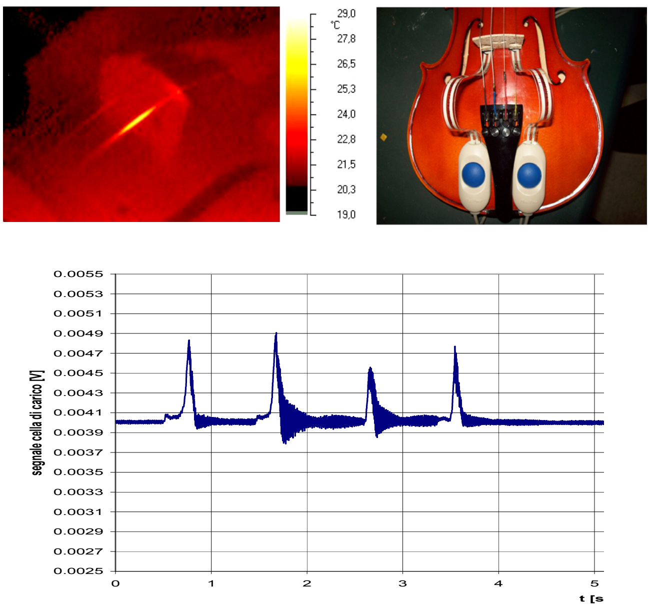


Figure 11: Thermo-graphic and force detection tests.

5 Some concluding remarks

Vibratory and acoustical analyses may strongly support manufacturers, contributing to the development of high quality production of violins. Vibro-acoustic characterization of single specimens of stringed instruments differently mounted is the base of a methodological and scientific approach of performance comparison.

The proposed approach can be applied also both to new products and to ancient instruments, supporting the market of high quality level stringed instruments. In addition, the approach is applicable to other classes of musical instruments (bowed and plucked instruments, woodwind instruments, brasses, percussions…). In restoration processes the modelling interacts with the reconstruction phases typically followed by violin and lute makers: parametric analyses, simulated dynamics and structural modification procedures, validated by experiments, aid the artisan to make correct choices.

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