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AIR CAVITY MODES IN THE RESONANCE BOX OF THE GUITAR: THE EFFECT OF THE SOUND HOLE

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1. INTRODUCTION

A complete study of the vibrational behaviour of the resonance box of the guitar must include not only the wood structure of the instrument but also the air cavity inside it. The fluid acts as an additional elastic element of the instrument and thus generates its own vibrational modes. These modes interact with those of the wood structure generating the vibration modes of the instrument. Several musical instruments have an internal cavity connected to the outside by one or several orifices and hence have vibration modes corresponding to the fluid. The lowest of these is the so-called Helmholtz resonance, named as A0. The higher modes of the cavity (named as A1, A2, ...) correspond to the stationary waves inside it and are not harmonically related to A0. These modes, and specially the Helmholtz resonance, have been studied by several authors in the case of the guitar box or the violin box [1–7] and their influence on the instrument has been demonstrated.

In this sense, Jansson [1] experimentally studied the fluid modes and compared them with a theoretical model that adapts the solution for simple cavities with simple geometries to the shape of the guitar by perturbation methods. Rossing *et al.* [3] attempted to assign the different modes to the individual parts of the instrument by imposing different boundary conditions. Recently, Runnemalm and Molin [5] have experimentally determined the cavity modes by means of TV holography.

The finite element method has been previously applied to obtain the cavity modes. Roberts [6] describes the work in which this method is used to calculate the internal air modes of violin and guitar-shaped cavities. The cavities were modelled with zero pressure boundary conditions at the location of the f-holes (violins) or sound hole (guitars), with no mass loading or radiation impedance. This causes loss of accuracy for the Helmholtz resonance and for several of the higher modes. In reference [7], the effect of the radiation

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through the f-holes of a violin-shaped cavity is simulated by incrementing the length of the neck [8], this being calculated following the use of Cremer's approximation [9]. Unfortunately, this kind of approximation is not valid in the case of guitar-shaped cavities as is explained later.

Here, the finite element method was applied to the fluid inside a rigid cavity. This cavity corresponds to the soundboard analyzed in previous works [10, 11]. As the sound hole's role cannot be easily simulated, a preliminary finite element model was used in order to define the boundary conditions. The calculated modes are compared to the aforementioned experimental results.

2. NUMERICAL MODEL

The numerical model and application of the finite element analysis were carried out using ABAQUS software [12] implemented on an Alpha 2100 workstation. The geometric design of the air cavity corresponds to the inner volume of the guitar box whose soundboard was constructed in real wood and was studied by modal analysis [10], and simulated by the finite element method [11]. The fluid was represented by first order cubic elements from the ABAQUS library; the geometry of the mesh is shown in Figure 1. The model consists of 10 788 nodes and 8474 elements and the element size guarantees the validity of the results up to 1 kHz [12].

The material parameters corresponding to the air were defined under standard atmospheric conditions: density $1{\cdot}2\,\mathrm{kg/m^3}$ and bulk modulus 142 kPa. No viscous effects were taken into account. The fluid was considered as being confined in a rigid cavity with an orifice, the sound hole, with additional boundary conditions. These conditions should guarantee the continuity of the fluid and should take into account the radiation of sound through the sound hole. The system resembles the Helmholtz resonator, although some remarks must be made.

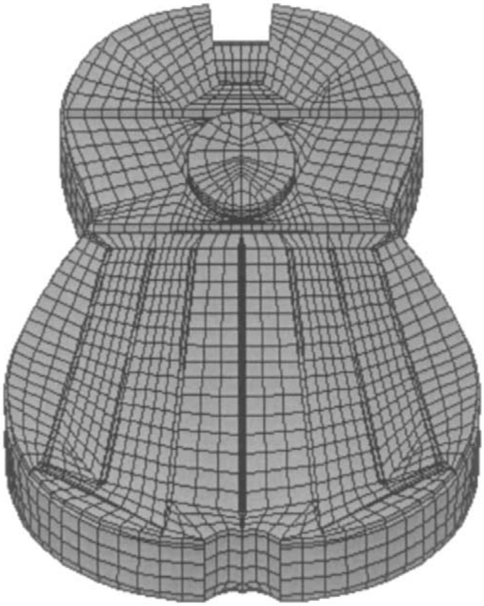

Figure 1. Finite element mesh for the air cavity of the guitar box.

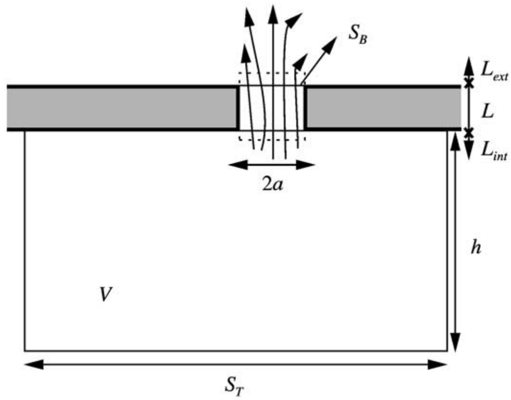

Figure 2. Key geometric parameters of a Helmholtz resonator.

Schematically, the Helmholtz resonator can be represented, as shown in Figure 2, by a rigid cavity of volume V (S_T is the area and h is the height of the cavity). The orifice has a radius a (area S_B) and length L. Detailed analysis [13] affords the resonance frequency, assuming that all the dimensions of the resonator are small in comparison with the acoustical wavelength:

$$f_{A0} = (c_0/2\pi)\sqrt{S_B/V(L + \Delta L)}, \tag{1}$$

where ΔL represents the contribution of the fluid around the sound hole (c_0 is the sound velocity in the fluid). This correction depends on the shape and size of the orifice, and adopts different values depending on these parameters [8]. In this model, the frequency of the resonator does not depend on the shape of the cavity but only on its volume and the dimensions of the orifice. However, the whole analysis implies some approximations, the most important of which is that the dimensions involved should be much smaller than the corresponding wavelength. Moreover, as has been pointed out in reference [14], the proximity of the back and sides to the opening has an additional effect in the case of the guitar. So the analytical calculation of the length correction ΔL may take into account the geometrical details of the cavity.

Even more important is the fact that the preceding analysis is referred to real resonators; that is, open to the air. The numerical model does not simulate the external medium: it is limited to the wood structure and the inner fluid, so the length correction and the pressure value over the sound hole take up the rest of the effects.

In view of the above-mentioned difficulties in calculating the length correction and the boundary conditions, the problem was focused in another sense, the finite element model developed without any additional considerations or analysis of the origin of the increasing mass–stiffness on the hole. The concept of length correction was used, although its value had been determined as follows.

A simple model of a resonance box was placed inside an enclosure filled with a fluid medium. Although the internal details were avoided, the dimensions of the box and the sound hole were similar to the guitar box and the size of internal elements similar to that of the final model, the cavity walls being rigid. No boundary conditions were imposed on the orifice. Both the inside and outside fluids were air under standard thermodynamic conditions. The enclosure had a cubic form and the box was placed approximately in its

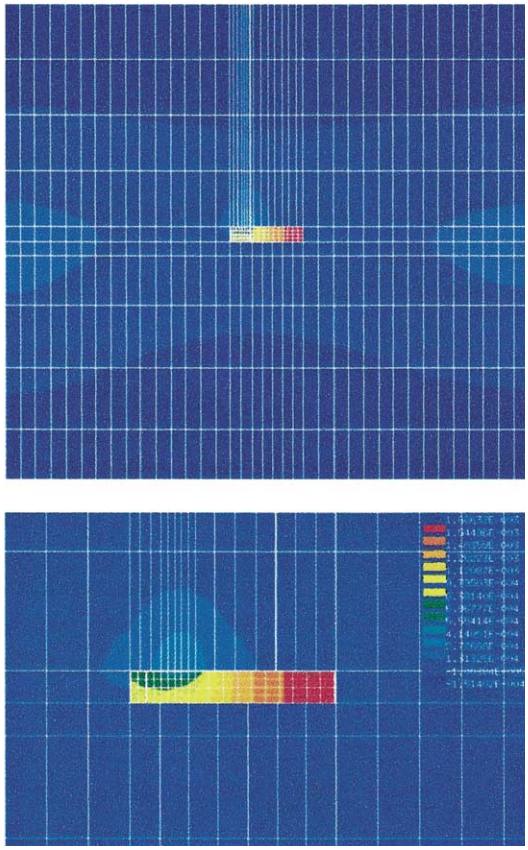

Figure 3. Longitudinal section of the vibration pattern corresponding to the mode A0 (155 Hz) of the guitar box (without internal details) immersed in air obtained by a finite element analysis. Details can be observed in the lower part of the figure.

centre. The analysis was sensitive to the external fluid dimensions and the enclosure was enlarged up to 3000 times the volume of the box to stabilize the inner frequencies. The internal details (internal bars and fan struts) were avoided in this case to save computer time. No significant difference in the internal modes was found when changing the size of the elements of the external medium and so the external discretization is quite coarse to avoid unnecessary calculations. The boundary conditions at the outer surface did not affect the cavity modes and rigid boundary conditions are presented here. No convergence difficulties in the results have been found with the elected discretization, iteration number and tolerances.

The first 25 modes of the system correspond to the external medium and in our case are of no interest. Figure 3 shows the central longitudinal section corresponding to the fundamental mode of the cavity. In the lower part this figure is amplified where the pressure variation over the sound hole and the pressure gradient inside the cavity can be observed. Since the pressure is not uniform inside the cavity this mode is not a pure Helmholtz mode.

The frequency of this mode is $f_{A0} = 155\,\mathrm{Hz}$. However, application of this model to the real internal structure of the guitar box to obtain the higher modes becomes excessively complex. The neck length was therefore increased ($\Delta L = 15\,\mathrm{mm}$), which provides this frequency (equation (1), in the present case, $S_B = 5{\cdot}675 \times 10^{-3}\,\mathrm{m}^2$, $V = 0{\cdot}0130\,\mathrm{m}^3$,

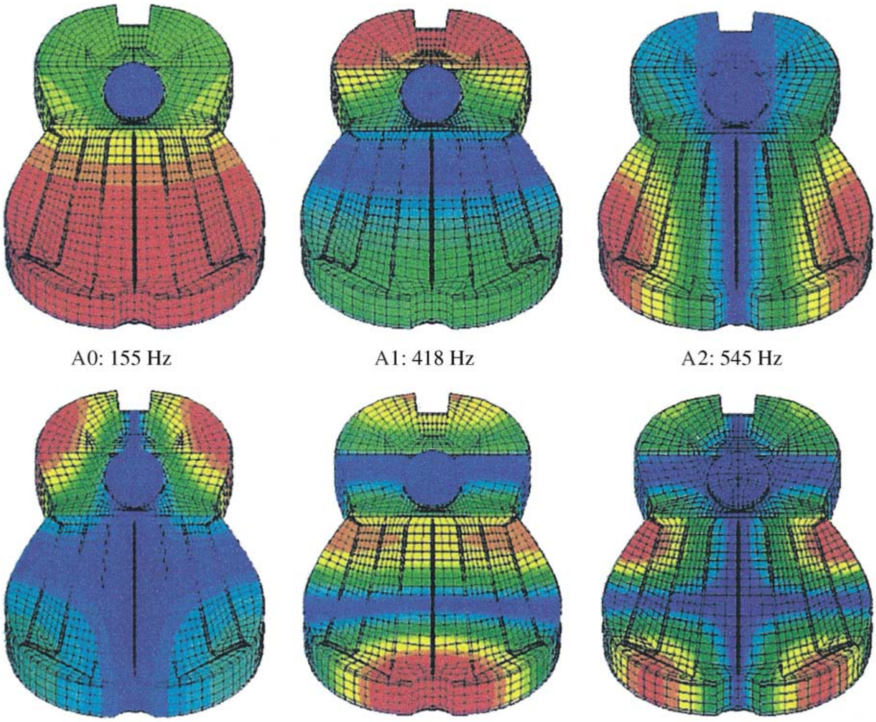

Figure 4. Vibration modes and natural frequencies of the air cavity of the guitar. The phase of the pressure variations in 0 or 180° due to the absence of viscosity in the air, and so only the vibration amplitudes are represented.

$L = 2{\cdot}7 \times 10^{-3}$ m and $c_0 = 343$ m/s) and the definitive mesh built up as shown in Figure 1 setting the sound pressure to zero on the top of the neck correction. This having been done, the numerical analysis provided the same vibration pattern and frequency as those shown in Figure 3 for the first cavity mode.

3. RESULTS AND DISCUSSION

The calculated vibration patterns and natural frequencies corresponding to the first six modes are shown in Figure 4. The modes are categorized as in reference [1] and are of normal character since no viscous effects were present. The blue colour indicates the nodal lines: i.e., the zero pressure zones. Different colours represent the pressure amplitude without differentiating between positive and negative values.

Figure 4 shows that the pressure patterns are not distorted around the sound hole except A0; besides, it is clear that A0 is not a pure Helmholtz mode because the sound pressure in the cavity does not feature a constant distribution. Moreover, the sound pressure in the zone of the sound hole varies perpendicularly. Although the results show an in-phase vibrational behaviour, they also reveal a different value for the sound pressure between the upper and lower part of the cavity. The natural frequency obtained is higher than the experimental values measured by other authors [1, 3, 5], see Table 1, although it should be noted that these measurements correspond to real, not completely rigid, structures; the similitude of the upper frequencies indicates that the guitar box dimensions are very much

TABLE 1

Natural frequencies of air cavity of the guitar

Modes	This work	Experimental work		
		(a)	(b)	(c)
A0	155	122	121	138
A1	418	395	383	380
A2	545	545	504	580
A3	718	—	652	710
A4	771	770	722	786
A5*	981	—	—	—

†Previous work: (a) Jansson [1]; (b) Rossing *et al.* [3]; (c) Runnemalm and Molin [5].

alike. The unavoidable air–structure coupling lowers the natural frequency, especially for this mode in which the compressions and expansions imply volume changes.

Modes A1–A4 are similar to those reported in the literature [1, 3, 5]. In the case of mode A2 the nodal line along the longitudinal axis of the cavity goes from the top to the bottom, as in Runnemalm and Molin [5]; in this case Jansson [1] and Rossing *et al.* [3] report a partial line. Mode A5* presents cross-shaped nodal lines. Jansson [1] and Runnemalm and Molin [5] have not identified this mode and hence the asterisk. In the present case, it was obtained when the fluid cavity takes into account the inner fan struts and bars of the soundboard and the back. When the internal struts were not present, all the patterns remained unchanged except mode A5*. In this latter case, the A5 pattern described in references [1, 5] was recovered. It may be concluded that the stationary waves of this mode are most sensitive to the internal irregularities due to bars and fan struts. In terms of the natural frequencies, all of them decrease by 5% when the struts are added, except, as expected, the Helmholtz mode.

4. CONCLUSIONS

The finite element method has been applied to the air cavity of a guitar box stressing the effect of the sound hole. The designed procedure can be applied to any cavity with an opening neck. The calculated modes are in good agreement with the experimental results reported in the literature as regards both shape and frequencies. An additional mode, sensitive to the internal bars and fan struts, has been found. The results will be applied in a future work to study the coupled modes corresponding to the resonance box–air cavity system.

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