A study of input admittances, vibration properties, and sound radiation of four violins

Alonso Moral, J.

journal: STL-QPSR
volume: 24
number: 2-3
year: 1983
pages: 119-143

http://www.speech.kth.se/qpsr
B. A STUDY OF INPUT ADMITTANCES, VIBRATION PROPERTIES, AND SOUND RADIATION OF FOUR VIOLINS

J. Alonso Moral

Abstract

Four violins were selected to study the relations between input admittances at the bridge, vibration properties, and sound radiation. Answers were sought to two main questions: "How many and which positions of the input admittances should be used to achieve the essential information?" and "Can the sound radiation be predicted from the input admittance?"

Analysis of the experimental results showed that the input admittance on the bridge outside the G-string and perpendicularly to the top plate gives the best information for the low frequency modes. This position also gives good information about the vibrational properties of the violin at the higher frequencies. The input admittance outside the E-string provides a good supplement for the higher frequencies.

The radiation was measured by means of a reciprocal method, and the results showed that the average radiation level can be predicted within ±3 dB from the input admittance curves.

In addition, the following was found about the vibrational properties: (1) The input admittance level varies noticeably more between the different positions than between the different violins. (2) The bridge has a similar motion for the resonances A0, C2, T1, and C3 but a different motion for C4. (3) A high level of the major resonances below 800 Hz implies a high level at the higher frequencies. Furthermore, the following was found about the radiation properties: (1) The sound radiation is rather independent on the direction for low frequencies but strongly dependent on the direction for high frequencies. At high frequencies, the radiation is stronger perpendicular to the top plate than to the back plate, and it is stronger along the violin than across it. (2) By using the ratio radiation to input admittance as a measure of the radiation effectiveness, it is found that the Helmholtz's resonance is a more effective sound radiator than the other resonances. The radiation effectiveness is especially low in the frequency range of the bridge resonance. (3) The results of the directionality of the radiation is, in large, in accordance with previous work with normally played violins.

1. Introduction

The input admittance curve summarizes the vibration properties in an illustrative way and it is easy to measure. Thus, in a previous report, the vibration properties of four violins were measured by means of the input admittance level from 0.1 to 10 kHz. The resonances, up to approximately 1 kHz, are also interpreted in terms of vibration patterns (Alonso Moral and Jansson, 1982a).

The most important way to set the violin in vibration is via the bridge and, furthermore, the bridge is the only place where a driving can be applied without damage to the instrument. Therefore, it is of great interest to investigate the information given by the input admittances at different positions and in different directions of the bridge.
It is also interesting to know how the resonances radiate sound and to establish a relation between the sound radiation and the input admittance.

Thus, the answers to the following two major questions are sought in this work:

1. How many and which positions of the input admittances should be used to achieve the essential information on the vibrational properties?
2. Can the sound radiation be predicted from the input admittance?

To answer the first question, the input admittance curves at five different positions were recorded, three perpendicular to and two in parallel with the top plate.

The sound radiation at different directions was recorded by means of a reciprocal method and the ratio sound radiation to input admittance was used as a measure of the radiation effectivity. In this way, the answer to the second question was sought.

Properties are described in terms of frequencies and levels of resonances below approximately 1 kHz and above in terms of average levels of Bark Bands. The major results of the measurements are analyzed and conclusions are drawn.

2. Experimental instruments

In this investigation the same four violins that we used in the previous work (Alonso Moral and Jansson, 1982a), i.e., a cheap Chinese violin, a Czech violin made in a non-traditional way, a new violin made in a traditional way, and an old violin of unknown origin.

The first two represent samples of violins made in factories in large numbers, the third and the fourth are carefully made by hand. These violins cover larger ranges of variations than for the violin in general (Alonso Moral and Jansson, 1982b).

3. Input admittance

The input admittance, i.e., the resulting velocity at the driving point for given force, represents a measure of how willingly the violin vibrates and how the strings and the body can cooperate.

3.1. EXPERIMENTS

Description of the method

In this work the same system was used to measure the input admittance level (IAL) as that in the previous investigation (Alonso Moral
and Jansson, 1982a,b). In this system the "impedance head" consists of a strong magnet of cobalt fastened to a miniature accelerometer (B&K 8307).

An electrical coil is fed with "constant" current. The coil acts over a small air gap with the magnet and gives a constant driving force. The accelerometer, which is fastened between the magnet and the vibrating object, records the acceleration of the vibrations. The acceleration signal is afterwards amplified and integrated so that the input admittance is obtained.

The "impedance head" is a very simple system possessing ideal properties, i.e., low weight and no internal losses. It moderately perturbs the vibrational properties of the analyzed instruments.

The accuracy of the measures is better than ±1 dB for the levels and is better than ±1 % for the resonance frequencies.

Selected positions

The most important forces caused by the strings can be separated into two directions of the plane of the bridge; one perpendicular to the top plate and the other parallel with the top plate. The string forces act in different points on the bridge. To get a good description of the acceptance of the vibrations, the input admittance was measured at the five positions shown in Fig. 1, i.e., three perpendicular and two parallel.

Conditions of the violins

The violins were complete for playing except for the chinrest. The strings were damped to obtain the resonances of the violin without the influences of the string resonances.

In these experiments, the violins were suspended in rubber bands to avoid any external influence from the holding, i.e., approximately freely suspended.

3.2 RESULTS AND DISCUSSION

The experimental material of our first series of experiments consisted of five input admittance curves for each violin. An example of these curves is shown in Fig. 2, where five prominent resonances marked with A0, C2, T1, C3, and C4 can be seen. They correspond to the Helmholtz-, Corpus 2-, Top plate-, Corpus 3-, and Corpus 4-resonances (Alonso Moral and Jansson, 1982a).
Fig. 1. Location of the piezoelectric elements.

Fig. 2. Typical admittance spectra as a function of frequency.

Fig. 3. Cross-section of the piezoelectric element.
The resonances $C_2$ and $T_1$ can split into several peaks in the input admittance curves. When this occurred, the most prominent peak was chosen for the calculations.

A broad hill around 3 kHz is, in large, the result of a bridge resonance.

3.2.1. Frequencies of the resonances $A_0$, $C_2$, $T_1$, $C_3$, and $C_4$

The frequencies of the $A_0$-, $C_2$-, $T_1$-, $C_3$-, and $C_4$-resonances were calculated in terms of the average of the four violins and their standard deviation, shown in Table I.* Every resonance fell in the same order in a specific frequency range for all the analyzed violins. Thus, the frequencies were generally sufficient to identify the major peaks below 1 kHz.

The $T_1$-resonance had the smallest variation ($\pm 3.6\%$) and the $C_3$- and $C_4$-resonances the largest ($\pm 7.1$ and $\pm 8.3\%$, respectively). This is reasonable because the properties of the $T_1$-resonance seem to depend mainly on the top plate, while the $C_3$- and $C_4$-resonances seem to depend on the top plate, the back plate, and the ribs, i.e., on more elements and on more properties that can vary.

For each violin the ratios between the frequencies of the resonances were calculated. These ratios varied little for the different violins, no more than $\pm 6\%$. This suggests that if one resonance frequency of a violin is known then the other resonance frequencies can approximately be predicted. Especially, the ratios between the $T_1$- and $A_0$-frequencies varied little, less than $\pm 2\%$.

3.2.2 Input admittance level (IAL)

The resonance frequencies give a measure of the ratio stiffness to mass, with no information on how effectively the violin can be driven. Therefore, a more detailed investigation of the violin properties should contain the level of the resonances at the different positions. For higher frequencies, i.e., between the 8th and 22nd Bark band, the levels were analyzed in terms of Bark Band average.

IAL of the $A_0$-, $C_2$-, $T_1$-, $C_3$-, and $C_4$-resonances as functions of the position

A survey of the IAL of the $A_0$-, $C_2$-, $T_1$-, $C_3$-, $C_4$-resonances and their averages as functions of the position for each violin and the average of the four violins is shown in Fig. 3. We can observe that the

* Tables I - IX are to be found on pp. 141-143.
IALs varied noticeably from one position to another and also from one violin to another. The IAL varied in average level mainly but also in shape.

The dissimilarities in the "average level" were analyzed in the following way. The standard deviation of the five positions were calculated for all pairwise combinations of resonances and violins. Thereafter, the average standard deviations for the different resonances were calculated and, finally, the average standard deviation for all pairwise combinations.

In the same way, the standard deviations for the four violins were calculated for all pairwise combinations of resonances and positions as well as the average standard deviations for the different resonances and for all combinations.

Thereby it was found that the dissimilarities (measured as standard deviations for all pairwise combinations) between the different positions were larger than between the different violins, 5.7 and 3.3, respectively. Thus, it is necessary to define the exact recording position for the IAL-comparisons between different violins. The resonance T1 has the highest dissimilarity (average standard deviations) for the five positions (7.2 dB) and the resonance C3 has the highest one between the different violins (4.6 dB). These results imply that the T1-resonance is the most sensible for the position of measurement. The C3-resonance varies most between the different violins.

We can also observe in Fig. 3 that the shape of the IAL-curves for the different violins tends to be similar for every resonance. The similarity is high for the A0-resonance and decreases progressively for the C2-, T1-, C3-, and C4-resonances.

It is also shown in Fig. 3 that position 2, i.e., besides the G-string on the bridge perpendicular to the top plate, gives generally the highest IAL for all the resonances. The resonance C4 is efficiently driven from the three perpendicular driving positions, but it is inefficiently driven from the two parallel driving positions. The numerical values (averaged for the four violins) for each resonance at different positions are shown in Table II together with the average for each position and each resonance. The table shows that the IAL at position 2 gives on the average the highest level (−27.9 dB). The second highest average is found in position 1, i.e., besides the G-string parallel with the top plate (−31.6 dB). The other positions give lower levels, especially position 3 (−38.8 dB). Thus, the major resonances below 800 Hz
Fig. 3. Input admittance level (dB) re 1 s/kg as a function of position.
are best driven from position 2 and somewhat less well from position 1, i.e., the lowest resonances are best driven close to the position where the G-string forces act.

**Similarity of the resonances as functions of the positions**

The IAL of the resonances A0, C2, T1, C3, and C4 as a function of the positions averaged for the four violins (the thick line of the Fig. 3a,b,c,d,e) shows that the relative levels as functions of the positions are similar for some resonances. The similarities between the different resonances as functions of the positions are calculated by means of the correlation coefficient, see Table III. A high correlation is found between the vibration levels of the resonances A0 and T1 (r=0.99). The high correlation verifies the similarity of the vibrations of the A0- and T1-resonances at the bridge. There is also a high correlation between the resonances A0 and C3 (r=0.89) and between T1 and C3 (r=0.87). These high correlations imply that an efficient driving for one of these resonances is also efficient for the other two. The results are in agreement with the similarity shown by the A0-, T1-, and C3-vibration patterns of the tap plates.

The IAL of the resonances C2 and A0 and the resonances C2 and T1 also correlate well (r=0.89 and r=0.85, respectively) while the resonances C2 and C3 correlate slightly less (r=0.79). The C2-resonance correlates well with the IAL of the A0-, T1-, and C3-resonances although the vibration patterns of C2 are rather different from those of the A0, T1, and C3. Still, if we observe that the bridge rocks in a similar way in C2 as in the A0-, T1-, and C3-resonances, then the results are reasonable. Furthermore, C2 is lying close in the frequencies to A0 and T1 and, thus, these resonances can add considerably to the vibrational properties at the frequency of C2 and, thus, make the vibrations at this resonance somewhat similar to A0 and T1.

The IAL:es of the C4-resonance, on the other hand, correlate negatively and moderately with the IAL:es of the A0-, T1-, and C3-resonances (r=−0.28, r=−0.34, and r=−0.45, respectively). The results show that in the position in which the A0-, T1-, and C3-resonances are efficiently driven, the C4-resonance has a tendency to be inefficiently driven. Thus, one can say that C4 has a supplementary character to the other three resonances. No correlation is found between the IAL:es of C4 and C2 (r=0.00).
Fig. 4. Input admittance level (dB re 3 s/kg) of the different positions as functions of the resonances.

Fig. 5. Input admittance level (dB re 3 s/kg) as a function of Bark Band (average of all the violins and positions). The vertical lines represent the standard deviation, for the different positions (broken lines), and for the different violins (full lines).
Level of the different positions as functions of the resonances

In Fig. 4 the average IAL of different positions and the average of all the positions as a function of the resonances are shown. T1 has the highest level in these averages. The numerical values shown in Table II give for the T1-resonance an IAL of -28.5 dB and a somewhat lower IAL for the C3- and C4-resonances (-32.2 and -31.0 dB, respectively). The C2-resonance has a lower level (-36.1 dB) and the AO-resonance a level approximately 13 dB lower than the T1-resonance. Thus, the prominent resonances in the vibration levels are T1, C3, and C4. In a previous investigation, the level of these resonances proved to correlate well with the quality of the violins (Alonso Moral and Jansson, 1982b).

Similarity of the positions as functions of the resonances

A comparison between the different curves, Fig. 4, shows that at some positions the curve courses are similar. These similarities between the different positions as function of the resonances were estimated by the correlation coefficient, see Table IV. The highest correlations were found between positions 3 and 4 and between positions 1 and 5 (0.90 and 0.88, respectively). This means that positions 3 and 4 give similar information about the resonances AO, C2, T1, C3, and C4. Positions 1 and 5 also give similar information between each other. The position pairs (1,2), (2,3), (2,4), (2,5) have a lower correlation between 0.60 and 0.75. The position pairs (1,3), (1,4), (3,5) and (4,5) have a low or negligible correlation. If we calculate the correlation average between the different position pairs, we find, that the pairs including position 2, give the highest average. It is to be interpreted that position 2 gives most information for the resonances.

Similarity of the resonance level as a function of the violin

An estimation about how much the relative level of the resonances AO, C2, T1, C3, and C4 are similar from one violin to another can we get through the correlation coefficient between the different resonances as function of the violin. The results, see Table V, show that the C3- and C4-resonances correlates highest, with a correlation coefficient of 0.99. This implies that the average of the five positions of one of these resonances determines the level of the another resonance. Also the AO- and T1-resonances have a quite high correlation (0.77). Some pairs of resonances correlate well but negatively, for example the pair of the resonances C2 and C3, and the pairs C2 and C4 correlate with a
correlation coefficient of -0.79 and -0.69, respectively. Thus, there is
a tendency that a low LAZl of the C2-resonance implies a high IAL of the
resonances C3 and C4 and vice versa.

If we compare Tables III and V, we can observe that the similarity
of the resonances as a function of the position and as a function of the
violin is quite different. The pairs C3 and C4, e.g., that correlate
well and positively as a function of the violin (0.99), correlate nega-
tively as a function of the position (-0.45). Thus, a high C3 implies a
high C4 on the average for all positions, but C3 and C4 are differently
driven from different positions.

**Input admittance level between the 8th and 22nd Bark Bands**

The IAL between the 8th and 22nd Bark Bands was analyzed in terms
of averages in Bark Bands. The average IAL of all the positions and all
the violins as functions of the Bark Bands is shown in Fig. 5. We can
observe a hill with a maximum at the 16th Bark Band; this hill is caused
by the bridge resonance (Alonso Moral and Jansson, 1982b).

The numerical values are shown in Table VI. The maximum of the
prominence at the 16th Bark Band is approximately 10 dB higher than the
minimum at the 12th Bark Band. Above the 16th Bark Band, the IAL de-
creases progressively and is 15 dB lower at the 22nd Bark Band. The
standard deviations between the different positions and the different
violins are highest around the 10th Bark Band. They tend to decrease
with increasing frequency. As for the resonances A0, C2, T1, C3, and C4,
the IAL between the 8th and the 22nd Bark Bands differs more between the
positions than between the violins.

**Input admittance level between the 8th and 22nd Bark Bands for different
positions**

The IAL between the 8th and 22nd Bark Bands for different positions
is shown in Fig. 6. The levels between the different positions are
different from the 8th to the 12th Bark Bands. For higher Bark Bands,
i.e., from the 15th to the 22nd, the IAL of the three perpendicular
positions has a similar level and they have approximately a 6-dB higher
level than the two parallel positions; also the two parallel positions
have a similar level between each other.

Numerical results for the average IAL (from the 8th to the 22nd
Bark Bands) show that the highest levels are given for positions 4 and 2
(-37.4 and -38.5 dB, respectively), a somewhat lower level for position
3 (-40.0 dB), and the lowest for the two parallel driving positions (position 1, -41.0 dB and position 5, -42.4 dB). Thus, the perpendicular drivings produce higher vibrations levels. Position 4 produces the highest levels.

Similarity between the IAL of the different positions and between the 8th and the 22nd Bark Bands

In Fig. 6 we can see a certain similarity of the curve courses for the different positions. A numerical estimation of the similarity between the IAL of the different positions is shown in Table VII. The pairs (1,4), (2,4), and (1,5) give the highest similarity. Positions 2 and 4 are symmetrical relative to the bridge and the directions in positions 1 and 5 are in parallel; thus, these common properties can explain the higher similarity. Positions 1 and 4 have the highest correlation and show a similar curve course between the 8th and the 22 Bark Bands but different levels.

The average correlation with all positions included was calculated. This average is highest with the including of position 4 (0.74) and position 2 (0.73). The average is lowest with the including of position 3 (0.59). We interpreted the results as that positions 4 and 2 give the most similar information about the other positions and that position 3 gives the most dissimilar.

Relation between the IAL of the resonances A0, C2, T1, C3, and C4 and the IAL at the higher frequencies

The relations between the IAL of the resonances A0, C2, T1, C3, and C4 and the IAL at the higher frequencies were also calculated through the correlation coefficients.

The correlation between these lower resonances and the average level from the 8th to the 22nd Bark Bands as a function of the position is shown in Table VIII, column a. The correlation between the resonances and the average levels from the 14th to the 18th Bark Bands is given in Table VIII, column b. The 14th to the 18th Bark Bands are calculated separately because they correspond to the frequency range of the main bridge resonance. It is shown that the level of the C4-resonance correlates very well with the level at the higher frequencies (0.994 from the 8th to the 22nd Bark Bands and 0.997 from the 14th to the 18th Bark Bands). The results imply that a strong C4-resonance means a high vibration level at the higher frequencies. The correlation
is negative or negligible between the high frequency levels and the levels of AO, C2, T1, and C3.

The correlation between the levels of the resonances and the Bark Bands as a function of the violins is shown in Table IX, columns a and b. All resonance levels correlate positively with the average level between the 8th to the 22nd Bark Bands. This implies that a high level for the resonances in the low frequencies corresponds to a high level at the high frequencies. The correlation between the levels of the resonances and the average level between the 14th and the 18th Bark Bands is positive and high for the resonances AO, C2, and C3, and slightly negative for the resonances C3 and C4. Thus, these results suggest that a high level for the resonances AO, C2, and T1 predicts a high level between the 14th and the 18th Bark Bands, i.e., in the bridge resonance.

4. Sound radiation

According to the acoustical reciprocity theory (Kinsler and Frey, 1982) we can drive the violin with a loudspeaker and measure the vibrations on the bridge to analyze the sound radiation. This transmission corresponds to the driving on the bridge and the measuring of radiated sound with a microphone.

It is practical to work with the reciprocal measures. We can remove the violin but the measuring condition remains constant; furthermore, it is easy to drive the violin with loudspeakers and obtain a high signal-to-noise ratio for the measurement.

The following sound radiation experiments are of pilot character.

4.1. EXPERIMENTS

Description of the method used

To analyze the sound radiation level (RL), the violins were driving a loudspeaker placed 2 m from the center of the violin body and the resulting bridge velocity was measured by means of the accelerometer. The resulting velocity level will be used as a measure of the radiation and will be called the radiation level (RL).

The employed six directions of driving are shown in Fig. 7. As the previous experiments showed that the IAL beside the G-string perpendicular to the top plate gave the most information, this position was selected for the accelerometer. In the experiments, the input admittance at the same position was also measured.

In the cases where the loudspeaker drives in directions 1 and 2,
Fig. 7. Definition of the six directions.

Fig. 6. Input admittance levels (dB re 1" s/ft²) for the different postures as functions of pitch bands (averages of the four positions).

Pitch (Bark)

Input Admittance Level (dB)

Frequency (kHz)
see Fig. 7, the violin was hanging in rubber bands. In the cases of driving in directions 3, 4, 5, and 6, the violin was clamped at the neck to hold it in a horizontal position. The input admittance was measured for both ways of holding.

The analyzed frequency range was from the 3rd to the 18th Bark Bands, i.e., from approximately 0.2 to 4.5 kHz.

Accuracy of the measures

In Fig. 8, the loudspeaker response as a function of frequency is shown. The level of the sound field of the loudspeaker at 2 m distance was measured with a measurement microphone (B&K 1").

Between the 3rd and the 8th Bark Bands, i.e., in the range of the frequencies where we analyzed the violins in terms of peak levels of the resonances, the loudspeaker response varies ±1 dB and between the 8th and 18th Bark Bands, i.e., where we analyzed the violins in terms of the Bark Band average, this average varies ±3 dB.

The loudspeaker has a diameter of 8 cm and the cone is 1 cm deep, which means that the loudspeaker geometry introduces deviations from a simple source. These deviations are less than ±1 dB in the analyzed frequency range.

The reproducibility of the experiments was better than ±1 dB.

4.2. RESULTS AND DISCUSSION

An example of a radiation curve (the full line) and an input admittance curve (the broken line) is shown in Fig. 9. Generally, the peaks coincide in frequency but there is not a simple relation between the levels of the two curves. The radiation curve has, in addition, a more complicated detail structure.

The IAL for the suspended violins is higher than for the clamped violins at the neck, at least below 2 kHz. Thus, we cannot make a direct comparison between the radiation properties of directions 1 and 2 ("clamped" violins) with directions 3 to 6 ("free" violins).

4.2.1. Input Admittance Level (IAL), Radiation Level (RL), and Radiation Effectivity (RE)

The IAL, RL, and RE for the A0-, C2-, T1-, C3-, C4-, and F-resonances* and the average in the Bark Bands between the 10th and 18th Bark Bands as a function of frequency are shown in Fig. 10.

* The next strong resonance after the C4-resonance in the present article we call the F-resonance since we do not know its vibration patterns.
Fig. 9. The full line shows the radiation level (dB) re 0.00002 Pa.

Fig. 8. Loudspeaker response (curve time) between 10 and 18 Bark, the average in Bark bands.

Fig. 7. Also drawn (the straight lines).
Input Admittance Level

The input admittance level outside the G-string perpendicular to the top plate is shown in Fig. 10a. The T1-resonance has the highest level of the resonances below 800 Hz, a somewhat lower level for the C2-, C3-, C4-, and F-resonances, and a noticeably lower level for the A0-resonance.

At the higher frequencies, from 10 to 18 Bark, a clean hill appears with a maximum at the 16th Bark Band, i.e., the maximum related to the bridge resonance.

Radiation Level

A detailed measure of the total sound radiation of a violin is difficult to make; it is easier to estimate how much sound the different resonances radiate.

The average sound radiation is shown in Fig. 10b. We can see that the maximal radiation level of the preceding resonances corresponds to the A0- and T1-resonances, with a level of -37.5 and -39.2 dB, respectively. A somewhat lower level is obtained for the C2-, C3-, C4-, and F-resonances.

Between the 10th and 18th Bark Bands, we can also observe the prominence around the 16th Bark Band, but it is weaker than in the input admittance curve. The standard deviations between the different violins have a tendency to decrease with the increasing Bark Band number.

Radiation Effectivity

A measure of the radiation effectivity can be expressed by the ratio RL to IAL, Fig. 10c. This ratio is highest for the A0-resonance, approximately 13 dB higher than the levels of the T1- and C3-resonances, and slightly lower for the C2- and C4-resonances. The standard deviations between the different violins are less than ±3 dB.

If we look at the higher frequencies, we can note that the effectivity of the radiation goes down strongly in the frequency range of the bridge resonance. In this range, the bridge vibrates in its own plane. Thus, it is reasonable to accept that a high IAL but a low RL can appear around the resonance frequency of the bridge as the bridge vibrations contribute little to the radiation. The deviations measured as standard deviations between the different violins decrease noticeably from the 10th to the 18th Bark Bands. The deviations are always within ±3 dB.

Both for the resonance peaks at the lower frequencies and for the
The vertical lines represent the standard deviations between the different violins. The vertical bars from the 10th to the 18th pitch bands indicate the A-weighted and A-weighted radiation effectiveness. The radiation effectiveness (dB) for the A-weighted bands is shown in the figure. The radiation effectiveness (dB) is shown in the figure.
Bark Band averages at the higher frequencies, the radiation effectiveness does not vary more than ±3 dB between the different violins. Thus, the radiation level can be predicted within these limits from the input admittance curve.

4.2.2. Radiation in different directions

The radiation level at the different directions is drawn in Fig. 11. For directions 1 and 2, the violins were "free", i.e., suspended in rubber bands. Thus, we can compare the results of these directions. We can also compare the results between directions 3, 4, 5, and 6, where the violins were clamped. We cannot directly compare the results between the hung and the clamped violins since the holding conditions noticeably affect the vibrational properties.

A comparison of RL between directions 1 and 2, i.e., perpendicular to the top and back plates respectively, see Fig. 12 (the upper diagram), shows that direction 1 has a tendency to a higher RL than direction 2 for the resonances below 1 kHz. Only the C4-resonance has a higher RL from the back side than from the top side. Between the 10th and the 18th Bark Bands, the top plate side has a noticeably higher RL than the back side (more than 3 dB). The difference becomes still higher in the 16th and the 17th Bark Bands, i.e., in the frequency range of the bridge resonance.

The RL:s for directions 3, 4, 5, and 6 (with the violin clamped at the neck) are given in Fig. 12 (the lower diagram). The RL:s of A0, C2, T1, C3, C4, and F are quite similar in directions 3, 4, 5, and 6. But above the 10th Bark Band, the RL (in Bark Bands) depends strongly on the direction. Direction 5, i.e., along the neck of the violin, gives the highest average RL between the 10th and the 18th Bark Bands. Also direction 3 has a high RL. Directions 4 and 6, i.e., across the violin, have a lower RL, especially direction 6. Thus, there is a clear tendency of a higher RL for the directions "along" the violin than "across" the violin.

4.2.3. Comparisons with a played violin

The radiation for the directions 3, 4, 5, and 6, has previously been analyzed by means of long-time-average-spectra of a violin in normal playing in an anechoic chamber (Jansson, 1976 and 1978). With normal playing, the player perturbs the sound radiation.

From the 15th Bark Band to the 18th, the highest level corresponds
Fig. 11. Sound radiation level for the A0-, C2-, T1-, C3-, C4-, and F-resonances and average level in Bark Bands from the 10th to the 18th Bark Bands. Directions 1 and 2: "freely suspended violins" (the upper diagram). Directions 3 to 6: violins clamped at the neck (the lower diagram).
to direction 5 in both investigations. The tendency to lower levels for
direction 6 relative to direction 4 is also found in both series. How-
ever, direction 3 has for the played violin a very low level but in this
work a high level. This can be expected as the player's body "shadows"
the sound radiated in direction 3.

Thus, there is, at least, a reasonable agreement between the radia-
tion measured of the played violin and the radiation of sinusoidally
driven violins with the played violin excluded.

5. Conclusions

In the introduction of this work we wanted to answer the following
questions about the vibrations and the sound radiation of the violins:

1. How many and which positions of the input admittance curve
should be used to achieve the essential information on the vibrational
properties?

2. Can the sound radiation be predicted from the input admittance?

We have described how the A0-, C2-, T1-, C3-, and C4-resonances are
driven at the different positions and directions on the bridge in terms
of input admittance levels. Furthermore, the average in Bark Bands
between the 8th and the 22nd Bark Band is described.

The analysis of our results shows that position 2, i.e., beside the
G-string perpendicular to the top plate, gives the highest level for the
resonances and that this position gives an information that is the most
similar to the other positions. Between the 8th and 22nd Bark Bands
position 4, i.e., beside the E-string perpendicular to the top plate,
gives the best information and position 2 the next best. Thus, in
answer to the first question we have found the following. With the
input admittance at position 2 only, we can get the essential informa-
tion about the vibrational properties of the violin. The inclusion of
the input admittance at position 4 can noticeably add to the informa-
tion. These two positions are shown to give information about the
vibrational properties that correlated well with the quality of 24
violins (Alonso Moral and Jansson, 1982a).

To answer question 2, the ratio radiation to input admittance was
analyzed. The results show that the average of the radiation level for
the six directions can be predicted within ±3 dB when the input admittance
is known.
In addition, the following was found about the vibrational properties of the violins: (1) The input admittance level between the different positions varies noticeably more than those of the different violins. (2) The bridge of the violin has a quite similar movement for the resonances A0, C2, T1, and C3, but different for the resonance C4. (3) A high level of the resonances below 800 Hz implies a high level at higher frequencies.

The following was found about the radiation properties: (1) The sound radiation is rather insensitive to the direction for the low frequencies but very sensitive to the direction for high frequencies. At high frequencies, the radiation is stronger perpendicular to the top plate than to the back plate, and stronger along the violin than across it. (2) Using the ratio radiation to input admittance as a measure of the radiation effectivity, it was found that the Helmholtz's resonance is a more effective sound radiator than the other resonances. The radiation effectivity is especially low in the range of the frequencies of the bridge resonance. (3) The results of the directionality of the radiation seem to be in accordance with previous work with a normally played violin.

Acknowledgments

The reported work was conducted under the guidance of my thesis advisor, Erik Jansson, and made in the Department of Speech Communication and Music Acoustics with financial support for my doctoral studies from the Royal Institute of Technology. All the cooperation and help are gratefully acknowledged.

References


<table>
<thead>
<tr>
<th>PEAK</th>
<th>A0</th>
<th>C2</th>
<th>T1</th>
<th>C3</th>
<th>C4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average frequency (Hz)</td>
<td>274.3</td>
<td>376.3</td>
<td>428.3</td>
<td>512.0</td>
<td>704.3</td>
</tr>
<tr>
<td>Standard deviation (Hz)</td>
<td>13.4</td>
<td>22.3</td>
<td>15.2</td>
<td>36.5</td>
<td>58.4</td>
</tr>
<tr>
<td>Standard deviation (%)</td>
<td>4.9</td>
<td>5.9</td>
<td>3.6</td>
<td>7.1</td>
<td>8.3</td>
</tr>
</tbody>
</table>

**Table I.** Measured frequencies of resonance peaks in terms of average and standard deviations for the four violins.

<table>
<thead>
<tr>
<th></th>
<th>Pos.1</th>
<th>Pos.2</th>
<th>Pos.3</th>
<th>Pos.4</th>
<th>Pos.5</th>
<th>Average stand.dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>(dB)</td>
<td>(dB)</td>
<td>(dB)</td>
<td>(dB)</td>
<td>(dB)</td>
<td>(dB)</td>
<td>(dB)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Resonance A0</td>
<td>-37.5</td>
<td>-36.0</td>
<td>-46.4</td>
<td>-46.0</td>
<td>-40.4</td>
<td>-41.3</td>
</tr>
<tr>
<td>Resonance C2</td>
<td>-31.6</td>
<td>-29.4</td>
<td>-44.4</td>
<td>-37.6</td>
<td>-37.5</td>
<td>-36.1</td>
</tr>
<tr>
<td>Resonance T1</td>
<td>-21.9</td>
<td>-20.5</td>
<td>-36.0</td>
<td>-37.4</td>
<td>-26.9</td>
<td>-28.5</td>
</tr>
<tr>
<td>Resonance C3</td>
<td>-30.3</td>
<td>-28.3</td>
<td>-38.4</td>
<td>-35.4</td>
<td>-28.3</td>
<td>-32.1</td>
</tr>
<tr>
<td>Resonance C4</td>
<td>-36.6</td>
<td>-25.1</td>
<td>-28.9</td>
<td>-25.4</td>
<td>-39.0</td>
<td>-31.0</td>
</tr>
<tr>
<td>Average</td>
<td>-31.6</td>
<td>-27.9</td>
<td>-38.8</td>
<td>-36.3</td>
<td>-34.3</td>
<td></td>
</tr>
<tr>
<td>Stand.dev.</td>
<td>5.6</td>
<td>5.1</td>
<td>6.2</td>
<td>6.6</td>
<td>5.7</td>
<td></td>
</tr>
</tbody>
</table>

**Table II.** Input admittance level for the resonance peaks at the different positions (average of the four violins).

<table>
<thead>
<tr>
<th>RESONANCE</th>
<th>A0</th>
<th>C2</th>
<th>T1</th>
<th>C3</th>
<th>C4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.00</td>
<td>0.89</td>
<td>0.99</td>
<td>0.89</td>
<td>-0.28</td>
</tr>
<tr>
<td>A0</td>
<td>1.00</td>
<td>0.85</td>
<td>0.79</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>C2</td>
<td>1.00</td>
<td>0.87</td>
<td>-0.34</td>
<td>1.00</td>
<td>-0.45</td>
</tr>
<tr>
<td>C3</td>
<td>1.00</td>
<td></td>
<td></td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.00</td>
</tr>
</tbody>
</table>

**Table III.** Correlation between the input admittance level of the resonances (average of the four violins) as functions of positions in terms of correlation coefficients.

<table>
<thead>
<tr>
<th>POSITION</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.00</td>
<td>0.73</td>
<td>0.13</td>
<td>-0.04</td>
<td>0.88</td>
</tr>
<tr>
<td>2</td>
<td>1.00</td>
<td>0.74</td>
<td>0.61</td>
<td>0.63</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1.00</td>
<td>0.90</td>
<td>0.23</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>1.00</td>
<td>0.05</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table IV.** Correlation between the input admittance level of the different positions (average of the four violins) as functions of the resonances in terms of correlation coefficients.
### Table V. Correlation between the input admittance level of the resonances (average of the five positions) as functions of the violins in terms of correlation coefficients.

<table>
<thead>
<tr>
<th>POSITION</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.00</td>
<td>0.72</td>
<td>0.41</td>
<td>0.86</td>
<td>0.80</td>
</tr>
<tr>
<td></td>
<td>1.00</td>
<td>0.75</td>
<td>0.82</td>
<td>0.62</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.00</td>
<td>0.55</td>
<td>0.65</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.00</td>
<td>0.74</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Table VI. Input admittance level of Bark Band average in terms of averages and standard deviations (average of the four violins and the five positions).

<table>
<thead>
<tr>
<th>BARK</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
<th>15</th>
<th>16</th>
<th>17</th>
<th>18</th>
<th>19</th>
<th>20</th>
<th>21</th>
<th>22</th>
<th>Av</th>
</tr>
</thead>
<tbody>
<tr>
<td>I A L Average violins</td>
<td>-37.0</td>
<td>-38.5</td>
<td>-41.1</td>
<td>-42.2</td>
<td>-43.6</td>
<td>-41.6</td>
<td>-39.1</td>
<td>-34.1</td>
<td>-33.3</td>
<td>-34.6</td>
<td>-36.5</td>
<td>-40.5</td>
<td>-43.1</td>
<td>-45.2</td>
<td>-48.6</td>
<td>-39.9</td>
</tr>
<tr>
<td>STANDARD DEV. Diff. positions</td>
<td>4.4</td>
<td>4.6</td>
<td>5.1</td>
<td>4.7</td>
<td>2.8</td>
<td>2.1</td>
<td>2.1</td>
<td>2.0</td>
<td>3.2</td>
<td>2.9</td>
<td>3.3</td>
<td>2.6</td>
<td>2.0</td>
<td>1.8</td>
<td>3.4</td>
<td>3.1</td>
</tr>
<tr>
<td>STANDARD DEV. Diff. positions</td>
<td>2.4</td>
<td>3.1</td>
<td>3.1</td>
<td>1.9</td>
<td>2.1</td>
<td>2.1</td>
<td>2.1</td>
<td>2.0</td>
<td>2.3</td>
<td>1.2</td>
<td>1.4</td>
<td>1.8</td>
<td>2.3</td>
<td>1.8</td>
<td>1.1</td>
<td>2.1</td>
</tr>
</tbody>
</table>

### Table VII. Correlation between the input admittance level of the different positions (average of the four violins) as functions of the 8th to the 22nd Bark Bands in terms of correlation coefficients.
Table VIII. Correlation between the input admittance level of the higher frequencies and the resonance peak levels of A0, C2, T1, C3, and C4 as functions of the position (average of the four violins) in terms of correlation coefficients.

<table>
<thead>
<tr>
<th></th>
<th>From the 8th to the 22nd Bark Bands</th>
<th>From the 14th to the 18th Bark Bands</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resonance A0</td>
<td>-0.27</td>
<td>-0.35</td>
</tr>
<tr>
<td>Resonance C2</td>
<td>0.12</td>
<td>-0.08</td>
</tr>
<tr>
<td>Resonance T1</td>
<td>-0.35</td>
<td>-0.41</td>
</tr>
<tr>
<td>Resonance C3</td>
<td>-0.40</td>
<td>-0.51</td>
</tr>
<tr>
<td>Resonance C4</td>
<td>0.94</td>
<td>0.997</td>
</tr>
</tbody>
</table>

Table IX. Correlation between the input admittance level of the higher frequencies and the resonance peak levels of A0, C2, T1, C4, and C4 as functions of the violin (average of the five positions) in terms of correlation coefficients.

<table>
<thead>
<tr>
<th></th>
<th>From the 8th to the 22nd Bark Bands</th>
<th>From the 14th to the 18th Bark Bands</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resonance A0</td>
<td>0.83</td>
<td>0.73</td>
</tr>
<tr>
<td>Resonance C2</td>
<td>0.36</td>
<td>0.75</td>
</tr>
<tr>
<td>Resonance T1</td>
<td>0.38</td>
<td>0.79</td>
</tr>
<tr>
<td>Resonance C3</td>
<td>0.29</td>
<td>-0.33</td>
</tr>
<tr>
<td>Resonance C4</td>
<td>0.43</td>
<td>-0.20</td>
</tr>
</tbody>
</table>