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Guitar analysis using measurements – V-braced/Q varying

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1 Introduction

A set of six guitars with Taylor's current V-bracing design was built for this study. Three guitars (group Aa) had tops with low density and stiffness and three guitars had tops with high density and stiffness (group Cc). Figure 1 shows the varying wood parameters.

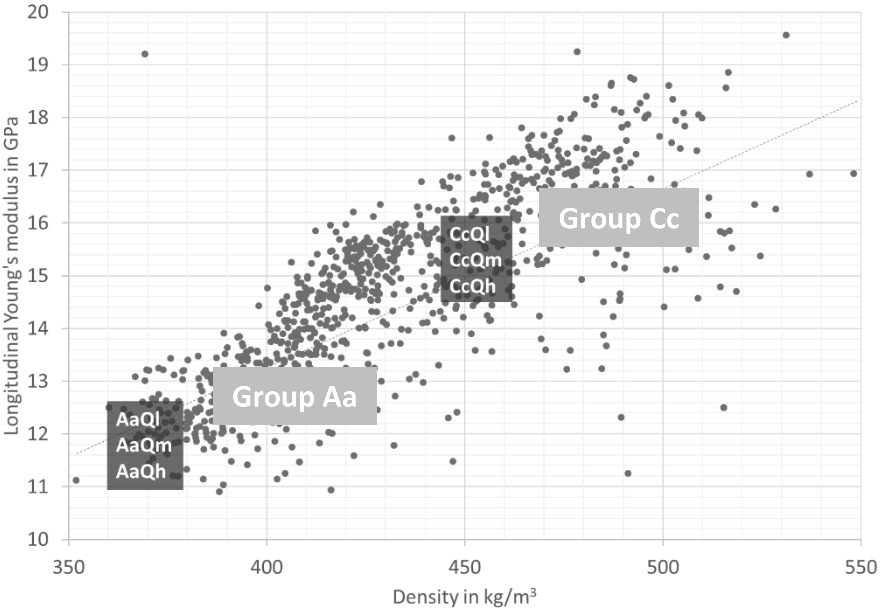

Figure 1 – Schematic representation of soundboard material properties for guitars with V-bracing.

Within each group, the quality factor Q was varied across the typical range. Three levels of damping were chosen with Q being approximately 130 (labeled 'Q low' or 'Ql'), approximately 150 (labeled 'Q mid' or 'Qm') and approximately 160 (labeled 'Q high' or 'Qh'). The selected boards and their material properties are summarized in Table 1.

Table 1 – Measured wood parameters.

Label	Q	Density ρ in kg/m³	Longitudinal Young's modulus E_{LONG} in MPa	Radial Young's modulus E_{RAD} in MPa	Shear modulus G in MPa	Ratio of longitudinal Young's modulus and density
AaQl	134	366	10730		701	29.3
AaQm	151	373	11987		620	32.2
AaQh	163	371	11952		638	32.2
CcQl	130	462	16195	1924	932	35.,0
CcQm	151	451	15097	1850	847	33.5
CcQh	159	461	15739	1956	687	34.1

A listening test revealed that group Aa was preferred over group Cc. Additionally, the quality factor Q of the top wood seemed to have an influence on the preference of the examined guitars. The results suggested that there is a tendency of high Q being preferred over lower Q. However, there seemed to be some interaction with density and stiffness of the tonewood as shown in Figure 2.

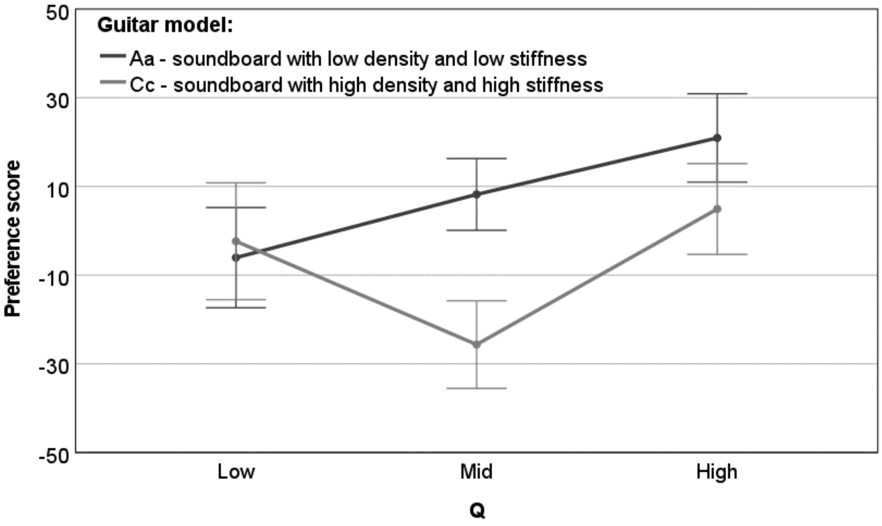

Figure 2 – Profile plot for the significant interaction between guitar group and Q. Plotted are mean preference scores with 95% confidence intervals.

The goal of the following analysis is to better understand the physical differences that could have led to the preference variation in the listening test. First, spectral differences in the recordings and measured transfer functions will be discussed. Then, the temporal behavior of some guitars will be analyzed.

2 Sequence analysis

The first approach was to directly search for systematic differences in the spectra of recorded music sequences. No systematic difference in overall loudness could be found in the recordings. Figure 3 shows the A-weighted averaged spectra of three strumming sequences used in the listening test and recorded with the three guitars of the first group Aa with a low, mid and high damping factor Q. A 1/3rd octave smoothing was applied for easier comparison. Some variation in the spectra can be observed between 100 Hz and 1 kHz. The level variation between 100 Hz and 500 Hz does not seem to correlate with the preference evaluation. Between 500 Hz and 700 Hz, a systematic decrease in level between the spectra from low to high quality factor Q can be seen. It will later be discussed that the change in level can be explained by a strong shift of a modal resonance in the corresponding frequency range (see Figure 10). Unfortunately, this resonance shift cannot be explained by the variation in Q. However, this variation of the frequency response could perhaps explain the tendency of decreasing preference for guitars with lower Q in group Aa found in the listening test. A schematic pictogram of the corresponding preference scores is plotted for comparison in Figure 3. Additionally, a second pictogram in the top right symbolizes the material parameters (low density and longitudinal stiffness) of guitars from group Aa.

In the frequency range below 100 Hz, AaQl shows up to 4 dB less bass level compared to AaQm and AaQh. This is difficult to see in the graph because of the strong roll-off toward lower frequencies. Note that guitar AaQl was least preferred in group Aa.

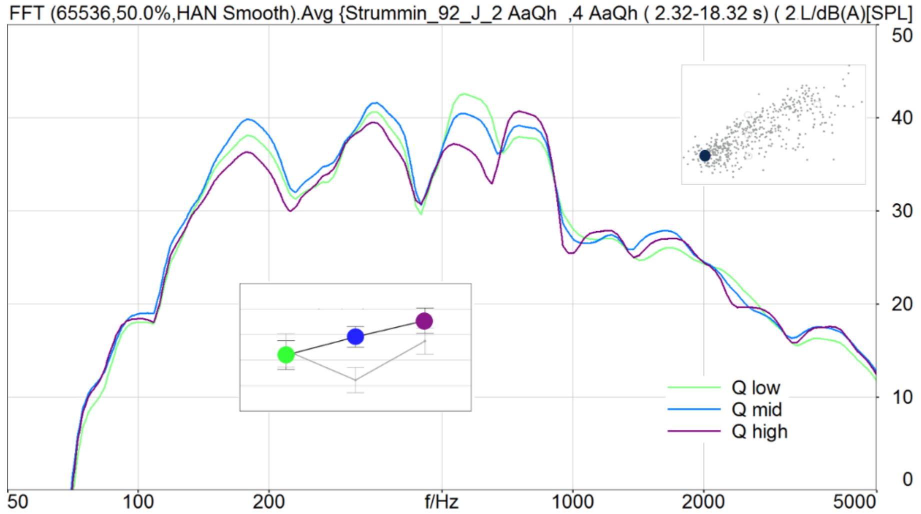

Figure 3 – Spectra of the strumming sequences for guitars from group Aa.

Less variation between different Q factors can be seen in the second group of guitars (Cc) in Figure 4 for the frequency range between 100 Hz and 1 kHz. However, the differences near and below 100 Hz are larger between the guitars, with CcQl showing the most bass followed by CcQh with slightly less bass. The weakest bass can be observed for guitar CcQm. Guitar CcQm was also the least preferred of group Cc in the listening test. For this group of guitars, the slight differences in the amount of bass below approximately 100 Hz could have influenced the preference rating.

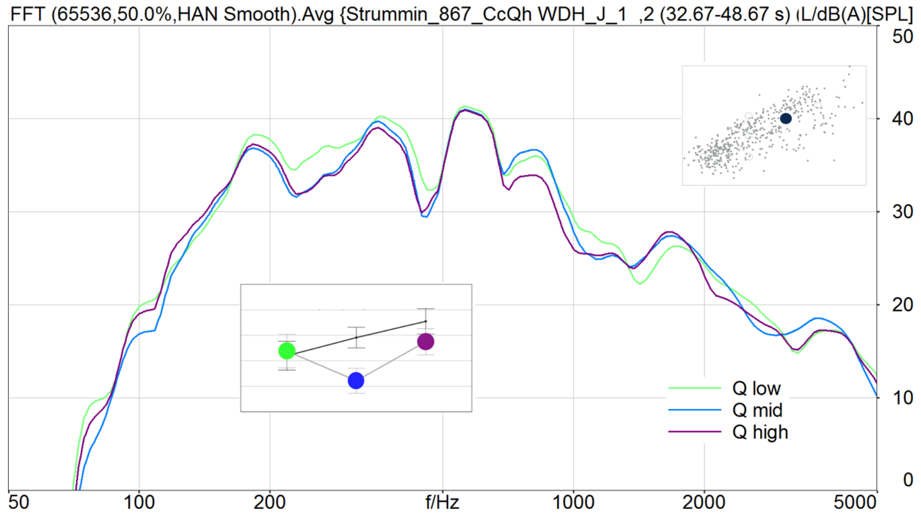

Figure 4 – Spectra of the strumming sequences for guitars from group Cc.

Figure 5 shows the spectra of the strumming sequences averaged over all three guitars in each group (i.e., Aa and Cc). Guitars from group Aa have on average more bass below 100 Hz but also show higher levels in some other frequency ranges (e.g., 120 Hz to 180 Hz or 700 Hz to 900 Hz). In the listening test, guitars from group Aa are on average preferred to guitars from group Cc.

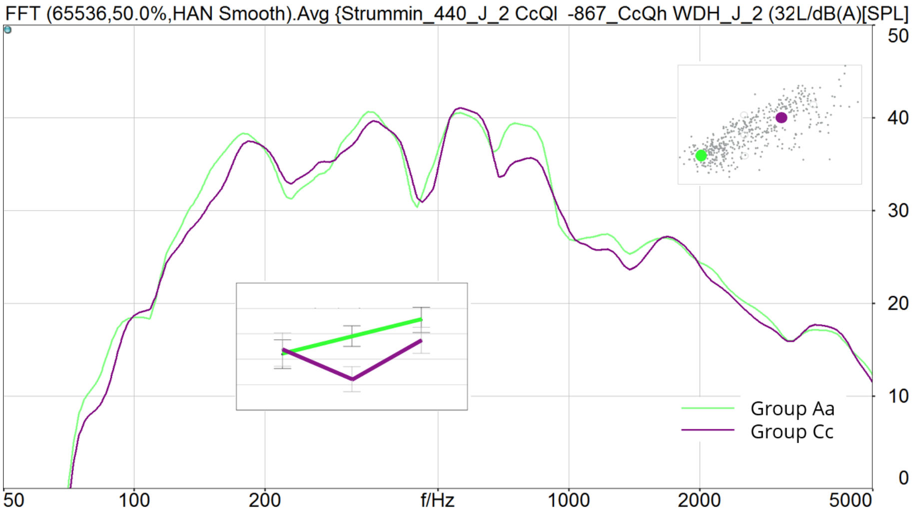

Figure 5 – Averaged spectrum of the strumming sequence for all three guitars in groups Aa and Cc.

The strongest preference difference was found in the listening test between guitars AaQh and CcQm. The corresponding spectra are shown in Figure 6. Clear differences can be seen in the frequency range below 200 Hz and between 500 Hz and 1 kHz.

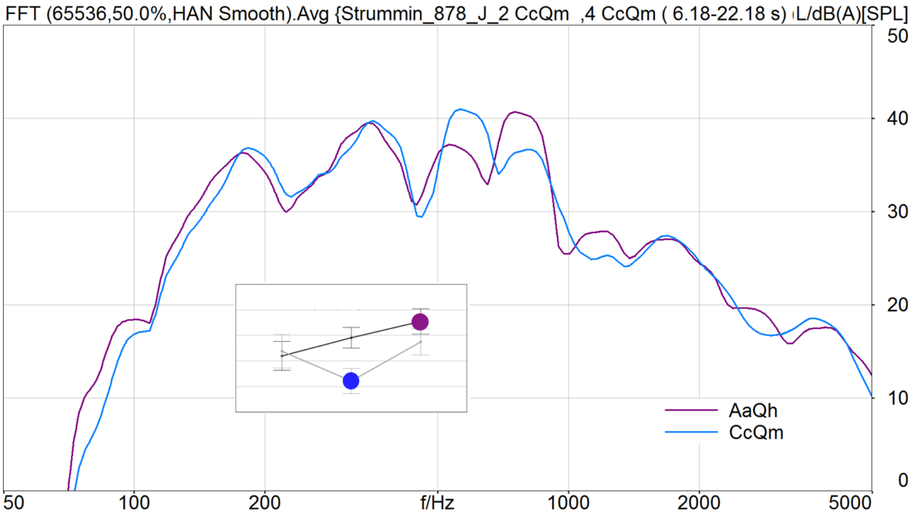

Figure 6 – Spectrum of the strumming sequence for the guitars with strongest preference difference in the listening test.

Please note that there is much speculation in the above interpretation regarding the perceptual effects of differences between the spectra. It can only be suspected here that some of the mentioned spectral differences are the cause of the preference differences found in the listening test. However, the preference of group Aa over group Cc (at least for the mid and maybe the high Q conditions) seems to be easier to explain with spectral differences than differences within each group of guitars.

3 Transfer function measurements

Transfer functions were measured in the same way as described for the X-braced guitars in part 3 of the report. An exemplary measurement can be seen in Figure 7 for all three hammer impact positions on the bridge (i.e., low, mid and high).

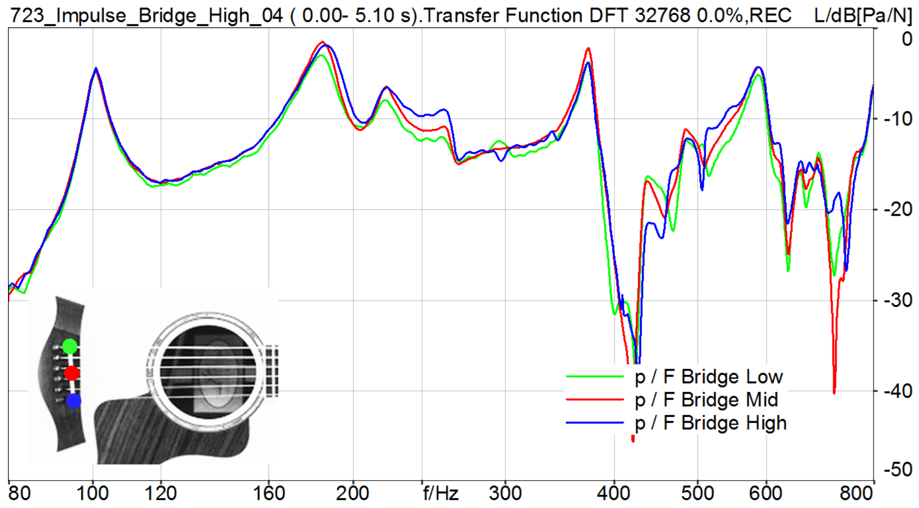

Figure 7 – Transfer function of sound pressure at frontal microphone to force input at bridge for guitar AaQI (723).

In all remaining figures, the average over all three positions will be plotted for each transfer function. Figure 8 shows the averaged response for guitar AaQI (blue). For comparison, the averaged transfer function of one of the X-braced guitars from the previous study is shown. A strong frequency shift of all low resonances toward higher frequencies is observable for the new V-braced design.

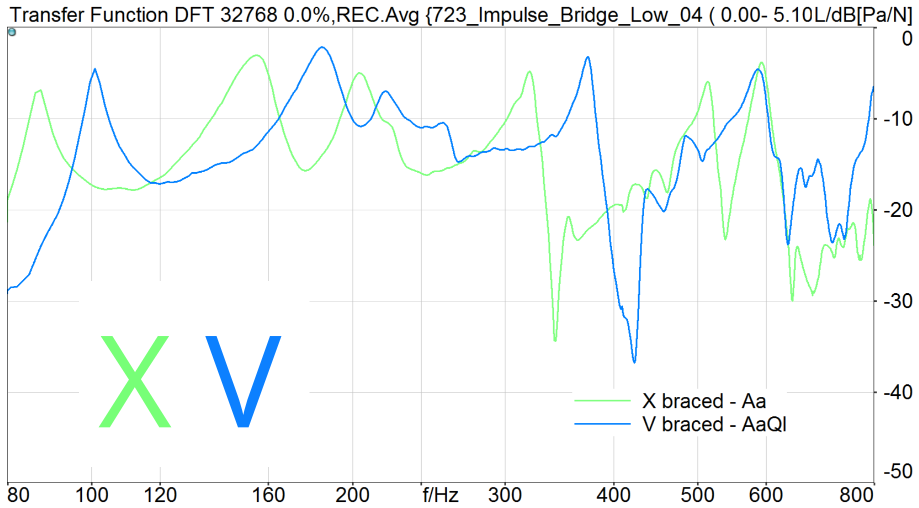

Figure 8 – Transfer function of frontal microphone to force input at bridge for guitar AaQI (723, V-braced) and Aa (114, X-braced) averaged over all three impact positions at the bridge.

Figure 9 shows a wider frequency range of the same transfer functions. A strong resonance at 800 Hz can be seen for the V-braced guitar. Toward higher frequencies (above 1 kHz) the difference between both designs becomes smaller.

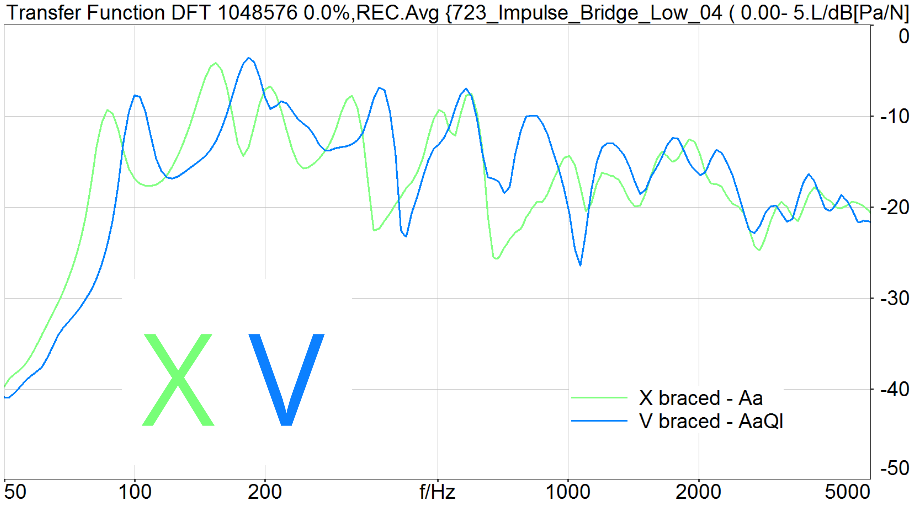

Figure 9 – Transfer function of frontal microphone to force input at bridge for guitar AaQI (723, V-braced) and Aa (114, X-braced) with 24th octave intensity averaging.

The resonance shift between the X- and V-braced design is slightly larger than the resonance shifts found for the natural variation of density and Young’s and shear moduli in part 3 of this report. No resonance shift is expected for varying Q in this study. However, the modal resonances of transfer functions for guitars from group Aa shown in Figure 10 are shifted slightly. The reasons could be manufacturing tolerances or that the remaining material parameters in addition to Q are not perfectly constant, as seen in Table 1.

An interesting strong frequency shift for the main resonance below 600 Hz can be seen. This could be the reason for variations in the spectral content within this frequency range in the sequence analysis shown in Figure 3. However, this resonance shift cannot be explained by the variation in Q. It is hypothesized that the corresponding mode is the cross tripole $\mathbf{T}_{3,1}$. This mode seems to be heavily influenced by the radial Young’s modulus and less influenced by the longitudinal stiffness (compare report part 2 “Guitar analysis using simulation”). Perhaps the unknown radial stiffness is varying and, therefore, the cause of the frequency shift.

Figure 10 – Comparison of three guitars with soundboards of low mass and stiffness (group Aa) but different Q using the transfer function of the frontal microphone to the force input at the bridge.

Figure 11 shows the transfer functions of the second group of guitars with soundboards of high mass and stiffness. Here, the peaks in the frequency response are more aligned; however, some slight frequency shifts continue to be observed.
Unfortunately, the gentle differences observed in the sequence analysis shown in Figure 4 (e.g., the slightly increased bass level for AaQl and AaQh compared to AaQm) cannot be explained with the measured transfer functions.

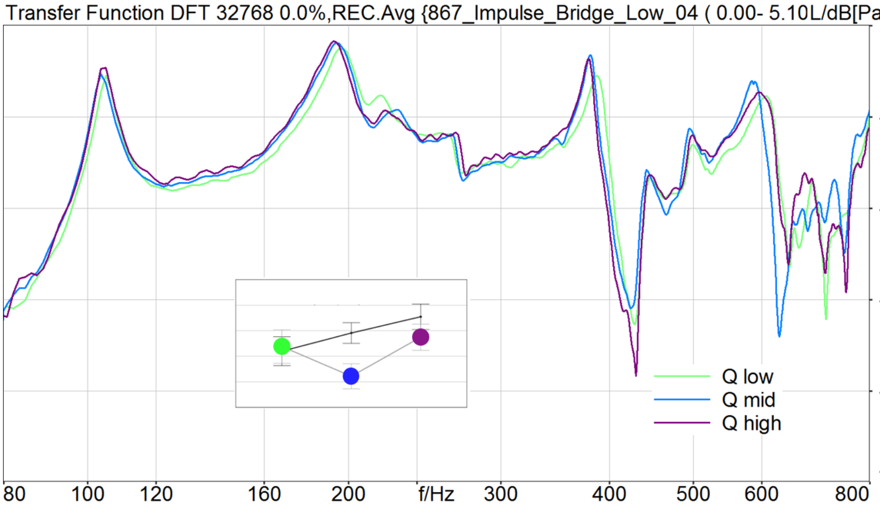

Figure 11 – Comparison of three guitars with soundboards of high mass and stiffness (group Cc) but different Q using the transfer function of the frontal microphone to the force input at the bridge.

It was expected to see the differences in damping as varying widths of the peaks in the transfer functions. For better illustration, the first three peaks are manually aligned in Figure 12. Interestingly, the frequency responses look perfectly congruent for the peaks at approximately 105 Hz and 190 Hz. For the third resonance at approximately 380 Hz, a tendency of increasing peak bandwidth is visible for low Q soundboard wood compared to material with mid and high internal damping. However, the effect does not appear to be strong. It is therefore hypothesized that other damping mechanisms, e.g., sound radiation, dominate the modal damping.

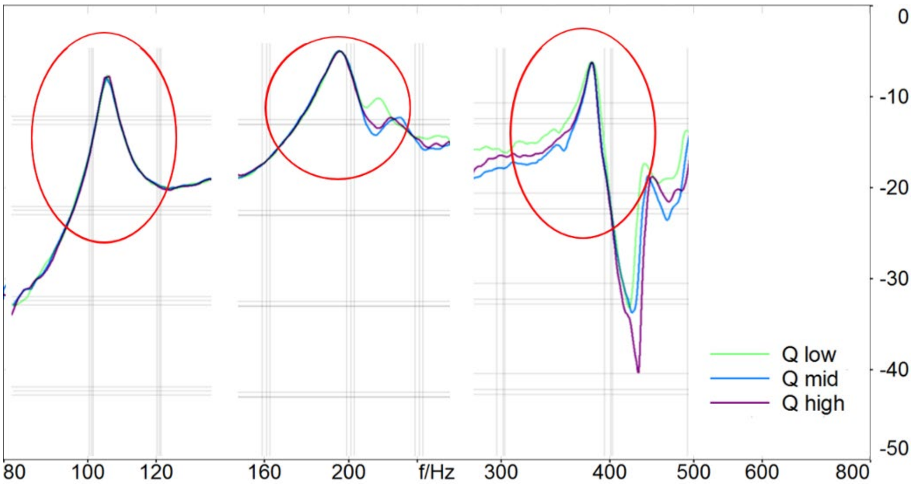

Figure 12 – Comparison of three guitars with soundboards of high mass and stiffness (group Cc) but different Q. Three selected peaks in the transfer function are manually aligned to visually inspect their respective widths.

Figure 13 shows the averaged transfer functions for all three guitars in each group (Aa and Cc). A significantly lower resonance can be seen in group Aa compared to group Cc. This is in line with the lower average ratio of longitudinal Young's modulus and density of 31.2 in group Aa compared to 34.2 in group Cc. The mean shear modulus of + 26% is also slightly higher in group Cc than in group Aa.

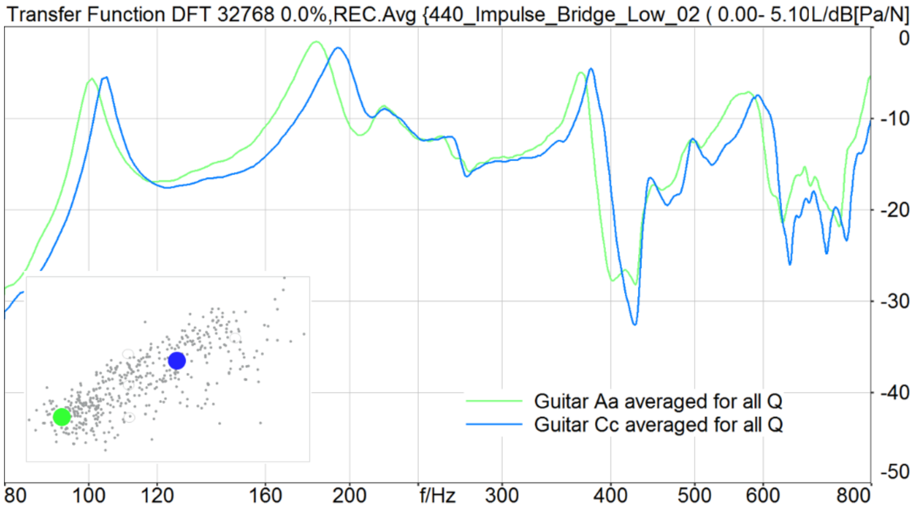

Figure 13 – Comparison of guitar groups Aa and Cc averaged for all Q using the transfer functions of the frontal microphone to the force input at the bridge.

Figure 14 shows the same comparison as Figure 13 but for a wider frequency range. A 1/6th octave smoothing was applied for better clarity. The resonance frequency shift between both groups of guitars can be seen for a wide frequency range. This modal behavior can explain some of the differences found in the averaged spectra of the strumming sequences shown in Figure 5, which might have led to the reported preference for guitars from group Aa over guitars from group Cc.

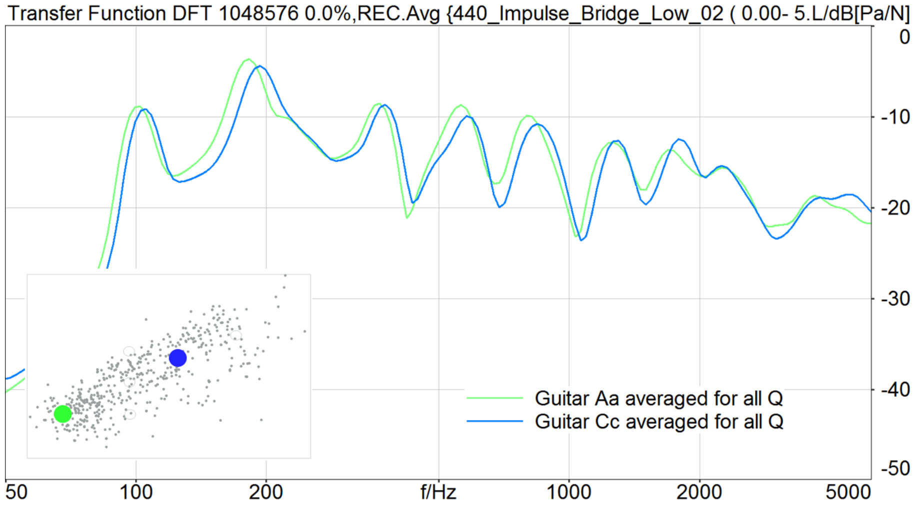

Figure 14 – Comparison of guitars Aa and Cc averaged over all Q using the transfer functions of the frontal microphone to the force input at the bridge with 1/6th octave smoothing.

The above discussion attempted to link spectral properties in the recordings and the measured transfer functions to preference tendencies from the listening test. However, some speculation was necessary in the interpretation of relations between frequency responses and perceptual preference, especially if only the material damping was varied.

4 Plugged single notes

It was expected that the internal material damping could influence the duration and temporal envelope of a tone or its partials. Therefore, plugged tones were recorded in the anechoic chamber using the same configuration as for the transfer function measurements. A helper tool was made using spring steel wrapped in an insulating hose. The strings were plugged in front of the sound hole as shown in Figure 15. A complete set of plugged tones (open to the 12th fret for each string) was recorded for guitars AaQh and AaQl. For the remaining guitars, plugged tones stopped at the 4th fret of each string were recorded.

Figure 15 – Manual plugging of single notes using a helper tool made of spring steel.

The influence of guitar resonances on the loudness of the fundamental and harmonics of each plugged tone was already discussed in detail in the measurement analysis for X-braced guitars. A strong influence of the transfer function on the loudness of partials was found for the low E string. Toward higher strings, this influence seemed to be reduced. Similar trends were found for the V-braced guitars measured here. In Figure 16, the overlaid spectra of 13 plugged tones of the low E and a strings measured at the frontal microphone position are shown. To better compare the spectra with the transfer function of the corresponding guitar, no A-weighting is applied. Figure 17 and Figure 18 show the spectra of plugged notes for the d, g, b and high e string. The loudness over time (ISO 532 B) averaged over all plugged tones was calculated. Similar to the X-braced guitars, no important loudness differences were found. The maximum value of the loudness was 12.8 sone for guitar AaQh and 13.9 sone for guitar AaQl.

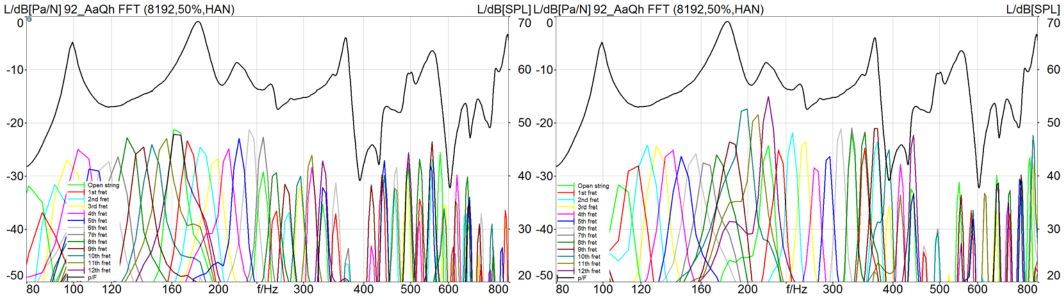

Figure 16 – Overlaid spectrum of 13 tones for the low E string (left) and a string (right). For comparison, the transfer function of the corresponding guitar AaQh is shown.

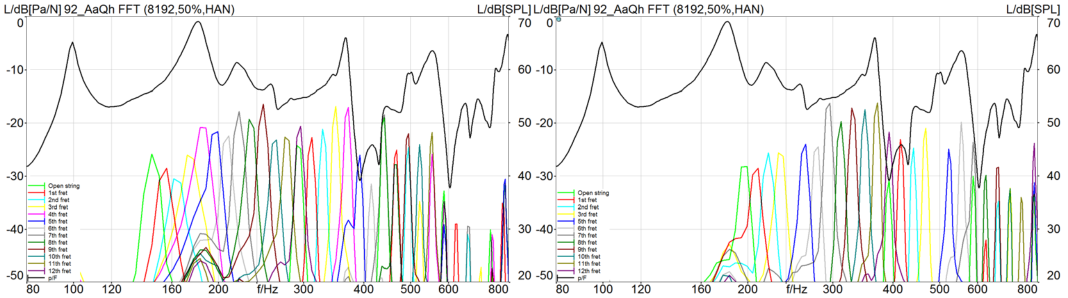

Figure 17 – Overlaid spectrum of 13 tones for the d string (left) and g string (right). For comparison, the transfer function of the corresponding guitar AaQh is shown.

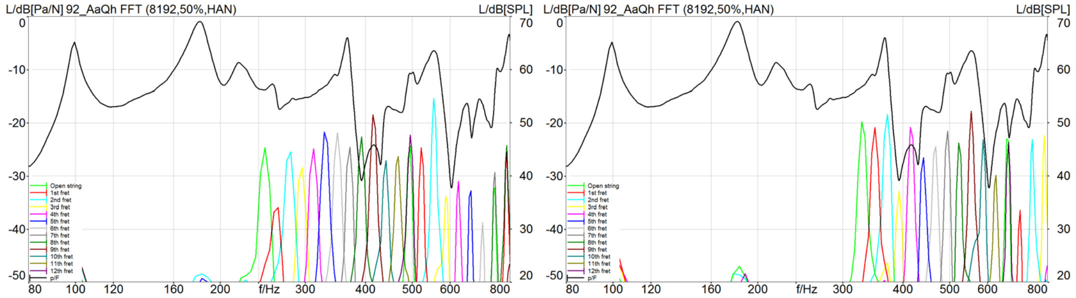

Figure 18 – Overlaid spectrum of 13 tones for the b string (left) and high e string (right). For comparison, the transfer function of the corresponding guitar AaQh is shown.

To analyze the influence of the material damping on the temporal decay of the fundamental and harmonics, a single plugged tone is selected. The note g# on the low E string (4th fret) is used as an example. A schematic illustration of the fundamental and the first seven harmonics is shown in Figure 19. The fundamental for this tone is approximately 104 Hz.

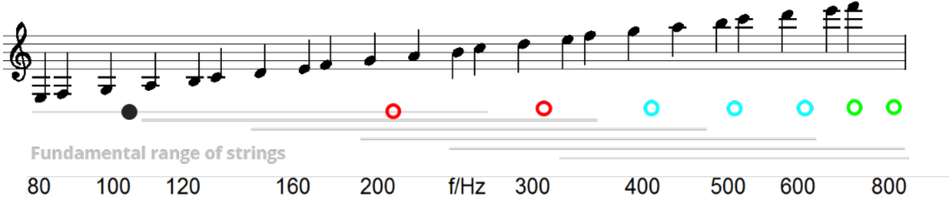

Figure 19 – Schematic illustration of the partial tones for note g# on the low E string. The fundamental is indicated with a black solid circle. Harmonics (open circles) with the same color are within one octave band; this is used for later analysis.

Figure 20 shows a spectrum (top left) and a spectrogram (top right) of this tone recorded with guitar CcQh. The upper limit of the frequency range of the graphs is extended to 5000 Hz because the frequency dependent decay of the higher harmonics might be interesting. A tendency of short decay at low and high frequencies and longer decay in the middle of the frequency range is observable. However, the calculation of frequency dependent tone duration T15 (as introduced in the measurement report for X-braced guitars) is difficult because of the amplitude modulation that can be seen for several partials in the spectrogram. Therefore, the frequency range was divided into octave bands to group neighboring harmonics with the goal of reducing amplitude modulation by averaging multiple partials. The lower row of Figure 20 shows an octave analysis (left) and an octave versus time plot (right) of the recording. The coloring scheme of the octave analysis corresponds to the colors used in Figure 19. The fundamental lies within the black octave band, the first and second harmonic lie within the red octave band and so on.

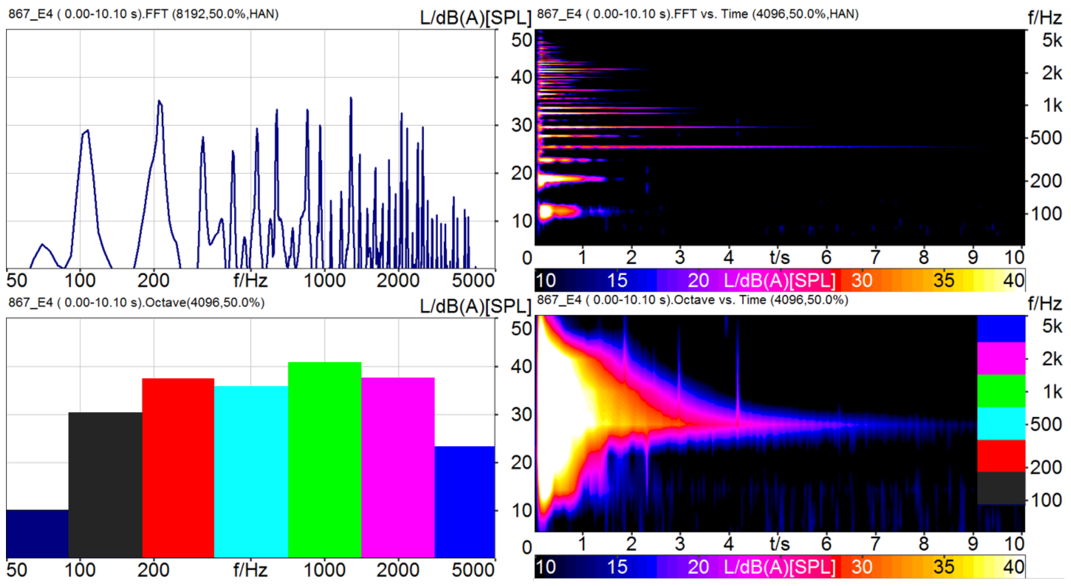

Figure 20 – Plugged tone g# of the low E string of guitar CcQh. Shown is the spectrum (top left), a spectrogram (top right), an octave analysis (bottom left) and an octave versus time plot (bottom right). A-weighting is applied in all cases.

After this octave filtering, the calculation of a frequency dependent tone duration T15 was possible. Figure 21 (right) shows an exemplary plot of sound pressure level over time for each octave band. Additionally, the regression lines for the decay between -5 dB and -20 dB below the maxima are plotted directly into each octave band curve. The goodness of fit for these linear regressions is checked with r^2 values. High r^2 values can be seen in the legend along with the calculated T15 values for each frequency band. The overall tone decay is shown for the original unfiltered plugged note in Figure 21 on the left side, again with a fitted regression curve.

Within the first second, the fast decay in the frequency bands at approximately 250 Hz (red), 1000 Hz (green) and 2000 Hz (pink) dominate the overall decay because of their high amplitudes. Later, the long decay at approximately 500 Hz (turquoise) becomes dominant. This is the reason that the overall level versus time plot (Figure 21, left) shows a nonlinear decay. Therefore, the calculated overall tone duration T15 of 4.7 s is heavily dependent on the fitted decay range (e.g., 15 dB or 30 dB) and should be interpreted with care.

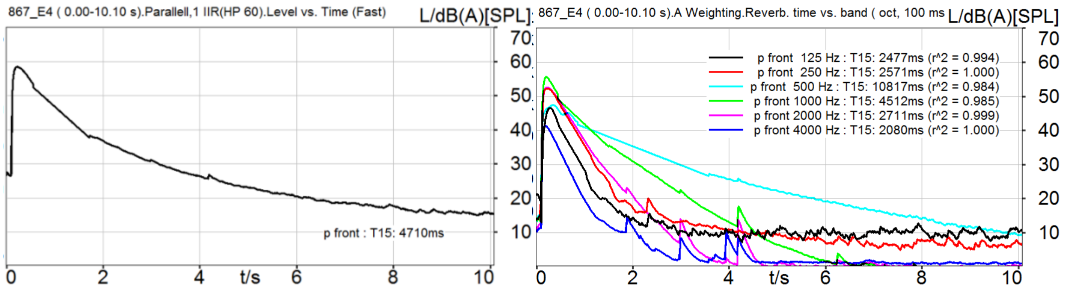

Figure 21 – Plugged tone g# of the low E string of guitar CcQh. Shown is the A-weighted level over time with fitted regression lines to calculate tone duration T15.

Nevertheless, before discussing the influence of Q, the mean tone duration obtained by averaging over all plugged tones where T15 is reliably calculable (strings E, a, d and g) will be used for a coarse comparison between the X- and V-braced guitars. For the X-braced guitars Aa and Cc, averaged T15 values of 8.8 s and 8.9 s were calculated, respectively. For the V-braced guitar AaQh, the mean T15 is 11.2 s and for guitar AaQl the mean T15 is 10.5 s. *This result suggests longer decay for the V-braced design than for the X-braced design.* Additionally, there seems to be a small difference in the decay of the V-braced guitars AaQh and AaQl of the current study. This difference will be discussed in the following.

Figure 22 shows the spectra of the same note as above (g#) stopped on the 4th fret of the low E string for four guitars. Guitars with high Q tops are shown in the top row and guitars with low Q tops are shown in the bottom row. The spectra of guitars CcQh and CcQl are very similar. Some differences can be seen between the harmonics of guitars AaQh and AaQl.

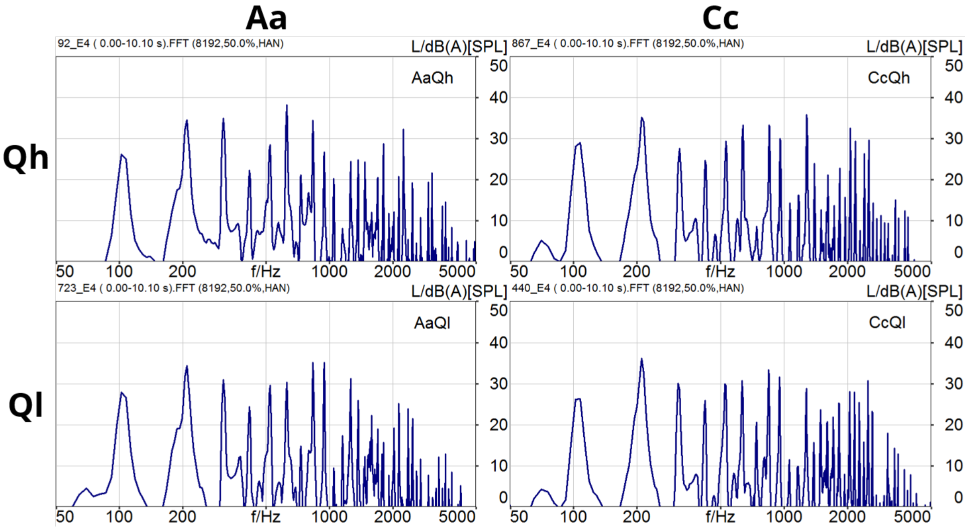

Figure 22 – Spectra of plugged tone g# of the low E string for guitars AaQh (top left), AaQl (bottom left), CcQh (top right) and CcQl (bottom right).

Spectrograms of the same plugged note are shown in Figure 23. For now, the frequency range is restricted to 800 Hz for better comparison with the corresponding transfer functions (averaged over low, mid and high hammer impact position on the bridge) that are plotted on the left side. All guitars have a very short fundamental and first harmonic. This can be explained by the small frequency distance to body resonances. The fundamental of the plugged tone coincides with the coupled air resonance. The first harmonic (at 208 Hz) always lies between the first resonance of the top and (probably) the first resonance of the back, which explains the short decay.

The second harmonic (at 311 Hz) is different. Guitar AaQh (top left) has a very long decay. The same harmonic decays much faster for guitar AaQl (bottom left). Interestingly, no nearby resonances can be seen in the transfer functions. Therefore, it could be hypothesized that the difference in internal damping of the wood between the two guitars can explain the varying decay. Surprisingly, this second harmonic also decays extremely fast for both guitars from group Cc. No correlation of the decay length with Q can be seen for guitars CcQh and CcQl. Figure 24 gives an explanation approach for the phenomenon. In this figure, the transfer functions of all four guitars are plotted if a hammer strikes the bridge at the position where the low E string is connected. In contrast to the averaged transfer functions, small peaks can be seen at approximately 300 Hz. They might belong to the "cross dipole mode" $T_{2,1}$, which is not radiating much sound. However, the resonance seems to have a strong influence on the decay of nearby tone partials. Both guitars CcQh and CcQl have peaks above 300 Hz, which can explain the short decays of the second harmonics at 311 Hz. For guitar AaQl, the peak is at 295 Hz and might still influence the decay. For guitar AaQh, the peak is at 283 Hz and furthest from the partial of the tone. Therefore, the influence of the body resonance on the decay might not exist for this guitar.

The third harmonic (at 415 Hz) coincides with the strong dip in the transfer function. Strong amplitude modulation can be seen for all guitars. Interestingly, the decay of this third harmonic is long for both Cc guitars, which somehow compensates for the short decay of the second harmonic.

In general, the frequency difference of a partial to the next guitar resonance seems to dominate the decay. No dependence of decay length on the internal damping is obvious.

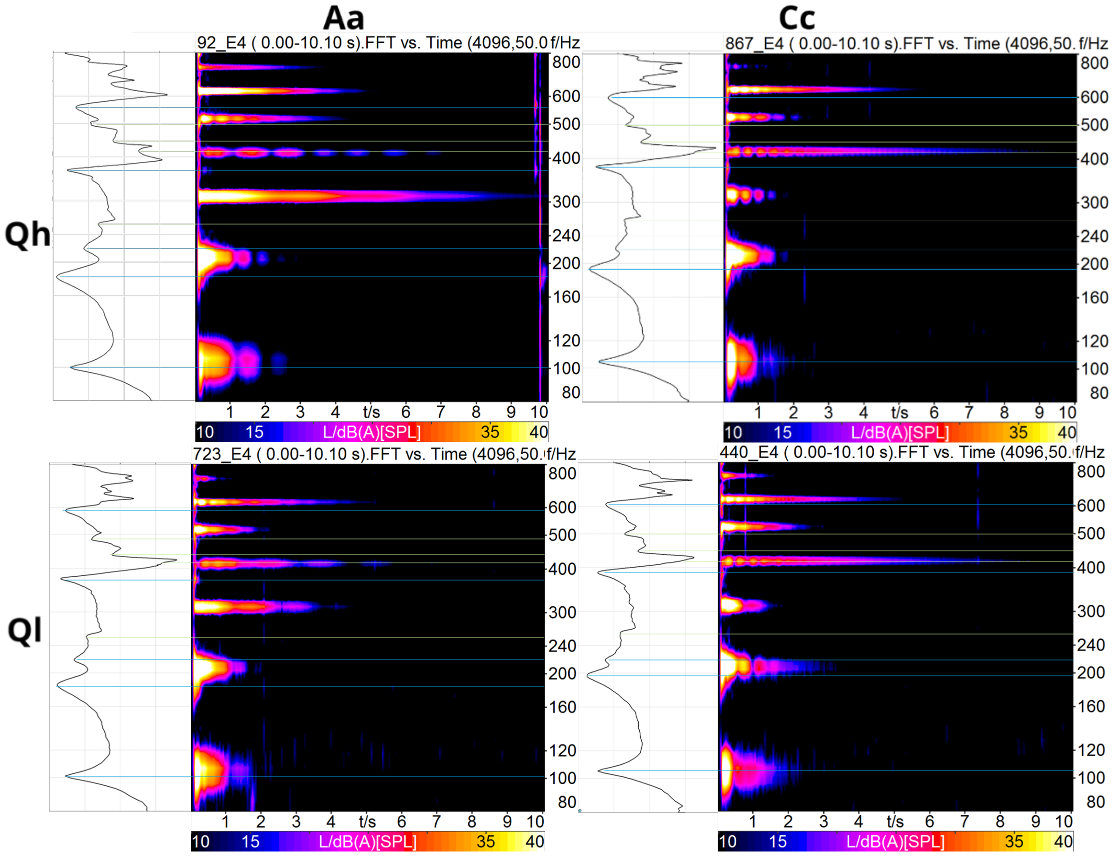

Figure 23 – Spectrograms of plugged tone g# of the low E string for guitars AaQh (top left), AaQl (bottom left), CcQh (top right) and CcQl (bottom right). For comparison, the measured transfer functions are plotted and prominent body resonances are marked.

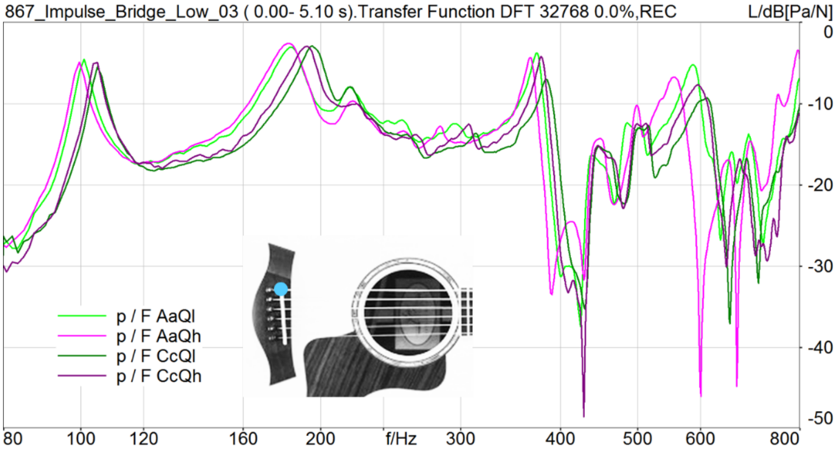

Figure 24 – Transfer function of sound pressure at frontal microphone to force input at the bridge where the low E string is connected.

At frequencies above 800 Hz, as shown in the spectrograms in Figure 25, the decay of all partials looks similar. For better visualization, octave versus time plots are shown in Figure 26. The differences between the guitars are mainly in the 250 Hz, 500 Hz and 1 kHz octave bands.

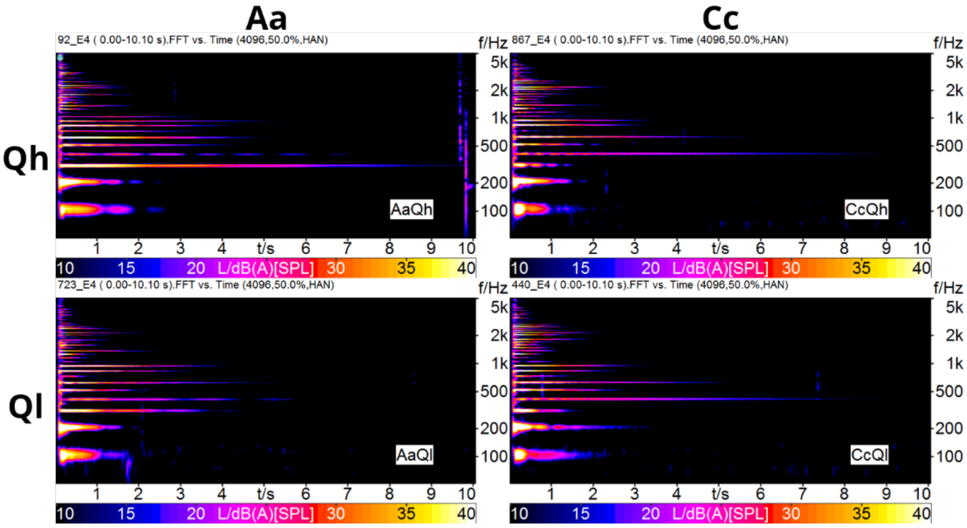

Figure 25 – Spectrograms of plugged tone g# of the low E string.

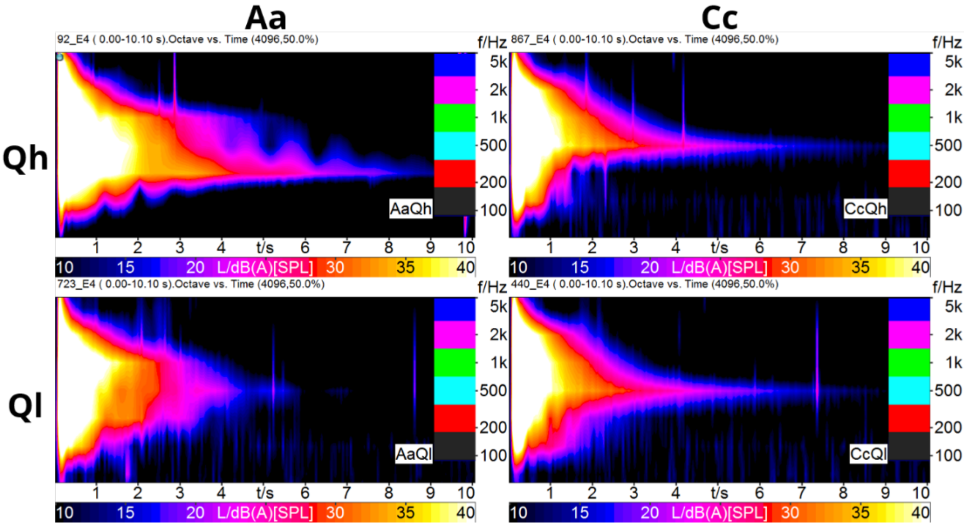

Figure 26 – Octave versus time plot of plugged tone g# of the low E string.

The decay within each octave is plotted as level over time in Figure 27. Regression curves are fitted to calculate T15 values for each frequency band. The high r^2 shown in the legend confirm that the regression lines fit very well with the measured data. However, despite the already discussed effect of varying decay of the second harmonic (at the border between the 250 Hz and 500 Hz octave bands) of guitars from group Aa, no systematic variations of T15 values were found.

For completeness, Figure 28 shows the overall A-weighted level over time for each plugged tone g# of the low E string stopped at the 4th fret. For this tone, guitars from group Aa show a longer decay than guitars from group Cc. The overall decay differences between the two groups with high and low Q can be explained by the frequency position of body resonances as discussed above.

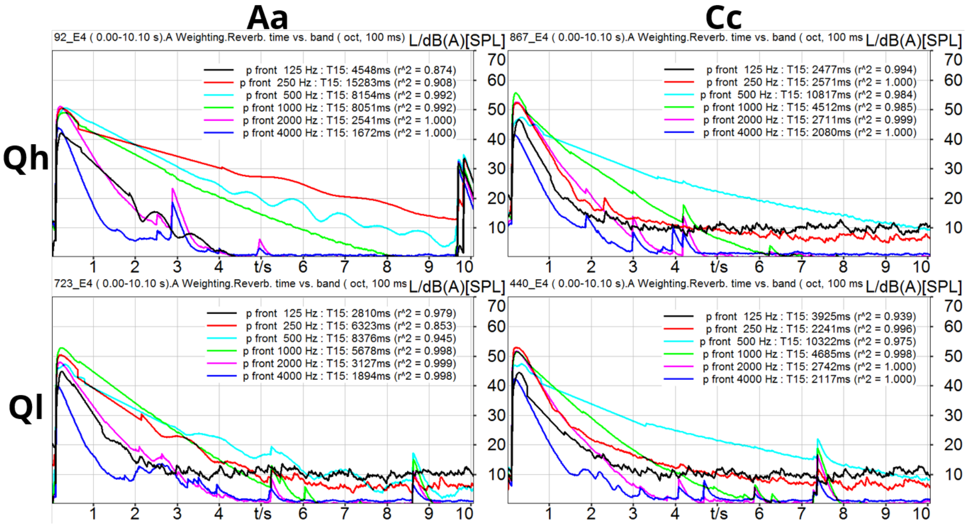

Figure 27 – Octave levels over time of plugged tone g# of the low E string with fitted regression lines to calculate the tone duration T15 for each octave band.

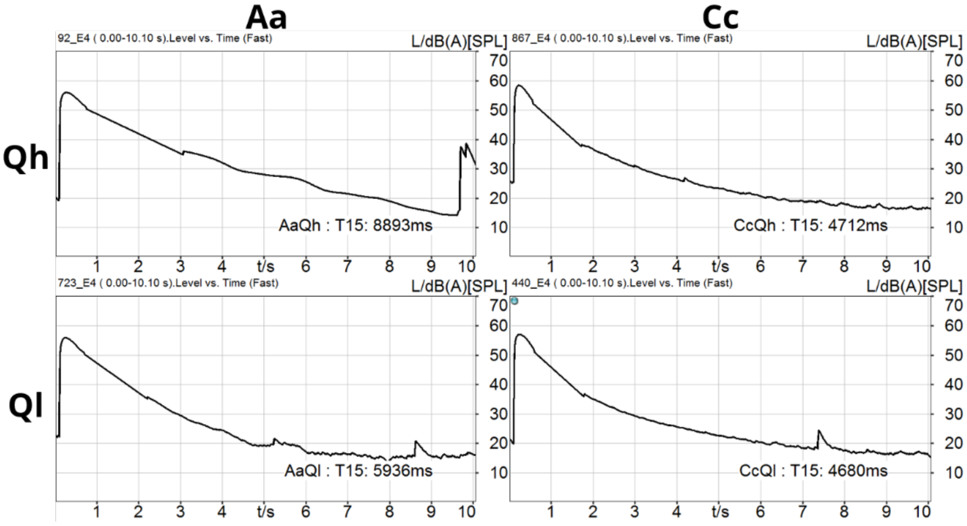

Figure 28 – Level over time plots of plugged tone g# of the low E string with fitted regression lines to calculate tone duration T15.

The above discussion shows that the decay of a single plugged guitar tone and its partials can vary greatly. To compare general trends in the temporal response of one guitar with another, it might be a good idea to average over multiple tones. Therefore, all 13 recorded plugged tones of the low E string (open to the 12th fret) were averaged in the temporal domain. The resulting averaged tone duration T15 of the low E string was calculated as before by fitting a regression line to the decaying curve of the A-weighted sound pressure level. Applying this method to the recordings with guitar AaQh yielded an averaged tone duration T15 for the low E string of 9.1 s (Table 2, top row, last column). For guitar AaQl, a value of 7.9 s (Table 2, second row, last column) was calculated. This is an increase in average tone duration with an increasing quality factor. Interestingly, the same tendency of increasing averaged T15 with increasing Q of the guitar top was found for other strings as well. This can be seen in the last column of Table 2 for strings a, d and g. Positive differences in T15 between guitars AaQh and AaQl are marked with a green color and upward pointing arrows. The values for the b and high e strings are also shown; however, they are not reliable because of strong amplitude modulation.

To discuss a possible frequency dependence of the decay, the averaged tones of each string were analyzed in octave bands. The resulting T15 values are also included in Table 2. The strongest pairwise absolute differences of T15 between high and low Q can be seen in the 500 Hz octave band. Toward higher frequencies the absolute differences of T15 become smaller. Except for a few pairs in the 1000 Hz band, in most frequency bands an increase in decay length for increasing Q can be seen. In conclusion, differences in the decay of plugged notes were found that can have an influence on the preference of guitars.

Table 2 – T15 values calculated for guitars AaQh and AaQl averaged over 13 plugged notes for each string. Positive differences between values for guitars AaQh and AaQl are marked green, and negative differences are marked red.

T15 in s		Center frequency of octave band in Hz					T15 of A-weighted average	
String	**Quality factor Q**	**250**	**500**	**1000**	**2000**	**4000**		
E	**high**	11.3	10.4	7.2	3.3	1.8	9.1	↑
	low	10.9	8.4	5.1	2.9	1.7	7.9	
a	**high**	14.1	11.7	6.1	4.2	2.5	10.2	↑
	low	14.1	9.3	6.9	3.6	2.2	9.2	
d	**high**	13.7	12.7	8.3	4.3	3.4	11.1	↑
	low	13.4	11.1	7.6	3.8	3.2	10.2	
g	**high**	17.9	14.3	5.8	5.3	3.3	13.6	↑
	low	16.2	11.9	6.4	4.3	3.2	12.2	
b	**high**		10.2	6.9	4.3	2.7	9.6	↓
	low		9.6	5.4	4.1	2.9	10.1	
e	**high**		8.4	5.2	3.3	2.6	8.5	↑
	low		7.0	5.7	3.1	2.6	6.7	

5 Summary

The spectral differences between recorded music sequences and measured transfer functions of the analyzed guitars here are small, especially within each group of guitars with soundboards of similar density and stiffness. Spectral differences between the two groups (Aa and Cc) and the resulting differences in tonal balance of the guitars are more pronounced and resulted in more apparent perceptual preferences. No systematic influence of varying wood density and stiffness or damping was found on the overall loudness of the guitars.

A strong influence of the guitar resonances on the decay of tone partials was already discussed for the X-braced guitars and is confirmed here for the V-braced guitars. Even a modal resonance (maybe the "cross dipole mode" $T_{2,1}$), which does not radiate much sound and was therefore not apparent in the transfer function, significantly shortened the decay of a nearby harmonic. Often the interaction of string and body resonances is accompanied by strong amplitude modulation of the corresponding harmonic. Additionally, the overall decay of some plugged tones was found to be nonlinear, which can result from the different decay speeds of their tone partials.

To compare general trends in the temporal behavior of guitars AaQh and AaQl, an averaged tone duration T15 was calculated for the four lower strings. A tendency of increasing T15 values with increasing quality factor was found. However, it cannot be concluded if these differences in tone duration are caused by the relative frequency distances between tone partials and guitar body resonances or if they are due to a decrease in material damping (increase in quality factor).