

Eigenmodes, Input Admittance, and the Function of the Violin

by J. A. Moral and E. V. Jansson

Department of Speech Communication and Music Acoustics, Royal Institute of Technology,
S-100 44 Stockholm

Summary

Four violins were investigated with a TV speckle interferometer (150 to 2000 Hz) and input admittance measurements (50 to 10 000 Hz). Thus obtained vibration patterns showed different kinds of eigenmodes, five body modes below 800 Hz (i. e., one-dimensional longitudinal and two-dimensional modes with the complete body vibrating in phase) and plate modes between 800 and 2000 Hz limited either to the top or to the back plate. In addition, the Helmholtz' air mode and the first top plate mode are found in the lower frequency range. The input admittance curves show that the vibration properties are set by single resonances below 1 kHz. Above 2 kHz, the bandwidths of the different plate resonances overlap, and the violin body properties are determined by the density of resonances and their damping. The bridge introduces a broad peak, about 3 kHz. The experiments showed that all modes but the lowest three body modes can radiate sound and can be driven via the bridge. Measurements of vibration levels indicate that the energy losses in the violin are considerable, and that the bridge region vibrations are smaller than those of the upper and lower halves between 900 and 3000 Hz but larger for higher frequencies. At the bridge below 900 Hz, the sound post introduces a large asymmetry favoring the left side vibrations but for higher frequencies the right side vibrations are tended to be larger. The magnitude of the different recorded measures seems to be related to playing qualities, but more experimental evidence is needed to settle these relations.

Eigenschwingungsformen, Inadmittanz und Funktion der Violine

Zusammenfassung

Vier Violinen wurden mit Hilfe eines TV-Speckle-Interferometers untersucht (150 bis 2000 Hz), und ihre Inadmittanzen gemessen (50 bis 10 000 Hz). Die auf diese Weise beobachteten Schwingungsbilder zeigten verschiedene Arten von Eigenschwingungsformen, fünf Korpusmoden unterhalb von 800 Hz (eindimensionale longitudinale und zweidimensionale Moden, bei denen der gesamte Korpus in Phase schwingt) und Plattenmoden zwischen 800 und 2000 Hz, wobei die letzteren entweder auf die Decke oder auf den Boden begrenzt waren. Zusätzlich wurden im tieferen Frequenzbereich die Helmholtzresonanz und die erste Deckenresonanz bestimmt. Die Inadmittanzkurven zeigen, daß die Schwingungseigenschaften durch einzelne Resonanzen unterhalb von 1 kHz festgelegt werden. Oberhalb von 2 kHz überlappen sich die Bandbreiten der unterschiedlichen Plattenresonanzen, und die Schwingungseigenschaften des Korpus werden durch die Dichte und die Dämpfung der Resonanzen bestimmt. Der Steg bedingt eine breite Resonanz bei etwa 3 kHz. Die Experimente zeigten, daß alle Moden, ausgenommen die niedrigsten drei Korpusmoden, Schall abstrahlen und über den Steg angeregt werden können. Messungen des Schwingungspegels zeigen, daß der Energieverlust innerhalb der Violine bedeutend ist und daß die Schwingungen der Stegregion zwischen 900 und 3000 Hz kleiner sind als die der oberen und unteren Hälften, aber größer für höhere Frequenzen. In der Stegregion bewirkt der Stimmstock unterhalb von 900 Hz eine starke Asymmetrie zugunsten der Schwingungen der linken Seite, aber für höhere Frequenzen zeigen die Schwingungen eine Tendenz, an der rechten Seite größer zu sein. Die Größe der unterschiedlichen Meßwerte scheint mit der Tonqualität im Zusammenhang zu stehen, aber es sind weitere experimentelle Daten nötig, um diese Beziehungen zu bestätigen.

Modes propres, admittance d'entrée et fonctionnement du violon

Sommaire

On a examiné quatre violons par interférométrie à speckles TV (entre 150 et 2000 Hz) et mesurage de l'admittance d'entrée (entre 50 et 10 000 Hz). Les configurations vibrationnelles ainsi obtenues ont montré divers types de modes propres: cinq modes globaux en dessous de 800 Hz (modes unidimensionnels longitudinaux et modes bidimensionnels avec le corps entier du violon vibrant en phase) et des modes tabulaires (modes limités soit à la table supérieure, soit à la table inférieure) entre 800 et 2000 Hz. On a également trouvé le mode aérien de Helmholtz et le premier mode de la table supérieure (dans le domaine des plus basses fréquences). Les courbes d'admittance d'entrée montrent qu'en dessous de 1 kHz les propriétés vibrationnelles du violon se manifestent par résonances isolées, alors qu'au dessus de 2 kHz les largeurs de bande des différentes résonances des tables se recoupent, de sorte que les propriétés acoustiques du corps du violon sont alors détermi-

nées par la densité des résonances et par leur amortissement. Le chevalet introduit un pic de résonance assez large centré aux alentours de 3 kHz. Nos expériences ont montré également que tous les modes, sauf les trois premiers modes globaux, peuvent émettre du son dans l'air et peuvent être excités par l'intermédiaire du chevalet. Les mesures des niveaux de vibration montrent que les pertes énergétiques sont considérables et que les vibrations au voisinage du chevalet sont plus faibles que celles des moitiés supérieures et inférieures du violon entre 900 et 3000 Hz, mais les dépassent aux fréquences plus élevées. En dessous de 900 Hz l'âme introduit au niveau du chevalet une asymétrie marquée favorisant les vibrations du côté gauche, tandis qu'aux fréquences supérieures les vibrations tendent à devenir plus intenses du côté droit. Les amplitudes des différentes intensités mesurées semblent en relation avec les qualités musicales du violon, mais il faudra des expériences supplémentaires pour expliciter mieux ces relations.

1. Introduction

The vibration properties of a violin are described by its eigenmodes. Therefore, many investigators have tried to map the eigenmodes of violins (see Hutchins [1]). A new optical technique, hologram interferometry, made it possible to obtain a complete mapping of a vibration mode in one recording.

Two series of such interferometric mappings of the violin have been published. In the first series, the vibration patterns were recorded with the violin clamped in a jig, at the chinrest position, the neck, and two corners [2]. It was later proved that the clamping influenced on the vibration patterns [3]. In the second series the mapping of the vibration patterns was obtained by Stetson & Taylor with the violin loosely held by rubberbands, i.e., approximately free edges [4]. The vibration patterns from the two series are quite different.

Still more recently, a so-called TV speckle interferometer has been developed at the Institute of Optical Research, Royal Institute of Technology, Stockholm [5]. With this interferometer the mapping of vibration patterns has been made still simpler – the stability demands on the holding of the investigation object are less severe and the vibration patterns are conveniently displayed on a television screen. By means of this interferometer it was decided to make a more complete recording of the eigenmodes of violins and thereby try to settle the differences between the two previous experimental series. Furthermore, input admittances were measured with a method developed by Jansson. Thereby the optical measurements were complemented with independent ones, and the range of measurements could be extended to the full audio-frequency range. In addition, resonance frequencies and Q -factors of the different eigenmodes could easily be obtained. A complete record of the experiments can be found in a preliminary report by Alonso Moral [6].

In this paper we shall present mapped eigenmodes and analyze their importance in terms of excitation and radiation. Furthermore, we shall study vibration properties at higher frequencies as mapped by input admittance plots. Finally, we shall discuss the func-

tion of the violin in terms of the presented experimental findings. Our paper is a report of an investigation of fundamental physical properties of the violin. It is planned to form a background for our future investigations of the function and the tonal quality more in detail. As controlled and the same recording conditions suffice for our present purposes no absolute measures were taken of force and vibration levels.

2. Experimental violins

In this investigation we have used four violins of different origins: (1) a cheap Chinese violin, (2) a Czech violin, made in a non-traditional way, (3) the violin previously used in the Jansson, Molin and Sundin [2] investigations, and (4) an old violin of unknown origin.

The first two represent samples of violins made in factories in large numbers, the third one was carefully made for the previous investigation by Sundin. The fourth violin is an old violin owned by Alonso Moral. It is much repaired. All violins investigated are owned by the authors or put at their disposal for investigations. No formal tonal quality test has been made with the violins, as a qualitative understanding of the function of the violin is our present main purpose.

Informally the authors and a professional player have ranked the violins in the order 4, 2 and 3, and 1, starting from the best one. Although no real high-quality violin was included in the experiments, we believe that our results are representative for the violin in general and recorded magnitudes of differences are representative for differences between instruments.

3. Eigenmodes

3.1. The recording of the eigenmodes

At the Institute of Optical Research a special TV speckle interferometer has been developed [5]. The interferometer displays the vibration patterns of the investigated object on a television screen. Thus, the vibrations can be photographed, recorded on video-

tape, or simply plotted on a paper with a pencil. This last method suffices for our purpose and was therefore used. As large series of experiments could be made with a moderate amount of work; we could investigate the four violins in a fairly complete way.

The mapping of the eigenmodes were made under the following conditions. In order to obtain a maximum of reflecting light from the violins, these were covered with especially prepared reflexion tape applied along the grains. During the experiments, the violins were placed on their right sides on two rubber supports. The violins were set into vibration by the electrodynamical system described in section 4. Its source impedance is mainly set by a 1 g mass-loading and was found to give neglectable influence for the present purpose. The reflexive tape, the driver, and the supports perturbed the resonance frequencies slightly. The tape and the driver lowered the frequencies max. 4%. The supportings increased the frequencies max. 4%. Thus, the measured resonance frequencies should differ less than 4% from those for the violin in a "free" condition. The damping of the eigenmodes are moderately influenced by the reflexive tape, cf. Fig. 6. By trying different ways and positions of driving and of supporting the violins, it was found that the vibration patterns, and thus the eigenmodes, were little influenced by the driving and by the supports. The phases of vibration were controlled by simultaneous driving in the same or opposite phases in two antinodal areas. With the interferometer, eigenmodes could be mapped up to approximately 2 kHz.

3.2. Experimental results

The experiments revealed three main kinds of eigenmodes. The first type, longitudinal one-dimensional eigenmodes, are displayed in Fig. 1. The eigenmodes are of one-dimensional char-

acter, as they have approximately parallel nodal lines. Furthermore, the two nodal lines are in the same position for the top and back plates and the antinodal areas of the top plate vibrate in phase with corresponding areas of the back plate. This means that the violin vibrates approximately as the first mode of a free bar.

Different eigenmodes should have different vibration patterns, not as similar in Fig. 1. Therefore, three simple follow-up experiments were made. First the free end of the fingerboard was massloaded, secondly the same massload was moved to the top plate under the fingerboard, and thirdly, two wedges were pushed in-between the fingerboard and the top plate. In the first experiment, the 285 Hz mode was considerably lowered in frequency, in the second little, and in the last experiment this mode vanished. The 185 Hz was moderately influenced in the three cases. Thus, all three experiments imply that the 285 Hz mode derives mainly from the neck with fingerboard. A complication is that the 285 Hz one-dimensional mode may vibrate in combination with the wall vibrations of the "Helmholtz air mode".

The same two eigenmodes can be traced in the vibration patterns at 201 and 303 Hz in the Stetson and Taylor records [4]. In our experiments we could find effects of higher longitudinal one-dimensional body modes, but they were weak compared to the other types of modes in these frequency ranges. For convenience we label the two modes found as C1 and N (Corpus and Neck).

In the next higher frequency range, a second type of eigenmodes was found: two-dimensional body modes, see Fig. 2. This type of eigenmodes is prominent in the frequency range of 350 to 800 Hz. The nodal lines are similar for the top

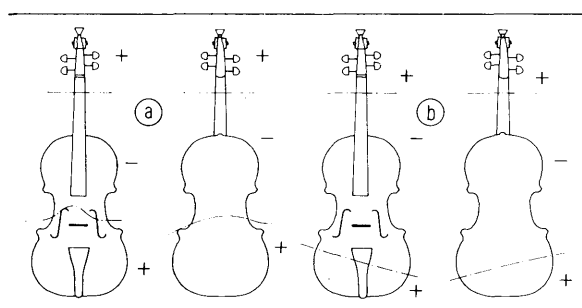


Fig. 1. One-dimensional body modes at (a) 185 Hz and (b) 285 Hz (average frequencies of the four violins). Driving point is marked with a triangle, the nodal lines with broken-dotted curves, and the phases of vibration relative to the driving with a plus sign for in phase and a minus sign for vibrations in opposite phase. The violin is shown as seen from the top and back sides, respectively.

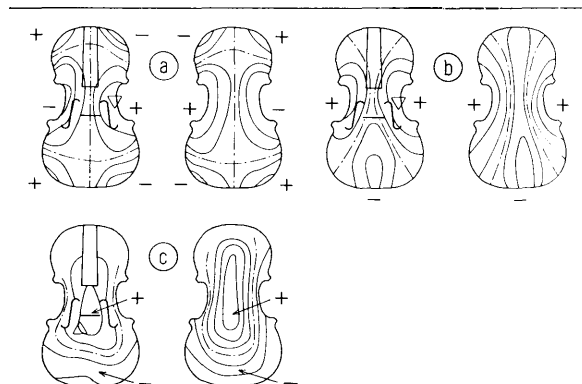


Fig. 2. Two-dimensional body modes at (a) 405 Hz, (b) 530 Hz, and (c) 700 Hz. The curved lines mark lines of equal amplitude; frequencies, triangles, broken-dotted lines, and plus and minus signs, as in Fig. 1.

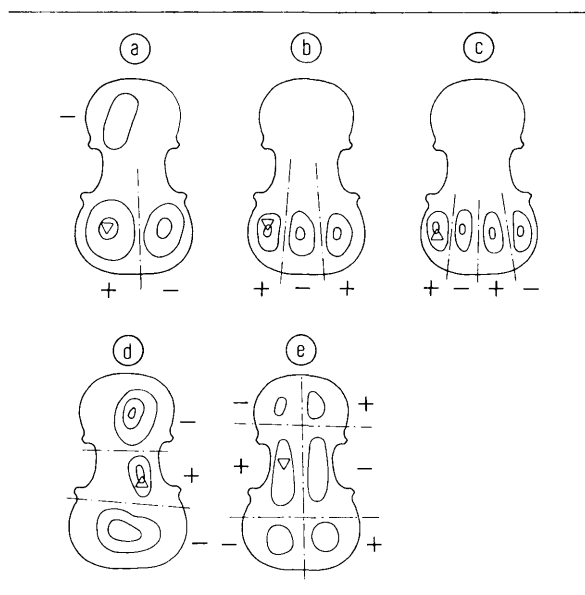


Fig. 3. Examples of plate modes: the back plate at (a) 775 Hz, (b) 1160 Hz, (c) 1490 Hz, (d) 1030 Hz, and (e) 1360 Hz. Frequencies, line markings and symbols as in Figs. 1 and 2.

and the back plates and corresponding areas of the top and back plates are vibrating in phase. The vibrations are maximum at the edges, i. e., at the ribs. The eigenmodes are of a two-dimensional character and the whole body is vibrating similarly to a free plate. More specifically, these body modes correspond to the eigenmodes number three, two, and five of a free violin plate [7]. (The eigenmode number five is often referred to as the ring mode and is regarded as the most important mode for plate tuning.) The two-dimensional body modes can be driven from both the top and the back plate. The same eigenmodes can be traced in the Stetson and Taylor interferograms at 382, 549, and 717 Hz [4]. Furthermore, the 405 Hz eigenmode can be found at 340 Hz in the records by Jansson, Molin and Sundin [2], i. e., for violin 3 held with clamps. For convenience we label these eigenmodes C 2, C 3, and C 4.

From 700 Hz to at least 2000 Hz (the upper limit of the experiments), a third type of modes dominates. These eigenmodes we shall call plate eigenmodes, as the vibrations are limited either to the top or to the back plate, i. e., they have nodal lines at the ribs. Similar patterns can be found in both the top and the back plates at different frequencies. The examples in the upper row of Fig. 3 show eigenmodes with vibrations in the lower part only — the upper part vibrations of the 775 Hz mode derive from another eigenmode. The same vibration patterns can generally be found in the upper part too. All these presented eigenmodes have small vibration

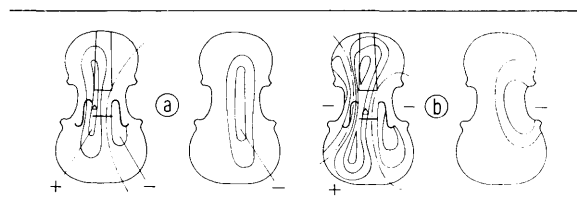


Fig. 4. Vibration modes at (a) the "Helmholtz" air mode" at 275 Hz and (b) the first top plate at 460 Hz. Frequencies, line markings and symbols as in Figs. 1 and 2.

amplitudes in the bridge region. There are plate eigenmodes, however, with large vibration amplitudes in the bridge region. Examples of such are shown in the lower row of Fig. 3. The plate eigenmodes are of the same type of modes as those recorded for violin 3 held with clamps, i. e., a boundary condition approaching clamped edges (Jansson, Molin and Sundin [2]).

So far we have neglected the two best known resonances of the violin, i. e., the "Helmholtz" air resonance" and "the main wall resonance". The Helmholtz' air mode (hereafter labelled A 0) generates plate vibrations, as shown in Fig. 4 a. The vibrations are limited within the ribs and the main vibrations are in the left half of the body. They are of the same magnitudes in the top and back plates but opposite in phase. This means that the top and the back plate vibrations work together to shrink or to increase the volume of the body. As stated earlier, the plate vibrations at the air resonance can be noticeably influenced by the one-dimensional 285 Hz eigenmode, which is mainly determined by the neck and fingerboard.

At approximately 460 Hz the so-called "main wall resonance" [8] and the first top plate resonance (labelled T 1) [2] are found, Fig. 4 b. At this frequency a complicated vibration pattern can be seen. The major vibrations are on the top plate side and on the left side along the bass bar. Furthermore,

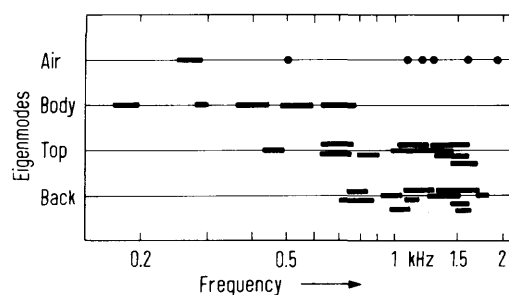


Fig. 5. Resonance frequency ranges (thick horizontal bars) for different eigenmodes. Air modes (the top line, the higher modes from Jansson [9]), body modes (C 1, N, C 2-C 4 the second line), the top plate modes (the third line), and back plate modes (the bottom line).

there are vibrations at the edges and two nodal lines at considerable distances from the edges. Finally, the left part of the back plate is vibrating. The vibrations were earlier shown to be dependent on the holding [3] and they can be traced in the records by Stetson and Taylor [4]. The vibration pattern seems to be a combination of the first top plate eigenmode with clamped edges [2] and the two-dimensional body mode at 530 Hz. Note the similarity with the "vibration patterns at the Helmholtz' air resonance", i. e., main vibrations in the left halves and opposite in phase.

The frequency ranges of eigenmodes recorded with the speckle interferometer are given in Fig. 5 together with the previously recorded air modes [9]. It is easily seen that the number of top and back plate resonances starts to dominate with increasing frequencies and that the frequency ranges of the plate modes are overlapping for higher frequencies. The different frequency ranges indicate, furthermore, that some modes can be tuned within wide ranges, while others are fairly frequency fixed, thus suggesting that the former ones are set by the maker while the later are set by the general construction.

3.3. Radiation

The radiation efficiency of the different modes is, in general, difficult to measure and to summarize in a simple way. The radiation efficiency can be estimated by means of a simple reciprocal measure, i. e., how efficient a loudspeaker in the room drives the different eigenmodes.

In our case we started with a loudspeaker at approximately 1.5 m distance and watched the plate vibrations by means of the speckle interferometer. Thereafter the loudspeaker was moved around in the room while the plate vibrations were watched. By doing so at different frequencies it was found that eigenmodes C 1, N, and C 2 are weakly driven. The last one can, however, be driven when the loudspeaker is moved closer to the violin in an asymmetric way. The A 0 and T 1 are strongly driven. The C 3- und C 4-modes, as well as the top and back plate modes, are clearly driven, at least those up to 2 kHz.

4. Input admittance — driving — vibration levels

The tone characteristics of a violin are determined by how the vibrational forces from the strings are transformed into bridge vibrations. A measure of this transformation is the input admittance, i. e., the driving point velocity for driving force of constant amplitude. Furthermore, it has been shown that the

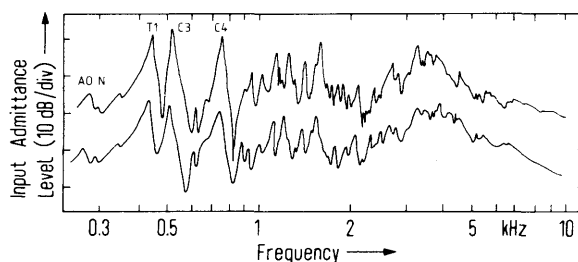


Fig. 6. Input admittance measured on the bridge to the left of the G-string and perpendicularly to the top plate for violin 4 with (upper curve) and without reflexive tape (lower curve) shifted -13 dB relative the upper curve. Identified resonance peaks are labelled.

input admittance is closely related to radiated sound power for frequencies below 1 kHz, Beldie [10, 11]. Thus, it gives a direct measure of driving conditions and, at least for low frequencies, a measure of radiated sound.

The input admittance is simple to measure with the technique developed at our laboratory. In 1975 Jansson utilized the recently developed strong magnets (of Cobalt and rare earth metals) to construct a very simple driving system possessing ideal properties (low weight and no internal losses), see Firth [12]. Firth developed this construction further and made a complete "impedance head" [13]. We have adopted this "impedance head" in a simplified version employing only the accelerometer. Thus, we are feeding an electrical coil with "constant" current. The coil acts over a small air gap with the magnet and gives a "constant" driving force. The magnet is fastened to a B & K miniature accelerometer (8307), which is fastened to the measurement object. This magnet-accelerator-transducer is easily adopted to a large variety of measurements.

Input admittance curves were recorded of the four violins to supplement the vibration pattern measurements. Furthermore, the investigation by means of the input admittance the measurement range was increased to 10 kHz, i. e., including the whole frequency range of importance according to Jansson [14].

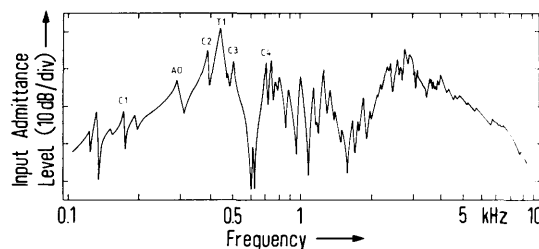


Fig. 7. Input inadmittance measured on violin 3 as in Fig. 6 (lower curve).

Input admittance curves for violin 4 without and with the reflexive tape are shown in Fig. 6. The curves were recorded with driving on top of the bridge "outside" the G-string and in perpendicular to the top plate. In the two curves shown it can be seen that a total mass of the tape (20 g) mainly has reduced the magnitude and the sharpness of peaks and dips. It also indicates the probable influence of the varnish, which thus mainly should be a moderate adjustment of the violin properties. The input admittance for another violin (no. 3) with the same driving conditions and a silent room is shown in Fig. 7.

The admittance curves of the two violins show two regions of similar features. In the lower frequency region, and, especially, in the range of 300 to 1000 Hz, there are several pronounced peaks. These peaks derive from the eigenmodes presented in the previous paragraph as labelled. If an eigenmode shows up as a peak at its resonance frequency, it means that it is driven. Thus, we can see that the driving varied somewhat between the two violins, but in general the following was found for all four violins. The eigenmodes C 1 and N are weakly driven via the bridge. The A 0- and T 1-modes are clearly driven via the bridge. The C 2-mode is weakly driven, but C 3 and C 4 are strongly driven. In the experiments it was furthermore found that the higher top plate and back plate modes in general are driven via the bridge, both those with small and those with large vibrations in the bridge region. For complete-

ness, resonance frequencies and Q -factors were measured after the experiments had been completed. The driving and supporting positions were selected to optimize the conditions for measurements (effective driving and small influence of the supports on the eigenmode investigated). The frequency and the -3 dB bandwidths of the resonance peak were recorded and the Q -factor calculated. The results are given in Table I.

In the higher frequency range there is a broad peak containing several minor peaks. The maximum of this broad peak falls at approximately 3 kHz, i. e., in the range of the first major resonance of the bridge, Reinicke [15, 16]. Two simple follow-up experiments were performed, one with massloading of the bridge and the second by pushing wedges in the bridge "cuttings". The frequency of this broad peak maximum decreased to 2.5 kHz and increased to 3.8 kHz in the two experiments, cf. Fig. 8. Furthermore, the 3 kHz peak does not show up in the input admittance recorded at the top plate close to the left bridge foot. These results support the interpretation that the broad peak derives from the first major bridge mode.

The peakiness of an input admittance curve depends on the internal losses in the violin (cf. Fig. 6) and the frequency difference between adjacent peaks.

Table I.
Resonance frequencies and Q -factors of the four violins, recorded with optimum conditions, and their corresponding centre and deviation measures. Violin No. 1 is covered with reflexive tape and No. 2 to 4 not.

Mode	Violin				centre \pm dev.
	No. 1	No. 2	No. 3	No. 4	
	Frequency				
	Hz	Hz	Hz	Hz	Hz
C 1	184	168	167	169	176 ± 9
N	282	287	263	283	275 ± 12
A 0	284	255	288	277	271 ± 16
C 2	401	369	384	326	363 ± 38
T 1	476	421	459	437	448 ± 27
C 3	578	489	512	518	533 ± 45
C 4	774	603	697	743	688 ± 85
<i>Q</i> -factor					
C 1	122	80	67	56	89 ± 33
N	51	46	61	41	51 ± 10
A 0	12	18	26	28	20 ± 8
C 2	48	74	69	35	55 ± 20
T 1	29	41	27	46	36 ± 10
C 3	33	49	41	34	41 ± 8
C 4	45	42	61	27	44 ± 17

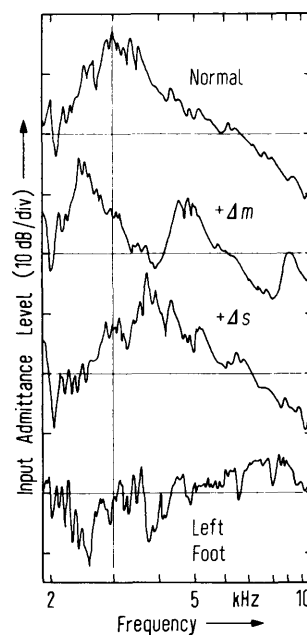


Fig. 8. Perturbations of the first main bridge resonance. Input admittance measured as in Fig. 7 for the bridge in normal condition (upper curve), two 0.5 g masses attached at each of the upper two corners of the bridge (second curve), and wedges in the cuts at the bridge waist (third curve). Input admittance perpendicularly to the top plate at the left bridge foot (bottom curve). The thin horizontal lines correspond to the same level.

For low internal friction and large differences in resonance frequencies, a sharp peak is obtained for every resonance and a sharp dip between every pair of peaks. When the internal friction is large and the frequency differences are small, i. e., the widths of the peaks are of the same magnitude as the frequency differences, we should expect a smoother frequency response (adjacent poles and the zeros of the polynomial describing the input admittance function “neutralize” each other). The number of resonances in the violin top plate can be estimated. We assume the top plate to be flat with a size of $0.15 \times 0.35 \times 0.003 \text{ m}^3$ (width(w) \times length(l) \times thickness(h)) and calculate a width to give the same resonance frequencies with the longitudinal velocity (c) (typical values for spruce, $c_{\text{long}} = 5460 \text{ m/s}$, $c_{\text{cross}} = 1260 \text{ m/s}$). This gives an effective width: $w_0 \approx 4w$.

Within the frequency band Δf we should obtain for one plate the number of resonances

$$\Delta N = \frac{w_0 l}{3.6 c h} 2 \pi \Delta f,$$

see ref. [17].

From the calculated numbers and the equation we should expect to find one resonance per 50 Hz. The back plate should have approximately the same resonance density, i. e. we should expect a magnitude of four resonances per 100 Hz in the violin. From our experiments identifying eigenmodes we have found one resonance per 100 Hz, cf. Fig. 5 and [2].

The input admittance plots Figs. 6 and 7 contain approximately 40 peaks from 50 to 10 000 Hz, i. e. one peak every 250 Hz. This number is somewhat smaller than the theoretically predicted and experimentally measured (four and one resonance per 100 Hz respectively).

By means of a special filter bank, MARS, Till [18], it was investigated what resonance properties are likely to be hidden in the details of the input admittance curve. The filterbank MARS is principally the same construction as used by Mathews and Kohut [19], i. e. a large number of electronic resonance circuits connected in parallel and with independently variable resonance frequencies and Q -factors. MARS contains 40 resonance circuits that can be evenly spread up to 10 kHz. In its normal function MARS reproduces curves equivalent to the input admittance of a mechanical multiresonance system such as that of the violin. The present investigation was limited to the frequency range 2 to 2.8 kHz. Input admittance curves, corresponding to different combinations of resonances and Q -factors together with input admittance plots of the four violins, are given in Fig. 9. The curve corresponding to one resonance per 200 Hz ($N=5$ and thus closest to one per 250 Hz)

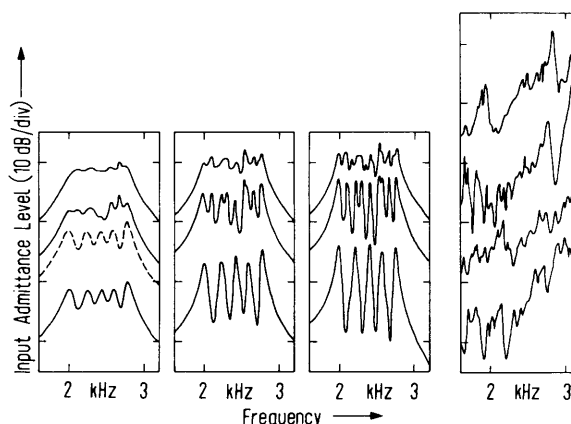


Fig. 9. Modelled (first three boxes) and recorded input admittances (the right box) curves between 2 and 3 kHz. The left box corresponds to $Q \approx 17$, the second to $Q \approx 35$, and the third to $Q \approx 50$. The upper curves contain 17 resonances, the middle curves nine resonances, and the bottom curve five resonances. The full line bottom curves are shifted -10 dB , their correct position is marked by the broken lines in the left box. The right box contains input admittance curves measured for the four violins (shifted along the vertical axis to make the detailed structure show up).

gives either reasonable level variations but too rounded peaks or reasonably sharp peaks but much too large level variations compared to measured input admittance curves. Doubling the number of peaks, $N=9$, gives a better fit, while a second doubling, $N=17$, with a Q -factor of 50 gives a good approximation of the detailed structure of the input admittance curve, i. e., after subtracting effects of one or two prominent peaks and the up-hill slope from the first bridge resonance, cf. Fig. 8. Thus, it seems safe to conclude that we have 10 to 20 resonances (i. e., close to the theoretical predictions) with Q -factors of 30 to 50 giving the detailed structure of the input admittance curve, at least at 2 to 3 kHz. This means that the violin in this range should be regarded as a multiresonator system with the spacing of the resonance of the same magnitude as the bandwidths of the resonances. In this system the input admittance level is better described by the density of resonances and their Q -factors than the properties of the closest two resonances.

Two more factors related to the driving should be discussed: the soundpost and the vibrations around the driving region. The input admittances recorded at the left and at the right foot of the bridge are rather different, see Fig. 10 a. At the T1-eigenmode we have already shown that the vibrations are large at the left foot and small at the right foot (i. e., at the soundpost). Measurements on violins 1 and 2 show that the differences are 20 dB in the input admittance level at the T1-resonance. This difference

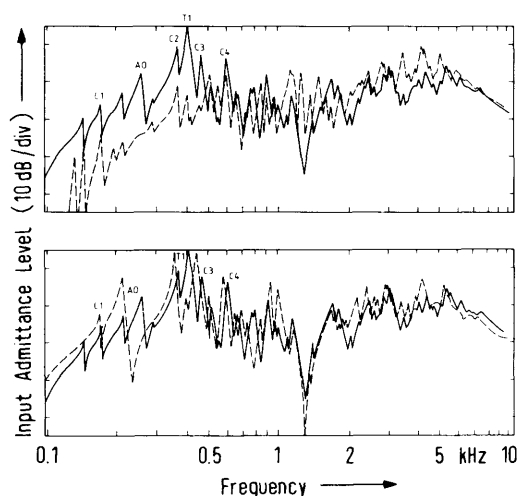


Fig. 10. Input admittance curves for violin 2 (with reflexive tape) recorded at the left bridge foot (full line), and at the right bridge foot with soundpost in (broken line, upper box), and at the left bridge foot with soundpost (full line) and without soundpost (broken line, lower box). The five lowest peaks are labelled.

holds, not only for the T1-eigenmode, but for the low frequency range up to approximately the C3-resonance (cf. Fig. 10 a). For higher frequencies there is a tendency for the opposite relation. A more careful analysis for the higher frequency range for all four violins gives that the driving point vibrations are on the average (2.6 ± 1.7) dB lower (averaged in critical bands of hearing) on the left side from 0.9 to 10 kHz. Thus, it was found that the G-string side of the bridge drives most efficiently for low frequencies (below 600 Hz) and the E-string side for high frequencies (above 1000 Hz). The two bridge sides drive approximately even in-between (600 to 1000 Hz), i.e., in the frequency range of the C4-resonance. With the soundpost taken out, the levels of the input admittances at the left and the right sides are approximately the same, and the same as at the left bridge foot with soundpost in, see Fig. 10 b.

Furthermore, the driving point vibrations at the left bridge foot were compared with the vibrations of four other points around the bridge (at approximately 1 cm from the bridge). In the higher frequency range (above 900 Hz) the vibration level is (3.1 ± 1.9) dB higher at the driving point than the other four points (averaged in critical bands of hearing) for all four violins. The result implies an energy loss in the driving.

Finally, the vibration levels were measured at the driving point, the other four points close to the bridge, two points within the upper bouts, and two points within the lower bouts. The measures were averaged in critical bands of hearing for all four

violins. In the region 900 to 3000 Hz, it was thus found that the vibrations close to the bridge tend to be smaller than those within the bouts, (-2 ± 2) dB, but larger for 3 to 10 kHz, $(+2 \pm 3)$ dB. This means that the bridge (the driving) is in an area of smaller vibrations than those of the upper and lower parts for frequencies to approximately 3 kHz. The average level drop close to the driving (of 3 dB from the previous paragraph) implies that the driving point vibrations are smaller than those in the upper and lower bouts up to 10 kHz.

5. Conclusions on the function

The vibration patterns of eigenmodes of the four violins were mapped with a TV speckle interferometer for the frequency range 150 to 2000 Hz. For higher frequencies it was difficult to separate different eigenmodes.

Our major findings were that in the lowest frequency range, i.e., 150 to 300 Hz, there are two one-dimensional modes in which the violin vibrates similarly to a free bar. The higher mode derives mainly from the neck with fingerboard and is close in frequency to the Helmholtz' air mode. The range of resonance frequencies of these modes are given in Fig. 5 by the left two short bars along the "body mode" line. The modes are not efficiently driven via the bridge, nor do they radiate sound efficiently. The modes are influenced by holding at the ribs.

In the frequency range 300 to 800 Hz there are three two-dimensional body modes marked by the right three bars along the "body mode" line in Fig. 5. The two highest modes can be driven via the bridge and can radiate sound. All three modes are influenced by holding at the ribs.

The Helmholtz' resonance is the only air resonance, that clearly showed up in wall vibrations. Its resonance frequency range is given by the bar along the "air mode" line in Fig. 5. A distorted first top plate mode, the first bar on the "top mode" line, shows up as a combination of the first top plate mode (obtained for a "clamped" violin) and the second two-dimensional body mode. The Helmholtz' air mode and the first top plate mode are efficiently driven via the bridge and they are efficient sound radiators. They are moderately influenced by clamping at the ribs.

From 700 to 2000 Hz there are many eigenmodes, either in the top or in the back plate, cf. the "top" and "back eigenmode" lines in Fig. 5. These modes can be driven via the bridge and they can radiate sound. They are little influenced by clamping at the ribs.

From the vibration patterns the influence of the holding of the violin can be estimated. If the magnitude of vibrations are large in holding positions, then the magnitude of influence on the vibration properties are large. Thus the normal holding for playing may effect the one- and two-dimensional modes considerably, via holding at the chinrest and the one-dimensional via the neckholding in addition. Moderate influence should be expected on the air-mode and the plate modes. These predictions are supported by previous input admittance measurements with normal violin holding [20].

Input admittance curves were recorded for frequencies from 50 to 10 000 Hz. A comparison of the measured curves with input admittance curves modelled on an electrical filter bank shows that the detailed properties above 2 kHz are set by the resonance density and the damping rather than by single resonances. This result is in agreement with the difficulty to visually separate the eigenmodes in the interferometer above 2 kHz. Gross properties in the high frequency range are set by the bridge main resonance at approximately 3 kHz.

The input admittance measurements have proved that the left bridge foot drives the violin more efficiently up to approximately 800 Hz (the third two-dimensional body mode). For higher frequencies, the right bridge foot tends to be the more efficient driving point. Thus, the low frequency driving is favored at the G-string side but the high frequency driving at the E-string side. The vibration amplitudes around the driving point imply that a measurable fraction is not distributed over the whole top plate.

Acknowledgements

The Institute of Optical Research has supported through many years our interferometric investigations of vibration modes of string instruments, by supplying equipment and technical expertise. For this investigation we were lent the TV speckle interferometer and supported by the expertise of Dr. Leif Ek. This support, for which we are greatly indebted, made this investigation possible.

(Received May 15th, 1981.)

References

- [1] Hutchins, C. M. (ed.), *Benchmark Papers in Acoustics*, Vol. 5: Musical acoustics, Part II, violin family components. Dowden, Hutchinson & Ross, Stroudsburg, Pa 1976.
- [2] Jansson, E., Molin, N.-E., and Sundin, H., Resonances of a violin body studied by hologram interferometry and acoustical methods. *Physica Scripta* **2** [1970], 243.
- [3] Jansson, E. V., An investigation of a violin by laser speckle interferometry and acoustical measurements. *Acustica* **29** [1973], 21.
- [4] Hutchins, C. M., How the violin works. In: *Sound generation in winds, strings, computers*. Royal Swedish Academy of Music, Stockholm 1980, Fig. 10.
- [5] Biedermann, K., Ek, L., and Östlund, L., A TV speckle interferometer. In: *The engineering uses of coherent optics*, ed. E. R. Robertson. Cambridge University Press, Cambridge 1976, p. 219.
- [6] Moral, J. A., Experiments with laser speckle-interferometry and input admittance. Preliminary report (in Swedish) 1980.
- [7] Hutchins, C. M., Tuning of violin plates. In: *Sound generation in winds, strings, computers*. Royal Swedish Academy of Music, Stockholm 1980, Fig. 2.
- [8] Hutchins, C. M., The new violin family. In: *Sound generation in winds, strings, computers*. Royal Swedish Academy of Music, Stockholm 1980, 182.
- [9] Jansson, E. V., On higher air modes in the violin. *Catgut Acoust. Soc. Newslet.* No. **19** [1973], 13.
- [10] Beldie, I. P., Vibrations and sound radiation of violin at low frequency. *Catgut Acoust. Soc. Newslet.* No. **22** [1974], 13.
- [11] Beldie, I. P., Darstellung des Geigenkörpers als ein Schwingungssystem mit vier Freiheitsgraden im tiefen Frequenzbereich. Thesis, Technische Universität, Berlin 1975.
- [12] Firth, I. M., Small device for measuring mechanical admittance. *Catgut Acoust. Soc. Newslet.* No. **25** [1976], 19.
- [13] Firth, I. M., Small mechanical impedance head for use with musical instruments. *Acustica* **35** [1976], 348.
- [14] Jansson, E. V., Tone characteristics of the violin. *Swed. J. Musicology* **60** [1978], 92.
- [15] Reinicke, W., Die Übertragungseigenschaften des Streichinstrumentensteges. Thesis, Technische Universität, Berlin 1972.
- [16] Reinicke, W., Übertragungseigenschaften des Streichinstrumentensteges. *Catgut Acoust. Soc. Newslet.* No. **19** [1973], 26.
- [17] Cremer, L. and Heckel, M., *Structure-borne sound* (transl. E. E. Ungar). Springer-Verlag, Berlin, Heidelberg, New York 1973, p. 453.
- [18] Till, O., Electrical simulation of resonances in string instruments (in Swedish). Dept. of Speech Communication, KTH 1977.
- [19] Mathews, M. V. and Kohut, J., Electronic simulation of violin resonances. *J. Acoust. Soc. Amer.* **53** [1973], 1620.
- [20] Jansson, E. V. and Alonso Moral, J., Recent violin research at KTH. In: *Sound generation in winds, strings, computers*. Royal Swed. Academy of Music, Stockholm 1980, pp. 229–245.
- [21] Jansson, E. V., Function and factors determining quality of the violin. In: *Sound generation in winds, strings, computers*. Royal Swed. Academy of Music, Stockholm 1980, pp. 204–228.