POSITIONING OF BRACES ON A GUITAR SOUNDBOARD

Samo Šali and **Janez Kopac**

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

ABSTRACT

Based on the analysis of several instruments, the first resonant peak in the frequency response function (*i.e.*, FRF) of a guitar was determined as a significant peak for guitar loudness. Next, experimentation with an additional 20-gram weight (mass) on the soundboard was used to predict an optimal brace position in terms of tone loudness. It was measured that due to the additional mass on a certain place of the soundboard the changes in the amplitude, damping and position of the first peak in the FRF of a guitar occurred. These changes are correlated to the changes (amplitude, damping, and position) due to the brace on the same place. The use of artificial neural network resulted in satisfactory accuracy of the predicted effect of the weight for any position on the soundboard. Therefore, the effect of the brace can also be predicted and the time for searching for an optimal brace position can be significantly reduced.

NOMENCLATURE

$b(x,y)$	coefficient of viscous damping of system (*m-b-k-A*) [weight on (*x,y*)]
b'	coefficient of viscous damping of system (*m-b-k-A*) (without weight)
$b_{rel}(x,y)$	relative coefficient of viscous damping of system (*m-b-k-A*) [weight on (*x,y*)]
$\mathbf{F}$	force vector
F	amplitude of sinusoidal driving force
$f_{0d}(x,y)$	frequency of system (*m-b-k-A*) [weight on (*x,y*)]
f'_{0d}	frequency of system (*m-b-k-A*) (without weight)
$f_{0d\,rel}(x,y)$	relative frequency of system (*m-b-k-A*) [weight on (*x,y*)]
$k(x,y)$	stiffness of system (*m-b-k-A*) [weight on (*x,y*)]
k'	stiffness of system (*m-b-k-A*) (without weight)
$k_{rel}(x,y)$	relative stiffness of system (*m-b-k-A*) [weight on (*x,y*)]
$m(x,y)$	mass of system (*m-b-k-A*) [weight on (*x,y*)]
m'	mass of system (*m-b-k-A*) (without weight)
$m_{rel}(x,y)$	relative mass of system (*m-b-k-A*) [weight on (*x,y*)]
$\overline{m}_{rel}(r)$	average of values $m_{rel}(x,y)$ corresponding to a certain brace position r
$P(x,y)$	amplitude of sound pressure p [weight on (*x,y*)]
P'	amplitude of sound pressure p (without weight)
$P_{rel}(x,y)$	relative amplitude of sound pressure p [weight on (*x,y*)]
p	sound pressure due to oscillation of system (*m-b-k-A*)
r	brace position
$\mathbf{v}$	complex velocity vector
X	maximal amplitude of displacement
(x,y)	weight's position
$\mathbf{Z}$	mechanical impedance vector
Z	magnitude of mechanical impedance vector
$d(x,y)$	damping factor of system (*m-b-k-A*) [weight on (*x,y*)]
d'	damping factor of system (*m-b-k-A*) (without weight)
$d_{rel}(x,y)$	relative damping factor of system (*m-b-k-A*) [weight on (*x,y*)]
w_{0d}'	circular frequency of natural damped oscillation of system (*m-b-k-A*) (without weight)
w_0'	circular frequency of natural undamped oscillation of system (*m-b-k-A*) (without weight)

1 INTRODUCTION

This paper is focused on the problem of positioning of braces (cross struts, fans) on a guitar soundboard. The idea for this work was initiated by investigations of the influence of struts on the guitar modes [1, 2] and by modeling of low-frequency guitar function [3, 4]. Another basis for the present paper is a measured correlation between the tone loudness and characteristics of the first resonant peak in the FRF of a guitar [5, 6]. A comparison of guitars with loud tones and guitars with more quiet tones showed that for the first group of guitars three properties of the first resonant peak in its

FRF are significant. First, the amplitude is larger, second the damping is rather smaller, and third the frequency is rather lower [5, 6]. This resulted in a definition of the aims of optimizing a guitar's frequency response as follows: (i) increase in amplitude, (ii) decrease or non-alteration of damping and (iii) decrease or non-alteration of frequency of the first resonant peak. Consequently, a procedure for optimizing a position of braces was introduced. This procedure is based on an approximation of the first resonant peak in the FRF of a guitar with a virtual one-mass system (*m*-*b*-*k*-*A*). This consists of a mass (discrete mass m), damper (coefficient of viscous damping b), spring (stiffness k) and sound radiating membrane with a constant area A [3, 6-8]. The starting phases of this concept are briefly shown in Figure 1. One can see that in the procedure for optimizing the position of braces the artificial neural network (ANN) was applied to reduce the number of measurements where the position of the weight on a soundboard (see Figure 1) was a variable. Because of a relatively simple use and the accurate interpolation of desired quantities the use and importance of the ANN [9] is presented in more details.

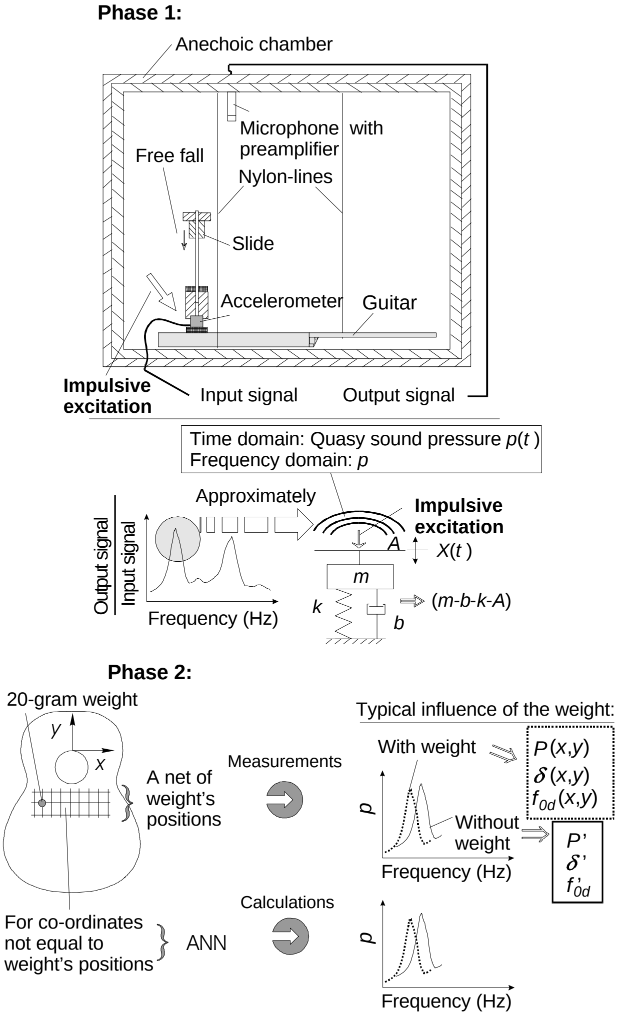

Figure 1: First two phases of a procedure for controlled brace positioning.

The main idea of the procedure for optimizing the position of braces is to start performing this optimization on a guitar without braces. More precisely, each additional brace should be glued on the soundboard after a careful analysis of the FRF of a guitar without this brace. The reason for this lies in the following two facts. First, due to non-homogeneity of wood an identical construction of a guitar body does not ensure an identical sound quality. Second, a number of braces on a soundboard should rather be small than high [10]. The latter is reasonable from several points of view. One of them is that energy contained in strings is limited and its transmission over the light soundboard (small number of braces) will logically be more efficient than over the heavy one (large number of braces). The latter is conditionally true, because tone loudness is not the only parameter to optimize in guitars.

According to Meyer [2] the quality factor Q and quantity $L_{80\,\mathrm{m}125}$ (which are related to the damping and amplitude, respectively, of the first resonant peak in the FRF) strongly depends on the position of a cross strut: Changing the position of this brace can result in improving one or another quantity but not both quantities at the same time [2]. Note that the analyzed brace position in these tests was perpendicular to the axis of soundboard symmetry and the variable was a distance between the brace and soundhole [2]. In contrast, in our tests we searched for an optimal brace position, which for instance in case of a cross strut does not need to be perpendicular to the wood grain.

2 METHODS AND RESULTS

2.1 Definitions

In the following analysis a theoretical basis for a method of positioning braces on the guitar resonant board is given. This method is based on the idea about returnable changes (putting the weight onto the top resonant board) performed on the assembled guitar. In this case the assembled guitar means a guitar without any or without some of the braces. Between the weight and the board a thin layer of bees-wax which replaced glue was piled.

A method for measuring the FRF of a guitar and its analysis are fully described in [8] and briefly shown in Figure 1. It is also evident from Figure 1 that FRFs of a test guitar were measured first for a guitar with and after that without the weight. As indicated in Figure 1, in each FRF only the first resonant peak was analyzed. Because a lag between the input and output signal was 90° this peak was considered as a consequence of a virtual and hybrid system (*m*-*b*-*k*-*A*) [see section 1]. Note from Figure 1 that this system consists of three mechanical elements (m, b, k) and a massless sound radiating surface A which is attached to the discrete mass m by a massless rod. A sound pressure (time dependent) around the membrane A was denoted as $p(t)$ [8]. Its Fast Fourier Transformation (*i.e.*, FFT) was denoted as p. An impulse response function of each measured FRF (filtered with a narrow-band inverse Chebyshev filter) was calculated. Next, it was approximated that FFT of this function is identical to *p* [8]. Finally, from each resulting *p* (with and without the weight) three characteristics were calculated: amplitude (*P*), viscous damping factor (*d*) and frequency ($f_{0d} = w_{0d}/2\pi$) [8, 10].

2.2 The influence of the weight on the soundboard

The weight on a soundboard in position (*x*,*y*) affects *P*, *d* and f_{0d} which can therefore be denoted as *P*(*x*,*y*), *d*(*x*,*y*) and $f_{0d}(x,y)$. Similarly, *P*, *d* and f_{0d} for the board without the weight may be denoted as *P'*, *d'* and f'_{0d}. By analogy *P'*, *d'* and f'_{0d} were determined from *p* for the guitar without the weight. Relative changes (denoted by subscript $_{rel}$) of *P*, *d* and f_{0d} for a guitar with the weight with respect to the guitar without the weight, are:

$$P_{rel}(x,y) = P(x,y)/\ P', \tag{1}$$

$$d_{rel}(x,y) = d\,(x,y)/d', \tag{2}$$

$$f_{0d\ rel}(x,y) = f_{0d}(x,y)/f'_{0d}, \tag{3}$$

From Figure 1 we can conclude that *m*, *b* and *k* were calculated from *P*, *d* and f_{0d}. By analogy, *m*(*x*,*y*), *b*(*x*,*y*) and *k*(*x*,*y*), which indicate *m*, *b* and *k* in dependence on the position of the weight (*x*,*y*), were calculated from *P*(*x*,*y*), *d*(*x*,*y*) and $f_{0d}(x,y)$. Quantities *m'*, *b'* and *k'*, which indicate *m*, *b* and *k* for a guitar without the weight, were calculated in the same way from *P'*, *d'* and f'_{0d}. By analogy to equations (1) to (3), the relative changes (denoted by subscript $_{rel}$) of quantities *m*, *b* and *k* for a guitar with the weight with respect to the guitar without the weight, are:

$$m_{rel}(x,y) = m(x,y)/m', \tag{4}$$

$$b_{rel}(x,y) = b(x,y)/b', \tag{5}$$

$$k_{rel}(x,y) = k(x,y)/k', \tag{6}$$

Figure 2 shows a top resonant board B1 without any large brace near the soundhole. The co-ordinates of the weight restrict the area of a possible position of a cross strut. For each position of the weight, *p* was measured and after that $P(x = x_i, y = y_j)$, $d\,(x = x_i, y = y_j)$ and $f_{0d}(x = x_i, y = y_j)$ were estimated. Figure 3 shows the resulting $P_{rel}(x = x_i, y = y_j)$, $d_{rel}(x = x_i, y = y_j)$ and $f_{0d\ rel}(x = x_i, y = y_j)$. As indicated in Figure 2, let the 13 positions of the weight ($x = x_i, y = 7$ mm) form line r1. By analogy, the positions of the weight ($x = x_i, y = 14$ mm), ($x = x_i, y = 0$ mm) and ($x = x_i, y = 21$ mm) form lines r2, r3 and r4, respectively. Lines r1 to r4 are also possible positions of a cross strut.

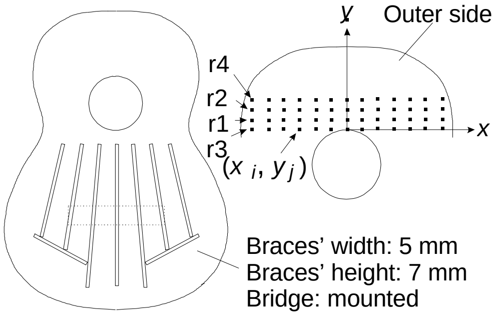

Figure 2: Top board B1 and the area of a possible cross strut position.

Table 1 shows 37 positions of the weight whose co-ordinates were the input data for an artificial neural network program NeuralWorks Professional II/PLUS [9]. The output data were quantities $P_{rel}(x = x_i, y = y_j)$, $d_{rel}(x = x_i, y = y_j)$ and $f_{0d\ rel}(x = x_i, y = y_j)$. The important settings in the program were as follows:

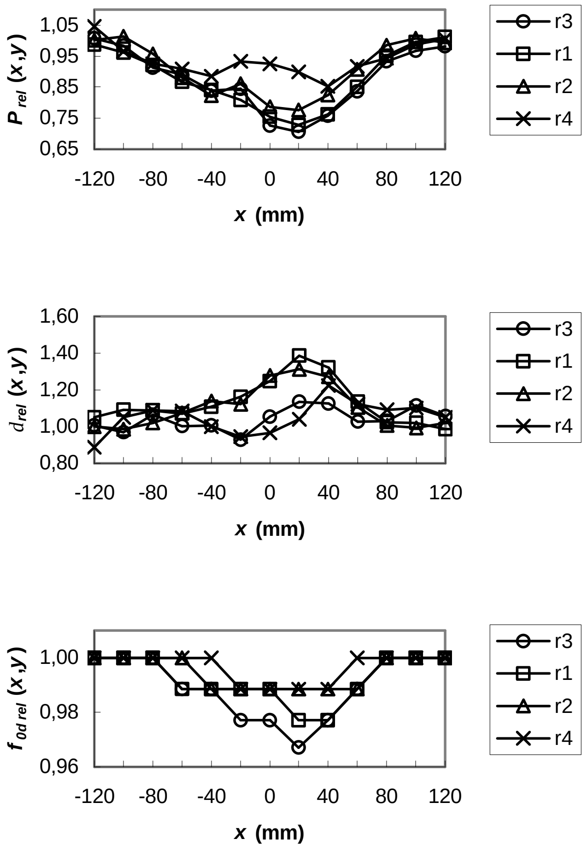

Figure 3: $P_{rel}(x,y)$, $d_{rel}(x,y)$ and $f_{0d\ rel}(x,y)$ in dependence on the weight's position (top B1, *y* Î r1,r2,r3,r4).

- number of input parameters - 2,
- number of output parameters - 3,
- number of hidden layers - 3,
- number of neurons in the hidden layer - 10.

After several minutes the resulting RMS error [9] was relatively low, which indicated a good correlation between the input and output data. The accuracy of prediction of the output data by ANN was tested with the rest of 15 weight positions ($x = x_i, y = y_j$) and the corresponding quantities $P_{rel}(x = x_i, y = y_j)$, $d_{rel}(x = x_i, y = y_j)$ and $f_{0d\ rel}(x = x_i, y = y_j)$. Relatively small differences between the measured and calculated (predicted) values for all three groups of output data are shown in Figure 4. Because $m_{rel}(x,y)$, $b_{rel}(x,y)$ and $k_{rel}(x,y)$ are calculated from $P_{rel}(x,y)$, $d_{rel}(x_i,y)$ and $f_{0d\ rel}(x,y)$ (see above), it seems that, based on a certain number of measurements, it is possible by putting down the weight on a certain area of the board to approximately predict $m_{rel}(x,y)$, $b_{rel}(x,y)$ and $k_{rel}(x,y)$ for any virtual position of the weight. This is true only if this virtual position is inside the area which was considered during the procedure of learning ANN. This feature can be used during the procedure for optimizing position of braces on a guitar soundboard.

2.3 The relation between position of the weight and position of the brace

In the following experiment a relation between the effect of the weight and the effect of the glued brace on system (*m-b-k-A*) was analyzed. It was assumed that inside each area the brace position could be slightly different for each different soundboard. To simplify matters, only two in advance defined brace positions are analyzed, thus the use of ANN to predict the effect of the weight on the neighboring places is omitted.

i	($x=x_i,y=y_j$) Line r1 j=1	($x=x_i,y=y_j$) Line r2 j=2	($x=x_i,y=y_j$) Line r3 j=3	($x=x_i,y=y_j$) Line r4 j=4
	mm	mm	mm	mm
1	(-120, 7)	(-120, 14)	(-120, 0)	(-120, 21)
2	(-100, 7)	(-100, 14)	(-100, 0)	(-100, 21)
3	(-80, 7)			(-80, 21)
4	(-60, 7)	(-60, 14)	(-60, 0)	
5		(-40, 14)	(-40, 0)	(-40, 21)
6	(-20, 7)			(-20, 21)
7		(0, 14)	(0, 0)	(0, 21)
8	(20, 7)	(20, 14)	(20, 0)	
9	(40, 7)		(40, 0)	(40, 21)
10	(60, 7)	(60, 14)		(60, 21)
11	(80, 7)	(80, 14)	(80, 0)	
12			(100, 0)	(100, 21)
13	(120, 7)			(120, 21)

TABLE 1: Positions of the weight ($x=x_i,y=y_j$) - input data in stage of ANN learning (top B1).

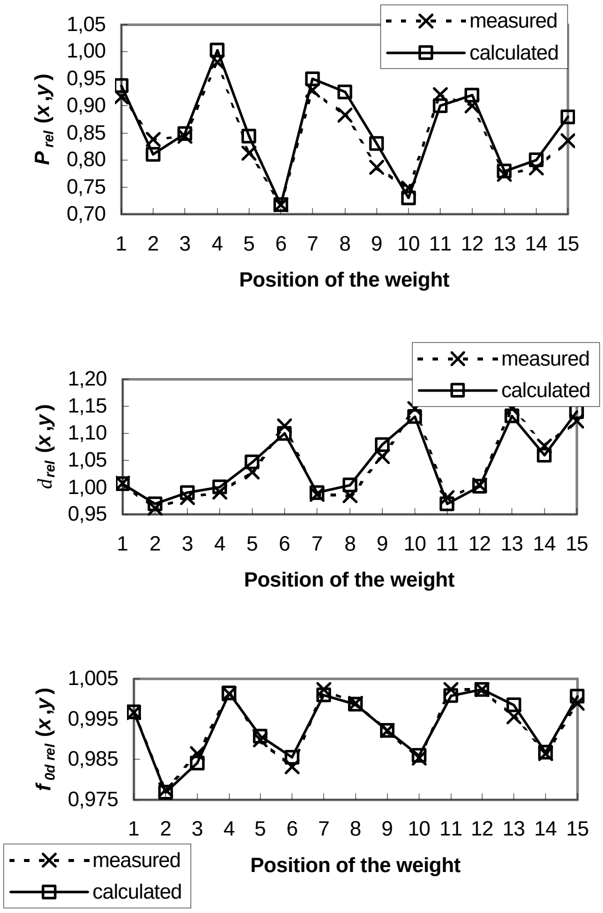

Figure 4: The differences between the measured and calculated quantities after ANN learning.

Figure 5 shows a shaded area of a possible position of a brace that lies parallel to wood grain in many soundboards (top board B2). In the following test for two possible brace positions denoted as r1 and r2 quantities $m_{rel}(x,y)$, $b_{rel}(x,y)$ and $k_{rel}(x,y)$ were measured as shown in sections 2.1 and 2.2. The values of $m_{rel}(x,y)$ are shown in Figure 6. One can see that the average of all values $m_{rel}(x,y)$ for each possible brace position separately is not significantly different (approximately 1%). Thus, we can conclude that the procedure of measuring the influence of the weight on the two different possible brace positions did not result in any significant differences. This was supported by an experiment where the same brace was successively glued on both possible brace positions on the outer side of the soundboard. The analysis of two resulting FRFs of a guitar for the two different brace's positions did not reveal any significant differences in terms of amplitude, damping and frequency of the first resonant peak. However, at those three co-ordinates (x,y) on both r1 and r2 which are closer to the soundhole the average of values $m_{rel}(x,y)$ is evidently smaller for r2 (approximately 27%). The new possible brace positions constrained with only three co-ordinates on r1 and

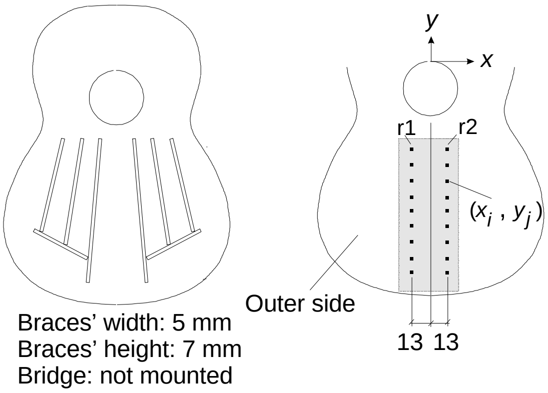

Figure 5: Two possible brace positions r1 and r2 on top B2.

r2 can be denoted as r1' and r2', respectively. Figure 7 shows a successive gluing of a short brace on both r1' and r2' and the resulting effect on P', d' and f'_{0d}. To ensure easy ungluing from the soundboard both soundboard and tested braces were varnished. In addition, glue in these experiments was non-resistant to heat thus a hair dryer was used during the ungluing. It is evident from Figure 7 that amplitude and damping of the first resonant peak in the FRF of a guitar is more favorable for a brace on r2' and its frequency is insignificantly higher (not desired [6]) in comparison to brace on r1'.

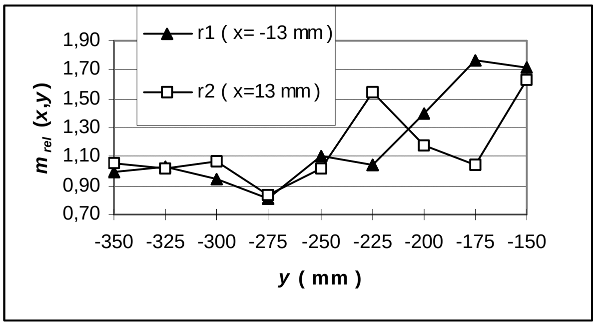

Figure 6: Values of m_{rel} (x,y) for two possible brace positions on top B2.

Several hundreds of measurements of values $m_{rel}(x,y)$ and 22 experiments with changing the position of different braces on different areas of different soundboards are in agreement with the above experiment [12]. Due to simplification of a real modal behavior of a guitar with this virtual and hybrid one-mass system, the analysis relies more on statistics than on physical features. In case of an external sinusoidal driving force (string vibration) which is applied to one-mass system, its mechanical impedance vector ($\mathbf{Z}$) is [11]:

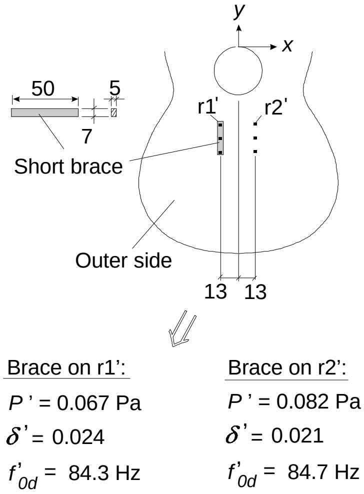

Figure 7: Two positions of a short brace on top B2 and resulting FRF of a test guitar.

$$\mathbf{Z} = \mathbf{F}/\mathbf{v} = b' + \mathrm{j}(m' w_{0d}' - k'/w_{0d}'), \tag{7}$$

where $\mathbf{F}$ and $\mathbf{v}$ are force and complex velocity vector, respectively and w_{0d}' is circular frequency of natural damped oscillation of system (m-b-k-A). The maximal amplitude of actual steady-state displacement of the analyzed system is [11]:

$$X = F/(w_{0d}' \cdot Z), \tag{8}$$

where F is amplitude of sinusoidal driving force and Z is magnitude of mechanical impedance vector. The analysis of experimentally obtained results (m', b', k', w_{0d}') showed insignificant contribution of the imaginary part in expression (7) thus the following was established:

$$Z \cong b'. \tag{9}$$

In addition, the relation between the amplitude of the analyzed peak in the FRF and displacement X [see expression (8)] for a considered situation can be logically denoted as:

$$P' \propto X. \tag{10}$$

Due to a constantly low damping factor d' of the analyzed peak in the FRF, in this analysis w_{0d}' is approximated with circular frequency of natural undamped oscillation $w_0' = \sqrt{\frac{k'}{m'}}$ [11, 13]. Finally, expression (8) results in the following relation between the parameters of system (m-b-k-A):

$$X \cong \frac{F\sqrt{m'}}{\sqrt{k'b'}}. \tag{11}$$

3 DISCUSSION

For 10 of 22 performed experiments impedance Z, displacement X and three characteristics of the analyzed peak in the FRF for a guitar without the brace and for a guitar after gluing this brace on two different positions r1 and r2 are shown in Table 2. This table actually represents the connection between experimentation and theoretical model whose essence is shown through expression (7). Next, Figure 8 shows a dependence of amplitude P' on impedance Z for a guitar before and after the brace gluing in the same chart. It is evident that impedance Z, which is calculated from parameters of system (*m*-*b*-*k*-*A*), is inversely proportional to the amplitude of the first resonant peak, in general. In addition, from Table 2 one can calculate approximately linear correlation between displacement X and amplitude P'. Together with Figure 8 this fact strongly supports relations between X, Z and P' indicated in expressions (7) to (11).

The average values of quantities $m_{rel}(x,y)$ corresponding to a certain brace position r [indicated as $\overline{m}_{rel}(r)$ in our tests] from the experiments with the weight are also shown in Table 2. We can conclude that there is a certain correlation between the influence of the weight on the one side, and that of the brace on the other side, on the FRF of a guitar. More precisely, based on expressions (7) to (11) a relation between quantity $\overline{m}_{rel}(r)$ from the experimentation with the weight and parameters of system (*m*-*b*-*k*-*A*) after the brace gluing is:

$$\left.\frac{1}{\overline{m}_{rel}(r)}\right|_{\text{weight on }(x,y)\in r} \propto \left.P'\right|_{\text{brace on }(x,y)\in r} \propto \left.\frac{\sqrt{m'}}{\sqrt{k'b'}}\right|_{\text{brace on }(x,y)\in r} . \qquad (12)$$

This expression is fulfilled for all experiments of brace positioning separately (see Table 2). Because of different shapes of braces and soundboards used in the experimentation, expression (12) requires an explanation. For instance, in experiment 8 $\overline{m}_{rel}(r)$ is relatively low for brace position r1 and consequently P' for a brace on this position is relatively high in comparison to the same brace on r2. However, in experiment 10 another brace and soundboard were used. Therefore, despite a relatively high $\overline{m}_{rel}(\text{r1})$ in this experiment in comparison to $\overline{m}_{rel}(\text{r1})$ in experiment 8, the corresponding P' is higher in experiment 10. Similarly, one can see from Table 2 that low damping factor d' for a situation after the brace gluing is related to high P' for all experiments separately. Therefore, (i) lower or slightly higher frequency, (ii) low damping and (iii) high amplitude of the first resonant peak in the FRF of a guitar are correlated to relatively high guitar tone loudness (see section 1) [6]. Finally, according to the estimated expressions and relations indicated above, expression (12) represents experimentally verified and partly physically explainable model for tone loudness control.

	Before brace gluing							**After brace gluing**				
	Without weight					With weight						
	Z	X (10^{-4})*	P'	d'	f'_{0d}	Brace position r	$\overline{m}_{rel}(r)$	Z	X (10^{-4})*	P'	d'	f'_{0d}
	kg/s	m	Pa		Hz			kg/s	m	Pa		Hz
1	15.9	1.17	0.072	0.0216	85.3	r1	1.58	16.3	1.16	0.067	0.024	84.3
						r2	1.23	13.3	1.41	0.082	0.021	84.7
2	15.2	1.12	0.079	0.0268	93.5	r1	1.56	15.5	1.10	0.077	0.032	93.5
						r2	1.27	14.8	1.15	0.080	0.029	93.6
3	10.9	1.65	0.104	0.0261	88.4	r1	1.14	9.4	1.82	0.130	0.021	93.2
						r2	1.16	9.6	1.78	0.125	0.022	93.0
4	8.7	2.02	0.133	0.025	90.2	r1	1.10	7.8	2.16	0.157	0.021	94.4
						r2	1.06	7.2	2.37	0.168	0.018	93.5
5	12.2	1.38	0.100	0.026	94.1	r1	1.84	20.3	0.67	0.073	0.024	116.3
						r2	1.63	19.9	0.69	0.075	0.023	117.0
6	10.3	1.59	0.121	0.025	96.9	r1	1.89	19.4	0.71	0.077	0.024	115.9
						r2	1.44	18.5	0.74	0.081	0.021	116.5
7	21.8	0.63	0.068	0.024	115.9	r1	1.11	18.0	0.76	0.083	0.022	116.3
						r2	0.97	17.0	0.81	0.088	0.020	115.6
8	24.6	0.77	0.044	0.025	84.3	r1	1.12	20.7	0.82	0.058	0.022	93.8
						r2	1.16	25.7	0.66	0.047	0.026	94.7
9	33.9	0.41	0.044	0.026	115.3	r1	0.86	33.4	0.41	0.045	0.025	115.4
						r2	1.01	46.7	0.30	0.031	0.043	113.4
10	6.6	2.51	0.184	0.018	94.9	r1	1.64	13.0	1.07	0.113	0.020	113.9
						r2	1.87	12.8	1.29	0.105	0.023	114.5

* For F is 1 N

TABLE 2: Results of experimentation and calculated Z and X (for F = 1 N).

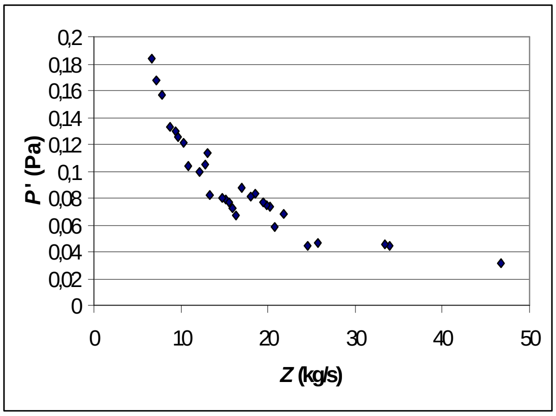

Figure 8: Dependence of displacement *X* on impedance *Z* (driving force *F* is assumed to be 1 N).

4 CONCLUSION

The current paper is based on a modeling of a first resonant peak of a guitar FRF with a virtual and hybrid system denoted as system (*m-b-k-A*) [8]. This consists of a discrete mass *m*, damper with coefficient of viscous damping *b*, spring with stiffness *k*, and sound radiating surface with constant area *A* (see section 1). In addition, the amplitude of the first resonant peak in the FRF of a guitar is proportional, whereas both damping and frequency are inversely proportional to the loudness of an instrument [6]. This feature was used during the procedure for positioning the braces on a guitar soundboard. The aim of this procedure is to increase the amplitude and not to alter or decrease both damping and frequency of the first resonant peak in the FRF of a guitar. Experimentation showed that depending on its position a 20-gram weight at co-ordinates (*x*,*y*) on a soundboard influences *m*, *b* and *k* of the system (*m-b-k-A*). For a constrained area on a soundboard the influence of the weight on *m*, *b* and *k* can be predicted by an artificial neural network for any co-ordinate (*x*,*y*). However, this co-ordinate has to be inside the net of co-ordinates for which the measurements with weight positioning were performed (see section 2.2). This results in enormous reduction of time consumed for the procedure of positioning the braces.

The effect of different brace positions on loudness of guitar tones [6] can be predicted after experimentation with 20-gram weight on the soundboard [see expression (12)]. The experimentation with the weight was used to perform returnable changes on the guitar soundboard instead of successive replacements of braces that would result in damaging of wood tissue. Due to approximation of a guitar response with a simple and virtual mechanical system (*m-b-k-A*) an exact physical explanation of the correlation between the effect of the weight and effect of the brace on the guitar's FRF is non-reasonable. So far, in spite of positive results of the presented method there is no reasonable and complete explanation of measured relations in terms of physics. This indicates that only additional experimentation can probably explain the presented measurements in a satisfactory way.

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