A comparison of vibration analysis techniques applied to the Persian setar

H. Mansour[a,b] and G. P. Scavone[a,b]

[a]Centre for Interdisciplinary Research in Music Media and Technology (CIRMMT), 527 Rue Sherbrooke Ouest, Montreal, QC, Canada H3A 1E3
[b]Computational Acoustic Modeling Lab, Schulich School of Music, McGill University, 555 Rue Sherbrooke Ouest, Montreal, QC, Canada H3A 1E3
hossein.mansour@mail.mcgill.ca

Modal analysis is a well-known technique and its application to stringed instruments has a long history, yet there is no universal agreement on the measurement setup to be used for this purpose. In this study, measurements of a Persian setar are compared using an impulse hammer or a handheld shaker as excitation and an accelerometer or Laser Doppler Vibrometer (LDV) to record the response. As well, measurements were made with the setar both suspended, to produce a free-free boundary condition, and clamped at its neck. Natural frequencies and mode shapes are extracted for the first 12 structural modes. In our results, both the accelerometer and shaker dramatically affect the structure and thus, depending on the context, they are probably best avoided if possible for the case of the setar and similar instruments. On the other hand, the modal map of the free-free setar was in close agreement with the clamped condition; therefore, measurements on the setar and similar instruments can be performed on a clamped instrument unless the accurate damping properties are of interest. Some of the experiments were repeated on a violin and similar results were found, except that the disturbance introduced by the accelerometer was negligible for the violin.

1 Introduction

Stringed musical instruments are complex vibrating systems from both the structural and the fluid-structure coupling perspective. The direct sound of the strings is a minor component of the sound output, with most of the radiated sound generated by the body and cavity of the instrument [1]. In fact, the whole instrument acts as a filter, converting and radiating the vibrations of the strings into the surrounding space [2]. In this regard, the modal properties of the body and cavity are key features that define the physical properties of the instrument [3].

In this study, the Persian setar is chosen as the test case, and its experimental modal analysis is described using different sets of excitation methods, sensors, and boundary conditions. After a brief introduction to the setar, the natural frequencies and mode shapes are extracted for an instrument clamped at its neck. After, some variations on the boundary condition, excitation method and measuring device are examined and the methods are compared to evaluate their advantages and disadvantages. In some cases, a violin is also measured to check whether the results are consistent with those for the setar.

2 Setar, a long-necked lute

The origin of the setar can be traced to the ancient Tanbour of pre-Islamic Persia. The setar has four strings normally tuned at C4 (262 Hz), G3 (196 Hz), C4 (262 Hz), and C3 (131 Hz), respectively. The setar is used mainly to play Persian classical music, called Dastgah. This instrument is played with the tip of the index fingernail, by strumming up and down. Its fingerboard usually has twenty-five adjustable gut frets, which provide the fundamental frequency range of 131 Hz to 831 Hz (two and a half octaves). Although each string can be played individually, melodies are usually played on the first two strings while the other strings provide drones.

Figure 1 shows a schematic of a setar. The soundbox consists of an approximately flat plate, installed on a pear-shaped bowl. The bowl is a shell made with several bent ribs glued together. Both soundboard and bowl are made from mulberry wood.

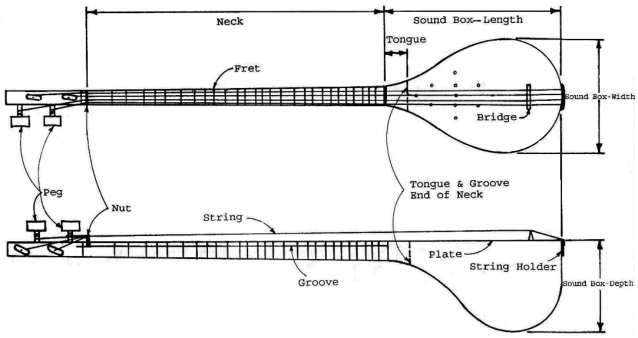

Figure 1: The schematic view of the setar [4].

3 Apparatus and method

3.1 Modal analysis of a clamped setar

An impact hammer (LDS® model 5200-B2 with metal tip) was used to excite the body, and the resultant velocity was measured by Laser Doppler Vibrometer (Bruel & Kjaer® LDV Type 8337). The setar was clamped by its neck in a stiff vice as shown in Figure 2.

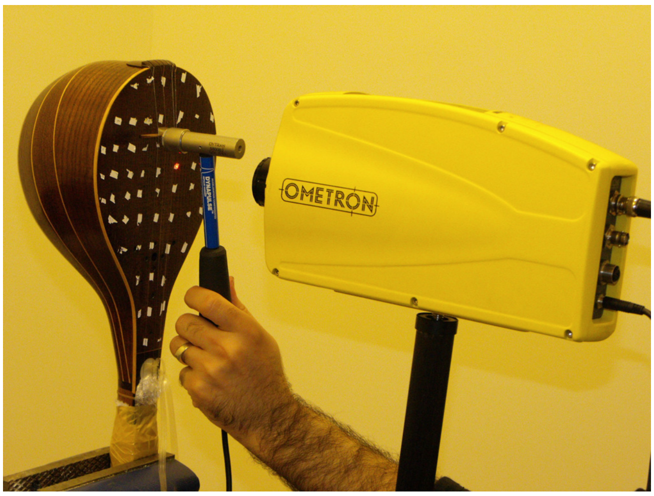

Figure 2: The experimental setup for modal analysis of the clamped setar using an impulse hammer and LDV.

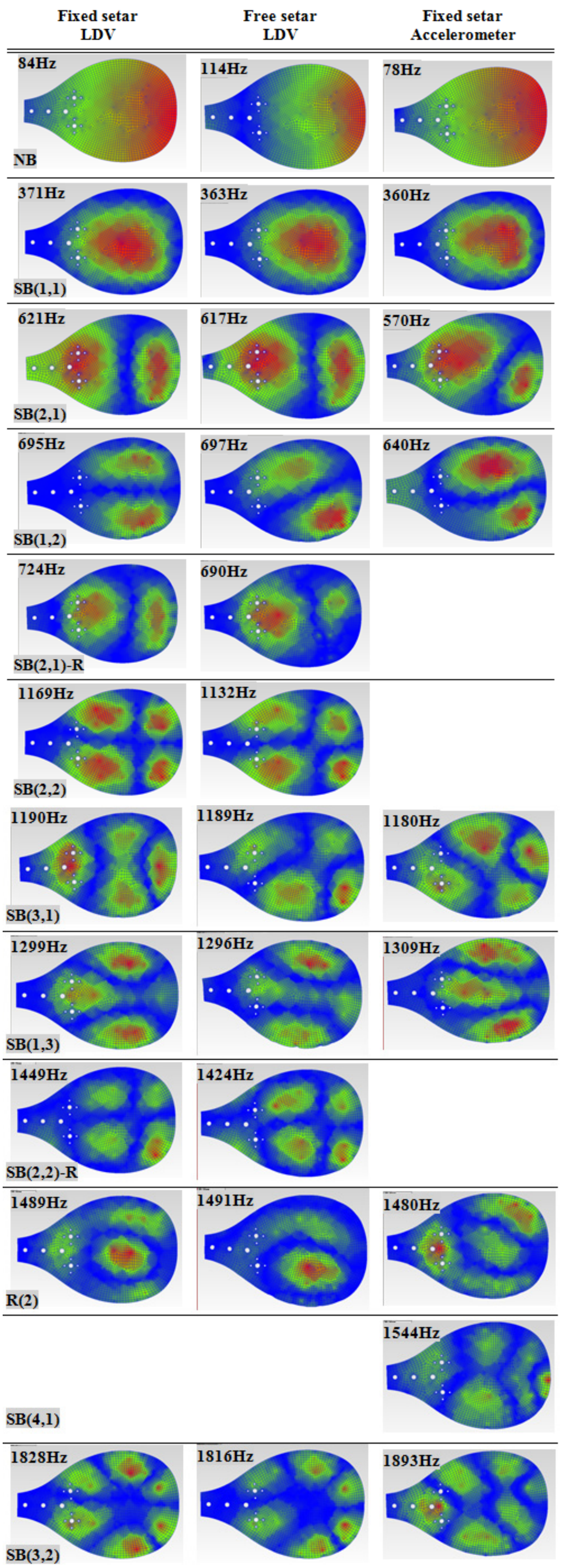

Figure 3: Modes shapes and natural frequencies of the setar's top plate. (First column) the setar clamped on its neck measured with LDV, (second column) free-free setar also measure with LDV, (third row) free-free setar measured with accelerometer. The experiments were performed on a fully assembled instrument, although the results are shown for the top plate only.

The excitation was imposed on a fixed point on the apex of the bridge, beside the notch where the first C4 string is passing, and the response was measured at 60 points all over the top plate. As can be seen in Figure 2 the measurement points were covered with lightweight white stickers to make them more visible to the LDV. The choice of the excitation point ensured that all prominent modes in the working condition of the setar are properly excited. The strings were damped by three rubber bands to eliminate their sound/vibration while keeping their preload on the structure.

The PHOTON II® data acquisition unit gathered the data, and RT Photon® V.6.33 software was used to calculate the Frequency Response Functions (FRFs) and coherence functions. Although the frequency range was limited to 2.5 KHz as recommended in the datasheet of the impulse hammer, we could still reach a very good coherence up to 4.5 KHz. The extracted FRFs were fed to ME'scope® commercial software to extract the modal properties up to 2 KHz.

The first column in Figure 3 illustrates the natural frequencies and mode shapes of the clamped setar's top plate. The SB(m,n) system is used to name different modes, where "m" represents the number of longitudinal half-waves on the top plate, and "n" stands for the number of transverse half-waves.

With only a few exceptions, the mode shapes fit well in the SB(m,n) format. Those exceptions are:

- The first mode, which is the neck bending mode (abbreviated as NB). It reflects the properties of the neck for a free-free experiment, while it contains no useful information for the clamped case.
- The modes SB(2,1) and SB(2,2) are repeated in higher frequencies with a little shift in the position of the anti-nodes. These repeated modes are abbreviated as SB(m,n)-R.
- The mode SB(4,1) was not captured with this set of measurements (it will be discussed later in Sec. 3.3).
- The eighth mode does not follow the SB(m,n) pattern. In this mode, an anti-node is located at the middle of the top plate surrounded by three other anti-nodes that form approximately a circle. Due to the radial distribution of the nodes and anti-nodes, this mode is called R(2), reserving R(1) as an alternative to SB(1,1).

3.2 Various boundary conditions

As mentioned in Sec. 3.1, the setar was initially clamped at its neck to find the natural frequencies and mode shapes. The reason for choosing a clamped boundary condition was to get cleaner results from the LDV; however, this may introduce some changes to the structure compared to a free-free condition. Figure 4 shows the setup used to evaluate the potential influence of the clamped condition. The excitation, measurement, and data processing remained the same as the previous case, but the setar was suspended from its peg by a soft cord. In addition, a rubber band was used to support the sound box and to limit its movement (see Figure 4). The second column of Figure 3 shows the mode shapes and natural frequencies for the free-free setar. Although the mode shapes are not as clean and orthogonal, the natural frequencies and mode shapes are in close agreement for both cases. The biggest difference occurs for the SB(2,1)-R mode with a 5% deviation of the natural frequency.

Figure 4: Experimental setup for modal analysis of the free-free setar. The structure is excited with an impulse hammer and the results are captured with an LDV

A similar approach was applied to a violin for the cases where the violin was suspended free-free, clamped (similar to the case shown in Figure 2 for the setar), and held in the hands of a player. As can be seen in Figure 5, the FRFs are in a close agreement in terms of their average amplitude and spectral peaks. The only noticeable difference is in the modal damping, which is associated with the 3-dB bandwidth of the spectral peaks. The general trend is that the least damping is observed for the case of the clamped violin (the sharpest peaks), the free-free case showed a medium damping, and the case where the violin was held by the player was the most damped.

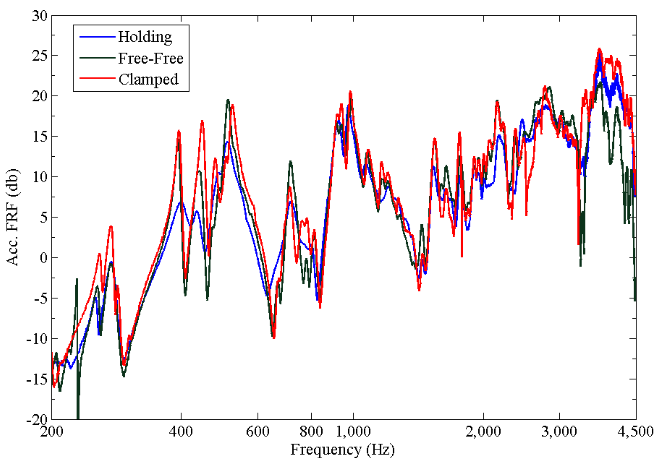

Figure 5: Acceleration FRFs of the violin excited with an impulse hammer and measured with an accelerometer for the cases of (blue) being held by the player, (green) free-free, (red) clamped in a stiff vice.

3.3 Various types of sensors

An LDV is a relatively expensive sensor and its application is limited to stationary structures with a relatively reflective surface. Due to these limitations, many of the studies in the field of musical acoustics have used accelerometers to measure mechanical vibrations. We repeated the experiment of Sec. 3.1 by replacing the LDV with an accelerometer. The accelerometer used was a Dytran type 3035AG with 2.5g mass. The accelerometer was attached to the top plate with permanent adhesive that ensures no low-pass filtering caused by the mounting condition. In this case the accelerometer was fixed right beside the treble side of the setar bridge and the excitation was roving on the 60 points previously marked on the top plate (as opposed to the previous cases where the measuring point was roving).

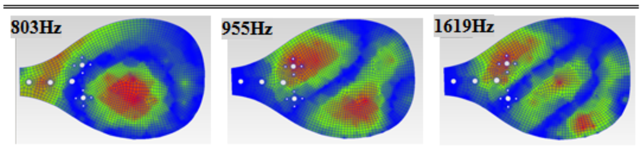

Figure 6: Extra modes appeared in the results when measuring with an accelerometer. The setar is clamped in a stiff vice and is excited by an impulse hammer

The third column of Figure 3 shows the mode shapes and natural frequencies that are extracted from this latter experiment. The natural frequencies are noticeably different with no obvious trend (some are lower and some are higher). Also, the mode shapes are skewed to move their anti-nodes apart from the mounting point of the accelerometer (see SB(2,1) and SB(3,1) for example). More importantly, three out of twelve modes are absent in the results with the accelerometer while three extra modes are observed in the frequencies far from the eliminated modes (shown in Figure 6). The only point of measuring with an accelerometer is that the results are less noisy compared with those obtained by an LDV, therefore we could capture the SB(4,1) mode with it, which was missing in the two previous measurements. This mode is both predicted intuitively and by our finite element model of the setar.

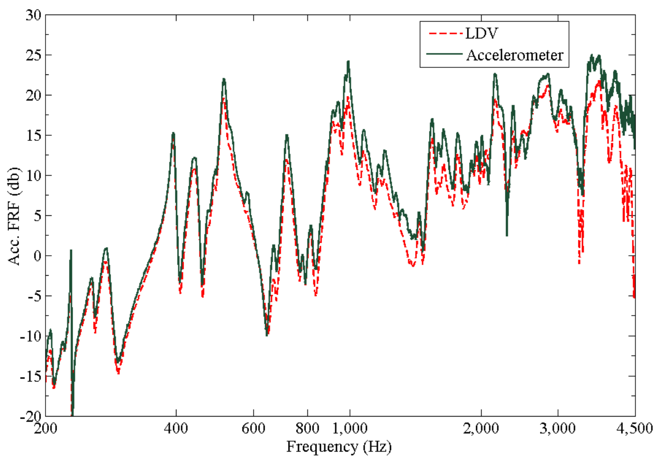

Figure 7: Acceleration FRFs of the violin suspended free-free excited with an impulse hammer and measured with (red) LDV, and (green) accelerometer, The result of the LDV has been differentiated to be comparable with the one of the accelerometer

We repeated this experiment for a violin to check if its body modes would be disturbed by the mass of the accelerometer. The accelerometer used in this experiment was a PCB 352C23 with 0.5g mass. As seen in Figure 7, the two FRFs are in perfect agreement, especially for frequencies below 2 KHz. This observation can be associated to the use of a lighter accelerometer and to the structure of the violin being more stiff compared to the setar's structure.

3.4 Various excitation methods

Continuing with an evaluation of different methods for vibration analysis of the setar, we examined the use of a handheld shaker to excite the structure with a swept sinusoid. Shaker excitation is generally a superior method over hammer excitation due to some advantages such as higher frequency range of excitation, possibility for monotone excitation and noise filtering, and possibility for adjusting the level of the excitation.

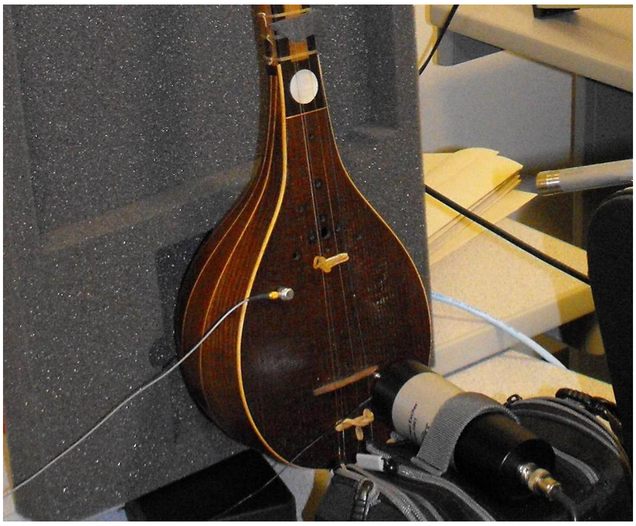

Figure 8: Experimental set up used to find the frequency response using a handheld shaker and an accelerometer

In our measurements, we used a B&K handheld exciter type 5961 together with a miniature load-cell type 8203. As in the previous measurements, the excitation was imposed on the treble side of the bridge with the impulse hammer and the shaker respectively. As shown in Figure 8, the output was measured by the Dytran 3035AG accelerometer mounted on the top plate while the setar was suspended free-free. The shaker was used to excite the structure with a swept linear sinusoidal waveform, 15 min in duration, ranging from 50 Hz to 12 kHz. H_1 formulation was used to extract FRFs from the time-domain response of the load-cell and the accelerometer. This formulation is based on dividing the cross spectrum of the input and output with the auto spectrum of the input.

As shown in Figure 9 the two FRFs are not in good agreement. Generally speaking, the natural frequencies are lowered in response to the added mass of the shaker; however, we could not find a straightforward transformation to convert one of the FRFs to the other. It is noteworthy that the response extracted by shaker excitation was much cleaner and more reproducible compared to the one extracted by impulse excitation and it could cover a much wider range of frequencies (easily up to 12 KHz).

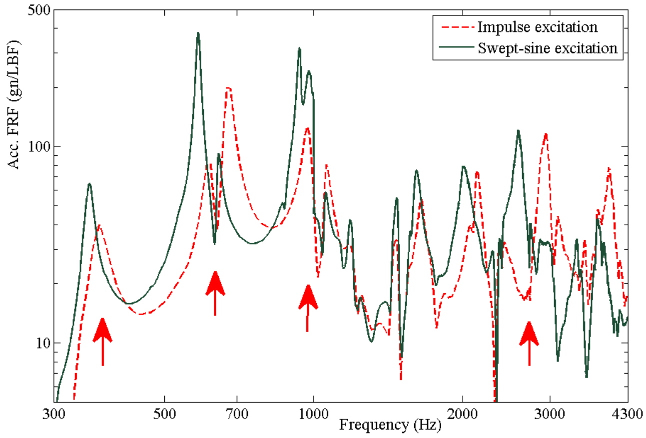

Figure 9: Acceleration FRFs of the setar suspended free-free measured with an accelerometer and excited with (red) an impulse hammer and (green) a handheld shaker. Red arrows are to highlight the frequency peaks that are highly affected by the mass of the shaker.

4 Discussion

Different measurement techniques are described in Sec. 3 and their results are presented. Here we will summarize the advantages and disadvantages of different boundary conditions, excitation techniques, and measuring methods.

4.1 Choice of the boundary condition

A free-free boundary condition is traditionally the most preferred in the literature of modal analysis as it minimizes the energy transferred to and from the target structure; however this is not necessarily a valid case for stringed instruments as they are held when played. In this regard, the instrument can be either free-free or held by the player to perfectly simulate the operating condition depending on the type of study being performed. On the other hand, neither condition is well suited to using an LDV, which requires the structure to be as stationary as possible. According to the results of Sec. 3.1, the setar, violin, and perhaps other similar instruments can be easily studied while they are clamped at their neck unless the accurate damping properties are of interest.

In addition to the above boundary conditions, using a fixture might be a good option for valuable instruments in order to avoid potential damage caused by a rigid vice. Based on our experience with a fixture of this kind, the results will remain consistent with the other three methods except that the modes of the fixture itself may appear in the results as well.

4.2 Choice of the sensor

As described in Sec. 3.2, LDVs are generally preferred over accelerometers. They cover a wider range of frequencies, they cause no disturbance to the structure, and they do not need mounting; however, there are some drawbacks associated with LDVs, which limit their application in some cases. LDVs are much more expensive than accelerometers, they need the measured object to be relatively stationary, they cannot measure all surface types, and they are more prone to noise compared to accelerometers. It is safe to say that LDVs are superior measuring devices compared to accelerometers, though accelerometers can be still useful when they have low mass and are properly mounted.

Microphones are another type of sensor with application to musical acoustics, though they were not used in this study. These sensors do not give any spatial information about the vibrating structure; hence, they cannot be used to extract the structural mode shapes. However, once the modal properties of the structure are identified, microphones can be used to find the change in natural frequencies in response to structural variations. Microphones are contactless and some of them can be very cheap (on the order of a few dollars). They capture the properties of the air cavity as well as the structure, which can be considered either an advantage or a disadvantage, depending on the context. One of the common problems with microphones is that they are much more prone to environmental noise compared to vibration sensors. A summary of the sensors discussed in this section is presented in Table 1.

Discussion Table 1: Summarized comparison of accelerometer, LDV, and microphone based on their application in musical acoustics.

	Freq. range	Noise tol.	Price range	Add. mass	Spatial detail	Fixed obj. needed
Acc.	12 KHz	Best	1K-2K	Yes	Yes	No
LDV	1 MHz	Mid	1K-3K	No	Yes	Yes
Mic.	80 KHz	Worst	5-3K	No	No	Almost

4.3 Choice of the excitation

Although a shaker excitation is a more flexible method compared to hammer excitation, the disturbance introduced by the shaker can dramatically affect the structure in the case of stringed instruments. Another problem with shakers is that they generate a noise with the same frequency as the excitation. This can produce a considerable error in the results if the output of the system is the sound.

Table 2: Summarized comparison of swept sine excitation with handheld exciter and impulse excitation with impulse hammer, based on their application in musical acoustics.

	Freq.	Noise	Price	Add. mass	Quick
Swept sine	Up to 12 KHz	Yes	4K-7K	Yes	Slow
Impulse hammer	Up to 5 KHz	No	1K-3K	No	Fast

In terms of cost and measurement speed, miniature impulse hammers are the ideal solutions for the excitation of stringed instruments. PCB Model 086D80 and B&K type 8203 are two examples of such hammers. Installing the impulse hammer on a pendulum can help to increase the excitation frequency and to produce more repeatable impulses. Table 1 summarizes the material discussed in this section.

5 Conclusion

The modal map of a clamped setar has been extracted primarily using an impulse hammer and an LDV. These results are then compared to those of a free-free setar. The comparison showed that the modal properties are not noticeably affected by this boundary condition. Some other variations are applied in the excitation and measuring devices. Replacing the LDV with an accelerometer highly affected the natural frequencies and mode shapes of the setar, and even generated some new modes, which were not observed in the measurements with an LDV. As well, replacing the impulse hammer with a handheld shaker dramatically affected the vibratory behavior of the instrument. The above-mentioned variations are also examined for the case of the violin to compare its sensitivity with the setar. The biggest difference seen there was that the natural frequencies of the violin did not change as much when using a lighter accelerometer on the top plate.

Based on our results (a) using a shaker to excite a stringed instrument is not recommended at all unless very high frequencies are being targeted and the exact frequency of mode shapes is not of interest; (b) an LDV is generally preferred over accelerometers; however, a lightweight accelerometer can still be used with some care; (c) the boundary condition of the stringed instruments is not that influential on the modal properties; therefore, one can use the easiest boundary condition unless the accurate damping properties are of interest.

Acknowledgments

I would like to thank Dr Siamak Arzanpour from Simon Fraser University for providing part of the experimental facilities used in this study. My special thanks to Indiana Wollman for helping me in repeating the experiments on the violin. This research was partially supported by the Centre for Interdisciplinary Research in Music Media and Technology (CIRMMT).

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