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Modification of the guitar bracing using optimization

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Abstract The form of modern guitars were shaped by Spanish luthiers in the XIX century. Especially Antonio de Torres Jurado is the one, whose designs are an inspiration for modern constructions. From the very beginning, guitars are struggling with not sufficient sound levels for all the desired applications. Apart from electroacoustic amplification, there were several attempts to modify the construction of the sound hole or the soundboard. Higher sound pressure levels were often connected with distorted sound, sometimes not acceptable to musicians. In this paper, inequalities in the frequency characteristics of the sound generated by the guitar with modern sound holes are presented. Resonant frequencies of the soundboard were pointed as being responsible for the too high amplitude of sound in the 600-800 Hz frequency range. Using optimization and finite element method modelling, the best patterns of bracings were proposed to equalize the frequency spectrum and improve the sound of the instrument.

Keywords: guitar bracing, optimization, vibration, resonances.

1. Introduction

A guitar is a fretted instrument with typically six strings. It is classified as a chordophone, so the sound is produced by a vibrating string. The string has a very small area, so it can produce only a very quiet sound. The most important element of the guitar is the soundboard which receives the vibrations from the strings transmitted by the bridge and the saddle. The soundboard together with a resonant cavity inside the guitar body radiates the sound. Its shape, material and structure influence the amplitude and the frequency characteristics of the sound. Soundboard is usually made of 2 – 3 mm thick piece of spruce wood, which provides good sound but is not strong enough to be used solely. Bracing used on the bottom surface of the soundboard improves its strength and is also useful in shaping the sound of the whole instrument. According to [1], "by varying brace design, each builder has sought to produce a sound that conformed to his concept of the ideal". There are several types of popular bracing dedicated to nylon or steel string guitars like Fan bracing, Kasha Bracing, X-Bracing, Double X-bracing, A-bracing, V-Class Bracing, etc. Most popular bracings are presented in Fig. 1.

Figure 1. Most popular bracings used in soundboards of guitars [2].

Each bracing provides a specific sound dependent not only on the luthier but also on the music, to which the instrument is dedicated to. Different kinds of bracings were measured (mode shapes and frequency characteristics) for most popular bracing types in [3]. The problem of bracing is much more important for new shapes of soundboards and sound holes, where different resonances are amplified and using classical bracing cannot provide satisfactory sound.

Piotr Aleksander Nowak from P.A.N. Luthier Instruments proposed a modern guitar with different shape of sound holes (Fig. 2). Variation of A-bracing was used for the soundboard. The guitar back is equipped with the ladder bracing.

Luthier and guitarists playing the new instrument complained about the too high amplitude of sound in the 600-800 Hz frequency range. The study aimed to localize the source of the problem and to provide solutions for improving the frequency characteristics of the instrument.

Figure 2. Analyzed guitar with a new shape of the sound holes (left).
Variation of the A-bracing used for the soundboard (right).

2. Methods

The improvement of the guitar bracing was divided into the following steps: measurements, numerical modelling, calibration of the model and modification of the bracing to find the best solution providing the best possible sound of the instrument.

The sound of the instrument and the vibrations of its soundboard were measured in an anechoic chamber [4] using a robotic player that allows to pluck strings repetitively. Only one string was plucked in one time, other strings were open. The velocity of the soundboard vibrations was measured using a laser doppler vibrometer Polytec in 20 points distributed in the one halve of the soundboard (Fig. 3). Apart from the vibration measurements, a microphone in a 1.5 m distance from the soundboard was used to record sound generated by the instrument. The signal from the microphone was used mainly to identify the problematic notes. Vibration analysis was used to analyze the shape of the resonant frequencies of the soundboard.

The numerical model was created and imported to the finite element method environment (Comsol Multiphysics [5]). Basing on the basic frequencies, its harmonics, and the distribution of the vibration's velocity, numerical model of the instrument was calibrated. Small correction to the geometry and the material properties were introduced to match the measurement and modelling results.

Finally, particle swarm optimization of bracing was performed [6], using a standard deviation of the frequency characteristics of the averaged over all points on the soundboard level of vibration L_v as the first optimization criterion:

$$J_1 = \sigma_{Lv} = \sqrt{\frac{\sum_{f=200}^{1000}(\overline{L_v} - L_v(f))^2}{15}}. \tag{1}$$

The second criterion was the averaged over all points on the soundboard value of the vibration velocity v in the 600 – 800 Hz frequency range:

$$J_2 = \frac{\sum_{f=630}^{800} v(f)}{3}. \tag{2}$$

The frequency range of 600-800 Hz was corresponding to second or third harmonic of notes, that sounds unpleasant in analyzed guitar. According to [7] the second harmonic being louder than the first one is typical for poor guitars. The optimized bracing was planned as four parts of wood connected symmetrically to the soundboard. Their position and dimensions were optimized with bounds listed in Tab. 1. The maximum number of iterations was set to 60. The population size was set to 50.

Figure 3. Positions of soundboard vibration velocity measurements.

Table 1. Lower and upper bounds for brace parameters under optimization.

Parameter	Unit	Range
Distance from the soundboard edge	mm	30 – 130
Length of the brace	mm	0 – 130
Distance from the middle of the soundboard (vertical)	mm	0 – 120
Width of the brace	mm	2 – 8
Angle of the brace rotation	degree	0 – 180

3. Results

3.1. Measurements results

The highest amplitude of the signal within the 600 – 800 Hz frequency range was observed for note A3, for which the third harmonic has a frequency equal to 660 Hz (Fig. 4, left). The amplitude of the third harmonic was five times higher than of the first harmonic. What is more, for some notes without a 660 Hz harmonic frequency, the vibrations were also observed as a non-harmonic component of the sound.

On the other hand, the sound pressure registered by the microphone presented a proper signal with the fundamental frequency almost five times higher than the third harmonic (Fig. 4, right).

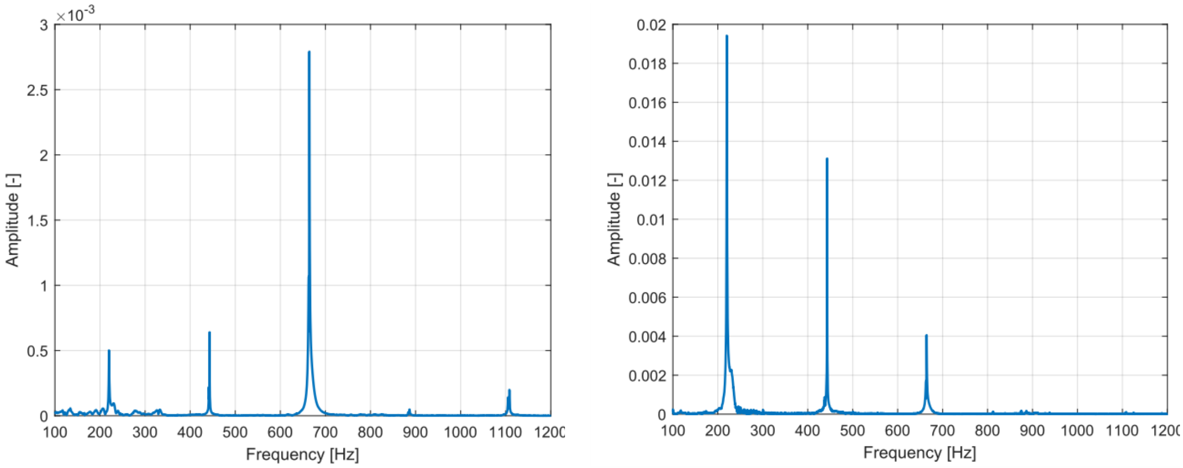

Figure 4. Frequency characteristics of the vibration of the soundboard (point 16th) of the note A3 (fundamental frequency 220 Hz). Vibration – left, sound pressure – right.

For another string playing higher note (E4), the fundamental frequency is 330 Hz, what gives second harmonic equal to 660 Hz in the most problematic frequency range. For this case both: vibration and sound pressure amplitude for the second harmonic is higher than for the first harmonic (Fig. 5).

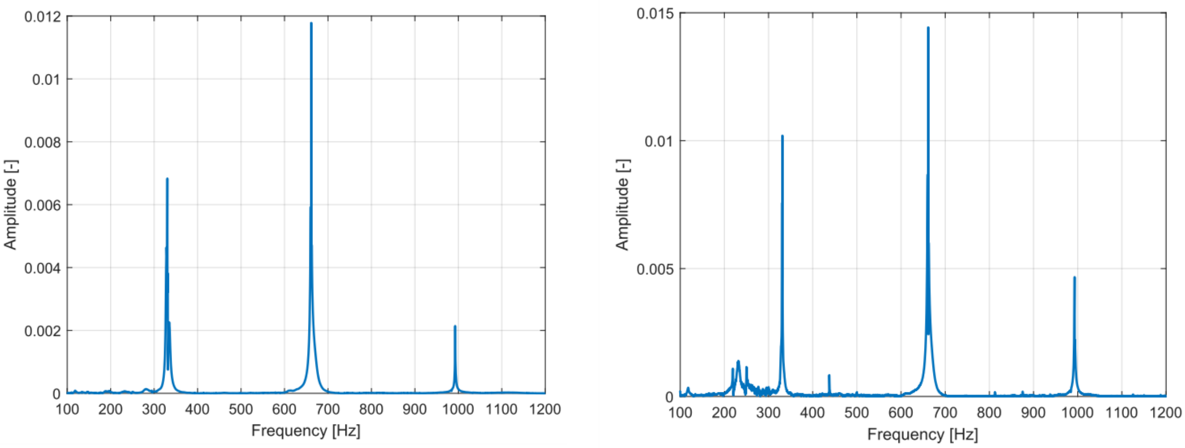

Figure 5. Frequency characteristics of the soundboard (point 16)
for the note E4 (fundamental frequency 330 Hz). Vibration – left, Sound pressure – right.

Distribution of the vibration velocity in the 600 – 800 Hz frequency range is presented in Fig. 6. The highest vibrations can be observed in the neighborhood of the point no. 16 ("x" mark in Fig. 6). The soundboard is not equally reinforced by the bracing and therefore it should be modified, especially around the area indicated by the point no. 16.

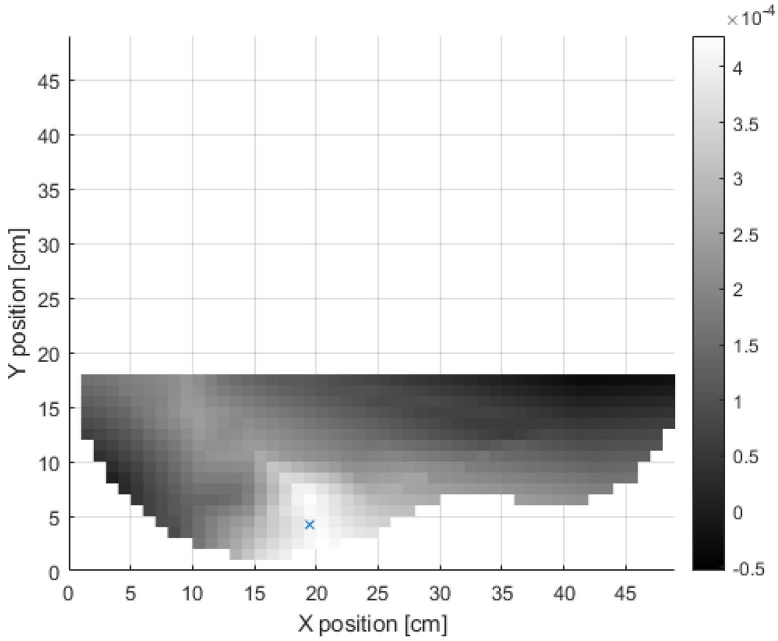

Figure 6. Vibration velocity distribution of the soundboard.
Results limited to the 600 – 800 Hz frequency range. Position of 16th point marked with x.

3.2. Optimization

Bracings for 20 best solutions with criterion J_1 are presented in Fig. 7, left side. All the solutions are very similar – the added pieces of bracing are almost in the same place, overlapping in the figure. Two of them (upper) are approximately parallel to the edge of the soundboard. The average width of the best 20 bracings was equal to 6.7 mm, with the angle of 118°.

In case of J_2 optimization criterion (lowest amplitude in the 600 – 800 Hz frequency range), the best 20 solutions are more differentiated (Fig. 7, right). Some of them have similar parameters like for the J_1, but there are also some solutions with braces close to the middle of the lower part of the soundboard. The most interesting solution is with the longest elements, which are approximately paralell to the soundboard edges (black thick lines, corresponding to brace_36 in Fig. 8). This kind of bracing strengthen the middle part of the soundboard, which is favorable also for the strength of the soundboard required to bear tension from the strings.

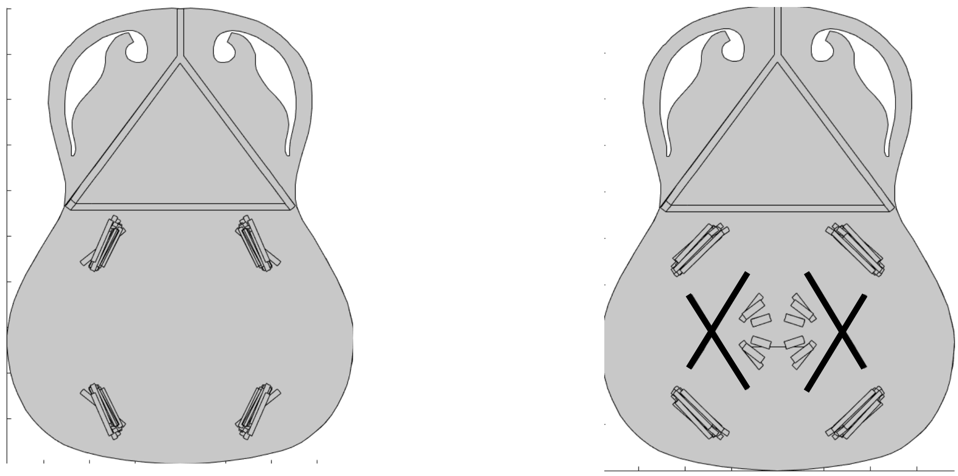

Figure 7. Bracings for the best solutions with optimization criterion J_1 (20 solutions, left) and J_2 (20 solutions, right).

Figure 8 presents the frequency characteristics of the best solutions according to the criteria J_1(brace_1079) and J_2 (brace_36). Peaks calculated for the geometry without bracing (w/o bracing) were equalized in bracing number 1079 and 36. The best bracing for J_1 (brace_1079) has the most equalized frequency characteristics within the whole analyzed range. Standard deviation of the vibration level calculated for the frequency characteristics is about 3.3 dB.

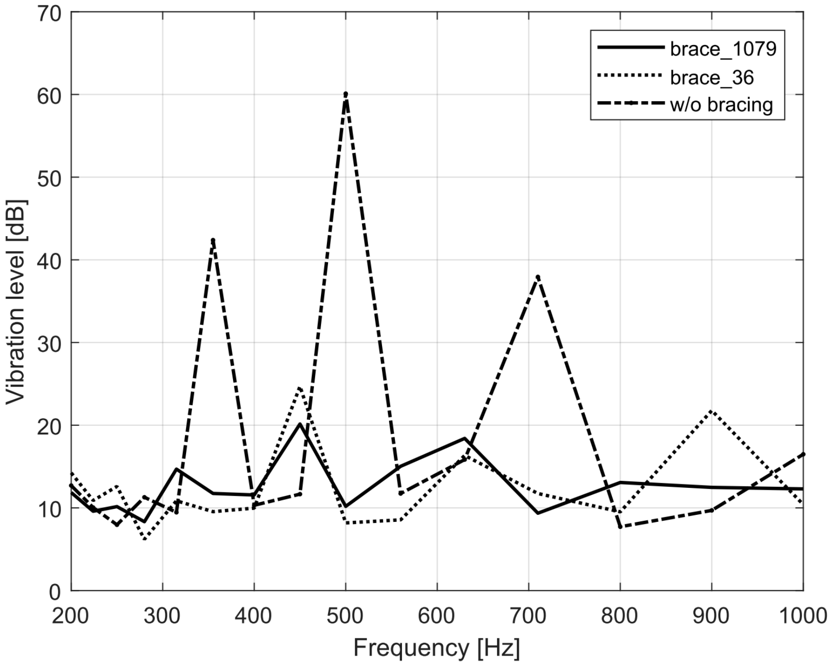

Figure 8. Frequency characteristics of the best bracings. Brace_1079 – criterion J_1, brace_36 – criterion J_2, w/o bracing – reference solution calculated without bracing.

The lowest amplitude in the problematic frequency range of 600 – 800 Hz was obtained for the bracing with more uneven frequency characteristics for remaining frequency ranges (brace_36 in Fig. 8, standard deviation about 5.0 dB). For the solution without the bracing, the standard deviation was above 15 dB.

4. Conclusions

In the paper, a modern guitar with an alternative localization of the sound holes was analyzed. Basing on the information from the luthier and the users of the instrument, sound and vibration measurements were conducted. The signals recorded by a microphone and a laser vibrometer were analyzed for different notes played using different strings. Fourier transform of the signals confirmed that the 600 – 800 Hz frequency range is the most problematic. Spatial distribution of vibrations together with a numerical model let us find the area of the soundboard responsible for the unfavorable sounds.

Particle swarm optimization was used to find the best position and shape of the bracing for the soundboard of the guitar with an alternative sound hole. The proposed bracings equalized the frequency characteristics and decreased resonances in the problematic range of 600 – 800 Hz. Further works should refine the brace shape and optimization ranges to find even more improvement in the frequency characteristics of the instrument. Special care should also be taken to provide sufficient strength of the soundboard.

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Additional information

The author(s) declare: no competing financial interests and that all material taken from other sources (including their own published works) is clearly cited and that appropriate permits are obtained.

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