Recent studies of wall and air resonances in the violin

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C. RECENT STUDIES OF WALL AND AIR RESONANCES IN THE VIOLIN

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Abstract

It is often assumed that higher air-modes in violins are non-existent because of the F-holes. Experiments with cavities with rigid walls show, however, that this is not true. The higher modes are in general only moderately affected by the F-holes. These modes are of two kinds, longitudinal standing waves in the whole cavity and transverse standing waves in the cavity on either side of the c-bouts. Detailed studies of the first air-mode above the Helmholtz mode in real violins have been performed. These studies show that this air-mode falls in the frequency range of the main wood resonance and it is excited from the bridge, i.e. the cooperation between this mode and the walls may be very important.

I. Introduction

The resonant box of a violin consists of a top plate and a back plate glued to the ribs, thus enclosing an air volume. In the top plate two sound holes are cut, i.e. the F-holes. The total area of the two sound holes taken together is about 12 cm$^2$ and that of the total area of the enclosing walls about 1200 cm$^2$. Thus the ratio between the two areas is about 1/100. This small ratio implies that only a small portion of the stored energy of standing waves set up into the air volume is likely to radiate through the F-holes and that several higher air-modes may be expected in the enclosed air cavity of the violin. However, it is usually assumed that the shape and the position of the F-holes are such that higher air-modes cannot effectively influence the sound producing mechanism of a violin, see for example a theoretical study of the violin by Schelleng$^{(1)}$. In earlier studies by Saunders traces were found of higher air-modes, but these modes seemed to give little influence on the total behavior of the violin$^{(2)}$. Preliminary experiments with a rectangular box gave that the energy leakage through the F-holes does not remove higher air-modes in general. This means that the acoustical inimpedance seen from the plates may be important although the sound radiation through the sound holes is negligible.

$^{(1)}$ This paper was given at the 84th meeting of the Acoustical Society of America, Miami Beach, Fla., USA, Nov. 28-Dec. 1, 1972

$^{(2)}$ The optical investigations are performed in cooperation with the Institute of Optical Research, KTH.
Therefore the present study was started to remove the ambiguity of the above summarized results and to give an understanding of the higher air-modes. In this paper we shall limit the discussion to the frequency range below 2 kHz.

II. Experiments with violin-shaped cavities

The first main question to answer is: Does it or does it not exist several higher air-modes in a violin-shaped cavity with "F-holes"? To find the answer of this question we measured the acoustical input impedance of the air volume of a violin encased in plaster thus blocking the motion of the walls and allowing examination of the air cavity in isolation. The impedance was measured by means of a specially designed measurement probe containing an STL-ionophone and a B&K 4133 microphone with a short and thin sond (length about 2 cm and effective diameter about 0.025 cm). The impedance was measured both with closed and with open F-holes. When the F-holes were open, then the area of top plate between the c-bouts (at the waist) and around the F-holes was free from plaster, so that the radiation at the F-holes should be the same as in playing. The result is exemplified by two measured impedance curves, the upper one with closed and the lower one with open F-holes (Fig. III-C-1). The upper and the lower diagrams show grossly the same number of peaks but the lower impedance curves have slightly less marked peaks.

The peak frequencies and the -3 dB bandwidths were accurately measured by means of a frequency counter for all resonances. From these measurements the Q-factors were calculated. The Q-factors obtained in this way are plotted as function of peak frequencies in Fig. III-C-2. For simplicity the modes are numbered starting from zero for the Helmholtz mode. From the diagram we find that the peak frequencies are only slightly changed by the F-holes. The Q-factors are moderately lowered by the F-holes in all modes but two, namely the third and the sixth mode. In the third mode the Q-factor is considerably lowered and in the sixth mode no traces of a peak shows up. These results support the hypothesis previously introduced; there are several resonances and these resonances are in general only moderately affected by the F-holes.
Fig. III-C-1. Acoustical impedance measured close to the end button of a violin encased in plaster.
Top curve - closed F-holes
Lower curve - open F-holes
Fig. III-C-2. Q-factors and frequencies of the first seven air modes of a violin encased in plaster.
Next question we asked ourselves was: Why are just the third and the sixth modes so affected by the F-holes? The oscillation modes of a cavity can be greatly affected by holes in the cavity walls. Not only the size but also the place of the hole are important, as pointed out by Schelling (1). A hole drilled at a sound pressure maximum can affect the standing wave considerably while a hole at a sound pressure minimum will have little effect on the standing wave. Thus we should first record the standing wave patterns. Thereafter we can see if these patterns explain what happens when the F-holes are opened. To simplify our measurements we made these experiments with a cavity shaped like the inside of a violin but with flat top and back plate. The resonance frequencies of this cavity approximate within a few percent those of the violin encased in plaster. This indicates that the arching of the top and back plates is not very important to the seven lowest modes. The different standing waves were excited and the sound pressures at different positions were measured through small holes drilled in the walls. The different standing wave patterns estimated are presented in Fig. III-C-3. The first, the third, and the fifth modes correspond to the first three modes of a pipe closed in both ends although moderately perturbed by the swelling and shrinking of the cross-sectional area. The second and the seventh modes are resonances of the cavity below the narrowing section between the c-bouts. The fourth mode is the mirror image of the second mode in the cavity part above the c-bouts. The sixth mode is made up by a combination of vertical and horizontal standing waves. The results allow the volume of a violin to be regarded as consisting of two coupled cavities. At some resonances the coupling between these cavities is strong and the energy is stored in the whole air volume, at some other ones weak and the energy is solely stored in either of the upper or lower cavity.

The F-holes are grossly situated between the c-bouts. This is at about the border area between the upper and lower cavity estimated from Fig. III-C-3, i.e. an area of low sound pressure for the second, the fourth, and the seventh modes. These modes will therefore be little affected by the sound holes. Furthermore, the first and fifth modes have sound pressure minimum between the c-bouts and are thus little affected. Only the third and the sixth modes have sound pressure maximum in the vicinity of the F-holes, which explains why their Q-factors
Fig. III-C-3. Standing wave patterns of the seven lowest modes of a violin-shaped flat cavity.
drop considerably when the F-holes are opened. The rule regarding
the position of holes in relation to sound pressure maximum has thus
proved to give results in agreement with the experiments.

To summarize, we may say that regarding the resonances of a cavity
shaped like a violin and with F-holes, higher air-modes exist and most
of them are moderately affected by the F-holes. The properties of the
air-modes obey at least qualitatively the simple rules regarding holes
in cavities with standing waves.

III. Experiments with violins

So far we have studied the modes of a cavity with rigid and heavy
walls. In a real violin this is not a good approximation. From earlier
studies by Jansson, Molin, and Sundin, we know that plates are vibrating
with little motion at the ribs at least for higher frequencies\(^1\). The air-
modes of the violin shaped cavities have sound pressure maximum gen-
erally at the "ribs", i.e. at the places where the plate motion is small.
The fact that the places of maximum sound pressure and maximum plate
motion are different, indicates that the coupling between plate motion
and air-modes is weak and that the higher air-modes are still present
in the violin.

In our experiments, yet not finished, we have begun with a detailed
study of the air-mode 1, which is at about 500 Hz and thus close to a
major resonance peak of violins - the so-called main wood peak. We
built a new measuring probe consisting of an STL-ionophone and a B&K
1/4 inch microphone with a sond. These we mounted on and into an "end
button" of plexi-glass. By means of this special "end button" we were
able to record the air vibrations with a well defined acoustical input on
violins, even stringed and tuned instruments.

With this device the acoustical input impedance at the end button of
six violins was measured in the frequency range of air-mode 1. A clear
peak showed up in all instruments. Test with a sond microphone in dif-
ferent positions inside the instrument verified that this was the air-mode.
The frequencies and Q-factors of these peaks are displayed in Fig. III-C-4.
The frequencies are lowered compared to those of the violin shaped cav-
ity with F-holes and fall close in frequency to A\(_4\) sharp, i.e. just in the
Fig. III-C-4. Q-factors and frequencies of the first air-mode in six complete violins.
region of the main wood peak generally found in good violins. The Q-factor averaged for six violins is only slightly lower than the Q-factors for the violin shaped cavity, i.e. the losses through the walls are moderate. Thus we have proved that air-mode 1 is set up in complete violins.

Our next question is: Can this air-mode be excited by the plate vibrations? We excited the bridge electro-magnetically and measured the frequency response by the microphone in the end button in the frequency range of air-mode 1. Probe measurements proved that the air was oscillating in air-mode 1. The pressure minimum of the air-mode was found to be roughly in the place of the bridge. A peak was still generally found (5 out of 6) corresponding to the air-mode. Furthermore the inside of the lower part of the top plate was found to be coupled in phase with the sound pressure of the air-mode.

IV. Conclusion

In a previous study of our test instrument HS 71, it was found that the wall vibrations are mainly in the first top plate mode in the region of the main wood peak\(^{(4)}\). In the present study we have found that the first air-mode above the Helmholtz mode falls in the same region. The experiments have proved that the two modes are coupled. Standing wave patterns of the two modes are drawn for comparison in Fig. III-C-5.

The entire top plate moves in phase, whereas the sound pressure in the upper and the lower parts are 180° out of phase. Thus a simple and direct coupling between the sound pressure of the air-mode and the vibrations of top plate is not possible. However, an estimate of the volume displacement by the top plate above and below the bridge, i.e. the pressure minimum, gives a difference of about 10%, the lower part giving the greater displacement. The phase relations of such a coupling agree with the experimentally determined phase relations, the sound pressure of the air mode 1 being direct coupled to the lower part of the top plate vibrations.

Thus we have proved, that at least one air-mode above the Helmholtz mode is present in violins, that this mode is coupled to wall vibrations. We have also given an explanation of the coupling mechanism. Although the air-mode does not radiate through the F-holes, the acoustical load on the top plate vibrations may be important. Especially as
Fig. III-C-5a. The first air-mode (470 Hz, \( Q = 65 \)), and
b. the first top plate mode of violin HS 71 (480 Hz).
(Fig. III-C-5b is from Jansson-Molin-Sundin, Physica Scripta, Vol. 2, pp. 243-256, 1970.)
the mode falls in a frequency range of great interest, the range where violins have a peak in their acoustical output and where the so-called wolfnote is to be found.

Our investigations are continued to study the importance of the higher air-modes and how the relation between the top plate mode and the air-mode influences the main wood peak, the wolfnote, and thus the quality of the instruments.

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References