Proceedings of The Institute of Acoustics

PREDICTIONS OF THE SOUND PRESSURE RESPONSE OF THE GUITAR

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INTRODUCTION

We have used data from a finite element model to calculate the free-field sound pressure response of a guitar. This is the first stage of a project which aims to predict the sound of a guitar in terms of the instrument's dimensions and material properties and the initial excitation of the string. In this paper we show preliminary results for calculations of input admittance and sound intensity fields. In each case the calculations are compared with measurements made on an experimental guitar.

THE FINITE ELEMENT MODEL

We are using finite element methods to determine the eigenmodes of guitar plates. Computation is carried out using a commercial package called LUSAS. Our current model consists of a top plate fixed at its edges; previous studies [1] have shown that this simple approach gives a good approximation to measured mode shapes and frequencies.

The plate is meshed into a finite number of elements (Figure 1). It is bilaterally symmetric and only half needs to be considered to determine a full solution. A mixture of thin-shell, beam and solid elements are used to define the structure. The combination of these different elements and difficulty of modelling struts [2] has been a source of problems, resulting in a large error in calculated mode frequencies; mode shapes and effective masses showed better agreement.

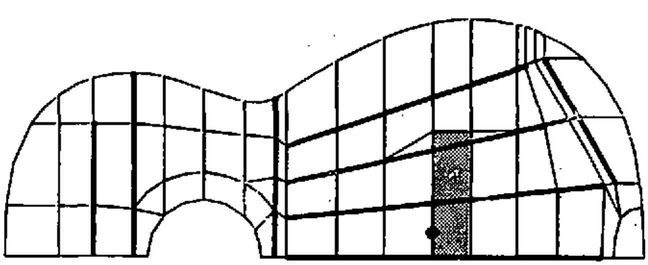

Figure 1. Finite element mesh of the guitar top plate. The thick lines represent struts and the shaded area represents the bridge. The dot indicates the driving point used for the input admittance and sound radiation calculations.

At each stage in our calculations we have compared results with measurements made on an experimental guitar designed specifically to mimic the finite element model. This consists of a conventional top plate glued to extremely rigid ribs, which effectively produce a fixed boundary for the plate. A removeable back can be attached to form an air cavity behind the top plate. The dimensions and material properties of this instrument have been used in the finite element calculations.

Figure 2 shows the effect of the air cavity on the response of the top plate. In the frequency range below 500 Hz two regions of strong coupling between the plate and air cavity produce resonance doublets; above this frequency range the air cavity has little influence [3]. No attempt has been made to include the effect of the air cavity in the finite element model.

RESPONSE CALCULATIONS

Input Admittance

The finite element method calculates the eigenfunctions and eigenfrequencies of the normal modes of the system and ignores damping. The eigenfunctions are arbitrarily normalised, but we need to know the absolute velocity over the whole surface in subsequent calculations of sound radiation. We start by determining the velocity at some reference point (the "driving point"). This also allows us to compute the input admittance of the plate.

The velocity of a single damped harmonic oscillator of natural frequency ω_m and effective mass M_m driven by a force $Fexp(j\omega t)$ is given by

$$u_m = \frac{Fe^{j(\omega t-\theta_m)}}{Z_m} \quad ,$$

where

$$Z_m = \frac{M_m}{\omega}\left[\gamma^2\omega^2+(\omega^2-\omega_m^2)^2\right]^{\frac{1}{2}} \quad ,$$

$$\theta_m = tan^{-1}\left[\frac{\omega^2-\omega_m^2}{\gamma_m\omega}\right]$$

and $\gamma_m = \omega_m/Q_m$, where Q_m is the Q-value of the resonance. The effective mass is obtained by adding a small lumped mass to the driving point and computing the frequency shift per added mass (see [4]). The complex velocity as a function of frequency is obtained by summing over all modes and the input admittance is then given by the ratio of $|u|/F$. The summation ought to be performed over an infinite number of modes, but in practice it is sufficient to include only those modes whose frequencies lie below the upper frequency of interest. Most of our calculations involve about 16 modes in the frequency range 0 to 1.5 kHz.

Figure 3 shows the input admittance calculated at the second string position on the bridge (see Figure 1). At present we have to use experimental Q-values in these calculations. This response can be compared with the measurements made on the plate without a backing air cavity (Figure 2). The general argreement is reasonable in spite of the large discrepancies between calculated and measured mode frequencies. Note that Modes 3 and 4 occur in reversed order. Mode 2 is much less prominent in the calculated response because its effective mass is much too high, the reason being that the driving point lies very close to a node, where it is very sensitive to errors in the eigenfunction. We have had more success modelling the response of violin plates [5].

Sound Pressure Response

To calculate the sound pressure response (and hence sound intensity), we consider each of the m elements of the mesh to be point sources of radiation mounted in an infinite baffle. The total radiated sound pressure is obtained by summing the contribution from each element over all modes, i.e.

$$p = \frac{j\omega\rho_0}{2\pi} \sum_m \sum_i \frac{u_{i,m} S_i}{r_i} e^{-jkr_i} ,$$

where, for the ith element, r_i is the distance to the observation point, S_i is its area and $u_{i,m}$ is its complex velocity when vibrating in its mth mode. The latter is determined from the input admittance calculated earlier in conjunction with the eigenfunction of each mode.

Figure 4 shows examples of the spatial variation of the sound fields for four different modes. These are calculated at a distance of 1 m from the top plate in the plane of the bridge. Figures 4a and 4b show a reasonable approximation to sound fields from the experimental guitar including a back plate. The presence of the back plate inhibits radiation from the rear of the plate and more closely matches a baffled source in the forward hemisphere. As one would expect, the calculated fields are in error for angles approaching ±90°, where the finite dimensions of the experimental guitar have a strong influence on the sound radiation.

Figures 4c and 4d show radiation fields of two higher modes. At "normal" frequencies (500 Hz) the fields are characteristic of dipole and monopole sources, and it is only at abnormally high frequencies (2 kHz) that the beam patterns become complex. These results suggest that a good approximation to the sound field could be obtained by considering only the monopole and dipole components of each mode. (Christensen [6] was able to predict accurate on-axis reponses using only the monopole component of each mode.)

Measured and calculated sound intensity curves are given in Figures 5 and 6. Responses have been calculated directly in front of the guitar (0°) and directly to the side (90°). The latter represents the position of the player and features several modes (e.g. Modes 2 and 5) which only appear off-axis. Again, we have only superficial agreement between calculated and measured results, demonstrating the severe limitation of modelling the guitar as if mounted in an infinite baffle. More accurate predictions will require more sensitive modelling of the instrument as an acoustic source and ought to include effects of the plate-air-cavity coupling and sound radiation from the sound hole.

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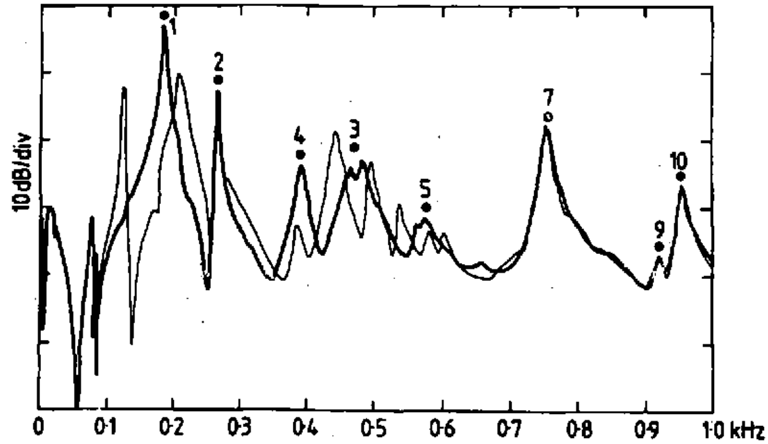


Figure 2. Input admittance curves for the experimental guitar. The figure compares the response of the plate without (thick line) and with (thin line) a backing air cavity. The numbers highlight resonances of individual modes.

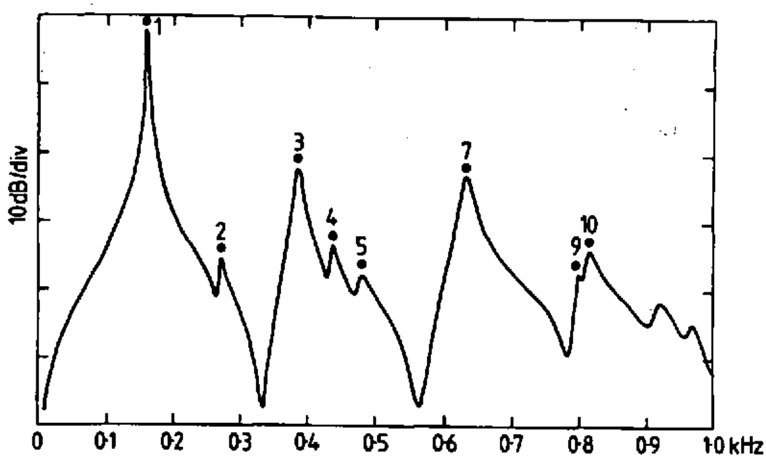
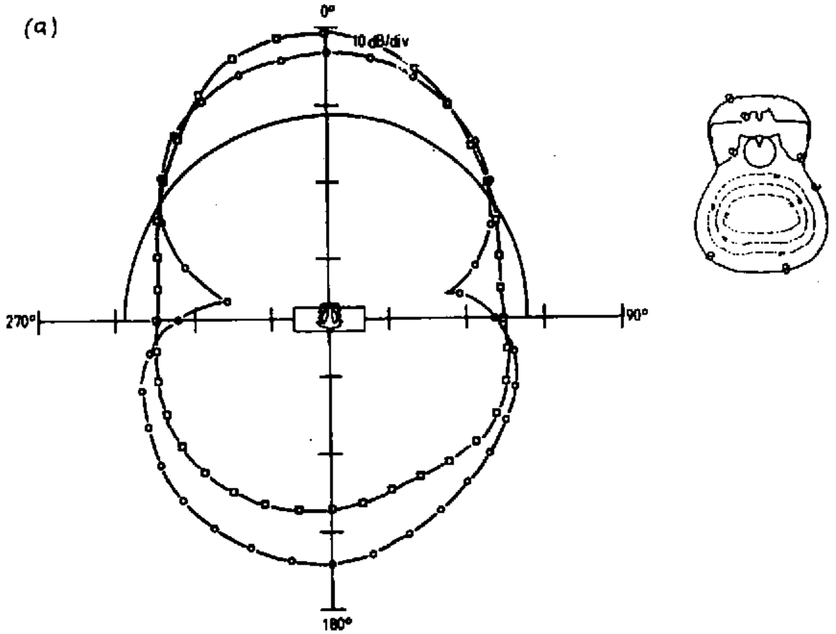


Figure 3. Calculated input admittance of the guitar top plate.

(a)



(c)

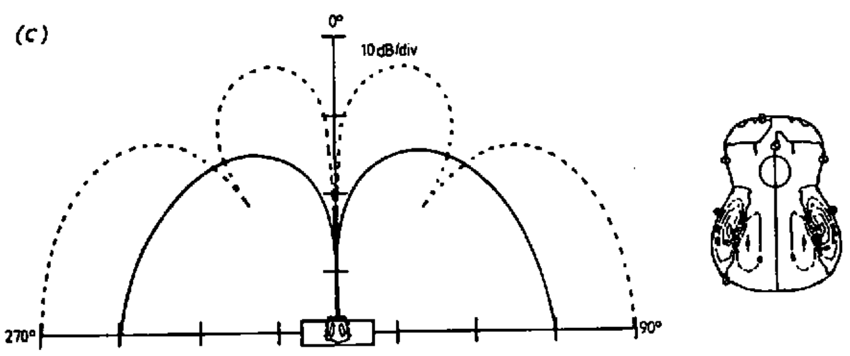


Figure 4. Polar plots of the radiated sound intensity fields for (a) Mode 1, (b) Mode 2, (c) Mode 5 and (d) Mode 7. In (a) and (b) the figures compare the the calculated field (——) with measured fields of the experimental guitar with (-□-) and without (-O-) a

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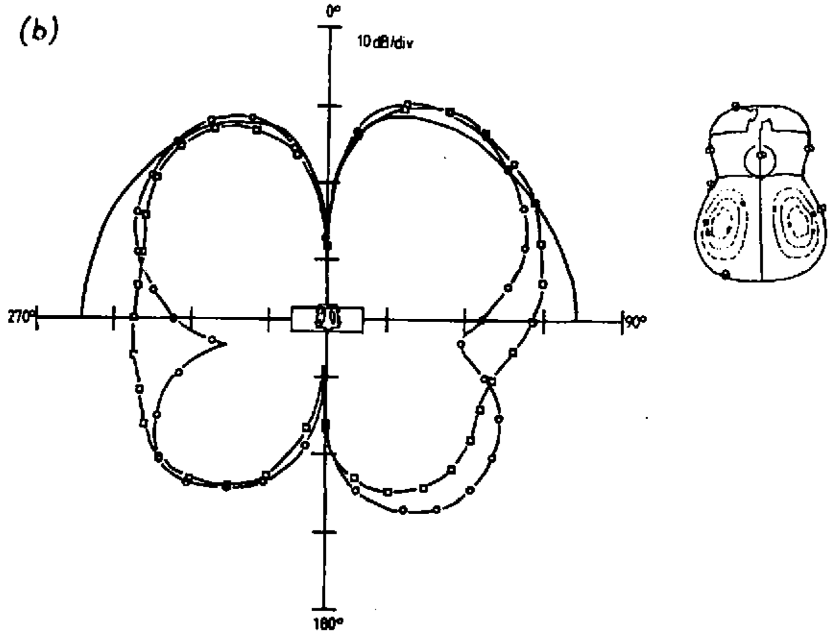
(b)



(d)

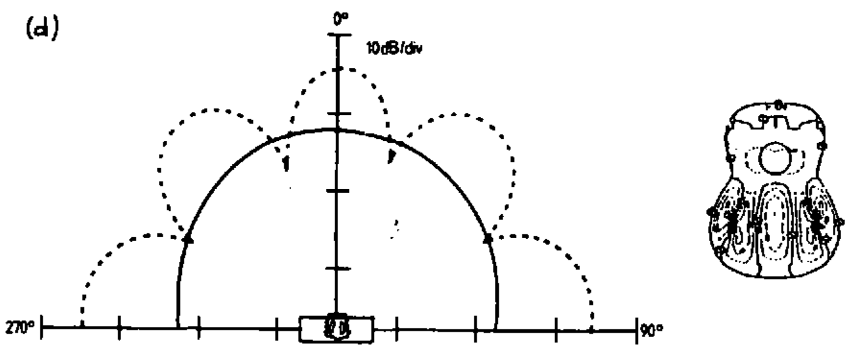


Figure 4 Continued ....
rigid back plate (note that in (a) the sound hole has been plugged to supress the Helmholtz resonance). In (c) and (d) fields have been calculated at 500 Hz (solid line) and 2000 Hz (dotted line).

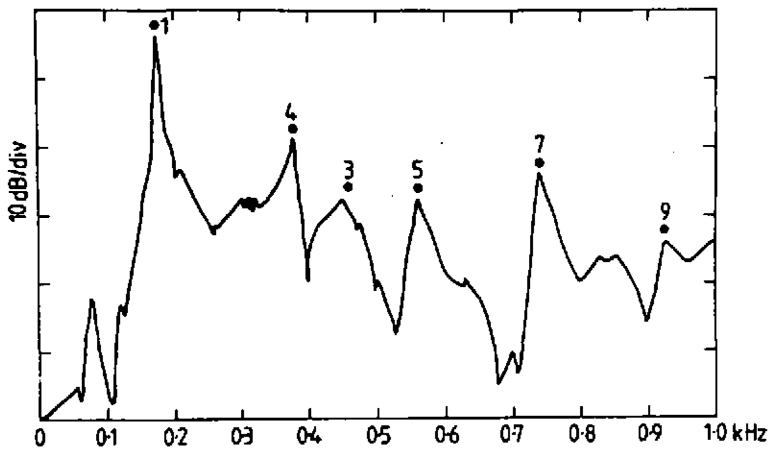


Figure 5. Measured sound intensity 1 m in front of the experimental guitar.

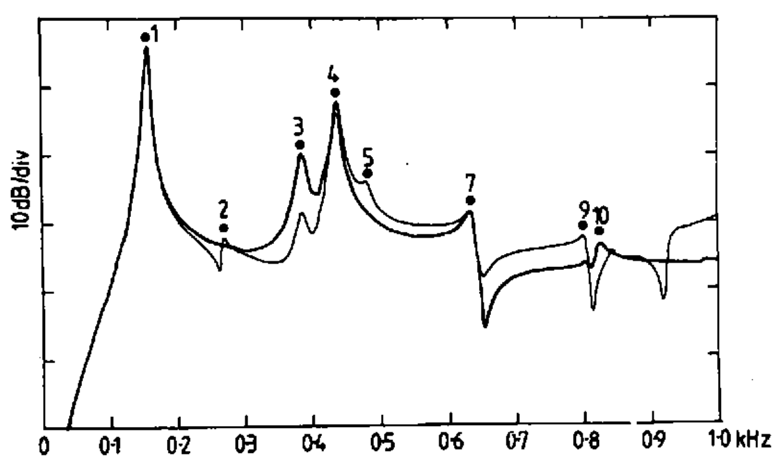


Figure 6. Calculated sound intensities 1 m to the front (thick line) and 1 m to the side (thin line) of the guitar top plate.