26th International Congress on Sound and Vibration
7-11 July 2019, Montreal

# MEASUREMENTS OF ACOUSTIC GUITAR TOP PLATES DURING THE VOICING PROCESS

Mark Rau
*Center for Computer Research in Music and Acoustics (CCRMA), Stanford University, Stanford, California, USA*
*email: mrau@ccrma.stanford.edu*

Richard Hoover
*Santa Cruz Guitar Company, Santa Cruz, California, USA*

Acoustic guitar top plates are typically constructed out of extremely thin wood which is not strong enough to hold up to the stress caused by the high tension of the strings, leading to the use of wood struts as braces. Bracing design has a significant effect on the vibrational characteristics of the top plate, and is seen as one of the fundamental steps to producing a desirable sounding instrument. Once a bracing pattern is chosen and the top plate is constructed, the braces are carved to minimize the added mass while maintaining stiffness. Luthiers will often make voicing decisions by ear by tapping on the top plate and listening to the response. During this study, two steel string acoustic guitar top plates were measured throughout the brace-voicing process. The measurements were analyzed to show how the vibrational modes of the structure evolve as the braces are carved.

Keywords: Guitar, Lutherie, Bracing

## 1. Introduction

The guitar is one of the most popular instrument in the world and there are many different acoustic designs suited for different styles of music. There have been multiple books and research papers written about the construction of acoustic acoustic guitars, but there remains significant debate among the luthier and player communities into the best methods of construction [1, 2, 3, 4].

This paper will focus on the design and construction of the steel string acoustic guitar, in particular, the carving of the braces used to strengthen the top plates of guitars. The top plate is considered to be the most acoustically important part of an acoustic guitar, so the bracing which supports this thin wooden plate is critical [5]. There has been research which investigated standard and alternative bracing patterns, as well as some which looked at the theoretical effects of brace designs, but the actual brace voicing process remains largely lore [6, 7, 8, 9]. The carving of the braces with the goal of emphasizing a desired musical behavior is often referred to as “voicing” the top.

Many luthiers consider the brace carving to be one of the most important aspects of building a guitar, and pay particular attention to it. A common method to test the affects of the brace voicing is to tap the guitar top and listen to the resulting vibrations; this is known as tap-testing. We choose to focus on how the brace carving process can effect the vibrational modes of the guitar top throughout the voicing process, attempting to draw insight into this method.

To study the vibrational modes, input admittance measurements were made on the guitar tops. The mechanical input admittance is defined in the frequency domain as the velocity of the structural vibrations divided by an input driving force [10]. Input admittance measurements can be used to show the vibrational characteristics of the structure being measured. Input admittance measurements were taken on the guitar tops at the location where the bridge would later be placed as this is the location where the strings will be most strongly coupled to the guitar body.

While it is acknowledged that the vibrational characteristics will continue to change as the guitar progresses through the construction process, it would be valuable to know how the effects of the top voicing propagate throughout the process. As well, knowing how the modes develop could help to teach apprentice luthiers to properly voice guitars based on the methods of master luthiers.

## 2. Brace Carving

While the main purpose of braces is to supply structural support to the thin guitar top, the braces can be carved to emphasize certain resonances. The bracing patterns used for this study were of the x-bracing style, a typical bracing pattern used for steel string acoustic guitars. Figure 1 shows the bracing pattern as well as the brace names.

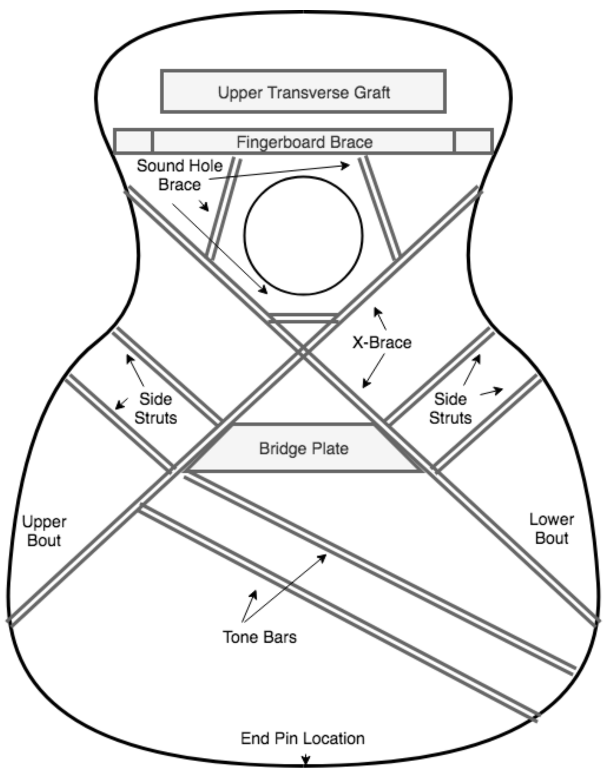


Figure 1: Bracing pattern diagram.

During the voicing, the upper transverse graft, soundboard braces, and bridge plate were either minimally carved, or not modified. Similarly, the fingerboard brace received minimal carving, with only tapering of the ends to meet the top plate. The majority of the carving was done on the x-braces, tone bars and side struts. The x-braces and tone bars were scalloped, meaning that wood was removed in the middle of the braces, leaving valleys and peaks. As well, significant tapering was done to the ends of these braces.

Two guitar tops were carved and measured for this study. Both guitar tops were shaped to become orchestra model (OM) sized guitars and will be referred to as OM1 and OM2 in this paper. The wood used for both tops and their bracing was Adirondack red spruce. OM1 had a tapered thickness of 2.75 mm on the bass side, and 2.95 mm on the treble side, while OM2 had a uniform thickness of 2.9 mm. The braces and top had a slight concave shape corresponding to that of a circle with radius 10.06 m.

The luthiers performed a tap test to listen to the response of the guitar tops. During the tap test, they would suspend the top with a finger or thumb through the sound hole and tap the front side of the top with a fingertip. The tapping method of the first luthier was to tap in multiple locations of the guitar top, listening to the decay of the different taps. The four main locations of tapping were: where the bridge will be located, on the lower bout, upper bout, and near the end pin. The tapping method of the second luthier was to tap only at the bridge location. While tapping, the perceived pitch and dominant frequencies heard at a particular location differed based on tapping location. While the perceived pitch differed, the mode frequencies and damping will be the same since the guitar top can be approximated as a linear system, where only the mode amplitudes will change with excitation location. The overall goal of voicing the tops as described by the luthiers was to bring out the resonances heard in the tap and try to create a rich tap tone from which multiple overtones could be heard.

Both luthiers followed a general method of carving which determined the points at which to measure the guitar tops. Figure 2 shows the braces at the beginning as well as after three carving steps of OM2. The first carving step involved removing a significant amount of wood to advance the guitar top to a reasonable starting point for more detailed voicing. This means tapering each brace, and scalloping the general outline of the x-braces and tone bars. The following carving steps involved more detailed carving where the luthiers were aiming to bring out musical qualities in the tap tone.

(a) Initial Bracing (b) Intermediate Carving Step 1 (c) Intermediate Carving Step 2 (d) Final Carved Braces

Figure 2: Brace carving of OM2.

## 3. Measurements

Admittance measurements were taken on the guitar tops using a force sensing impact hammer (PCB 086E80) to impart a known force, and a laser Doppler vibrometer (Polytec PDV 100) to measure the resulting velocity. The coherence was observed throughout the process and poor quality measurements were discarded. Although the guitar tops did not yet have bridges, it was decided that admittance measurements would be taken at the location where the bridge would later be placed, as this is where the strings will later be coupled to the instrument. These measurements will be referred to as the pseudo-bridge admittance. Two microphones were also used to record the sound radiated by the impulses, but the measurements were made in an active luthier shop thereby rendering the microphone signals noisy and not useful. The guitar tops were suspended vertically from the sound hole using a padded arm which minimized movement of the tops which is similar to how the luthiers would suspend the tops from their thumb while tap testing. The measurement setup is shown in Fig. 3. To ensure that the untreated wood was not damaged by the impact hammer, a vinyl tip was used, effectively bandlimiting the signal to around 2 kHz.

Each guitar top was measured before the braces were carved, at two intermediate carving stages, and after the braces were fully carved. The ambient temperature and humidity were 47 % and 22 °C during the carving of OM1, and 49 % and 22 °C during the carving of OM2.


Figure 3: Measurement setup.

# 4. Results

## 4.1 Pseudo-Bridge Admittance

The pseudo-bridge admittance was calculated for each top voicing step by deconvolving the force impulse recorded by the impact hammer from the velocity measurement recorded by the vibrometer. Single admittance measurements are shown in Figs. 4 and 5 for OM1 and OM2 respectively. The admittance measurements were not averaged, as it was chosen to fit the modes to the individual measurements, then average the modal parameters. It is noted that the velocity measurements of OM1 were slightly clipped and reconstructed. The reconstructions were not perfect and we do not have confidence in the measurements below approximately 120 Hz.

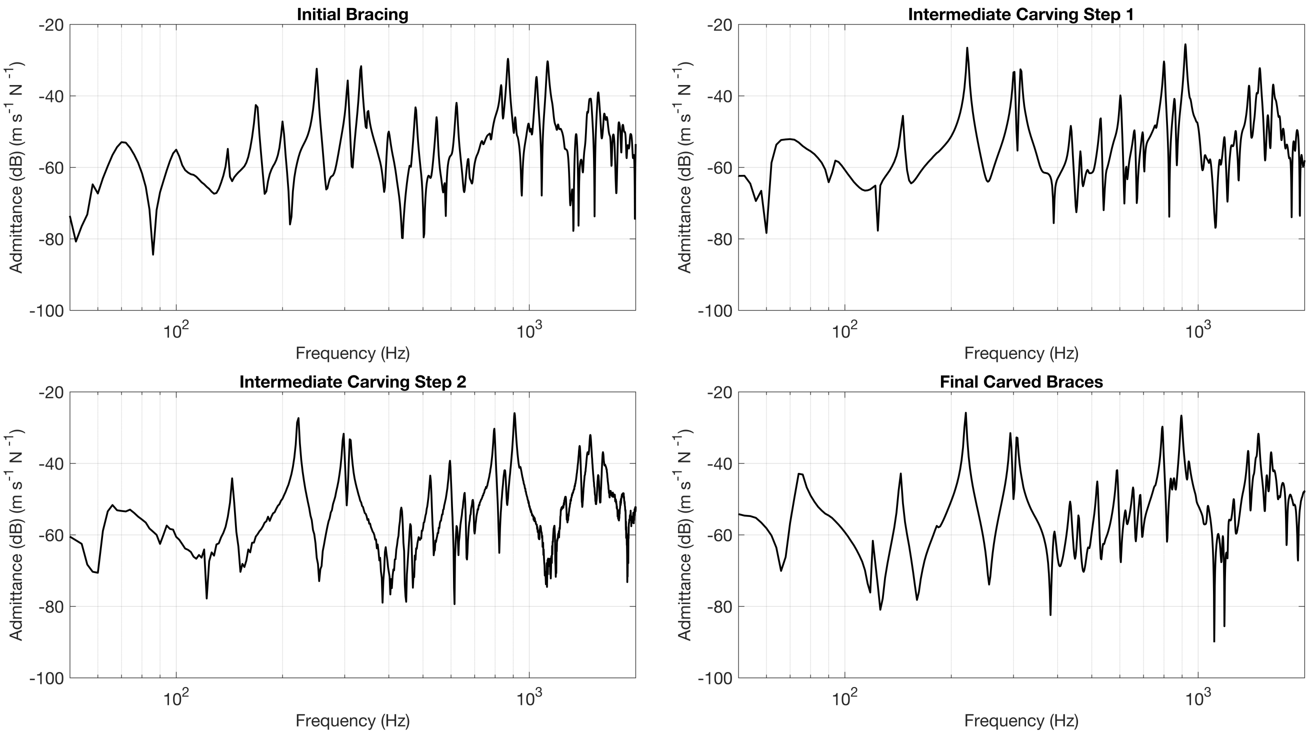


Figure 4: Pseudo-bridge admittance of OM1 at the four bracing stages.

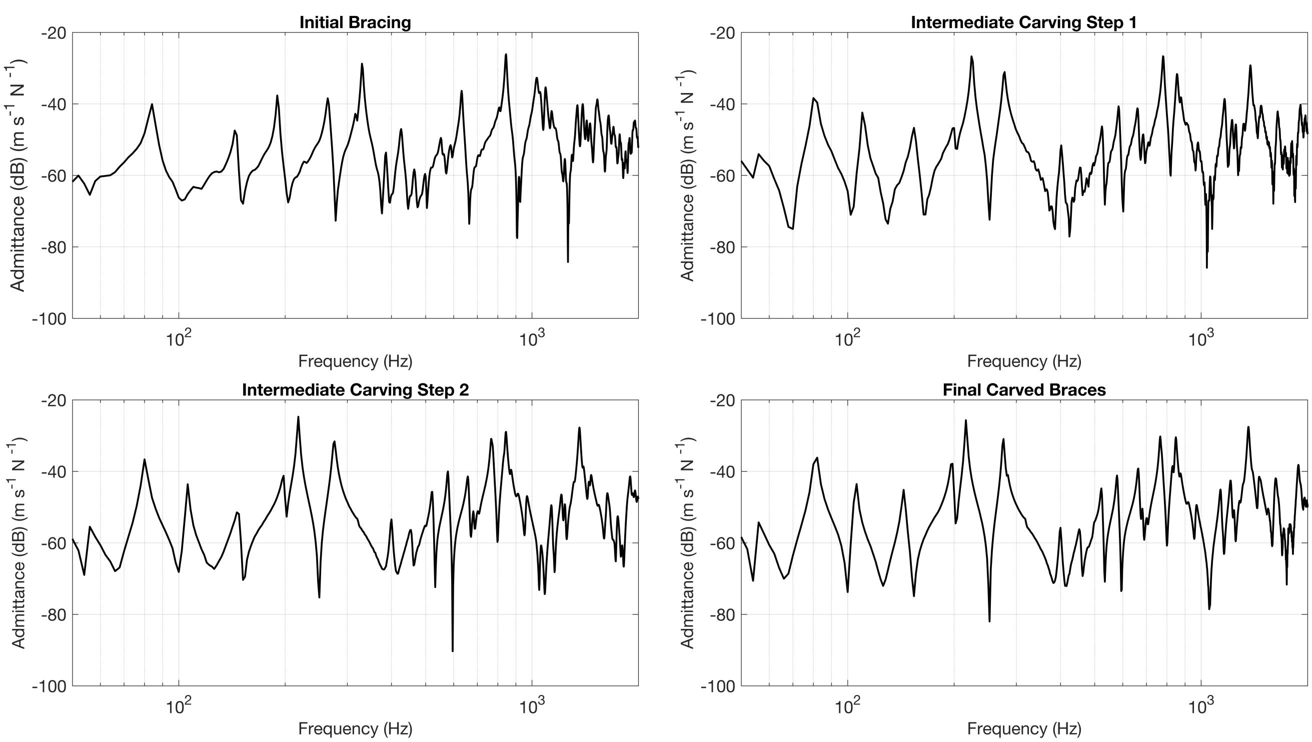


Figure 5: Pseudo-bridge admittance of OM2 at the four bracing stages.

### 4.2 Mode Fitting

Mode fitting was performed on the pseudo-bridge admittance measurements to gain insight into the mode frequencies, damping, and amplitudes. The mode fitting was performed assuming the modal response of a damped harmonic oscillator having an impulse response of the form,

$$h(t) = \sum_{m=1}^{M} \gamma_m e^{(i\omega_m - \zeta_m \omega_m)t}, \tag{1}$$

where $\gamma_m$, $\omega_m$, and $\zeta_m$ are the amplitude, natural frequency, and damping ratios of modes $m = 1, 2, ..., M$ [11, 12]. There are multiple classical modal parameter extraction methods [13], however the mode fitting was performed using a method derived by Jonathan Abel involving analysis of the eigenstructure of a Hankel matrix of impulse response samples [14]. The model order was derived from the $M$ largest singular values of this decomposition, which can be viewed as the singular values associated with the signal space as opposed to the noise space. Figure 6 shows the mode fitting for two admittance measurements of OM2 taken at different voicing steps.

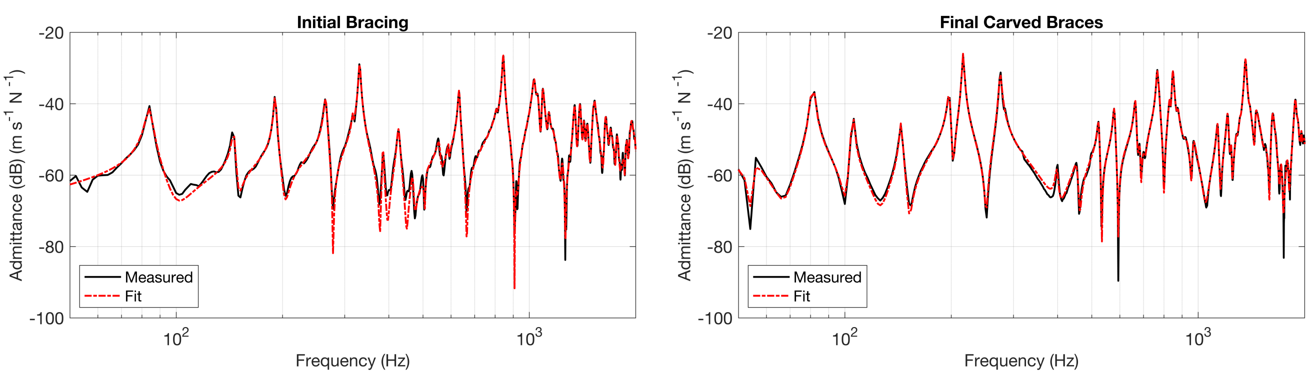


Figure 6: Example of mode fitting for OM2.

To facilitate comparison of how the modes develop as the braces are carved, the mode frequencies and damping rates of a number of prominent modes are shown in Fig. 7 for each guitar top at various stages of the voicing process. The modes chosen were those below 1 kHz with admittance greater than -50 dB. Only the modes found in the intermediate bracing steps and final bracing are shown here because the modes change quite drastically from those present with the initial uncarved braces. The average mode frequency and damping rate extracted from the mode fittings of multiple measurements are shown as well as the uncertainty of $\pm$ one standard deviation in the frequency and decay rate. The averaging was done with between 3-5 measurements for OM1 and 9-10 measurements for OM2.

## 5. Discussion

Upon inspecting the admittance frequency response measurements shown in Figs. 4 and 5, it is clear that the biggest changes to the modes occurred between the initial bracing stage and the intermediate carving stage 1. This is understandable since the brace carving during this step involved removing quite a bit of wood while scalloping out the braces to get to a reasonable starting point for the finer tuning. The parts of the braces hanging over the sides of the guitar tops were also removed during this step. Unlike the initial bracing, the admittance at the intermediate steps and after the tops when fully carved are quite similar with only subtle differences.

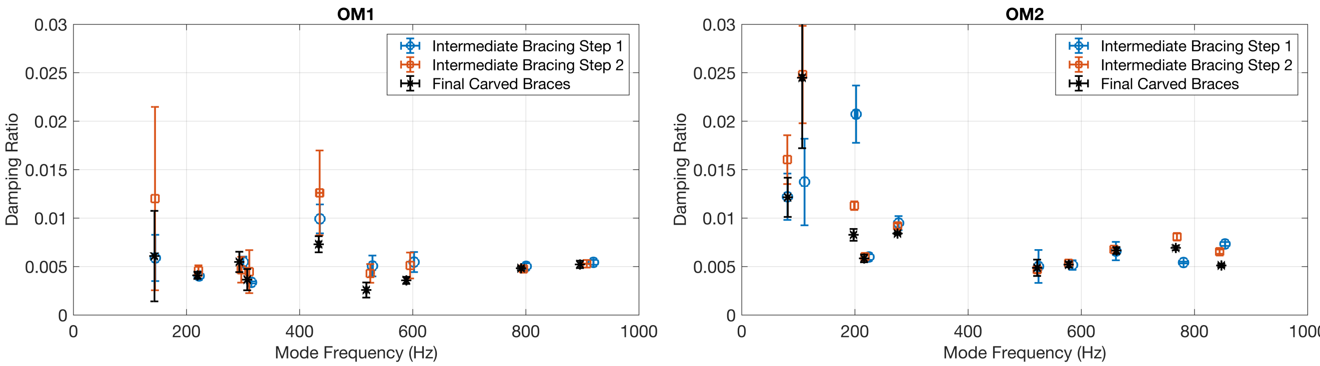


Figure 7: Mode frequencies and damping ratios of select modes of OM1 and OM2 $\pm$ one standard deviation.

Both guitar tops have a similar overall pseudo-bridge admittance mode layout of a few strong modes below 350 Hz, a slight lull around 400 Hz, a group of stronger amplitude modes around 800 Hz, and another lull around 1 kHz. While the guitar tops may have similar mode amplitude envelopes, there is quite a large variance in the mode frequencies between the two guitar tops. These differences could be explained by the different thicknesses of the top plates, material properties of each specific piece of wood, or the bracing methodology of the different luthiers.

Figure 7 allows us to take a closer look at how a few select low frequency modes develop as the tops are voiced. In general, the modes shift slightly lower in frequency as more wood is carved away which implies that the overall stiffness is decreasing at a faster rate relative to the decrease in mass. For some modes, the damping ratio is decreased quite significantly, while for some, the change is subtle. In most cases the modal damping ratios decrease slightly, meaning the modes will take longer to decay. This confirms the goal of the luthiers to make the guitar body more resonant. However, the damping ratio of some modes actually increases, so there must be a balance to be made regarding the damping characteristics of each mode.

One possible use for measurements like this would be to aid apprentice luthiers in the process of voicing guitar tops. If they were able to see how the modes can change, it could help them gain an understanding of how carving each brace will alter the sound. Knowing information about the initial modal response could also be used to avoid problem areas by shifting the frequencies of specific modes.

Future work may include investigating an ideal damping ratio for a mode to resonate well in a certain musical context. A low damping ratio will mean that the string energy is easily transferred to the instrument at that frequency, possibly resulting in a strongly radiated sound. However, if the string energy is transferred to the instrument too quickly, it will result in a shorter string decay, known as a dead note [15].

These measurements are part of an ongoing project which will include measurements made when the tops are glued to their backs and sides as well as when the final guitars are completed. The measurements throughout the building process will be analyzed to see how they progress so that predictions could be made about the final modal response based on the modes at intermediate stages.

## 6. Acknowledgements

We would like to thank Eric Lawrence and Polytec for lending the laser Doppler vibrometer as well as Julius Smith, Jonathan Abel, and Chris Chafe for helpful discussions. We would also like to thank the folks at the Santa Cruz Guitar Company, in particular Adam Rose and Rick Barto.

## References

1. Cumpiano, W. R. and Natelson, J. D., *Guitarmaking: Tradition and technology: A complete reference for the design & construction of the steel-string folk guitar & the classical guitar*, Chronicle Books (1994).

2. Gore, T. and Gilet, G., *Contemporary acoustic guitar design and build: Build*, vol. 2, Trevor Gore (2011).

3. French, R. M., *Engineering the guitar: Theory and practice*, Springer Science & Business Media (2008).

4. Inta, R., *The acoustics of the steel string guitar*, Ph.D. thesis, University of New South Wales, (2007).

5. Richardson, B. E. The acoustical development of the guitar, *Catgut Acoustical Society Journal*, **2** (5), 1–10, (1994).

6. Caldersmith, G. Designing a guitar family, *Applied acoustics*, **46** (1), 3–17, (1995).

7. Luo, D., *Measuring the frequency response function of X-braced guitar top and guitar*, Ph.D. thesis, Tufts University, (2016).

8. Dumond, P. and Baddour, N. Can a brace be used to control the frequencies of a plate?, *SpringerPlus*, **2** (1), 558, (2013).

9. Dumond, P. and Baddour, N. A structured approach to using a rectangular brace to design a soundboard section for a desired natural frequency, *Proceedings of the Stockholm Music Acoustics Conference*, pp. 613–618, (2013).

10. Woodhouse, J. and Langley, R. Interpreting the input admittance of violins and guitars, *Acta Acustica united with Acustica*, **98** (4), 611–628, (2012).

11. Brandt, A., *Noise and vibration analysis: Signal analysis and experimental procedures*, John Wiley & Sons (2011).

12. Agilent Technologies. Fundamentals of modal testing, (2000).

13. Ewins, D. J., *Modal testing: Theory and practice*, Research Studies Press LTD. (1984).

14. Abel, J. S. Direct modal filter design, *Personal Communication*, (November 2018).

15. Fleischer, H. and Zwicker, T. Investigating dead spots of electric guitars, *Acta Acustica united with Acustica*, **85** (1), 128–135, (1999).