Archtop Guitar Dynamics

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Abstract

This is a modal analysis tracing acoustic changes along each step of the build process of an archtop guitar. The eigenmodes and corresponding eigenfrequencies were theoretically modeled and experimentally measured for the archtop guitar through finite element analysis, frequency sweep analysis, and Chladni figure analysis. The archtop guitar shares acoustic behaviors with instruments in both the violin and guitar families, resulting in its own acoustic signature.

INTRODUCTION

Research of stringed instrument acoustics coalesced in 1962 with the creation of the Catgut Acoustical Society (CAS). It comprised a group of amateur string players with professional scientific backgrounds: Carleen M. Hutchins, Frederick A. Saunders, John C. Schelleng, and Robert E. Fryxell. The CAS began collecting and publishing their research in the *Catgut Acoustical Society Journal*. The journal had a two-part mission: "to increase and diffuse the knowledge of musical acoustics, and to promote the construction of fine stringed instruments" [1]. In 2004, the CAS merged with the Violin Society of America (VSA, founded in 1973), continuing to promote the art and science of stringed instruments. The combined efforts of the CAS and the VSA result in an influential body of general and scientific knowledge on stringed instruments. This shared knowledge continues to grow through publications, conferences, and workshops, and continues to push the boundary between art and science.

This study examines vibrational acoustics of an archtop guitar top plate and body (corpus) *via* modeling and finite element analysis (FEA). In support of the FEA, an archtop guitar identical to the models was constructed for experimental analysis using Robert Benedetto's design of the 17-inch (431.8 mm) Gibson L5C, featured in his publication "Making an Archtop Guitar" (1996). The L5 was originally designed by the acoustic engineer Lloyd Loar and introduced by Gibson Mandolin-Guitar Mfg. Co. Ltd. in 1922 as a 16-inch lower bout instrument. By 1935, the L5 grew into a 17-inch lower bout. The plate graduations are discussed in the following text. The guitar used in this study has an x-brace with small cross braces along the top and bottom of the "x," as shown in Fig. 1 [2,3].

This study is a modal analysis of the fundamental modes of vibration of the archtop guitar. This study focuses on a traditional Gibson-style archtop guitar measuring 17 inches (431.8 mm) across the lower bout with a scale length of 24.750 inches (628.7 mm), a side depth measuring 3 inches (76.2 mm), and arch heights of the top and back plates of .875 inches (22.2 mm). The completed instrument has a standard plate graduation of .250 inches (6.4 mm) at the center tapering to .187 inches (4.7 mm) at the sides, and a .125-inch (3.2 mm) recurve thickness. The top plate and bracing are Alaskan Sitka spruce. The back plate, sides, and neck are Michigan curly maple.

For each step of the build process, a computer-aided design (CAD) model was drafted and FEA was performed in Autodesk Fusion 360 and Comsol Multiphysics. Fundamental eigenmode vibrational patterns are primarily determined by the

Figure 1. Left, a CAD drawing shows the inside carve of the top plate with braces attached. Right, a Sitka spruce top plate showing the inside carve and x*-brace of the constructed archtop guitar. The model on the left was used to cut the top on the right with a CNC milling machine.*

profile of the arch and boundary condition of the guitar shape. To correlate the FEA with an instrument, the CAD drawings were used to cut the top and back plates on a computer numeric controlled (CNC) milling machine. The specific frequency for each eigenmode was determined experimentally using a frequency sweep technique.

The free-plate frequency sweep technique consisted of a driving transducer placed at the edge of the plate approximately 1 inch (25.4 mm) below the bass side ff-hole. The receiving transducer was placed midway between the lower half of the ff-hole and the centerline on the bass side of the plate. The corpus frequency sweep technique consisted of a driving transducer approximately 2 inches (50.8 mm) from the location of the free plate driver, toward the centerline. The receiving transducer remained in the same location for both free-plate and corpus measurements. A fast Fourier transformation (FFT) was generated from the sampled waveform of the receiving transducer. The measured frequencies were used for Chladni figure analysis and to compare only the changes in frequencies along the build process [4].

The FEA and experimental results reveal the resonant modes of vibration or eigenmodes and corresponding eigenfrequencies of the archtop guitar top plate and corpus.

Wood

Every tree grows differently. The acoustic and material properties of timber vary from species to species, from tree to tree within a species, and within a single tree. There is established research into the material properties of instrument wood by the CAS, the VSA, and the Acoustical Society of America (ASA). M. E. McIntyre and J. Woodhouse explain the theoretical physics of thin-plate instrument wood in their three-part publication *On Measuring Wood Properties I-III* (1984–1986) [5]. It is understood that wood is orthotropic, meaning its properties, such as speed of elastic wave propagation, vary depending on relative grain orientation. Although it is important to consider the material properties of all timbers used in instrument construction, "the success of a guitar depends largely on the strings' ability to accelerate the inertia of the soundboard" [6]. Thus, the spruce used for the top plays a critical role and will be the focus of this study. It has been determined that the most important material properties to quantify raw timber are density (ρ), speed of elastic wave propagation (c), and elastic modulus (E) [7].

Ideal wood used in fine-instrument making is radially cut or "quarter-sawn," meaning the grain runs parallel to the length of the board (Fig. 2) and

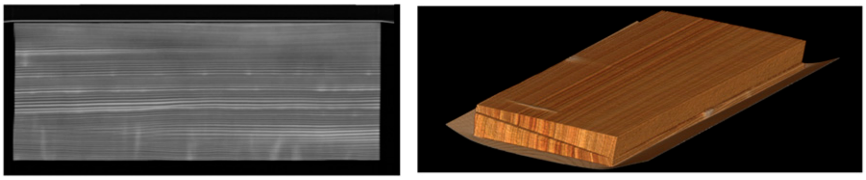


Figure 2. Left, a CT image taken by the author of a quarter-sawn Sitka spruce board dimensioned as a thin rectangular plate with dimension 22 × 8.5 × .150." Note the grain lines running the length of the board. The CT scan reveals the varying densities of the annual growth rings as light and dark bands across the board. Right, a CT image of spruce wedges used for constructing the archtop guitar top plate.

is dimensioned into rectangular plates. The grain varies in density between the annual growth rings. For ideal, quarter-sawn wood, the grain lines or annual growth rings run normal to the plate's surface and the medullary rays run perpendicular or across the grain. For wood that is less than ideally quartered, the angle of the annual growth rings to the surface of the plate has great effect on the elastic constants which govern the material properties of the plate. The elastic constants manifest as the modes of vibration of the thin spruce plate. In ideal, quarter-sawn wood, the elastic constants are mathematically expressed in terms of well-known quantities: Young's modulus, shear modulus, and Poisson's ratios [5]. For the spruce plate, the lowest (in frequency) mode of vibration is the twisting mode, dominantly governed by the shear elastic modulus (Fig. 3). The second lowest mode is the long bending mode, governed by Young's modulus in the direction of the grain. The cross-grain bending mode is the highest fundamental mode, governed by Young's modulus in the direction across the grain. Instrument makers prefer wood with a high ratio of stiffness to density for the top plate or soundboard.

Resonant frequencies for modes 1, 2, and 3 of the thin rectangular plate vary, but are approximately 45 Hz, 70 Hz, and 130 Hz, respectively. Wood for making violins and archtop guitars is often milled to a wedge shape. The wedge shape shares similar fundamental modal shapes to the thin plate. Resonant frequencies for violin spruce wedges, smaller in dimension but similar in shape to archtop guitar spruce wedges, measure at 272 Hz, 562 Hz, and 630 Hz for modes 1, 2, and 3, respectively [7,8].

FEA ANALYSIS

The modes of vibration or eigenmodes of the archtop guitar were modeled using Comsol Multiphysics software. The procedure is based on Colin Gough's article, "Violin Plate Modes" [9]. The acoustics of a thin square plate are established [10,11]. To understand the physics of a guitar-shaped, arched top plate with grain lines of varying material properties, the first set of free-plate models follows the acoustics of the thin isotropic square plate, to a thin isotropic rectangular plate, to a thin anisotropic rectangular plate, to a guitar-shaped anisotropic thin plate, and finally, to the guitar-shaped anisotropic arched top plate. All of these models have a thickness of .187 inches or 4.75 mm (Fig. 4).

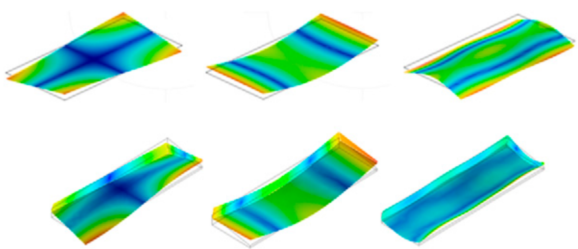


Figure 3. Top row, the 3 lowest modal shapes of a free rectangular plate. L–R mode 1 (twisting), mode 2 (long-grain bending), mode 3 (cross-grain bending). Blue corresponds to nodal lines. Bottom row, a variation of the fundamental resonant modes of the thin rectangular plate as modeled for the wedge plate. Analysis was performed with Fusion Autodesk 360 using composite isotropic models to approximate orthotropy.

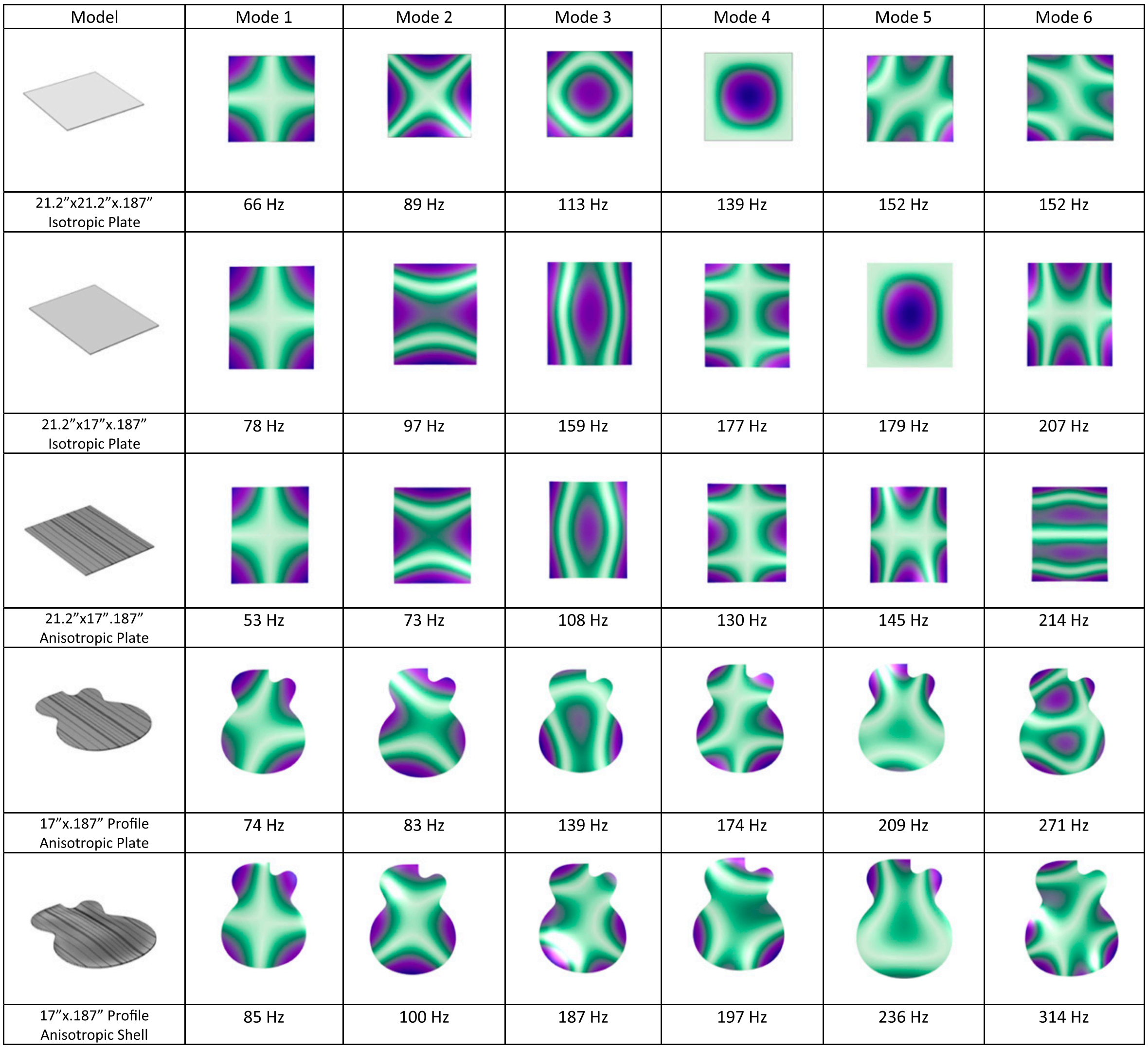


Figure 4. The first six eigenmode shapes and corresponding eigenfrequencies of the free plate. The first column is an image of the model used for the Comsol Multiphysics FEA.

The second set of free plate models follows the process of constructing an arched top plate. The first model is an anisotropic arched plate of the aforementioned, standard graduation. The second model shows the ff-hole area removed, and the third model includes *x*-bracing (Fig. 5).

The third set of free-plate models is the same as the aforementioned models. However, the results in Fig. 6 are from an isotropic FEA performed in Autodesk Fusion 360. All other free-plate and corpus FEA were performed with Comsol Multiphysics.

The fourth set of models follows the same procedure as the first and second sets combined but includes the boundary condition of a pinned-edge around the guitar's perimeter. The pinned-edge models the guitar top after it has been adhered to its sides (Fig. 6).

The purpose of this modeling is to understand the general vibrational eigenmodes of the archtop guitar plates. This study is less concerned with "predicting mode shapes and frequencies for specific arching profiles, thickness graduations, and elastic anisotropies." It is

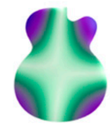
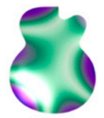
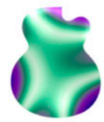
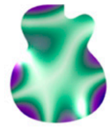
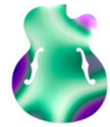
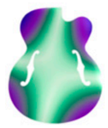
Model	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Mode 6
						
.250”-.187” Graduated Anisotropic Shell	86 Hz	101 Hz	187 Hz	198 Hz	231 Hz	311 Hz
						
Graduated, ff-holes Anisotropic Shell	94 Hz	109 Hz	176 Hz	185 Hz	225 Hz	282 Hz
						
Graduated, ff-holes, x-brace Anisotropic Shell	96 Hz	107 Hz	184 Hz	196 Hz	221 Hz	295 Hz

Figure 5. The first six eigenmode shapes and corresponding eigenfrequencies of the archtop free plate at various working steps. The first column is an image of the model used for the Comsol Multiphysics FEA.

understood that the low frequency eigenmodes, like the ones studied here, are largely determined by the arched guitar shape of the plate and averaged material properties. The results of the FEA suggest this is generally true for the archtop guitar. In accordance with Gough’s procedure, the models used for FEA include anisotropy of “grain-lines” spaced 2.5 or 5 mm wide with varying Young’s modulus values [9].

The FEA results (Fig. 4) depict the shifts in mode shapes as the models move from an isotropic square plate to an anisotropic arched plate. The slight shifts in mode shapes are well defined from the first to the last model, revealing the eigenmodes of the arched plate do share similar physics to the anisotropic rectangular plate. The corresponding eigenfrequencies shift with changes in the mode shape of each model. The overall modal patterns of the anisotropic rectangular plate are traced through to the arched plate with the *x*-brace (Fig. 5). The FEA results are similar for the pinned-edge analysis. When the ff-holes are perforated in the model, modes 1 and 2 trade order. Mode 1 is the twisting mode, and mode 2 is the long grain bending mode. Once the *x*-brace is attached, modes 1 and 2 change places again, reverting back to their original order.

Based on these models, the physics of the archtop free plate is different from the violin free plate. Both are arched plates with anisotropic material properties but possess different aspect ratios. The isotropic square plate from the first set of models depicts mode 2 as an “*x*-shaped” mode and mode 3 as a “ring-shaped” mode. The symmetry of a square plate (1:1 aspect ratio) dictates the standing wave resonance to be the same frequency from top to bottom and side to side of the plate. Depending on the phase relation between the standing waves, the vibrational shape is either the *x*-shaped or the ring-shaped mode [10]. These characteristic mode shapes appear in violin free plates and are referred to as the 2 and 5 modes. The violin plate has an aspect ratio of 2:1, meaning it is twice as long as it is wide. The 2:1 aspect ratio, coupled with

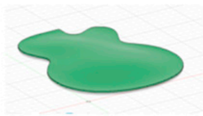
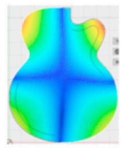
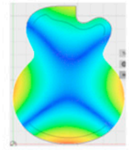
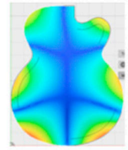
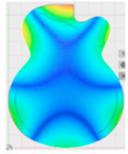
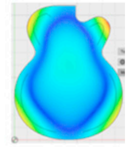
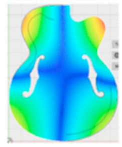
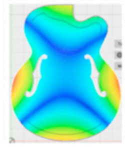
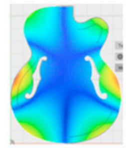
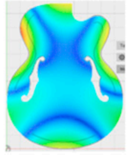
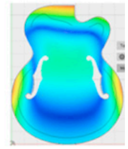
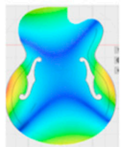
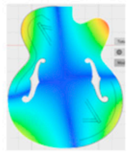
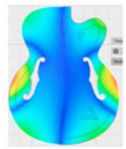
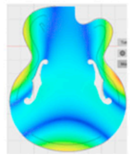
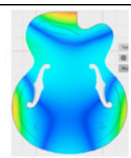
Model	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5
					
.250”-.187” Graduated Isotropic Shell	50 Hz	60 Hz	107 Hz	118 Hz	145 Hz
					
Graduated, ff-holes Isotropic Shell	48 Hz	56 Hz	97 Hz	109 Hz	124 Hz
					
Graduated, ff-holes, x-brace Isotropic Shell	66 Hz	72 Hz	106 Hz	119 Hz	133 Hz

Figure 6. The first 5 eigenmode shapes and corresponding eigenfrequencies of the archtop free plate at various working steps. The first column is an image of the model used for the Autodesk Fusion 360 FEA.

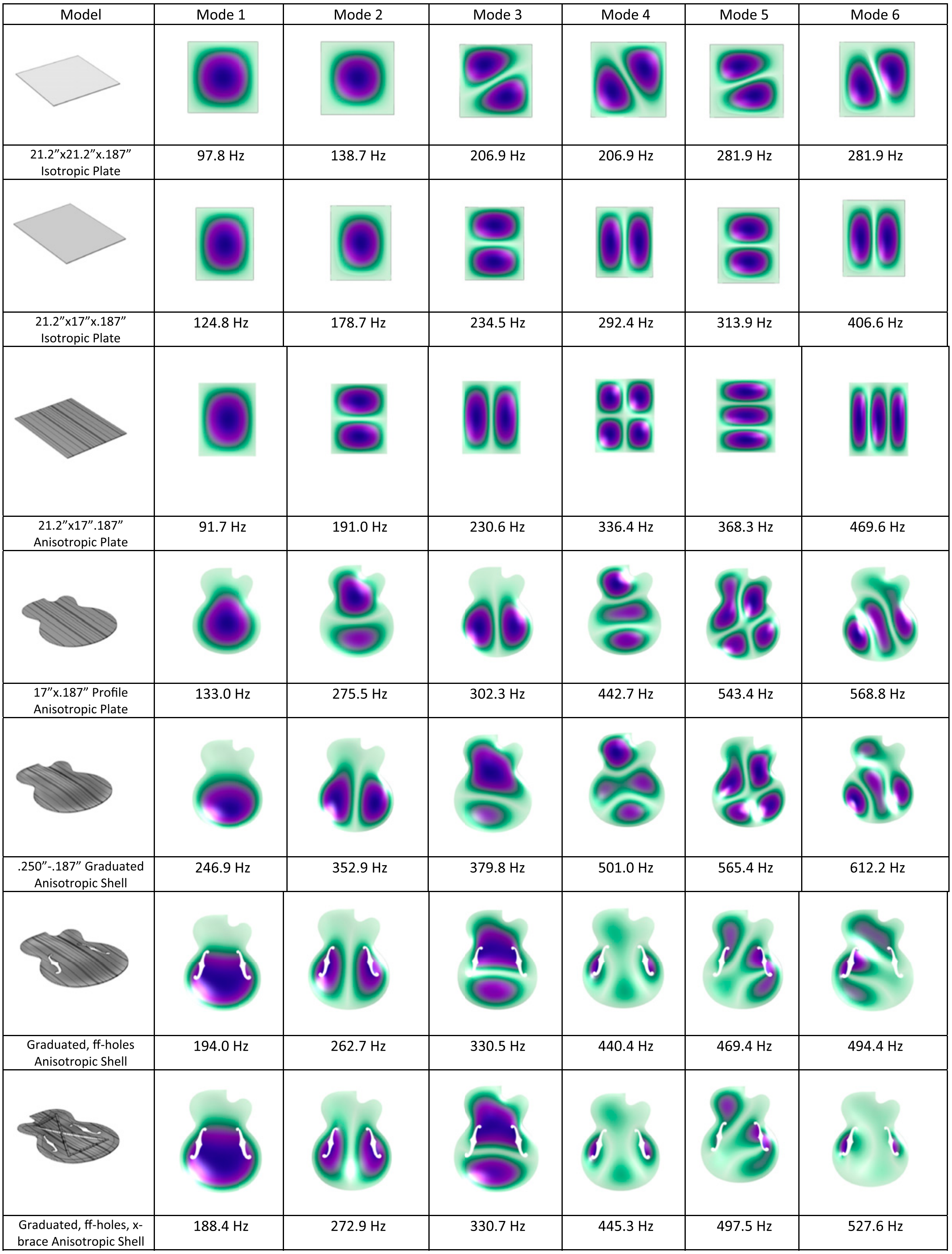
the arching of the violin plate, compensates for the anisotropic nature of wood. Thus, the *x*-shaped and ring-shaped modes, characteristic of an isotropic square plate, are revealed. The guitar shape used for the models in this study has an aspect ratio of 1.25:1. Thus, there is no *x*-shaped or ring-shaped mode in the Comsol FEA. Mode 2 in Fig. 4 depicts an *x*-shaped mode but appears to be related to the long grain bending mode of the arched plate [11].

Figure 7 shows the results of an isotropic free-plate FEA conducted in Autodesk Fusion 360. The models used for this analysis were the same as those used for Fig. 5. These results were included because they differ from Comsol Multiphysics results. The isotropic results of Fig. 7 show the five mode as a ring-shaped mode. This mode shape is absent from the Comsol Multiphysics analysis of both the isotropic and anisotropic arched free plate.

The pinned-edge FEA results depict the similarity in eigenmode shape between the archtop and flat-top, steel-string guitar. For the archtop top with ff-hole perforations and *x*-bracing, modes 1, 2, and 3 are the same as those of the flat-top, steel-string guitar. In the accepted guitar literature, mode 1 is the monopole or T(1,1) mode, mode 2 is the cross-dipole or T(2,1) mode, and mode 3 is the long-dipole or T(1,2) [5]. The fundamental modal shapes of the FEA results for the archtop top with ff-hole and *x*-bracing are all traced back to related modal shapes of the anisotropic rectangular plate.

FREQUENCY SWEEP ANALYSIS

The standard graduation FEA model was used to cut a top plate made from Sitka spruce on a CNC milling machine. Next, ff-holes were perforated in the top and *x*-bracing attached. Then, the top was glued to the sides and back. The neck was then attached using a dovetail joint. Finally, the guitar was tuned to pitch. In conjunction with each step, a frequency sweep analysis was performed. The resulting FFTs are plotted in the following text (Figs. 8–13).



Model	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Mode 6
21.2"x21.2"x.187" Isotropic Plate	97.8 Hz	138.7 Hz	206.9 Hz	206.9 Hz	281.9 Hz	281.9 Hz
21.2"x17"x.187" Isotropic Plate	124.8 Hz	178.7 Hz	234.5 Hz	292.4 Hz	313.9 Hz	406.6 Hz
21.2"x17".187" Anisotropic Plate	91.7 Hz	191.0 Hz	230.6 Hz	336.4 Hz	368.3 Hz	469.6 Hz
17"x.187" Profile Anisotropic Plate	133.0 Hz	275.5 Hz	302.3 Hz	442.7 Hz	543.4 Hz	568.8 Hz
.250"-.187" Graduated Anisotropic Shell	246.9 Hz	352.9 Hz	379.8 Hz	501.0 Hz	565.4 Hz	612.2 Hz
Graduated, ff-holes Anisotropic Shell	194.0 Hz	262.7 Hz	330.5 Hz	440.4 Hz	469.4 Hz	494.4 Hz
Graduated, ff-holes, x-brace Anisotropic Shell	188.4 Hz	272.9 Hz	330.7 Hz	445.3 Hz	497.5 Hz	527.6 Hz

Figure 7. The first six eigenmode shapes and corresponding eigenfrequencies of the pinned-edge models. The first column is an image of the model used for the Comsol Multiphysics FEA.

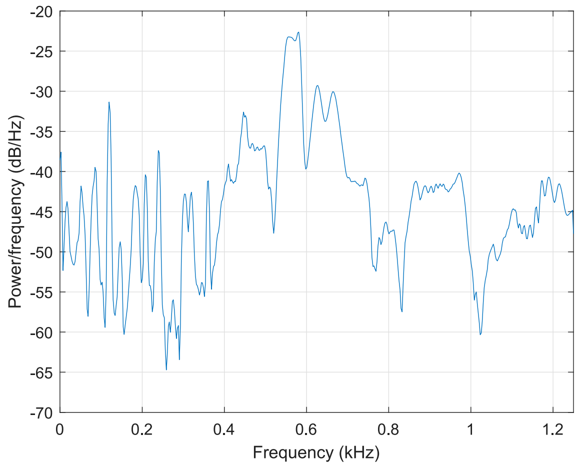


Figure 8. Left, FFT of the free-plate frequency sweep, standard graduation (see Table 1 for measured frequency values).

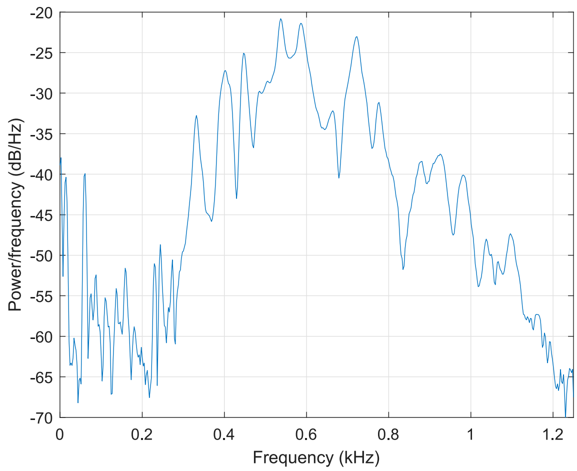


Figure 9. Right, FFT of the free-plate frequency sweep, standard graduation with ff-holes (see Table 1 for measured frequency values).

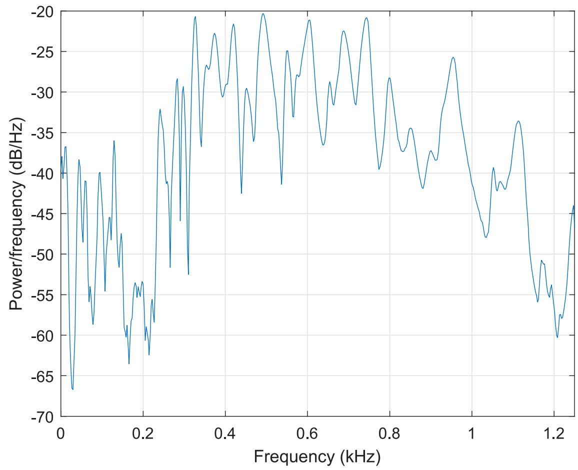


Figure 10. Left, FFT of the free-plate frequency sweep, standard graduation with ff-holes and x-bracing (see Table 1 for measured frequency values).

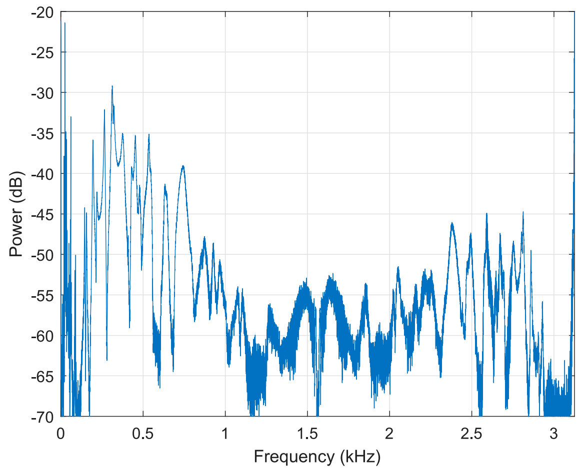


Figure 11. Right, FFT of the corpus frequency sweep (see Table 2 for measured frequency values).

After the top is glued to the sides and back, the lowest eigenfrequency is the fundamental air resonance of the newly created cavity. This T(1,1) monopole is also known as the "breathing mode" (Fig. 11). The second "peak" is the main top resonance, also a T(1,1) monopole modal shape [11]. The eigenfrequencies of these two modes were measured at 137 Hz and 221 Hz, respectively. A simple harmonic oscillator, often referenced in the guitar literature, describes the behavior of these two coupled component eigenmodes [12]. Acoustician Evan Davis describes an observation of the main top resonance of musical instruments, referenced $f_{\text{“wood,”}}$ as the "(estimated) geometric mean of the playing range's frequency limit" Eqn. (1). That is to say an approximated relationship exists between the main top resonance, the lowest

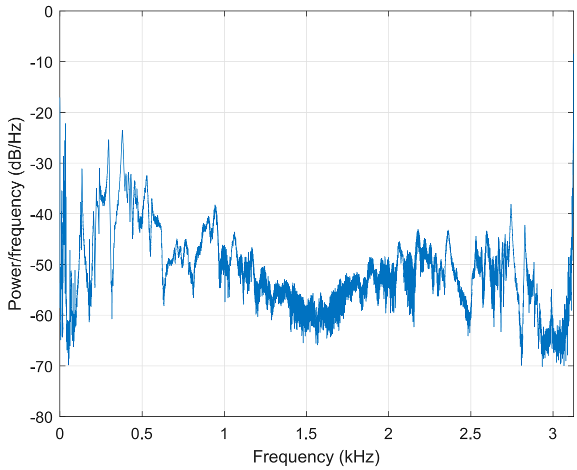


Figure 12. Left, FFT of the corpus frequency sweep. In the white, loaded under string tension.

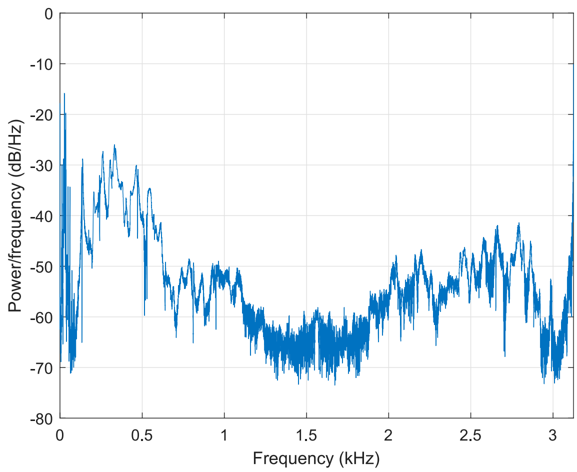


Figure 13. Right, FFT of the corpus frequency sweep. Finished, under string tension (see Table 2 for measured frequency values).

open-string pitch (*E*, 82.4 Hz), and the highest open-string pitch (*E*, 329.6 Hz) below in Eqn. 1:

$$f_{\text{"wood"}} \cong \sqrt{f_{\text{low-open}} \times 2 f_{\text{high-open}}} \qquad (1)$$

The archtop guitar supports this relationship where $f_{\text{wood"}}$ is calculated to be 232 Hz, and the measured value of the main top resonance of this archtop guitar body is 221 Hz [13].

The next peak higher in frequency than the main top resonance is the T(2,1) cross-dipole eigenmode measured at 250 Hz. This modal shape divides the lower bout of the guitar body into two halves, vibrating out of phase. This eigenmode reflects the transversal flexural pattern of the top plate. Above the T(2,1) eigenmode is the main monopole of the back plate. This T(1,1) modal pattern, measured at 281 Hz, reflects the main coupled component resonance of the back plate. The final fundamental eigenfrequency corresponds to the T(1,2) long-dipole eigenmode (Fig. 7). The modal pattern divides the top plate longitudinally into halves, vibrating out of phase. This is the longitudinal flexural pattern of the top plate and was measured at 315 Hz. The higher-order eigenfrequencies and corresponding eigenmodes of the archtop guitar will be explored in a future study, as well as further analysis of the air or "breathing modes" [14].

Figure 12 shows the FFT from the corpus frequency sweep after the neck is attached and the tuners, bridge, and tailpiece are installed. The instrument is tuned to pitch under 169 N of downward string pressure. The guitar is considered to be in the "white" as no finish has been applied, the raw wood exposed. The eigenfrequencies shift lower because of the string tension and additional component coupling of the hardware. A final frequency sweep was taken after the guitar had a thin layer of finish applied, resulting in increased eigenfrequencies between 2 and 7 Hz. Tables 1 and 2 reflect the frequency sweep analysis for each step of the build process.

CHLADNI FIGURE ANALYSIS

Results from the frequency sweep analysis were used in conducting a Chladni figure analysis. This is a study of the fundamental eigenmodes and corresponding eigenfrequencies. For this reason, the lowest five peaks of the FFT were analyzed. Based on the FEA results, the higher-order eigenmodal shapes of the guitar corpus and free plate are vibrational subdivisions of the fundamental eigenmodes.

Figures 14 and 15 show the Chladni figures for the free plate with standard graduation and standard graduation with ff-holes. The Chladni figures best correspond to the Autodesk Fusion 360 FEA (Fig. 6). The Chladni figures reveal

Table 1. Results from the frequency sweep analysis for the lowest five eigenmodes of the archtop guitar free plate.

Mode (fig.)	1	2	3	4	5
Standard graduation (10)	53 Hz	89 Hz	121 Hz	145 Hz	173 Hz
ff-hole (11)	45 Hz	63 Hz	118 Hz	130 Hz	150 Hz
x-brace (12)	61 Hz	92 Hz	134 Hz	150 Hz	178 Hz

Table 2. Results from the frequency sweep analysis for the lowest five eigenmodes of the archtop guitar corpus and completed instrument.

Mode (fig.)	Air T(1,1)	Top T(1,1)	Top T(2,1)	Back T(1,1)	Top T(1,2)
Corpus (13)	137 Hz	221 Hz	250 Hz	281 Hz	315 Hz
White, ST (14)	134 Hz	221 Hz	242 Hz	263 Hz	297 Hz
Finish, ST (15)	138 Hz	223 Hz	248 Hz	268 Hz	304 Hz

ST, string tension.

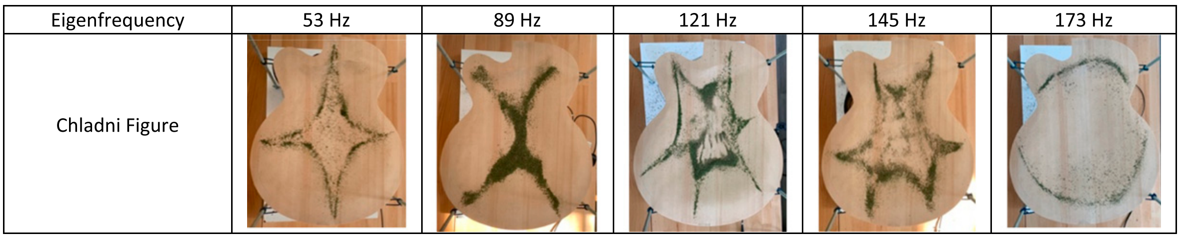


Figure 14. Chladni figures of the archtop guitar free plate, standard graduation. The eigenfrequencies correspond to Fig. 8.

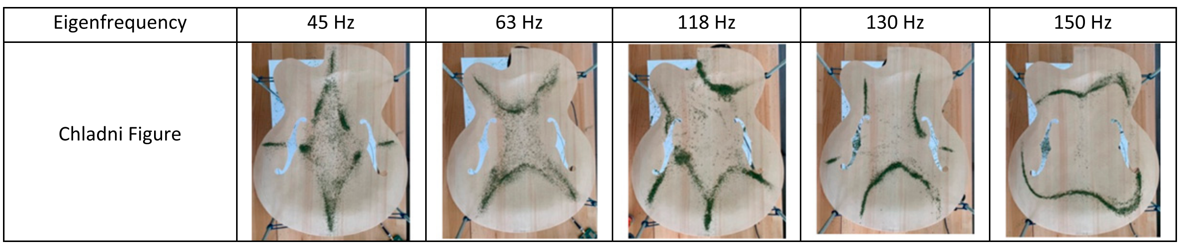


Figure 15. Chladni figures of the archtop guitar free plate, standard graduation with ff-holes. The eigenfrequencies correspond to Fig. 9.

mode 5 to be a ring-shaped mode, different from the ring mode of the violin free plate due to the difference in the aspect ratio. Chladni figure analysis could not be performed for the x-braced free plate as the braces interfere with the nodal patterns that form on the inside of the vibrating plate.

In accordance with the guitar and violin literature, the lowest peak of the corpus and completed instrument FFTs correspond to the breathing mode, or fundamental air resonance. Chladni figures were analyzed for the guitar corpus, and the guitar in the white, under string tension (Figs. 16 and 17). The Chladni figures for the archtop guitar corpus and under string tension are in accordance with the pinned-edge FEA results [15,16].

The measured frequencies for the Chladni figure analysis are all lower than the predicted values of the FEA. The arched models used for the FEA do not take into account that arched top plates for instruments are carved and not bent or pressed, traditionally. Cutting the longitudinal grain or radial rays, as is done when carving a top plate, affects the long-grain and cross-grain Young's modulus. This results in reduced stiffness and lower corresponding eigenfrequencies. Higher arch profiles result in steeper cuts to the grain and rays, further reducing stiffness [6].

IMPULSE MEASUREMENT ANALYSIS

This study establishes the fundamental eigenmodes and corresponding eigenfrequencies of the archtop guitar. The frequency sweep analysis used for this study is adequate to distill the resonant frequencies of a sample although it has limitations as a measurement technique for instrument acoustics. The receiving transducer is sensitive to where it is located in reference to the driver. Findings reveal that different driver and receiver locations are more or less responsive to different eigenmodes and frequencies. Furthermore, the signal-to-noise ratio is low because of the input of all frequencies across the sweep bandwidth. With an understanding of the fundamental eigenvalues of the archtop guitar, an impulse hammer measurement technique will be used in future studies. This technique is more representative of how the eigenvalues affect the emitted sound of the guitar body.

The impulse measurement rig developed by Joseph Curtin and used at the VSA's Oberlin Acoustics Workshop is a comprehensive measurement device for instrument acoustics. The original measurement rig is intended for violin family instruments. An adapted version for guitar was used for this study (Fig. 18).

Eigenfrequency	137,221 Hz	250 Hz	281 Hz	315 Hz
Chladni Figure				
Mode	Mono-pole T(1,1)	Cross-dipole T(2,1)	Mono-pole T(1,1)	Long-dipole T(1,2)

Figure 16. Chladni figures of the archtop guitar corpus. The eigenfrequencies correspond to Fig. 11.

Frequency (Hz)	134,221 Hz	242 Hz	263 Hz	297 Hz
Chladni Figure				
Mode	Mono-pole T(1,1)	Cross-dipole T(2,1)	Mono-pole T(1,1)	Long-dipole T(1,2)

Figure 17. Chladni figures of the archtop guitar in the white, under string tension. The eigenfrequencies correspond to Fig. 12.

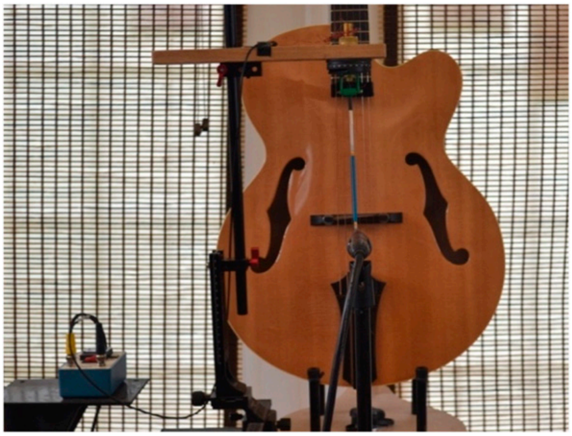


Figure 18. The impulse measurement rig adapted for guitar. Pictured with microphone for near-field radiation measurements.

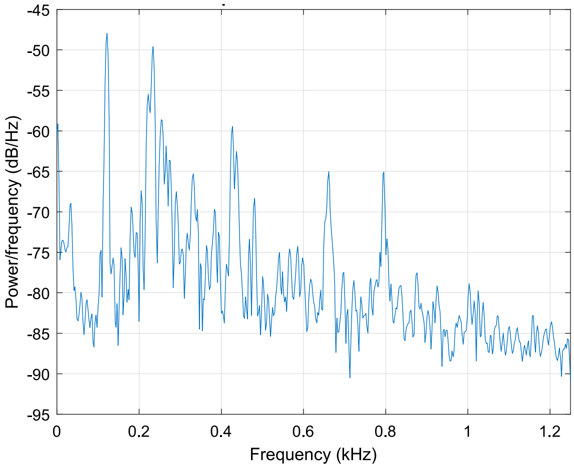


Figure 19. The impulse hammer measurement/ NF radiation FFT of the archtop guitar.

A guitar is suspended in the device, and an impulse hammer lightly taps the bridge of the instrument; the hammer records the applied force of the impact and acts as a trigger for the measurement. A near-field reference microphone can be used to capture an acoustic radiation measurement. Through FFT analysis, the impulse sound created by the hammer reveals the eigenfrequencies of the guitar body [17].

Figure 19 is an FFT plot of the impulse hammer measurement of the finished archtop guitar under string tension. The hammer tapped the center of the bridge, perpendicular to the top plate. The reference microphone was placed approximately 12 inches (25.4 mm) directly in-front, centered between the ff-holes. The forces exerted on the guitar top plate from a plucked steel string are described as a longitudinal force associated with the changes in tension of the excited string, along with the transverse force waveform oscillating perpendicular to the axis of the strings. The fundamental monopole and cross-dipole modes are most efficiently driven when the transverse force waveform acts perpendicular to the top plate [12].

The fundamental eigenfrequencies of the archtop guitar used in this study are in agreement between the frequency sweep and impulse hammer measurements.

Ultimately, the sound of the instrument when played is of most value. Figure 19 is a better representation of this fact. Certain eigenmodes vibrate to a greater magnitude and thus have a greater influence on the overall emitted sound. In the near field, directly in front of the instrument, the T(1,1) air resonance and T(1,1) and T(2,1) top-plate resonances contribute significantly to the projected sound.

CONCLUSION

Understanding the eigenmodes and corresponding eigenfrequencies is the first insight into the archtop guitar's dynamics. Sound radiation and admittance measurements of completed instruments are underway to further understand the near- and far-field projection of the archtop guitar. Sound radiation measurements using techniques practiced at the Oberlin Acoustics Workshop will provide a clear picture of how the archtop resonates without coupled transducers. Further avenues for research include archtop bridge dynamics and measuring the specific mobility of the archtop top. An additional modal study focusing on the higher-order resonances is a necessary endeavor. A study to analyze the air resonance modes and the impact of the double ff-holes will further enhance the understanding of archtop guitar physics.

Combining the physical measurements of a guitar with its acoustic signature provides a potent dataset to catalog and chronicle Golden Era instruments, new and vintage. Archtop guitars built in the early 20th century and current century, by the finest makers, have served as the inspiration for this study. The results are intended to inspire further evolution in the guitar-making community. This study was carried out for free. Through the collaborative efforts of many people and institutions, this study was performed for the good of guitars.

ACKNOWLEDGMENTS

The author sincerely thanks Ilan Levine, Edward Behnke, and Henry Scott of Indiana University South Bend for their knowledge and support. Many thanks to Indiana University South Bend and the National Science Foundation (Grants 1506377 and 1828609) for supporting this work and providing laboratory space and equipment. The guidance and encouragement of Evan Davis and the VSA Oberlin Acoustics Workshop faculty has been of pivotal importance in the trajectory and completion of this work. The author especially thanks Bryan Galloup and the Galloup School of Guitar Building and Repair for supporting this work. Special thanks to Matthew Van Arnam, William Hylton, Zack Bawlinski and Sam Guidry. This work could not have been completed without the unconditional support of my wife and editor, Rebecca Nania, and the Nania and Rosswurm families.

REFERENCES

[1] Catgut Acoustical Society, 1998. Available: www.catgutacoustical.org/journal/index.html. Accessed 27 April 2020.

[2] A. Ingram, Gibson L5 - its Histroy and its Players (Centerstream Publishing, Anaheim Hills, CA, 1997).

[3] R. Benedetto, Making an Archtop Guitar (Centerstream Publications, Anaheim Hills, CA, 1996).

[4] E. F. F. Chladni, Discoveries on the Theory of Sound (Weidmann & Reich, Wittenberg, Germany, 1787).

[5] M. McIntyre and J. Woodhouse, On Measuring Wood Properties, Part I, Catgut Acoust. Soc., No. 42, pp. 11–15 (Cambridge, UK, 1984).

[6] T. Gore, Wood for guitars, J. Acoust. Soc. Am., Vol. 12, pp. 1–22 (2011).

[7] M. Schleske, Speed of sound and damping of spruce in relation to the direction of grains and rays, Catgut Acoust. Soc., Vol. 1, No. 1, pp. 16–20 (1990).

[8] M. Tinnsten and C. Peter, Important spruce properties determined by the use of numerical optimization, Proceedings of the International Symposium on Musical Acoustics (Nara, Japan, 31 March to 3 April 2004).

[9] C. Gough, Violin plate modes, J. Acoust. Soc. Am., pp. 139–530 (2015).

[10] A. W. Leissa, Vibration of Plates (Ohio State University - National Aeronatuics and Space Administration, Columbus, OH, 1969).

[11] D. C. Hurd, Left Brain Lutherie (Ukuleles by Kawika, Hilo, Hawaii, 2004), pp. 14–69.

[12] T. Gore and G. Gerard, Contemporary Acoustic Guitar Design and Build, Vol. 1 (Trevor Gore, NSW, Australia, 2011), pp. Chapter 1-5.

[13] O. Christensen, Simple model for low-frequency guitar function, J. Acoust. Soc. Am., pp. 758–66 (1980).

[14] E. Davis, Designing soundboards with flexural disk models, Proc. Mettings Acoust., Vol. 12, pp. 1–13 (2011).

[15] C. Hutchins, The acoustics of violin plates, Sci. Am., Vol. 245, No. 4, pp. 170–88 (1981).

[16] M. Elejabarrieta, A. Ezcurra, and C. Santamaria, Coupled modes of the resonance box of the guitar, Acoust. Soc. Am., pp. 2283–92 (2002).

[17] J. Curtin, Measuring violin sound radiation using an impact hammer, Violin Soc. America Pap., Vol. 22, No. 1, pp. 186–204 (2009).