DOI: 10.61782/fa.2023.0926

forum acusticum 2023

EXPERIMENTAL UNCERTAINTY IN MEASUREMENTS OF VIOLIN IMPULSE RESPONSE

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ABSTRACT

Experiments that investigate how an individual musical instrument changes in response to subtle alterations must contend with measurement uncertainty, which typically arises from inconsistencies in the measurement setup. We quantify uncertainty in violin response measurements by measuring bridge admittance and radiatively of a single instrument that is repeatedly removed and reinstalled in our measurement apparatus. From this set of baseline measurements, we calculate the average and standard deviation of admittance and radiativity. The amount of variation observed in the baseline data is compared to the change in bridge admittance that occurred over several days due to a large and abrupt change in humidity. The overall change in admittance from 85% RH to 25% RH is much larger than the experimental uncertainty, but the change from 30% to 35% is within our uncertainty. Our goal is to establish a reliable threshold for measurable changes in violin response due to mechanical stimulation (i.e. “playing-in”), which is the subject of a concurrent experiment.

Keywords: *violin acoustics, bridge admittance, measurement methods, uncertainty*

1. INTRODUCTION

Standard measurements for characterizing the frequency response of violins include admittance (response velocity divided by input force) and radiativity (radiated sound pressure divided by input force) [1-4]. Such measurements are used in a variety of ways: to make comparisons among instruments, often with the intent to identify characteristics of especially good sounding instruments [5]; in conjunction with modal analysis or numerical modeling to gain insight into the physical behavior of an instrument [6-7]; or to inform the process of designing and constructing instruments [8]. In such applications, it is normally sufficient to conduct a single measurement (consisting of an average of multiple hammer taps) per instrument or condition. It is not common practice to report quantitative measures of uncertainty (e.g. error bars) for frequency response measurements. However, for an experiment that requires repeated measurement of the same instrument over some period of time, error bars are essential to assessing the significance of any changes that are observed. In preparing for an experiment to measure effects of “playing-in” a violin, we noticed that our measurements of bridge admittance were not identical from one day to the next, even when averaged over many taps. We hypothesize that this is a result of inconsistencies in how the instrument is mounted during the test. We have previously measured the effect on bridge admittance of small variations in the hammer strike location on the bridge and the positioning of the laser vibrometer [9]. But even controlling for these factors does not eliminate measurement variability. Our goal is to quantify the experimental uncertainty in measurements of admittance and radiativity and to develop a tool for assessing the significance of changes observed in subsequent measurements.

2. EXPERIMENTAL SETUP

We use two methods to measure bridge admittance, both of which use a hammer tap on G-string side of the bridge to provide the applied force. Method (1) uses the velocity of the top plate just below the foot of the bridge on the same

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side as the tap; method (2) uses the velocity measured at the opposite side of the bridge from the hammer tap.

The violin used in the present study is a Yamaha model V-5 4/4 (#21667), built in 2009. The measurement apparatus, which includes the violin support, impact hammer, and positioning system, was adapted from the design by Joseph Curtin [4]. The hammer swings from a support that is mounted on an optical bench positioning system that enables precise adjustments of the impact location. Resonance frequencies associated with the rubber band supports are in the range of 10 Hz – 20 Hz, so these supports act as highly compliant boundaries above 100 Hz. A piece of nylon ribbon is used to damp the string vibrations. Figure 1 shows the violin in the apparatus for both method configurations.

Figure 1. Experimental rig, with impact hammer and violin. (left) method 1: velocity measured below bridge foot; (right) method 2: velocity measured at opposite side of bridge from hammer tap.

Velocity measurements were made using a Polytec PSV-500 scanning laser Doppler vibrometer, which incorporates the signal produced by a PCB miniature impact hammer (model 086E80) to compute admittance. A small piece of reflecting tape is placed at each measurement location on the bridge and top plate. Every measurement consisted of a complex frequency domain average of ten taps, with a sampling rate of 25 kHz and a frequency resolution of 781 ms.

Radiativity measurements are made in an anechoic chamber with two GRAS 46AE ½-inch free-field microphones, one located 1.0 m directly in front of the violin, the other located 1.0 m directly behind. This setup is shown in figure 2.

Figure 2. Experimental setup in anechoic chamber for radiativity measurements. The microphone is aligned with the center of the bridge and located 100 cm from the top of the bridge.

3. QUANTIFYING UNCERTAINTY IN FREQUENCY RESPONSE

To quantify variability, we repeatedly measured bridge admittance (using both methods) and radiativity of a single violin over the course of a few hours, during which environmental changes, such as humidity, were negligible. After each measurement, which consisted of multiple taps that were averaged, the violin was removed from the rig. The damping ribbon was then removed, the tuning adjusted as needed, and the ribbon replaced. The violin was then put back into the rig, with care taken to reproduce the alignment from the previous measurement. This often required making small adjustments in the hammer position and (in the case of admittance measurements) the aim of the vibrometer laser. Each type of measurement was repeated ten times.

Figure 3 shows all ten measurements of the bridge admittance using method 1 (velocity of the top plate just below the bridge foot). The frequency range displayed is between 240 Hz and 880 Hz, which shows the peaks associated with the Helmholtz mode (A_0) and the primary plate and bending modes (CBR, A_1, B_1-, B_1+, and A_2). The color scheme ranges from red to blue in the order that measurements were taken. The amount of variation among measurements is clearly larger for some regions of the frequency response than others. In particular, the peaks between 400-500 Hz (the CBR, B_1- and A_1 modes) display shifts in both frequency and amplitude, although there is no correlation with sequence. The A_0 mode, on the other hand, shows very little variance.

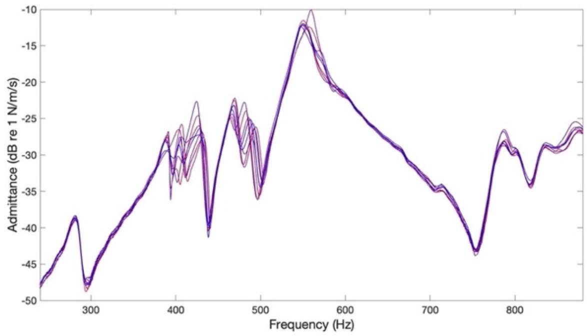

Figure 3. Repeated measurements of bridge admittance using method 1. Vertical scale is in decibels re 1 N/m/s.

A more useful way to represent the variation is to plot the average admittance, with the standard deviation added or subtracted, at each frequency. This is shown in Figure 4(a) for the same data in Figure 3. This representation more clearly depicts the uncertainty associated with this type of measurement for this particular violin; the vertical distance between the two blue curves is essentially the “error bar” for the admittance measurement at each frequency. This type of plot represents the baseline response of the instrument, which can be compared with future measurements that explore the effect of a particular control parameter, such as physical modifications to the instrument, environmental conditions, or simply being played over a period of time.

The results in this format using method 2 to measure bridge impedance (velocity of the opposite side of the bridge) are shown in Figure 4(b). This method has a smaller standard deviation throughout the frequency range shown, probably because the laser positioning is more constrained.

The average and standard deviation for the radiativity measurements are shown in Figure 4(c). As expected, the A_0 mode is more pronounced, and the CBR mode less pronounced, in the acoustic measurement than in the vibration measurements. Interestingly, the variance in radiativity is relatively smaller for the B1+ mode at 560 Hz than for either of the A_1 and A_2 modes (480 Hz and 825 Hz, respectively).

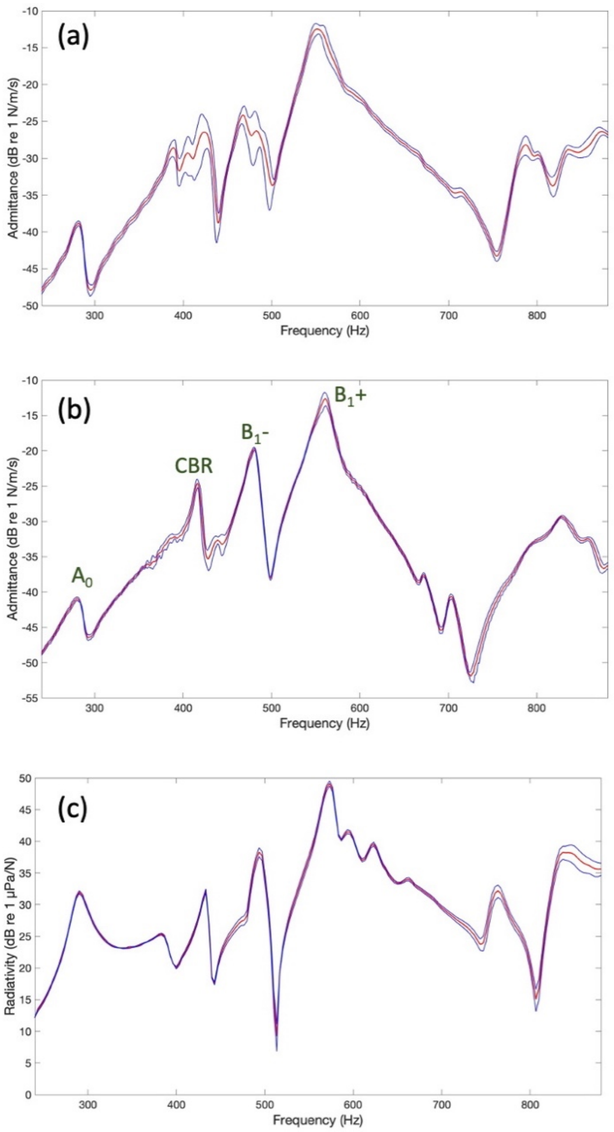

Figure 4. Uncertainty in frequency response for three measurement methods on the same violin: (a) bridge admittance, method 1; (b) bridge admittance, method

2, with major modes labeled; (c) radiativity. In each plot, the red curve shows the average of ten trials; blue curves show the average plus or minus the standard deviation.

The standard deviation divided by the average value (of admittance or radiativity) can be summed over a specified frequency range (f_1 to f_2) to characterize the amount of variation associated with a particular vibrational mode or set of modes. Table 1 shows this normalized total variation within three frequency ranges for each of the three types of measurements. These values can be compared to the normalized total deviation of a specific measurement from the baseline average to determine whether that measurement falls "within the error bar" in a given frequency range.

Table 1. Normalized total variation within three different frequency ranges for three types of frequency response measurements. Y_1 is bridge admittance using method 1, Y_2 is bridge admittance using method 2, and *R* is radiativity.

	240-880 Hz	460-490 Hz	540-580 Hz
Y_1	.1035	.2068	.1136
Y_2	.0468	.0397	.0515
R	.0979	.1119	.0803

In the next section, the utility of determining measurement uncertainty will be demonstrated for a violin with changing moisture content.

4. EFFECT OF MOISTURE CONTENT ON BRIDGE ADMITTANCE

After recording the baseline measurement uncertainty described in the previous section, we placed the violin in an environmental chamber with a relative humidity of 85% and temperature 21º C for 36 hours. The violin was then transferred back to our lab, which had the same temperature, but a relative humidity of 25%. Over the next few days, as the violin dried out, the bridge admittance was repeatedly measured using method 1, along with the mass of the violin. After each measurement, the violin was removed from the apparatus and placed back in its case. Results of seven measurements are shown in Figure 5; the difference in violin mass between consecutive curves is approximately 2 g.

As expected, the peaks shift higher in frequency as the violin loses moisture content. Notably, the shift is much smaller for the A_0 Helmholtz mode (about 2%) than for modes with significant plate motion (more than 8% for the CBR and B1- modes and 5.3% for the B1+ mode).
A visual comparison of the plots in Figure 5 and Figure 4(a) confirms that the full range of variation in admittance due to a loss of 12 g of moisture content is significantly larger than the uncertainty of this measurement method. But it is instructive to see how the change in admittance associated with the gain or loss of just 1-3 grams compares with the baseline uncertainty.

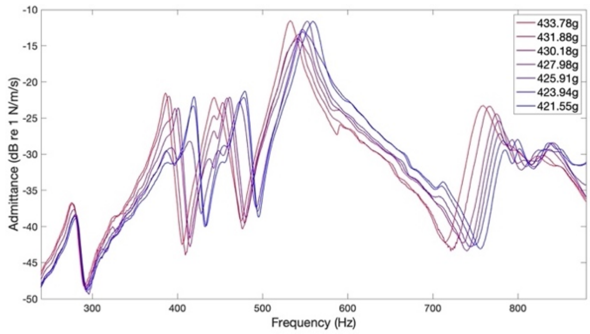

Figure 5. Bridge admittance (method 1) of the same violin with different values of moisture content, which is indicated by the weight of violin.

In Figure 6 is plotted the admittance for the three lightest masses shown in Figure 5 (425.9g, 423.9g, 421.6g) together with the baseline average and standard deviation for method 1, shown in Figure 4(a), which was measured while the violin had a mass of 422.9 g.

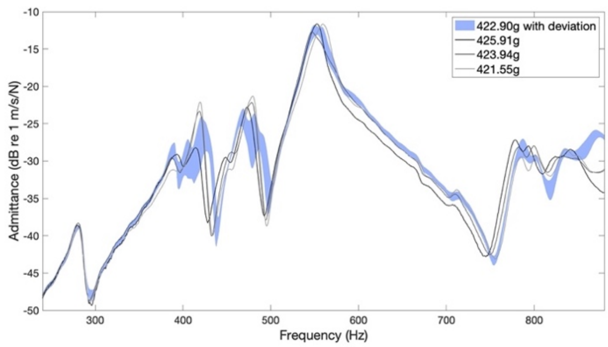

Figure 6. Bridge admittance for three different levels of moisture content (grey curves); the blue shaded

area corresponds to the average admittance with standard deviation measured prior to the humidity test.

Visually, it is easy to see that the grey curves corresponding to the two lightest violin weights fit within the uncertainty window represented by the blue shaded area between 510 Hz and 700 Hz (containing the B1+ peak), whereas they lie outside the shaded area for some portion of the CBR and B1- peaks. We can quantitatively compare the agreement between the admittance measured when the violin was 421.55g and when it was 422.90g by calculating the normalized squared difference using a method similar to that described in section 3 for the normalized squared deviation. Over the frequency range 540 – 580 Hz, the normalized difference is .0261, which is much less than the normalized deviation of .1136 for admittance measured using method 1; it is also less than the normalized deviation using method 2 (see Table 1). However, for the frequency range 460 Hz – 490 Hz, encompassing the B1- peak, the normalized difference is .0683, which is smaller than the normalized deviation of .2068 for method 1, even though the curve does not lie completely within the shaded area in Figure 6.

These results suggests that a variation of one gram in water weight absorbed by the violin is not significant for the B1+ peak using either measurement method, although it may be significant for the B1- peak. In our experience, a humidity increase from 28% to 35% over a 48 hour period results in an increase of about one gram in violin weight.

In addition to demonstrating threshholds of humidity variation that are measurably significant, having a set of admittance and radiativity measurements over a broad range of violin moisture content can provide a useful calibration for future long-term measurements, during which large variations in humidity may occur.

5. CONCLUSIONS

We have developed a method for determining the experimental uncertainty associated with violin admittance and radiativity measurements. Given a set of baseline measurements, the range of standard deviation can be displayed in graphical form for comparison with other measurements. A normalized total variation among the baseline data for specific frequency ranges may also be computed to compare with normalized variance of specific measurements from the baseline average.

We compared three types of frequency response measurements and found that the direct bridge admittance (method 2) had the smallest amount of experimental uncertainty.

6. ACKNOWLEDGMENTS

The authors wish to thank Mr. Peter Zenčak for constructing the experimental rig and Dr. Robert Pritchett for allowing us to use the environmental chamber in the newly constructed Health Sciences building at Central Washington University.

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