VIBROACOUSTIC ANALYSIS FOR VIOLIN AND DISCUSSIONS ON SOUND GENERATION MECHANISM

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Sound radiation from violin is a complex mechanism. Violinist plays the bow acting on strings which vibration transmits through the bridge and induces the sound box vibration. The sound box structure vibration with coupling effect on surrounding air radiates sound. This work aims to construct the violin finite element model to perform vibroacoustic analysis and examine sound generation mechanism. A violin is first performed modal testing to obtain structural modal parameters. The finite element model of violin structure is built to perform modal analysis and frequency response analysis for structure-only. This is to verify the numerical model is correct enough for further vibroacoustic analysis. The violin-air coupling model is then constructed and performed both modal and harmonic analysis, so as to examine the violin-air coupling system's modal properties as well as structural vibration and radiated sound frequency response. Results show the dominated sound radiation below 500 Hz is due to sound box cavity acoustic modes, while those above 500 Hz to 1000 Hz are from structural resonant modes, mostly from top and back plates. Different directional forces applying on the bridge simulating the string vibration inputs are also studied to explore the difference of sound response. This work establishes the infrastructure approach for violin structure-only and vibroacoustic coupling analysis and reveals convincing results. Different geometry of violin can then be examined accordingly.

Keywords: violin, vibroacoustic, modal parameters, cavity acoustic modes

1. Introduction

Violinist plays the bow acting on strings which vibration transmits through the bridge and induces the sound box vibration. The sound box structure vibration with coupling effect on surrounding air radiates sound. It is of great interest to examine sound radiation mechanism of violin as well as violin structural vibration. Bretos *et al*. [1] studied vibration characteristics of violin structure and compared to other's experimental data with good agreement. Gough [2] discussed the change of violin geometry, including the plate thickness, f-shape area, sound post and bass bar, for the influence on top plate mode shapes. Hutchins [3] measured the top plate and back plate of violin and consequently tested and recorded the nodal lines of particular modes by the Chladni technique in making process, so as to justify the well-tuned and poorly tuned plates according to the resultant nodal line pattern. Bissinger [4] experimentally examined a complete Hutchins–Schelleng violin octet and showed violin's typical vibration modes and related sound radiated modes. He characterized vibration modes as whole body modes and substructure modes as well as corpus modes. The cavity modes and some of strongest acoustic modes were also classified.

Model verification (MV) is an important process to obtain reliable and feasible numerical model of real structure by performing experimental modal analysis (EMA) and finite element analysis (FEA) on the target structure. Marshall [5] adopted EMA to explore violin's vibration characteristics and featured bending modes and air modes as well as the "plate modes" exhibiting a nearly bewildering variety of vibrational patterns. Gliga *et al*. [6] tested violin plates, both top and back plates, for different types of wood materials. The structural natural frequencies were reported and compared as well as quality factor, but lack of mode shape information. Yu *et al*. [7] proposed the violin top plate design base on prescribed nodal lines for optimization of plate thickness distribution. They constructed finite element model of violin to analyse the target vibration modes for the prescribed nodal line pattern and showed the well match with the target nodal lines.

Violin is made of wood, and different types of wood will effect different vibration characteristics. Stanciu *et al*. [8] applied FEA to examine different material models, such as isotropic, transverse isotropic and orthotropic, to simulate different types of wood materials for their mechanical properties and compare their violin plate vibration modes. Aditanoyo *et al*. [9] compared two violins made of two materials, i.e. bamboo and wooden materials. Violin's sound box vibration spectrum were compared to show the differences in vibration modes. Bamboo made sound box revealed less radiated and more damped resonator. Duerinck *et al*. [10] presented the use of different carbon fibre reinforced polymer (CFRP) composites in making violins with the same geometry and compared their structural frequency response functions between the acceleration and impact force.

Sound generation mechanism is of interest. Wang and Burroughs [11] applied near-field acoustic holography (NAH) to visualize the acoustic radiation of three violin continuously bowed by a bowing machine. They found the clear dominance of top plate in sound energy production makes the tuning of top plate crucial than that of back plate. Bissinger [12] experimentally explored 17 good and bad violins for their structural acoustics. All violins revealed similar modal frequencies and total damping below 600 Hz. The main difference is that Helmholtz-type cavity mode near 280 Hz has significantly higher radiativity. Nia *et al*. [13] theoretically examine the f-hole characteristics and effect on the Helmholtz cavity mode for sound radiation that is more significant than the flexible body modes.

This work will construct the violin finite element model to examine sound generation mechanism and tentatively show the structural acoustic coupling analysis to identify the global and local modes of violin as well as those sound radiated acoustic modes from cavity and exterior sound field acoustic modes. Section 2 shows the process for MV of violin FE model that is sufficient enough for further application to violin vibroacoustic analysis. Section 3 conveys the concept for structure-only and structural acoustic coupling analysis, and Section 4 details the numerical analysis on violin's structural vibration and sound spectrum so as to examine its sound generation mechanism.

2. Violin Structure Model Verification

This section shows model verification (MV) of violin structure in order to get the reliable numerical model to study violin sound generation mechanism. Figure 1 details the process in performing MV for the violin, including two parts, i.e. finite element analysis (FEA) and experimental modal analysis (EMA). First, it is to build up the finite element (FE) model of violin and perform theoretical modal analysis (TMA) to obtain modal parameters, including natural frequency f_r and mode shape ϕ_r. Harmonic response analysis is also carried out to obtain frequency response function (FRF) $H_{ij}(f)$. Second, the violin is performed EMA to measure system FRFs $\widehat{H}_{ij}(f)$and proceed curve-fitting process to obtain experimental modal parameters, including natural frequency $\hat{f}_r$, mode shapes $\hat{\phi}_r$, modal damping ratio $\hat{\xi}_r$. Both modal domain and frequency domain data will be compared to verify the feasibility of violin FE model.

The concept of MV is to verify both modal and frequency data are comparable between FEA and EMA. Figure 2 shows the comparison of FRF $H_{ij}(f)$ for i=56 and j=69 between FEA and EMA with displacement mode shapes and natural frequencies depicted at corresponding peak resonances. The physical meaning of mode shapes agree well, though there is little discrepancy for natural frequencies. Therefore, the numerical violin FE model is sufficient enough and further applied to study structural acoustic coupling analysis.

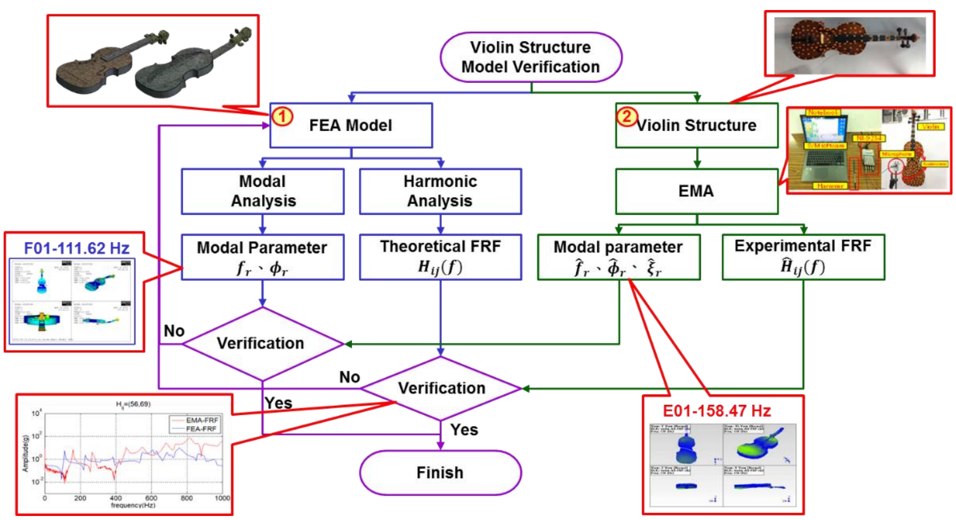


Figure 1: Flow chart for model verification of violin analysis.

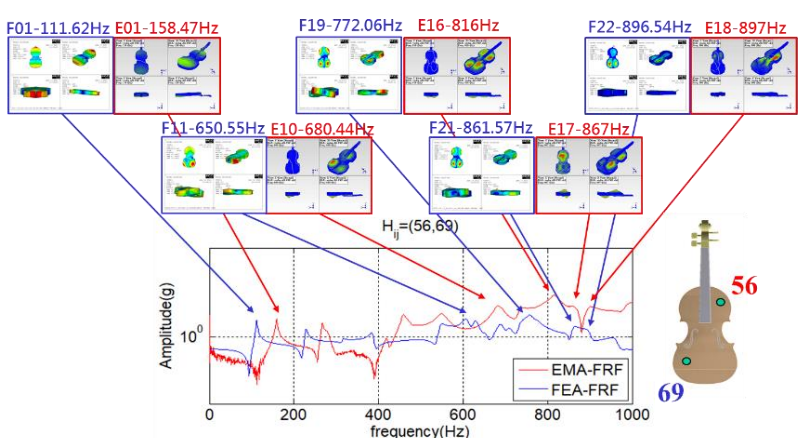


Figure 2: Comparison of frequency response functions between EMA and FEA.

3. Concept for Structure-only and Structural Acoustic Coupling Analysis

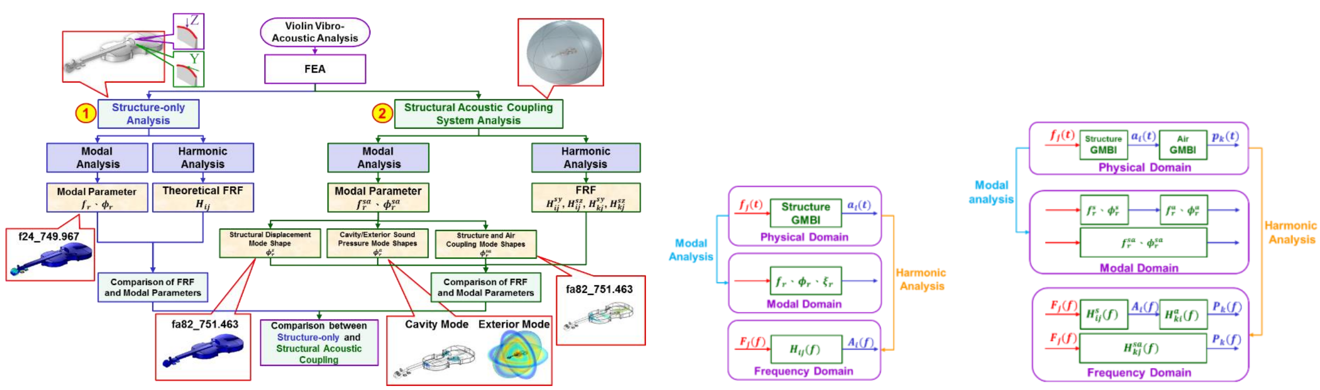
This work adopts FEA to study violin structural acoustic coupling analysis. Figure 3(a) shows the flow chart for violin vibroacoustic analysis. There are two approaches for the study. One is for the structure-only analysis, and the other is the structural acoustic coupling analysis, i.e. examining the structural path and air path coupling effect. Both modal analysis and harmonic response analysis are conducted for both systems, respectively. The structure-only system is just like those introduced in Section 2, and there is no air path involved in numerical model. For structural acoustic coupling analysis, the air elements are included in numerical model for both inside and outside of sound box and coupled with violin structure for fluid interaction effect. The system model is depicted on the top-right of Figure 3(a).

Figures 3(b) and 3(c) show block diagrams of modal analysis and harmonic response analysis for both structure-only and structural acoustic coupling systems, respectively. System model can be examined in three types of domains: (1) Physical domain, (2) Modal domain, and (3) Frequency domain.

In physical domain, system's geometry, material, boundary and interface (GMBI) should be defined accordingly, while structural force $f_j(t)$ is applied and system output such as acceleration on structure $a_i(t)$ or sound pressure $p_k(t)$ can be obtained. Symbols *j*, *i* and *k*, respectively, indicate the location and direction of force, acceleration and sound pressure response.

In Modal domain, system modal parameters can be obtained by modal analysis. For structure-only system, modal parameters as shown in Figure 3(b) are natural frequency f_r, displacement mode shape ϕ_r, and modal damping ratio ξ_r where *r* is the *r*-th natural modes of vibration with infinite number. It is noted that real mode analysis neglects damping effect adopted in this work, and damping ratios are generally determined by EMA. For structural acoustic coupling system as shown in Figure 3(c), modal parameters are natural frequency f_r^{sa} and mode shape ϕ_r^{sa} where *s* and *a* stand for structure and air, respectively. System mode shapes can be categorized as three types: (1) Structural displacement vibration mode shape ϕ_r^s, (2) Cavity or Exterior sound pressure acoustic mode shape ϕ_r^a, and (3) Structural and air coupling mode shape ϕ_r^{sa}. These mode shapes characteristics will be discussed in numerical study.

In Frequency domain, FRF is defined as the output spectrum over the input spectrum and can be determined from harmonic response analysis. For structure-only system as shown in Figure 3(b), $H_{ij}(f)$ is the acceleration spectrum $A_i(f)$ over the applied force spectrum $F_j(f)$. For structural acoustic coupling system as shown in Figure 3(c), the structural path FRF $H_{ij}^s(f)$ and air path FRF $H_{ki}^a(f)$ can be identified as well as structure-air path FRF $H_{kj}^{sa}(f)$.



(a) Analysis flow chart (b) Structure-only (c) Structural acoustic coupling

Figure 3: Flow chart and system block diagram for violin vibroacoustic analysis.

4. Vibroacoustic Analysis of Violin

4.1 Structure-only system

Figure 4 shows the comparison of vibration acceleration spectrum of structure-only system between top-plate and back-plate of violin. The unit force is applied at the bridge in Z-direction. The acceleration response spectrum for top-plate and back-plate are shown, respectively. Those peaks of spectrum are structural modes. A few typical displacement mode shapes are shown with different frame colors and discussed as follows.

- Red-frame modes, such as f07, f09 and f23, reveal the back-plate response is higher than the top-plate. For Modes f07 and f09 in global view, vibration are the neck's local modes which induce higher response in the back-plate, and both modes for sound box only are actually Y-direction rotational rigid body modes. For Mode f23, its vibration is local model of top-plate and back-plate.
- Blue-frame modes, such as modes f12 and f16, reveal the top-plate response is higher than the back-plate. In global view, both modes are flexible body modes of sound box. While Mode f12 is (X,Y)=(1,2), Mode f16 is (X,Y)=(3,1).
- Green-frame mode f26 reveals the top-plate response similar to the back-plate. This mode is also a type of local for top-plate and back-plate, respectively, with different mode shape characteristics.

The idea here is that different response location may result in different level of response either on the top-plate or back-plate. As known, the main difference is that there are two f-holes on the top-plate. More importantly, violin structure displacement mode shapes can be categorized as two types: (1) Global modes and (2) Local modes. Those local modes can be neck, top-plate, back-plate, or sound box.

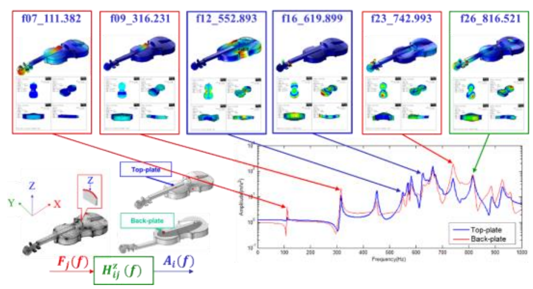


Figure 4: Comparison of vibration response between top-plate and back-plate.

4.2 Structural acoustic coupling system

While Figure 4 revealed top-plate vibration spectrum for structure-only system, it is interested to compare the top-plate response for both structure-only and vibroacoustic coupling systems as shown in Figure 5. The unit force is applied at the bridge in Z-direction. The acceleration response spectrum of top-plate for structure-only and vibroacoustic coupling systems are shown, respectively, and discussed as follows:

- Red-frame modes, such as fa12 and fa23, reveal peaks in FRF for vibroacoustic system but not seen for structure-only system. These types of modes are cavity acoustic modes of sound box that cannot be determined from structure-only system model.
- Green-frame modes, such as f07, f09, f18, are what can be observed in both structure-only and vibroacoustic system. This imply that structural flexible mode and air acoustic modes are coupling together. Results show the three modes are kinds of structural modes but also with cavity acoustic modes.
- Purple-frame mode f11, which is quite special, reveals peak for structure-only but not for vibroacoustic system. By examining the sound radiation plot, it shows the acoustic mode is a kind of exterior air sound pressure mode that may reduce vibration response at the observed location.

Figure 6 shows the comparison of frequency response between top-plate vibration and sound radiation of violin for vibroacoustic system. The force is also applied at the bridge in Z-direction. The outputs are top-plate velocity in Blue and radiated sound in Red and expressed in dB. Discussions are as follows:

- Blue-frame modes, such as f07 and f10, reveal peaks in vibration spectrum but not in sound spectrum. Sound box's structure modes are rigid body modes, while there are cavity acoustic mode effect inside of sound box. However, they don't contribute to the sound radiation. This imply that rigid body modes of sound box has little effect on sound radiation.
- Red-frame mode f12 is the cavity air acoustic modes of sound box that will significantly contribute to exterior sound radiation. This imply that the sound box cavity modes may result in significant sound radiation and be of concern.
- Green-frame modes, such f14 and f18, reveals higher vibration response than sound spectrum, and the sound radiation is also significant. While Mode f14 is the global sound box's flexible body mode, Mode f18 is the top-plate and back-plate's local flexible body mode. This imply that the flexible body modes of sound box, either its global modes or local modes, will contribute to exterior sound radiation. Therefore, the design of top-plate, back-plate and assembly of sound box is known crucial, including their geometric parameters and material properties even their assembly conditions.

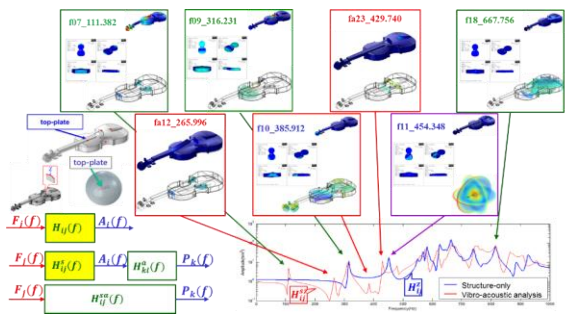


Figure 5: Comparison of top-plate vibration response between structure-only and vibroacoustic analysis.

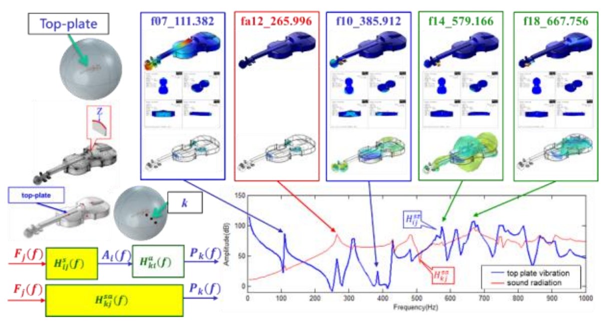


Figure 6: Comparison of frequency response between top-plate vibration and sound radiation of violin.

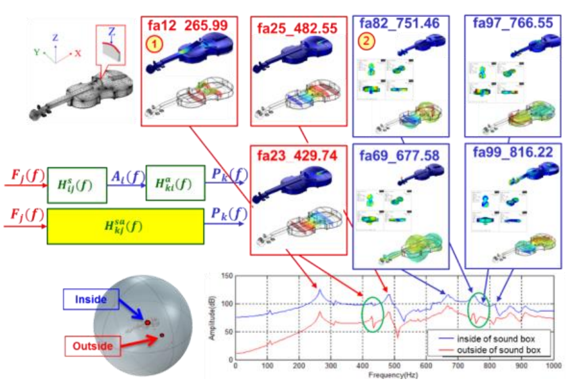


Figure 7: Comparison of sound spectrum between inside and outside of sound box.

For vibroacoustic analysis of violin, the air inside of sound box as well as the exterior air are included in the model. It is interesting to examine the sound spectrum inside and outside of sound box as shown in Figure 7. The unit force is applied at the bridge in Z-direction. The sound response at the depicted location in Figure 7 is blue line for inside and red line for outside. There are two types of effects discussed as follows:

- Sound box's cavity modes: Red-frame modes, such as fa12, fa23 and fa25 which are below 500 Hz, are cavity acoustic modes of sound box. These types of cavity modes can significantly contribute to exterior sound radiation.
- Sound box's flexible body modes: Blue-frame modes, such as fa69, fa82, fa97 and fa99 roughly above 500 Hz, also have quite contribution to exterior sound. In examining these modes, the common effect is they are actually sound box's flexible body modes, although they might reveal some local mode effect in global view. The sound box's flexible body modes may also have coupling with the exterior air acoustic modes and result in high sound radiation.

4.3 Effect of Y- and Z-forces acting on the bridge

In playing violin, the bow induces string vibration transmitted to the bridge then to the sound box. There may have three directional forces applying to the bridge. It is interesting to know what the differences are due to different directional forces on the bridge. Figure 8 shows the differences of sound spectrum due to Y- and Z-direction forces on the bridge. Sound spectrum is red for Z-force and blue for Y-force. There are three main effects discussed as follows:

- Sound box's cavity modes: Red-frame modes, such as fa12, fa23 and fa25 which are below 500 Hz, are cavity acoustic modes of sound box. Both Y- and Z-forces have about the same SPL response, because structural forces have little effect on cavity modes that can be easily resonated and contribute to sound radiation.
- Sound box's exterior acoustic modes: Blue-frame mode fa69 is the sound box's flexible mode that will incur the exterior acoustic modes such that both Y- and Z-force induce about the same SPL response.
- Sound box's flexible body modes: Green-frame modes, such as fa09, fa16, fa82 and fa152, reveal higher SPL for Z-force than that for Y-force, because those modes are basically the Z-directional bending modes. That is why Z-force will result in higher SPL response than Y-force.

From the above discussions, the acting force transmitted from bow, string to bridge can generate three directional forces. This work presents the effect due to Y- and Z-forces on the sound generation mechanism. For either the cavity or exterior acoustic modes, both Y- and Z-forces result in about the same SPL. Z-force may generate much more SPL than Y-force because sound box having the flexible body modes that are mostly Z-directional bending modes.

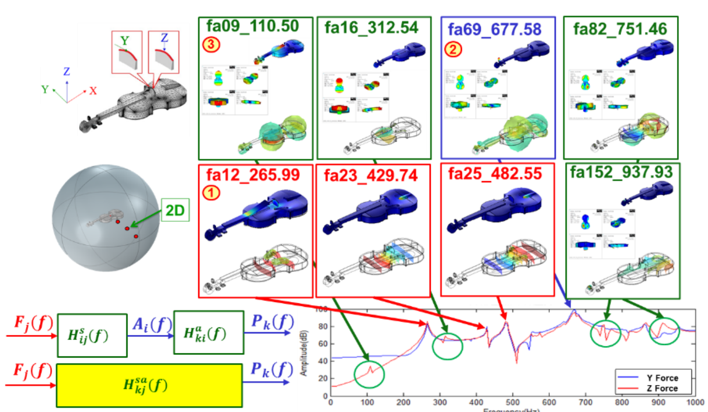


Figure 8: Comparison of sound spectrum between Y- and Z-direction forces.

5. Conclusions

This work carries out EMA on the violin to experimentally validate the FE model of violin, which is equivalent to the real structure and feasible for adoption in structural acoustic coupling analysis. In numerical simulation, both structure-only and vibroacoustic coupling system for the violin are, respectively, presented to perform modal analysis and harmonic response analysis. Violin's structural vibration and sound spectrum are examined to study the sound generation mechanism. Results are summarized as follows:

- Through MV process, FE model of violin is validated. Although there is a slight discrepancy in natural frequencies, structural mode shapes reveal reasonable agreement in physical meanings. The FE model is suitable for violin vibroacoustic analysis.
- For structure-only analysis, one can examine violin structural modal properties and compare vibration response such as top-plate and back-plate as well as for different directional forces acting on the bridge. Violin structural mode shapes can be categorized as global modes and local modes.
- For vibroacoustic analysis of violin, structural velocity or acceleration on violin and sound pressure response inside of sound box or exterior sound radiation can be obtained. Sound generation mechanism of playing violin can be shown as three types of vibration and acoustic coupling modes of sound box, i.e. cavity acoustic modes, exterior acoustic modes and flexible body modes.
- The dominated sound radiation below 500 Hz is due to sound box cavity acoustic modes, while those above 500 Hz to 1000 Hz are from structural resonant modes, mostly from top and back plates.

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