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Comparison of Radiated Power From Structurally Different Violins

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The acoustic power has been determined from intensity measurements on three structurally different violins: a Scherl and Roth student violin, Hutchins' SUS295, and Hutchins' mezzo violin SUS100. While each violin was bowed with an open-frame mechanical bowing machine, the intensity measurements were made by scanning each side of the bowing machine with an intensity probe. One-third octave band sound power levels of the acoustic radiation from each of the three instruments as each of the four open strings is bowed show that the structurally different mezzo violin produces greater power at low frequencies when the lowest (G) string is bowed, but this behavior is not evidenced on the other strings.

Acoustic power is a quantity that may be used to describe the sound radiation from a source. Because sound power is independent of the environment and the distance of the observation from the source, it is useful as a measure to compare the overall acoustic radiation from different sources. Violins differ in acoustic power output, depending on their construction and the method of playing. Radiation from violins has been the subject of several studies (Hutchins 1983, Hutchins and Benade 1997). Some of these studies have focused on specific aspects of acoustic radiation, such as directivity patterns (Meyer 1972, Bissinger 1995, Wang and Burroughs 1999), or frequency spectra (Saunders 1937, Gabrielsson and Jansson 1979, Langhoff 1994). However, a comparison of the total acoustic power radiated from different types of violins bowed in a consistent manner has not been shown. Such a comparison is reported in this paper.

In an in-depth study on the radiation mechanisms of violins (Wang and Burroughs 2001), three violins were tested which vary in quality and construction: a Scherl and Roth student violin and two violins by renowned violin maker Carleen Hutchins, SUS295 and mezzo violin SUS100. Of particular interest was the mezzo violin, which has larger top and bottom plates with longer and thinner ribs than a standard violin. The mezzo violin is a part of the Violin Octet and was constructed to produce greater power than the standard violin (Hutchins and Schelling 1967). Here we compare measured levels of acoustic power radiated by the mezzo violin to the measured levels of power radiated by two violins of conventional design. The acoustic intensity around a closed surface surrounding each violin was measured, while the instrument was bowed with an open-frame mechanical bowing machine. Details on the bowing machine are provided elsewhere (Wang and Burroughs 1999). The radiated power was then determined by integrating the sound intensity over the measurement surface that enclosed the violin.

DETERMINING ACOUSTIC POWER FROM ACOUSTIC INTENSITY

Acoustic intensity is a measure of sound energy flux, or sound power per unit area. Standards for determining the acoustic power from sound intensity measurements have been published only in the past decade (ANSI S12.12 1992, ISO 9614/1 1993, ISO 9614/2 1994), since equipment to measure intensity directly has been only recently introduced. The intensity probe employed in this study consists of two facing phase-matched condenser microphones, separated by a known distance, which measure the pressures at the two locations simultaneously (referred to as the 'p-p method'). These two pressure values are averaged to estimate the pressure at a midpoint between the microphones. The particle velocity at the midpoint is calculated from the pressure gradient between the microphones by Euler's equation:

$$\rho_0 \frac{\partial \vec{u}}{\partial t} = -\frac{\partial p}{\partial n} \vec{n}$$

(1)

where $\rho_0$ is ambient density, $\vec{u}$ is particle velocity, $p$ is acoustic pressure, and $\vec{n}$ is a unit vector in the direction of interest.
Integrating both sides and applying a finite difference approximation produces:

\[
\tilde{u}(t) = -\frac{\bar{n}}{\rho_0 d} \int_{-\infty}^{t} \left[ p_1(\tau) - p_2(\tau) \right] d\tau
\]

(2)

where \(d\) is the distance between the microphones, and \(p_1\) and \(p_2\) are the pressures measured by the two facing microphones.

The time-averaged acoustic intensity is then determined from the pressure and particle velocity by:

\[
\bar{I} = \frac{1}{T} \int_{0}^{T} p \tilde{u} \, dt
\]

(3)

where \(T\) is the period of time over which the average is taken. Note that intensity is a vector quantity, which will be considered positive when sound energy is traveling across the surface away from the source under study and negative in the opposite direction.

The scanning method detailed in ISO 9614/2 (1994) was used in this study. First a measurement surface that encloses only the sound source of interest is defined. The total measurement surface is split into a number of defined subsurfaces, and each of the subsurfaces scanned with the intensity probe. The average value of the measured intensity across each subsurface is multiplied with the subsurface area to produce the sound power radiating across the area of the subsurface. Finally all of the powers across the various subsurfaces are added to determine the total radiated acoustic power.

**EXPERIMENTAL MEASUREMENTS AND RESULTS**

The intensity probe used in this study consisted of two Bruel and Kjaer (B&K) phase-matched 1/2" microphones (type 4181), suitable for measurements between 50 and 6300 Hz (Hewlett Packard 1992), connected to a Hewlett Packard 3569A real-time frequency analyzer. Two spacers were employed to separate the microphones: a spacing of 50 mm was used for measurements up to 1250 Hz, and a spacing of 10 mm for measurements from 125 to 5000 Hz (Wasner and Crocker 1984). The microphones were first individually calibrated with a pistonphone calibrator (B&K type 4230). Then, the two microphones were placed in a cavity calibrator (model #HP353236A) to check their residual pressure-intensity index, \(L_{pa}\), which is the difference between the measured sound pressure level and sound intensity level in the field, was measured while the violin was bowed to determine if the testing environment was highly reactive which would lead to inaccurate intensity results (Fahy 1995). Values of \(L_{pa}\) were found to be acceptable with both the 10 mm and 50 mm spacers. The second field check involved two measurements of the bowed violin, first with the probe oriented in the direction of the source and then with the probe turned 180° so that it was oriented in the opposite direction away from the source. Both positions displayed intensities which were approximately the same magnitude (within 2 dB), but with opposite sign, as expected.

The intensity probe was manually swept across the five planar surfaces delineated by the bowing machine’s frame. Each of the five surfaces was scanned in a uniform manner while the analyzer performed a linear average of the intensity in one-third octave bands.

**Table 1: Test parameters applied during intensity probe sweeps for each string excitation. The fundamental frequency of the string is provided.**

<table>
<thead>
<tr>
<th>One-third Octave</th>
<th>Open G (196 Hz)</th>
<th>Open D (294 Hz)</th>
<th>Open A (440 Hz)</th>
<th>Open E (660 Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Band Center</td>
<td>160-3150 Hz</td>
<td>200-3150 Hz</td>
<td>250-3150 Hz</td>
<td>400-3150 Hz</td>
</tr>
<tr>
<td>Frequency Range</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bow Force</td>
<td>1.15 N</td>
<td>0.55 N</td>
<td>0.55 N</td>
<td>1.4 N</td>
</tr>
<tr>
<td>Belt Velocity</td>
<td>0.35 m/s</td>
<td>0.35 m/s</td>
<td>0.35 m/s</td>
<td>0.35 m/s</td>
</tr>
<tr>
<td>Bow-bridge</td>
<td>2.5 cm</td>
<td>2.5 cm</td>
<td>2.5 cm</td>
<td>2.5 cm</td>
</tr>
<tr>
<td>Distance</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

An open-frame mechanical bowing machine was used to produce a controlled excitation of the violin that closely approximated the manner in which violins are excited while being played by a violinist (Wang and Burroughs 1999). Measurements were conducted as each of the four open strings on each violin was excited. Since the magnitude and harmonic distribution of the power depend on bowing parameters, constant values of these parameters were maintained during the measurements on the same string for each of the three instruments (Table 1). However, values of bow force did differ between measurements from different string excitations. This parameter was adjusted so that the bowing machine produced a similarly strong sound on each string. Because the bowing parameters changed between string excitations, comparisons of the measured powers can be made between instruments with the same string excitation, but not when different strings are excited.

The bowing machine was placed on a concrete floor in a semi-anechoic chamber with dimensions of 5.5 m by 6.8 m by 9.3 m. Two sets of preliminary measurements were conducted to ensure that recommended field conditions were met. First, the pressure-intensity index, \(L_{pa}\), defined as the difference between sound pressure level and sound intensity level in the field, was measured while the violin was bowed to determine if the testing environment was highly reactive which would lead to inaccurate intensity results (Fahy 1995). Values of \(L_{pa}\) were found to be acceptable with both the 10 mm and 50 mm spacers. The second field check involved two measurements of the bowed violin, first with the probe oriented in the direction of the source and then with the probe turned 180° so that it was oriented in the opposite direction away from the source. Both positions displayed intensities which were approximately the same magnitude (within 2 dB), but with opposite sign, as expected.

The intensity probe was manually swept across the five planar surfaces delineated by the bowing machine’s frame. Each of the five surfaces was scanned in a uniform manner while the analyzer performed a linear average of the intensity in one-third octave bands.
Figure 1: The dB difference between averaged intensity measurements over the front side of the bowing machine frame, using two different bowing belts. Differences are low, indicating good repeatability between belts. Measurements were made while bowing the open G string, using the 50 mm spacer and 10 mm spacer in the intensity probe.

One-third octave bands

<table>
<thead>
<tr>
<th>One-third octave bands (Hz)</th>
<th>2000</th>
<th>1600</th>
<th>1250</th>
<th>1000</th>
<th>800</th>
<th>630</th>
<th>500</th>
<th>400</th>
<th>315</th>
<th>250</th>
<th>200</th>
<th>160</th>
<th>125</th>
<th>100</th>
<th>80</th>
<th>63</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 mm spacer</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td>■</td>
</tr>
<tr>
<td>10 mm spacer</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
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<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
</tr>
</tbody>
</table>

One-third octave band sound power levels for the three violins are shown in Figures 2 through 5 for the bowing of each of the four open strings, along with the background noise levels. Also shown in Figures 2 through 5 are the number of bowed harmonics with frequencies that fall within the respective one-third octave band.

Figure 2: Radiated power in one-third octave bands whose center frequencies are listed, from bowing the three test instruments on the open G string. Also shown are the background noise levels in the test environment and the number of bowed harmonics which lie in each frequency band.

Open G string excitation

Sound Power Level (dB re 10⁻¹² W)

<table>
<thead>
<tr>
<th>One-third octave bands (Hz)</th>
<th>160</th>
<th>200</th>
<th>250</th>
<th>315</th>
<th>400</th>
<th>500</th>
<th>630</th>
<th>800</th>
<th>1000</th>
<th>1250</th>
<th>1600</th>
<th>2000</th>
<th>2500</th>
<th>3150</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scherl&amp;Roth</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td>■</td>
</tr>
<tr>
<td>SUS295</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td>■</td>
</tr>
<tr>
<td>Mezzo</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td>■</td>
</tr>
<tr>
<td>Background Noise</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td>■</td>
</tr>
<tr>
<td>Bowed harmonics</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td>■</td>
</tr>
</tbody>
</table>

over the chosen measurement time period, typically 60 seconds. At least two sweeps were made per side, and the resulting data were averaged. Data for the open G and open D strings were acquired with both the 50 mm and 10 mm microphone spacers. The results from the two spacers at overlapping one-third octave frequency bands from 400 to 1000 Hz were typically within 2 dB of each other and subsequently averaged. For the open A and open E strings, tests were only conducted with the 10 mm spacer. Two different belts for bowing were used during the intensity measurements. The use of different belts had little effect on the intensity results, as shown in Figure 1.

One-third octave band sound power levels for the three violins are shown in Figures 2 through 5 for the bowing of each of the four open strings, along with the background noise levels. Also shown in Figures 2 through 5 are the number of bowed harmonics with frequencies that fall within the respective one-third octave band.
ANALYSIS OF RESULTS
Figure 2 shows the sound power levels for the radiation from the violins with the G string bowed. The behavior of the three violins do differ. The mezzo violin radiates the most sound power in the frequency band which includes the second harmonic (392 Hz), but the other two instruments radiate the most at the third harmonic (588 Hz). Also apparent is the mezzo violin’s greater power at frequencies below 500 Hz compared to the other two instruments. In the 400 Hz one-third octave band, it produces levels which are more than 10 dB greater than the levels for the other two violins. Apparently the input signal produced by bowing the G string couples well with low frequency modes of the mezzo violin, radiating more sound power at low frequencies. This is supported by other data from the mezzo violin, including admittance measurements from SUS100 which demonstrate more peaks in the low frequency range than for standard violins such as the Scherl and Roth (Fig. 6). Also the radiativity of another mezzo violin measured by Weinreich (1985) indicated that the instrument has a greater radiativity at low frequency resonances than standard violins.

The results in Figure 2 show furthermore that SUS295 has a strong response not seen in the other two instruments in the 630 Hz band, but above 1250 Hz, all three instruments have similar levels. Even with the increased number of bowed harmonics, the radiated power at these higher frequency bands is moderate. The overall radiated power with the G string bowed is similar for the two Hutchins’ violins, at a level noticeably greater (at least 5 dB) than for the Scherl and Roth violin.

For the bowed D string, a comparison between instruments as shown in Figure 3 fails to show a similar dominance of the mezzo violin at low frequencies. All three instruments radiate the most power in the one-third octave band which encompasses the fundamental frequency or first harmonic (294 Hz), but SUS295 exhibits a smaller response than the other two in the low frequency range. The mezzo violin and the Scherl and Roth appear similar in the lowest bands but then diverge at higher frequencies. Overall, the three violins radiate a comparable amount of total power when the D string is bowed, within 4 dB of each other.

In Figure 4 for the open A string excitation, the radiated sound power levels for the mezzo violin were found to be lower than the levels for the other two instruments. The total radiated sound power level for the mezzo violin is the lowest among the three violins, although they all produce levels within 4 dB. There is a lack of sound power radiation from the mezzo violin at the lower frequencies, up to the band occupied by the third harmonic (1320 Hz). Its dominance in this range which was apparent when the open G string was bowed is not evidenced here. The frequency band with the third harmonic is the one in which it radiates the most power. The other two standard instruments show the largest levels at the second harmonic (880 Hz), although their first harmonic responses (440 Hz) are also predominant.

When the A string is bowed, radiation from the fundamental frequency of 440 Hz is expected to be great, because this driving frequency lies close to an eigenmode of the standard violin, often called the T1 or ‘main wood’ mode near 460 Hz. The mezzo violin was produced to have this same resonance, as seen in its admittance curve in Figure 6; however, its radiation in the 400 Hz one-third octave band is significantly less than the radiation from the other two, which was not true when the G string was excited (Fig. 2). One reason for the change in the low frequency power output with the bowed A string versus the bowed G string may have to do with how the bridge transmits the string vibrations into forces on the body. The mezzo violin has powerful low frequency modes which can radiate a large amount of sound energy; however, if the string vibration is not well coupled to the body through the bridge, the excitation of these modes may be considerably less.

Finally, for the open E string excitation in Figure 5, the three instruments seem to produce a similar amount of total radiated power, within 3 dB of each other. However, their harmonic distributions are different. SUS295 has a large component in the 630 Hz one-third octave band, while the other two violins exhibit stronger responses at the second bowed harmonic in the 1250 Hz band.

Summarizing across the four bowed strings studied, one can state that the mezzo violin does not appear to radiate more overall acoustic power than the standard instruments. In fact, the three violins have similar total sound power levels on the upper three strings; only on the G string is there an obvious difference between the Hutchins’ violins and the Scherl and Roth violin. The most obvious dissimilarity between the structurally different mezzo violin and the other two is the fact that the mezzo violin’s low frequency response is significantly greater when the G string is bowed.

"...the mezzo violin does not appear to radiate more overall acoustic power than the standard instruments."

For each of the four bowed strings, the power levels in the one-third octave bands containing at least one harmonic are higher than the levels in the adjacent bands that contain no harmonics. Radiation in the bands containing the harmonics dominate the overall levels, as expected. However, there are three bands in which there are no harmonics where the power levels are high: the 315 Hz band for the G string, the 250 Hz band for the D string and the 500 Hz band for the A string. For the G string, the high level in the 315 Hz band may be due to noise generated by the bowing, apparent in other background noise spectra taken with the bowing machine (Wang and Burroughs 1999). For the 250 Hz band for the bowed D string, the 294 Hz fundamental falls close to the cross-over frequency.
Figure 3: Radiated power in one-third octave bands whose center frequencies are listed, from bowing the three test instruments on the open D string. Also shown are the background noise levels in the test environment and the number of bowed harmonics which lie in each frequency band.

Open D string excitation

Figure 4: Radiated power in one-third octave bands whose center frequencies are listed, from bowing the three test instruments on the open A string. Also shown are the background noise levels in the test environment and the number of bowed harmonics which lie in each frequency band.

Open A string excitation
Figure 5: Radiated power in one-third octave bands whose center frequencies are listed, from bowing the test instruments on the open E string. Also shown are the background noise levels in the test environment and the number of bowed harmonics which lie in each frequency band.

![Open E string excitation](image)

between the 250 and 315 Hz one-third octave band filters, so that part of the response shown in the 250 Hz band may be due to the leakage through the skirt of the filter (Fig. 7(a)). A similar case is made for the 500 Hz band of the A string. The 440 Hz fundamental falls in the 400 Hz one-third octave band, but close to the cross-over between the 400 and 500 Hz one-third octave band filters (Fig. 7(b)). Thus, the response in the 500 Hz band may again result from leakage through the skirt of the filter.

The same bowing parameters were used on different violins for each string, but not on different strings for each violin. Therefore, a direct comparison of the power levels and harmonic distribution of one violin across different strings should not be made. However, it is interesting to note that the relative levels between the three instruments do not stay the same in all frequency bands across different string excitations. For example, in the 630 Hz one-third octave band for the G string excitation (Fig. 2), SUS295 has the largest response, followed by the Scherl and Roth violin, and then the mezzo violin. These relative levels are not the same, however, for the same band with the D string excited (Fig. 3), where the Scherl and Roth violin radiates the most power, followed by SUS295 and the mezzo violin. Also, the 630 Hz one-third octave bands for the A string and E string excitations show different relative sound levels between the three instruments. Apparently, changing the bowed string excitation modifies each violin's sound power magnitude and harmonic distribution differently, even when the same bowing parameters are maintained between the instruments. These differences may arise from variations in string impedances which were not recorded, in efficiency of energy transfer through the bridge, and in violin material and construction.

**SUMMARY**

The mezzo violin has been shown to produce noticeably more sound power than standard violins at low frequencies when the lowest string (G) was bowed, but the increase in radiated power was not evident when the other strings were bowed. Instead, the total radiated sound power between the three instruments was comparable when one of the other three strings was bowed. Why the sound power radiated at low frequencies by the mezzo violin when strings other than the G string were bowed is not apparent, but it may be because the string vibrations couple differently for each string through the bridge to the violin body. From informal trials, this property was subjectively noted by violinists who commented that both the mezzo violin and SUS295 had rich and powerful low tones, particularly on the G string, but their levels seemed to decrease in the middle ranges (Hutchins 1995). This study has further shown differences in how violins redistribute energy as different strings are bowed, even with similar bowing parameters on the same string. This may be attributed to differences...
Figure 6: Admittance measurements were made on the (a) mezzo violin SUS 100 and (b) Scherl and Roth violin, with an accelerometer at the foot of the bass side of the bridge, due to tangential MLS (Maximum Length Sequence) excitation on the upper bass side of the bridge. Frequencies of peaks are labeled. Absolute levels should not be compared.

Figure 7: Some of the bowed harmonics fall near the cross-over frequencies of two adjacent one-third octave band filters, which causes leakage across the skirt of the filters: (a) the D string’s fundamental frequency at 294 Hz falls between the 250 Hz and 315 Hz one-third octave band filters; and (b) the A string’s fundamental frequency at 440 Hz falls between the 400 Hz and 500 Hz one-third octave band filters.

in violin construction as well as in how energy is transferred through the bridge with each bowed string excitation. It is clear that each instrument has a unique response which inevitably leads to violinists preferring certain violins over others.

ACKNOWLEDGEMENTS
The authors are grateful to Carleen Hutchins for the loan of her violins, SUS295 and SUS100; Dr. Gary Koopmann and the Penn State Center for Acoustics and Vibration for the loan of the intensity probe; and to Lars Henrik Mørset of WinMLS for help in making admittance measurements. This work has been supported by a National Science Foundation (NSF) Graduate Research Fellowship, American Association for Women (AAUW) Selected Dissertations Fellowship, and Bell Laboratories Graduate Research Program for Women (GRPW) Grant.
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