MEASURING A FREQUENCY RESPONSE OF A GUITAR

Samo Šali and **Janez Kopač**

Faculty of Mechanical Engineering, University of Ljubljana
Department of Manufacturing Engineering
Aškerčeva 6
1000 Ljubljana
Slovenia

ABSTRACT

A method for measuring a frequency response function (FRF) of a classical guitar is presented. Instead of measuring a response signal on the guitar body, which is often performed in modal analysis of musical instruments, a sound pressure at 1 m from the impulsively excited guitar at the bridge was recorded. Under the given circumstances the measured FRF showed a high degree of linearity between 70 - 250 Hz as well as high value of the coherence function. The first resonant peak of FRF which corresponds to a normal radiating mode showed a significant correlation with the quality of six tones: The amplitude of this peak, which is presumably related to an interaction of both resonant boards and the air between them, was significantly higher for a good guitar. For this reason, and because of its simplicity, the described method presents a good starting point for guitar tone improvement by modifications of both resonant boards with braces.

NOMENCLATURE

FRF	frequency response function
TD	time domain
d	distance
SPL	sound pressure level
E	tone
A	tone
D	tone
g	tone
h	tone
e1	tone

1 INTRODUCTION

A FRF of a classical guitar (i.e., guitar) should correlate with quality of its tones. If this is not true, then measurement of FRF was not designed in a proper way. For many structures a response signal is measured with sensors mounted on the structure, but in the guitar this approach seems to be unproductive: What the listener hears are changes in sound pressure around the guitar which are in complicated relations with the modal behavior of guitar body, in general [1]. Namely, not all vibrating modes detected on the guitar body are also radiating modes [2], which means that measuring the sound pressure at some distance from the guitar can characterize its sound performances better than measuring the vibrations on the guitar body.

Usually in FRF measurements of the guitar the excitation is performed by a driving force with variable frequency at the bridge [3]. But in spite of the fact that such measurements are an objective indicator of guitar response, violin makers (guitar makers) prefer so called “tap toning” [4] by which they establish the response characteristics of the resonant board (i.e., board) before building it into the final product - guitar. This is logical, because it is easier to optimize free-supported board (by gluing or trimming the braces) than the built-in one. However, after joining the board with the side, the FRF of the guitar may not be as expected [1, 4]. Distinctly the reason for this is the changes in the mode of board support (free-supported or fixed at the edge) [1].

The method presented in this paper is based on the measurements of FRF of the assembled guitar where excitation at the bridge is an approximation of tapping with fingers as described above. Thus, physical explanation of the resulting FRF where the response is sound pressure at 1 m from the guitar, is not so clear as in case of FRF of free-supported boards. The reason for this is an interaction of modal behavior of both top and back board and the air between them, which is not the case when measuring FRF of free-supported boards. However, the additional analysis not presented in this paper, showed applicability of herein described measurements in terms of tone quality improvements after guitar’s assembly [5].

2 METHODS AND RESULTS

Experimental arrangement for measuring the FRF of a guitar is shown in Figure 1. The guitar was suspended on

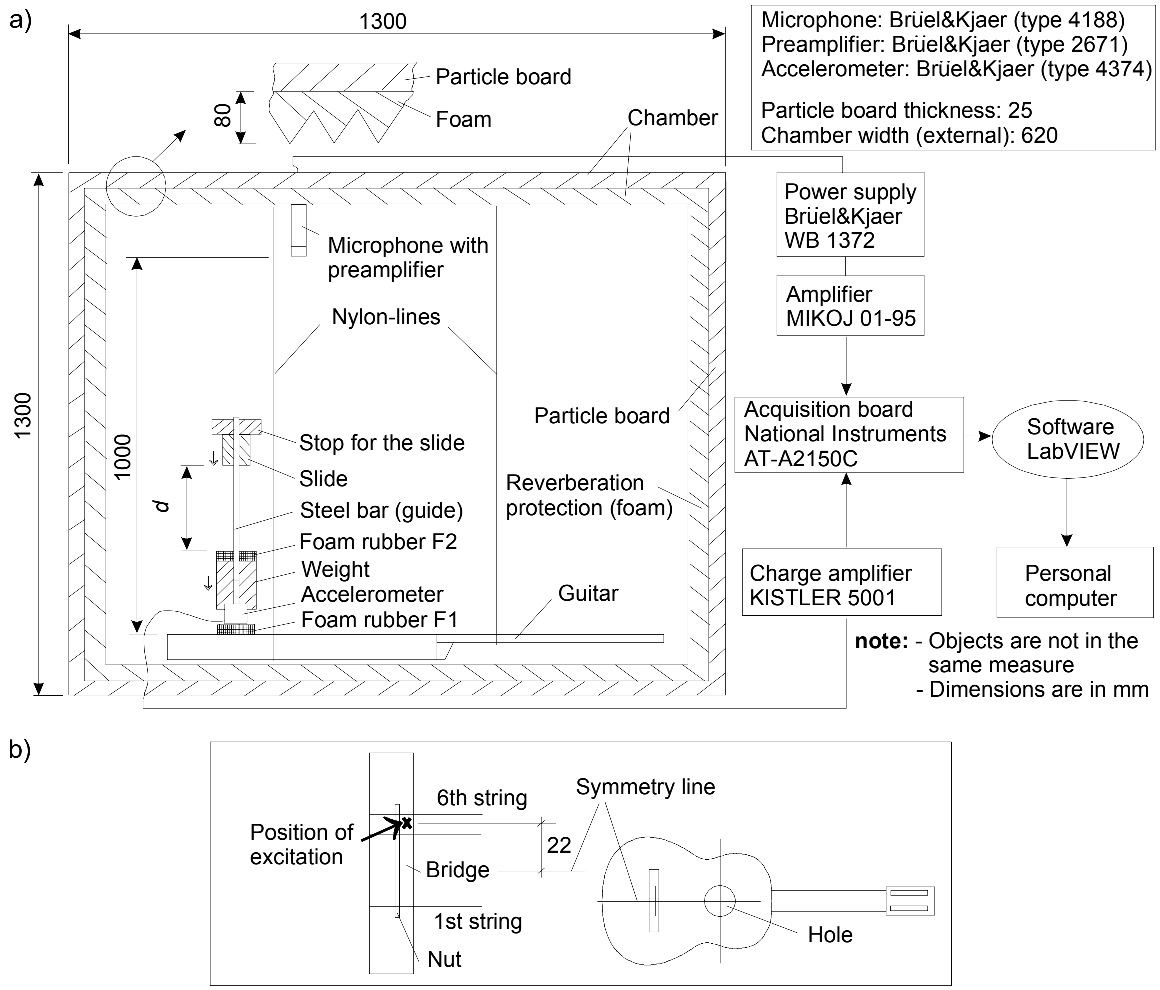
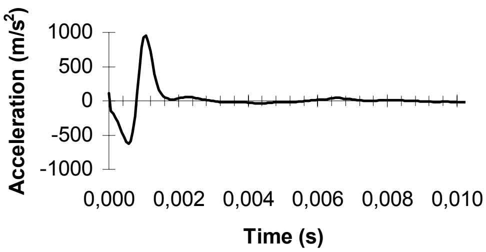


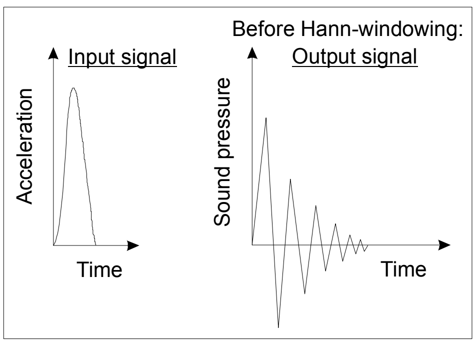
Figure 1: Experimental arrangement: a) Chamber and excitation device; b) Position of excitation.

two elastic nylon-lines and its FRF was obtained by measuring the excitation and response signals simultaneously. The excitation of the guitar was carried out with the device shown in Figure 1a). The main problem was to ensure an impulse excitation with no additional pulses after the first one. It is evident from Figure 1a) that the problem was solved with a relatively small mass of the weight and the accelerometer on the one hand, and with low stiffness of the contacting surfaces (foam rubber F1) on the other hand [6]. The accelerometer was pressed into the weight made of relatively elastic material. Therefore the weight and the accelerometer are considered as one part. The slide bumped into the weight-with-accelerometer, and then this impulsively excited the guitar indirectly over the foam rubber F1, which resulted in only one notable pulse and several pulses with relatively small amplitude. Foam rubber F2 provided only one pulse since it prevented additional impacts between the slide and the weight-with- accelerometer after the first impact. Because of small area (15×15×5 mm) and mass of the foam rubber F1 its influence on guitar vibration is presumably negligible. During FRF measurement (1.024 second) the guitar was not in contact with the weight-with-accelerometer. Namely, the foam rubber F1 provided a rebound of the weight-with-accelerometer after the impact into the bridge. The 0.65 g heavy accelerometer was actually used instead of a force transducer which means that the units of the input signal are m/s^2, but because of the constant mass of the weight-with-accelerometer these units are proportional to Newton units. The position of the pulse excitation was 22 mm from the top plate symmetry line and 170 mm from the center of the hole towards the bottom rim (see Figure 1b)). The response of the guitar was measured by a condenser microphone, so the response signal was measured in Pa.

Figure 2a) shows a typical plot of the pulses in TD: (i) the first pulse corresponds to the impact between the slide and the weight-with-accelerometer, (ii) the second pulse corresponds to the impact between the weight-with-accelerometer and guitar (bridge), (iii) several small pulses correspond to the additional impacts between the weight- with-accelerometer and guitar. By software processing only the second pulse was considered as input signal for FRF estimation, because the first pulse occurred before



a)



b)

Figure 2: Input and output signal: a) Input signal before processing; b) Input and output signal after processing (schematically).

excitation of a guitar and the small pulses were assumed insignificant. After the use of a Force-window [6], both input and output signals started and ended with amplitude 0, which is shown schematically in Figure 2b). In addition, the output signal (sound pressure) was weighted with Hann-window [6] and then multiplied by factor 2 in order to compensate the influence of windowing on the magnitude of the processed signal [7]. Figure 3 shows an average FRF of 10 single FRFs for a bad and good guitar. For each pair of 10 measurements the coherence function in the range 70 - 250 Hz was higher than 0.95, which indicates a high reliability of measurements in this range. The quality of both guitars was assessed regarding to their price at a ratio 1:10 which was also in accordance with subjectively judged characteristics of tones: The richness of the timbre of the tones of the good guitar in comparison to the bad guitar was obvious. The good guitar enabled quality playing of quiet tones as well as loud tones, which was not the case for the bad guitar with bad dynamic capability. The buzz tone for a bad guitar was relatively frequent. As shown in Figure 1, the position of impulse excitation of a guitar was at the bridge between the 5th and 6th string. For both guitars changing the position of the excitation at the bridge did not significantly influence their FRF.

Figure 4 shows the average FRF of 50 single FRFs for a bad guitar in dependence on the distance between the slide and the weight-with-accelerometer - *d* (see Figure 1a)). In this case the position of excitation was between the bridge and hole, but such non-significant effect of *d* was typical for many measurements when excitation was applied at the board or at the bridge. In addition, the shape of the resonant peaks was not significantly changed due to different *d* which shows that the analyzed *excitation-guitar* system can be considered as approximately linear in the region 70 - 250 Hz (*d*=230 - 300 mm) [6]. In the following experiments *d* was always 290 mm.

According to [8, 9] the first resonant peak of both FRFs from Figure 3 corresponds to the mode which represents the interaction between top and back plate and the air inside the resonance box. According to this and Figure 3, one can assume that bad acoustic response of both plates and the air between them (bad guitar) results in bad characteristics of the first resonant peak - low amplitude. Namely, low amplitude in FRF indicates bad acoustic response of musical instrument in general [10]. There are reports that frequency of the first resonant peak in FRF of a guitar

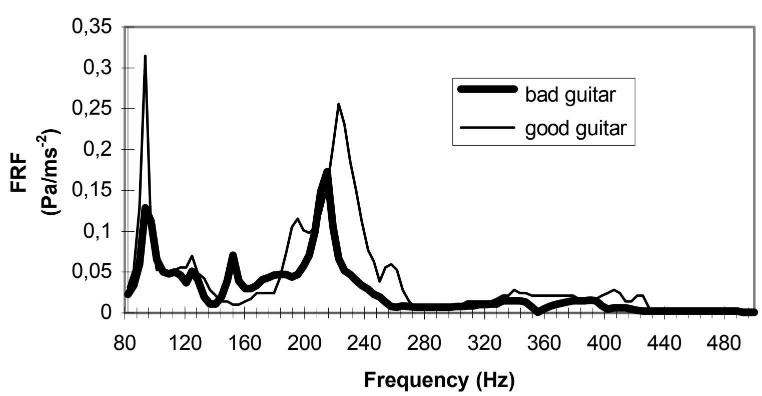


Figure 3: Average FRF for a bad and good guitar.

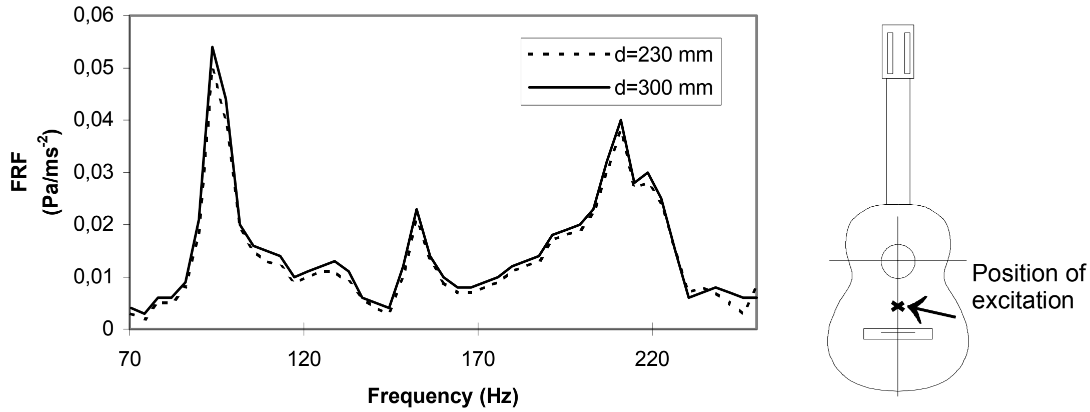


Figure 4: Average FRF in dependence on *d* (bad guitar).

should be between 85 - 99 Hz and that rather lower than higher resonant frequency is preferred [8, 9]. For damping no such trivial conclusions can be made. Damping of each guitar component should be optimal, because too high damping indicates high internal losses and too low damping indicates slow response on the string vibration [10]. In addition, the analyzed resonant peak is an interaction of vibrations of three main components of a guitar, thus the physical meaning of the damping of this peak is hard to explain.

Six tones of the bad and good guitar were recorded at 1 m from a guitar to prove the differences in their tonal quality: E (82.407 Hz - 6th string), A (110.0 Hz, 5th string), D (146.83 Hz, 4th string), g (196.0 Hz, 3rd string), h (246.94 Hz, 2nd string), and e1 (329.63 Hz, 1st string). Excitation of the strings was performed by a special device which ensured that intensity, mode, and position (195 mm from the nut) of the excitation were constants. The operation of the device is shown schematically in Figure 5: During the tone recording the electromotor stopped to provide the tone recording without disturbances. For each of the recorded tones with duration of 1.024 s a total sound pressure level (SPL) of first 15 frequency components in dBA units was calculated from the discrete amplitude spectrum which was obtained with Fast Fourier Transformation of the recorded signal (frequency resolution was 0.976 Hz). A variable in these measurements was a time interval between the string excitation and start of tone recording. For values of this interval between 0 and 0.5 s SPL was always significantly higher for the tones corresponding to the good guitar. Figure 6 shows the results of tone recording when the time interval between the string excitation and start of tone recording was 0.2 and 0.6 s, respectively.

3 DISCUSSION

We can see that SPL of tones D and h with a start of recording 0.6 s after the string excitation was slightly higher for the bad guitar. According to the results of recently made measurements [11], it is reasonable to present the differences in SPL of tones as shown schematically in Figure 7. One can see that SPL of a good tone is higher than SPL of a bad tone at least in the beginning of tone duration.

For the tones recorded at 0.5 s or sooner after the string excitation we can assume that relatively high SPL is related to relatively high amplitude of the first resonant peak in FRF. In practice a quality of guitar tones is usually similar for a certain guitar, thus we can assume that the amplitude of this peak is a reliable criterion for the quality of all tones recorded relatively soon after the string excitation. Because a relatively fast response of a guitar (significant for good instruments) means also a relatively strong decay rate of the played tones [10], lower SPL of tones D and h pertaining to the good guitar (0.6 s after string excitation) is not surprising (see Figure 6).

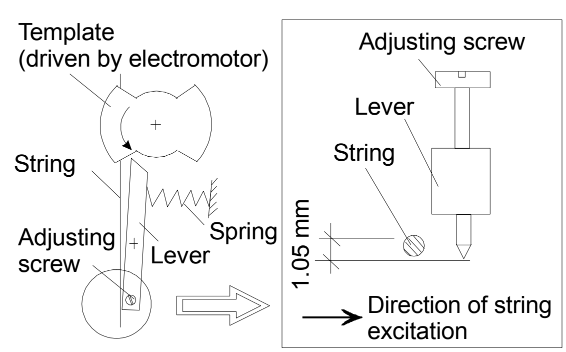
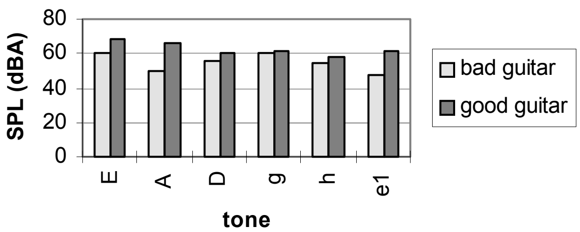
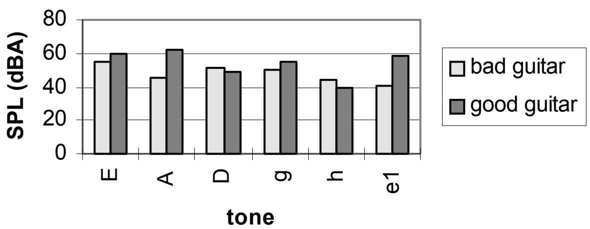


Figure 5: String excitation (schematically).



a)



b)

Figure 6: Characteristics of the tones: a) 0.2 s after string excitation; b) 0.6 s after string excitation.

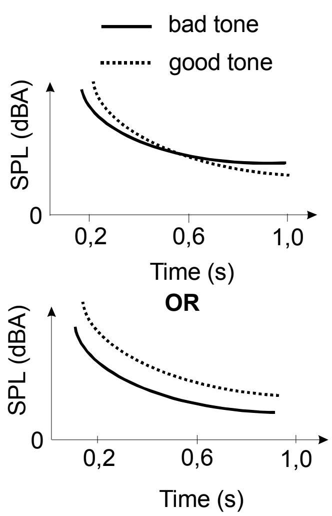


Figure 7: The difference between bad and good guitar tone (schematically).

4 CONCLUSION

Excitation of a guitar at the bridge which was realized by an impulse (input) and sound pressure at 1 m from a guitar (output) resulted in a FRF where the first resonant peak corresponds to an interaction between the top and back plate and the air inside the resonance box. For a bad guitar considerably lower amplitude of this peak in comparison to a good guitar was measured. For tones with duration of approximately 1.0 s and with a start of recording 0.5 s or sooner after the string excitation, the analysis indicated proportionality between the loudness of the tones and the amplitude of the first resonant peak of FRF. Evidently higher decay rate for two of the six tones (D and h) corresponding to the good guitar is logical, because higher decay rate is connected with a shorter response time on string vibration which is a desired feature and characteristic of good guitars. It seems that the presented method for measuring FRF of a guitar is a good starting point for guitar tone improvement by modifications of both resonant boards with braces. However, only additional tests will show if the amplitude of the first resonant peak in FRF is a sufficient criterion for estimating the tonal quality of a guitar.

REFERENCES

[1] **Richardson, B. E.**, *The influence of strutting on the top-plate modes of a guitar*, Catgut Acoustical Society Newsletter, No. 40, pp. 13-17, November 1983.

[2] **Bissinger, G.**, *Mode-ling the Sound of the Violin: the V-R Model and the Role of the Soundpost*, Catgut Acoustical Society Journal, Vol. 3, No. 5, pp. 29-37, May 1998.

[3] **Boulosa, R. R., Boustamante, F. O.** and **Benade, A. H.**, *On sound radiation in the classical guitar*, International symposium on musical acoustics, Leavenworth, pp. 85-89, Washington, 1998.

[4] **Hutchins, C. M.**, *Plate tuning for the violin maker*, Catgut Acoustical Society Newsletter, No. 39, pp. 25-32, May 1983.

[5] **Kopač J.** and **Šali, S.**, *Optimizing the Position of Braces on the Resonant Board of a Guitar*, in preparation.

[6] **Ewins, D. J.**, *Modal Testing; Theory and Practice*, Letchworth: Research Studies Press Ltd., 1984.

[7] *The Fundamentals of Signal Analysis, Application Note 243*. Hewlett-Packard.

[8] **Eban, G.**, *The Relation of Musical Acoustics Research to Guitar design and Building*, International symposium on musical acoustics, Leavenworth, pp. 97-102, Washington, 1998.

[9] **Davis, E. B.**, *A "New" Window on Tone, Re-scaling Frequency response Functions*, International symposium on musical acoustics, Leavenworth, pp. 91-95, Washington, 1998.

[10] **Curtin, J.**, *Innovation in Violinmaking*, International symposium on musical acoustics, Leavenworth, pp. 11-16, Washington 1998.

[11] **Kopač, J.** and **Šali, S.**,: *Measuring the Quality of Guitar Tone*, submitted to Experimental Mechanics, February 1999.