Frequency Response Evaluation of Acoustic Guitar Modifications

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Abstract—This paper investigates the effect of various modifications to an acoustic steel string guitar on low-frequency dynamics and sound pressure level. Modifications include string tension, sound-hole area and depth, bridge pin mass, top plate mass, stiffness and damping. Frequency response measurements are provided for all modifications considered. A lumped parameter model is found to capture the changes in measured frequency response and sound pressure level remarkably well. The measurements and model results are found to be consistent with player and listener perceptions in most cases. Results from a parametric study identify a unique combination of physical parameter adjustments for broadband increase in sound level. In addition, a technique for obtaining low-frequency free-field sound pressure without the need for an anechoic chamber is successfully applied to the acoustic guitar. This technique uses near-field, time-selective impulse response sound pressure measurements to determine the low-frequency free-field sound pressure.

I. INTRODUCTION

The acoustic steel-string guitar is a ubiquitous instrument enjoyed throughout the world. There exist many choices for variations in a steel string acoustic guitar. Major features such as construction materials, shape, size, and bracing patterns are set at the time the instrument is built. However, there are a number of post-build modifications available to help optimize an instrument. These range from something as simple as string size or tension, to as involved as shaving of braces. Common modifications include changes in saddle, nut and bridge pin materials, as well as the addition of pickups and electronics. Less common changes include sound-hole alterations from simple covers for feedback control to tuned sound-hole tubes to enhance bass response.

Although not necessary, the introduction of a body access panel [1] provides easier access for post-build modifications as well as repairs.

Modifications typically alter the dynamic response characteristics which can be sensed by the player and listener. Subjective evaluations and claims abound, but little comparative data is available.

Vibration and acoustic frequency response measurements have been used to determine and study the dynamics of stringed instruments. It has been shown that the first two modes of the acoustic guitar are the result of coupling of the Helmholtz resonance of the body and the top plate fundamental [2] – [4]. Although there exist many more modes of the guitar at higher frequencies [5], the first two modes define the low-frequency (typically 0 to 250 Hz) response.

The coupling between the Helmholtz and first plate mode of the guitar has been studied and modeled [2] – [4]. The Christensen and Vistisen [4] model provides remarkably accurate quantitative values of sound pressure level and top plate vibration over the low-frequency range. Other work has used this model for sensitivity analyses of structural modifications [6], [7] and as a basis for extension to include additional higher frequency modes [8], [9].

In this paper, comparative data is provided for a range of modifications. The data is provided in the form of sound pressure level frequency response. This provides a means of quickly comparing shifts in frequency and sound level associated with a particular modification. In many cases, these shifts are readily perceived, at least qualitatively, by ear.

In addition, a lumped parameter model [4] is used to model the low-frequency response of the guitar and the modifications tested. Agreement between the measured frequency response and the model is very good. This provides further support to such models at least over the lower frequency range, and offers insight into the relationship between a particular modification and physical model parameters.

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II. TEST SET-UP AND GUITAR

A small body, inexpensive steel string acoustic guitar (**Photo 1**) is used to obtain the data presented in this paper. Specifically, a Loar LH-200 with a solid spruce top, a body depth of 10.8 cm, and a lower bout width of 37.5 cm is used as the test guitar. It has a bone nut, bone saddle, plastic bridge pins, and light gauge phosphor bronze strings. The results presented in this paper are representative of tests with other guitars. During testing, the guitar is placed on a pad with its neck resting on foam to level the guitar horizontally. The strings are damped with foam material inserted between the strings and the neck at the seventeenth fret.

Photo 1 – Test guitar.

A miniature piezoelectric impact hammer (PCB model 086D80) with a vinyl tip is used to provide a short pulse input force (i.e., an impulse) to the guitar. Hammer impacts are applied to the center of the flat section on the bass side of the bridge as shown in **Photo 2**. A miniature piezoelectric accelerometer (PCB model 309A) is attached with wax 1 cm from the bridge directly below the sixth string. This is used to measure the acceleration of the top plate.

Two microphones (Quest model QE7052) are used to measure the sound pressure level. Both are positioned 2 cm above the top plate. One is centered over the top plate 1 cm from the bridge and the other is centered over the sound-hole as shown is **Photo 2**. These near-field microphone measurements are used to obtain the low-frequency free-field sound pressure from the guitar in an ordinary room without the need for an anechoic chamber or outdoor measurements. This approach has been used with excellent results to assess low-frequency response of ported loudspeakers [10], [11] which is analogous to low-frequency response of acoustic guitars. The effective top plate area and sound-hole are viewed as circular piston sound radiators. Their combined near-field sound pressure p_N is determined from the complex summation [11]

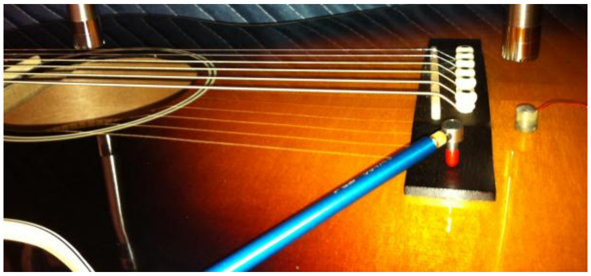

Photo 2 – Miniature accelerometer attached near bridge, miniature impact hammer applied on bridge, and microphones positioned above top plate and sound-hole.

$$p_N = p_p + \sqrt{\frac{S}{A}}\ p_a \qquad (1)$$

where p_p is the near-field sound pressure over the plate, p_a is the near-field sound pressure over the sound-hole, S is the sound-hole area, and A is the effective area of the top plate. For sound radiating into a full space, the far-field sensitivity p_F at a distance r from the guitar top plate is obtained from

$$p_F = \frac{a}{4r}\, p_N \qquad (2)$$

where a is the radius of the effective top plate area. This is valid for

$$\frac{2\pi\, f\, a}{c} < 1 \qquad (3)$$

where f is frequency (in Hz) and c is speed of sound in air (343 m/s). Since the radius of the effective area of the top plate for the test guitar is a = 10.9 cm (see Section III), this approach is valid for frequencies up to about 500 Hz, well above the maximum frequency of 270 Hz considered in this work. In addition, the requirements for near-field measurement distance, 2 cm << a, and for far-field sensitivity distance, r = 2 m >> a, are satisfied.

The low-frequency free-field sound pressure is determined from **Equation (2)** using **Equation (1)** with near-field impulse response sound pressure measurements of p_p and p_a. These response measurements are time-selective in that only direct sound (i.e., no reflected sound) is included in the response [11]. This approach avoids the need for and difficulties associated with an anechoic chamber.

Measurements are recorded and analyzed with a Siglab model 20-42 four-channel dynamic signal analyzer set with a frequency resolution of 0.5 Hz over a frequency range of 70 to 270 Hz. Each frequency response plot consists of an average from eight impacts. Baseline or as-is frequency response measurements are presented in **Figure 1**. Both the sound pressure level and the acceleration are normalized with respect to the hammer force input. The measurements reveal the first two resonant modes at 116 and 219 Hz. The antinode in the acceleration response at 130 Hz corresponds to the Helmholtz frequency of the body cavity.

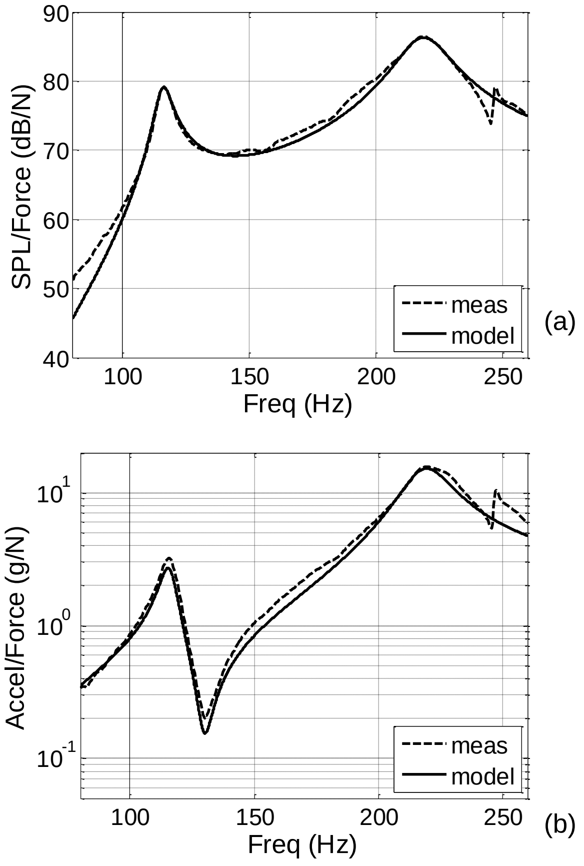

Figure 1 – Baseline frequency response: (a) SPL/force and (b) acceleration/force.

III. LOW-FREQUENCY MODEL

The frequency response data is modeled in this work to provide insight into the relationship between the modifications and physical parameters. The Christensen and Vistisen [4] lumped parameter model is particularly well suited because it provides excellent quantitative fit to both sound pressure and acceleration frequency response. The model is shown in **Figure 2** with parameters identified. The top plate is modeled with equivalent mass m_p, stiffness k_p, area A, and displacement x_p. The force input F is shown acting on the plate. The acoustic or air mode is modeled with equivalent sound-hole air mass m_a, area S, and displacement x_a. The volume of the body cavity is defined by V. The equations of motion are

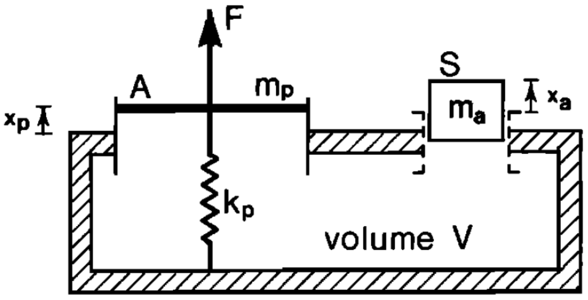

Figure 2 – Lumped parameter model [4].

$$m_p\,\ddot{x}_p = F - k_p\,x_p - R_p\,\dot{x}_p + A\,\Delta p \tag{4}$$
$$m_a\,\ddot{x}_a = S\,\Delta p - R_a\,\dot{x}_a \tag{5}$$

where R_p and R_a are damping constants. The change in pressure is proportional to the change in volume which depends on displacements x_p and x_a as

$$\Delta p = -\frac{c^2\,\rho}{V}\,\Delta V = -\frac{c^2\,\rho}{V}(x_p\,A - x_a\,S) \tag{6}$$

where c is the speed of sound in air and ρ is the density of air. The dependency of Δp on x_p and x_a is the source of coupling of the equations of motion.

Model parameter	Symbol	Baseline value	Units
Speed of sound in air	c	343	m/s
Density of air	ρ	1.205	kg/m^3
Volume of body cavity	V	0.01183	m^3
Magnitude of applied force	F	1.0	N
Distance from top plate for SPL	r	2.0	m
Sound-hole area	S	0.008107	m^2
Effective area of top plate	A	0.03747	m^2
Equivalent mass of top plate	m_p	0.06653	kg
Equivalent stiffness of top plate	k_p	9.995e4	N/m
Equivalent mass of air piston	m_a	0.001182	kg
Equivalent damping of top plate	R_p	8.994	Ns/m
Equivalent damping of air piston	R_a	0.03803	Ns/m

Table 1 – Baseline model parameters.

Estimation of the model parameters and formulation of the frequency response equations are presented by Christensen and Vistisen [4]. Following this approach, the model parameters for the baseline or as-is configuration of the test guitar are estimated and listed in **Table 1**. The computed frequency response for far-field sound pressure and acceleration using these parameters is shown in **Figure 1**. The excellent fit of model computed frequency response to both SPL and acceleration frequency response provides significant confidence in the model parameter estimates and measurement techniques.

IV. EFFECT OF MODIFICATIONS

A. Sound-Hole Area

Sound-hole covers are often used to control feedback problems in amplified acoustic guitars. For this modification a piece of corrugated cardboard is completely taped over the sound-hole. The measured and computed sound level frequency response is shown in **Figure 3**. The only change in the model parameters is setting the sound-hole area S equal to zero. The model response fits the measured response very well, adding further confidence to the model parameters and measurement techniques.

The effect of covering the sound-hole is to remove the first resonance. This significantly lowers the sound level at lower frequencies (below 190 Hz) which is easily perceived by ear. In addition, the second resonance frequency and SPL decrease from 219 to 212 Hz and 87 to 83 dB, respectively. This loss in low-end response can be compensated for in amplified sound with equalization. The results illuminate the role of the sound-hole on the first resonance. Further, the model can be used to explore different sound-hole area sizes.

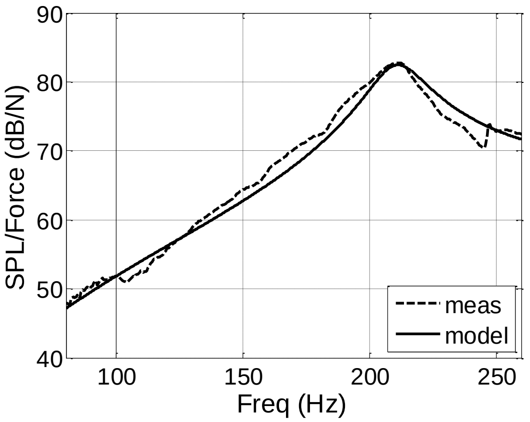

Figure 3 – Frequency response with covered sound-hole.

The acceleration frequency response (not shown) reveals no decrease in the acceleration level at the second resonance as a result of covering the sound-hole.

B. Top Plate Mass and Brass Bridge Pins

It is widely appreciated that decreasing top plate mass through choice of top material and brace design is desirable. However, bridge pins made of dense material such as brass are available with claims of improved sound. The effect of adding 22.5 g mass at the bridge is shown in **Figure 4**. This is implemented on the test guitar with a steel wrench socket with double-sided tape as suggested by French [7]. This amount is added to m_p in the model. This corresponds to a 34% increase in equivalent top mass.

The data and model reveal the effect of adding mass to the top plate is a decrease in SPL, acceleration and frequency of the second resonance.

Replacing plastic bridge pins with brass pins equates to an increase in mass of 22.4 g, and comparable results to that shown in **Figure 4**. Even though the presented response does not provide an indication of how the pins alter higher frequency response, a difference is detectable by ear.

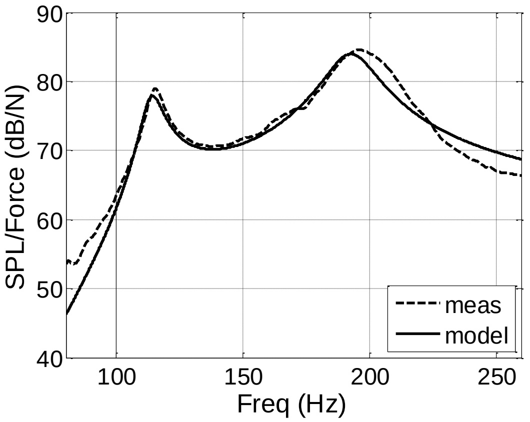

Figure 4 – Frequency response with added bridge mass.

C. Sound-Hole Tubes and Cones

Although not widely found in guitars, sound-hole tubes and cones have been used for many years. An interesting history of the design and use of a sound-hole cone referred to as the Torres tornavoz is provided by Romanillos [12]. Variations of such devices are in limited use today. Materials for these components range from instrument grade wood or brass to plastic or heavy paper.

An application of a simple sound-hole tube is with the contrabass guitar which is an octave below the classical guitar in pitch. The Hampshire Guitar Orchestra website documents the making and tuning of a sound-hole tube for lowering the first resonance to improve the low-frequency response of this instrument. The addition of a 7.5 cm long tube attached to the sound-hole lowered the first resonance from 80 to 64 Hz.

The frequency response of the test guitar with a 5 cm long sound-hole tube is shown in **Figure 5**. The tube is cylindrical, made of card stock and tape, and has a mass of 7.3 g. Comparing this response with the baseline response in **Figure 1** reveals a decrease in the first resonance from 116 to 98 Hz and a slight decrease in the second resonance from 219 to 216 Hz. The acceleration frequency response (not shown) indicates the Helmholtz frequency decreases from 130 to 110 Hz. This modification is captured by the model as shown in **Figure 5** by increasing the sound-hole air mass m_a by 45%.

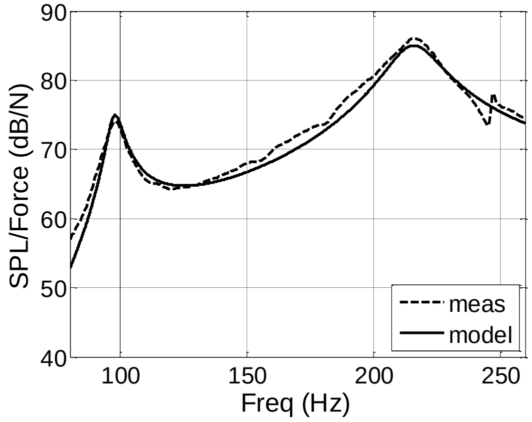

Figure 5 – Frequency response with 5 cm long sound-hole tube.

Sound-hole tubes tested with a length less than 5 cm produce a smaller decrease in the frequencies. A 7.5 cm tube yields a larger decrease of the first resonance to 88 Hz and of the Helmholtz frequency to 101 Hz. This is close to the limit length of a tube in the sound-hole of the test guitar due to the depth of the guitar body. A benefit of the cylindrical shape is the ease of tuning, i.e., adjusting tube length to achieve desired frequencies.

Relatively inexpensive plastic versions are commercially available in cone and diverging shapes. As with the cylindrical shape, these are flexible and easily removable compared to built-in wooden or brass versions. Test results with these are comparable to that obtained with the simple cylindrical shape. However, these plastic units are more massive (e.g., one example is 34 g) and even though this is offset from the bridge and plate center, an increase in the model plate mass is necessary to fit the model with the data. In addition, existing commercial units are not designed to be adjusted to tune the frequencies. One commercial unit tested lowered the first resonance to 103 Hz and the Helmholtz frequency to 116 Hz comparable to a 2.5 cm cylindrical tube.

Adding a sound-hole tube or cone has a very noticeable effect on the low-frequency response. Useful applications of these devices to improve bass response of guitars, in addition to contrabass guitars, include baritone guitars, standard guitars used in lower tunings, and small body travel guitars.

D. String Tension

Some solo guitarists believe that every guitar has an optimum pitch for a given string size, and as soloists are able to move away from concert pitch tuning. It is more widely appreciated that heavier strings (e.g., medium compared to light) provide improved tone. Furthermore, many guitarists use open and drop tunings which changes the net string tension. Use of lower tunings on twelve string guitars for the purpose of lower tension is a fairly common practice.

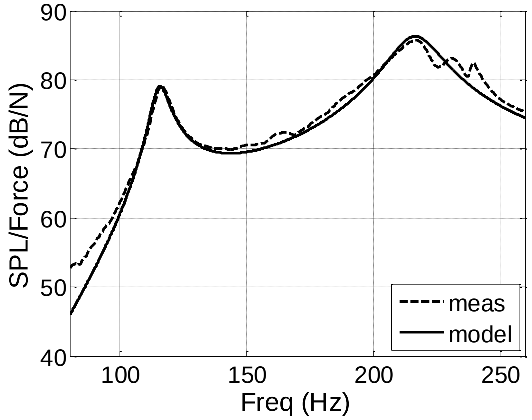

Figure 6 – Frequency response with reduced string tension.

To examine the effect of string tension on low-frequency response, tests are performed with standard tuning to E, to D# and to D. These tests are performed with light gauge phosphor bronze strings with string diameters of 0.30, 0.41, 0.61, 0.81, 1.07, 1.35 mm (or 0.012, 0.016, 0.024, 0.032, 0.042, 0.053 inch) from high to low string with only the lower three being wound. The total string tensions with standard tuning to E, to D# and to D are 740, 660 and 580 N, respectively. Tuning each string down one-half step reduces total tension by 11% and one-whole step reduces it by 22%.

The measured frequency response with the guitar tuned to D# is shown in **Figure 6**. Compared to the response with the guitar tuned to E in **Figure 1**, the first natural frequency and the Helmholtz frequency (the latter determined from the acceleration frequency response not shown) do not change, but the second natural frequency decreases by 2 Hz from 219 to 217 Hz. This shift in second natural frequency is captured with the model by decreasing the top plate stiffness k_p by 3%.

With the guitar tuned to D the second frequency drops to 215 Hz and decreasing the model top plate stiffness k_p by 6% provides the best fit. These results suggest that the top plate exhibits a hardening nonlinear stiffness, i.e., the top plate stiffness increases with tension. No notable decrease in sound pressure level is observed over the frequency range studied.

E. Damping

The effect of damping is examined with the model by changing the damping parameters R_p and R_a by plus and minus 50%. As shown in **Figure 7**, changes in damping result in localized changes in SPL near the natural frequencies.

It is widely appreciated that a decrease in damping provides increased response level. As a result, low damping is generally viewed as desirable in instruments. Sali and Kopac correlate frequency response measurements of guitars with higher peaks and lower damping in the first two resonances with superior sound quality [13].

Reumont [14] developed what is referred to as a “de-damping” vibration treatment for stringed instruments to improve the response and sustain of string instruments. The underlying mechanisms for physical changes (damping or other) from such treatments are not well appreciated or understood. However, studies on the behavior and changes in wood under dynamic loading provide some insight [15], [16].

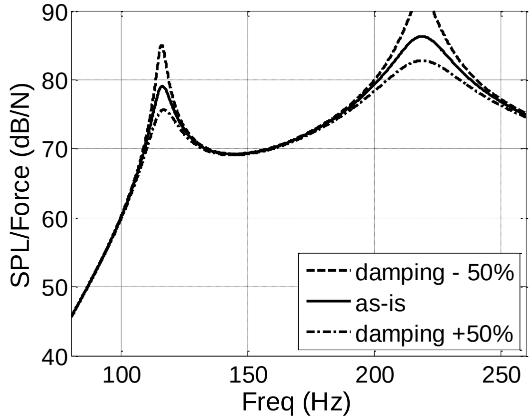

Figure 7 – Frequency response with different damping levels.

V. SOUND LEVEL

Everything else being equal, high sound level is a preferred quality of string instruments. Sound radiation efficiency and therefore sound level below 1,000 Hz have been correlated with good sound quality [7], [17].

It is widely appreciated [4], [8] that sound pressure level is proportional to the equivalent top plate area A and inversely proportional to the equivalent top plate mass m_p. Minimizing top plate mass is implemented in practice by using low density materials for the top plate and braces. Maximizing top plate area is implemented in practice by choice of lower bout size and shape as well as thinning or routing near the perimeter of the top plate.

The effect of changes in A and m_p are illustrated in **Figures 8** and **9** using the low-frequency model. The expected increase in SPL with a 20% increase in A or a 20% decrease in m_p certainly occurs above the second resonance, however, the improvement is not over the entire low-frequency range.

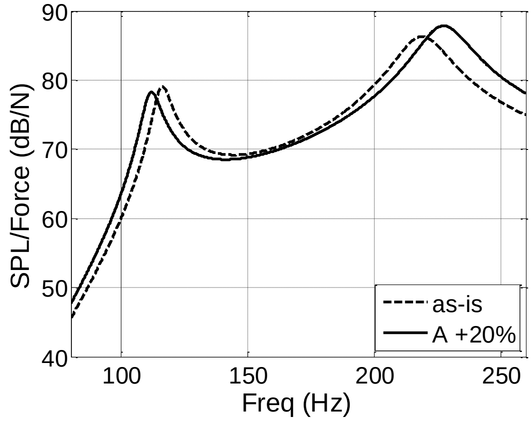

Figure 8 – Increasing equivalent area of top plate.

A parametric study with the low-frequency model revealed a combination of changes of the equivalent top plate mass m_p, stiffness k_p and area A that yields a uniform increase in SPL. Specifically, the changes are a decrease in both m_p and k_p by some percentage P in combination with a decrease in A by nine-sixteenths of P. For example, decreasing m_p and k_p by 50% in combination with decreasing A by 28% results in an increase in SPL of 3.2 dB over the entire frequency range as shown in **Figure 10**.

These percent changes may seem excessive to justify the increased SPL. However, with the use of alternative designs in top plate and bracing, and perhaps nontraditional materials, such changes may be possible.

The SPL/Force frequency response magnitude in **Figure 10** indicates the SPL for a force of 1 N. As one would expect, increasing the force input (whether from a test hammer impact to the bridge or from the strings), results in an increase in SPL.

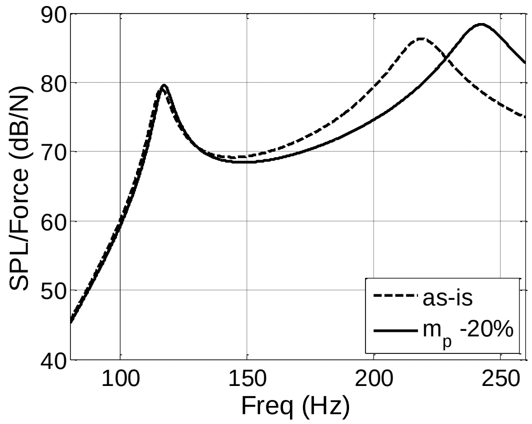

Figure 9 – Decreasing mass of top plate.

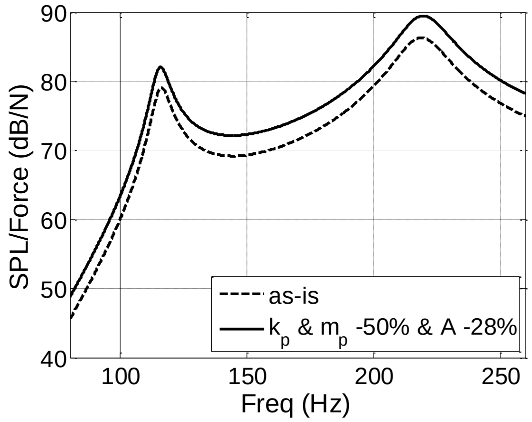

Figure 10 – Decreasing mass, stiffness and area of top plate.

VI. CONCLUSIONS

Low-frequency acceleration and sound pressure frequency response measurements were used to quantitatively assess the effect of various modifications to a steel string acoustic guitar. A low-frequency model related the modifications to changes in physical model parameters. Excellent agreement was found between the measurements and model. Parametric analysis revealed a combination of model parameter adjustments for broadband increase in sound pressure. Finally, this work tested an existing technique used for obtaining low-frequency free-field sound pressure for loudspeakers without the need of an anechoic chamber. The technique used near-field, time-selective, impulse response sound pressure measurements to determine the low-frequency free-field sound pressure and was successfully applied to the acoustic guitar.

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