Evaluation and classification of steel string guitars using bridge admittances

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In this study, 18 nominally identical acoustic guitars coming off the same production line and post-classified by the manufacturer as either *bassy* (i.e., with a more prominent bass response), *mid-even* (i.e., well-rounded and sounding even from string to string) or *treble* (i.e., with a brighter sound that cuts through the band) were investigated. The goal is to find features of the guitar admittance that can help musicians make a more informed instrument selection based on their preferred playing style (e.g., strumming, fingerpicking). We conducted dynamic (input admittance) and acoustical (live recordings) measurements to examine features such as frequency, amplitude and modal damping of the first few structural modes, trend of the band-averaged admittance, harmonic content of the admittance, temporal features of the plucked response, and long-time average spectra (LTAS). These physical properties were investigated independently as well as in conjunction with perceptual assessments by musicians collected during a classification task. Despite very low agreement across guitarists as well as between musicians and the manufacturer, results show that guitars categorized as *bassy* by the manufacturer have a lower frequency for their breathing mode. This is an indicator of the respective guitar bodies having a lower stiffness-to-weight ratio, which may be caused by using thinner plates or plates carved from softer and denser wood. The most common feature of the *treble* guitars was lower averaged mobility in the frequency range of 600 Hz - 2 kHz. This suggests a weaker string-to-body coupling at those frequencies, which may contribute to a longer sustain for higher partials.

1 Introduction

This paper presents the results of a recent study investigating possible correlations between an objective characterization of 18 nominally identical acoustic guitars (model Godin Seagull Maritime SWS) and their perceived classification proposed by the manufacturer. Although the guitars are issued from a modern factory with precise control of the geometry, the manufacturer noted variations of sounding characteristics that we assume to be mostly due to variation of wood properties between the different instruments. In this context, the manufacturer is looking for a way to classify the instruments using an objective measurement and ultimately help musicians choose an appropriate instrument according to their playing style.

The subjective classifications was performed by a single employee at the end of the production line according to three categories: *bassy* (i.e., with a more prominent bass response), *mid-even* (i.e., well-rounded and sounding even from string to string) and *treble* (i.e., with a brighter sound that cuts through the band). A first objective is to find appropriate measurable features allowing to automatically classify the guitars. A second goal is to evaluate the level of agreement among a pool of skilled guitar players with respect to the categories proposed by the manufacturer.

Recent works have investigated the link between measurable features and manufacturing characteristics of string instruments [1, 2]. Among possible choices, the input admittance measured at the bridge is a good candidate as it relates to the ability of the sound board to be displaced and to radiate acoustic energy as a function of frequency. Furthermore it also describes the amount of energy absorbed from the string by the resonator, which ultimately influences the decay rate of the string vibration and consequently the sound sustain. Long-term average spectra (LTAS) offers an alternative approach to the analysis of sound from complex sources such as music instruments by highlighting longer-term aspects of the recorded sound spectrum [3]. Extensively applied to the analysis of voice sounds and singing voice (e.g. [4]), only few study have reported the use of LTAS for the analysis of music instrument sounds [4, 5]. Because it involves more realistic excitation conditions, we also chose to performed LTAS measurements to further explore the acoustic response of the instruments.

2 Methods

2.1 Input admittance

Figure 1: Experimental setup for input admittance measurements.

The guitar was held vertically by mean of a wooden stand holding the guitar ribs by two rigid bars covered with foam, at the level where the body of the instrument is the narrowest as shown in Fig. 1. Input admittance measurements were performed using an impact hammer (PCB Model 086E80) and laser velocimeter (Polytec LDV-100) focused as close as possible to the impact location (between the low E and A strings). The hammer was mounted on a pendulum in order to provide relatively repeatable impacts normal to the surface of the bridge. The strings were damped using a foam clamp fixed between the 9th and 10th frets. The part of the strings above the nut was also damped using a piece of cardboard. Measurements were conducted in a semi-anechoic environment and data acquisition was performed after pre-amplification using a National Instrument interface running at 44.1 kHz. For each guitar, input admittance measurements were averaged over five repetitions, each of which was validated by the operator based on the calculated and displayed coherence. In the low frequency range where the modal overlap factor is low (< 600 Hz), modal fitting was performed using an method developed by Woodhouse [2] and based on the optimization of a pole-residue fitting for the extraction of modal parameters. In addition, a condenser microphone (Bruel & Kjaer 4190-L-001) was placed one meter from the instrument, at the level of the neck to body junction and pointing towards the center of the sound hole, hence allowing a measurement of the radiativity of the instrument.

2.2 LTAS

LTAS were calculated for each guitar from a sequence of 8 strummed chords that excited a wide frequency range. Recordings were performed by a professional guitar player at a tempo of 80 bpm and with a *mezzoforte* dynamic. The microphone (Bruel & Kjaer 4190-L-001) was placed 75 cm from the guitar, facing the sound board between the center of the sound hole and the fingerboard. The LTAS were then computed using the Matlab function `pwelch.m` with a Blackman-Harris window and subsequently smoothed using a constant-Q sliding window with roughly 50% overlap.

3 Results

3.1 Input admittance

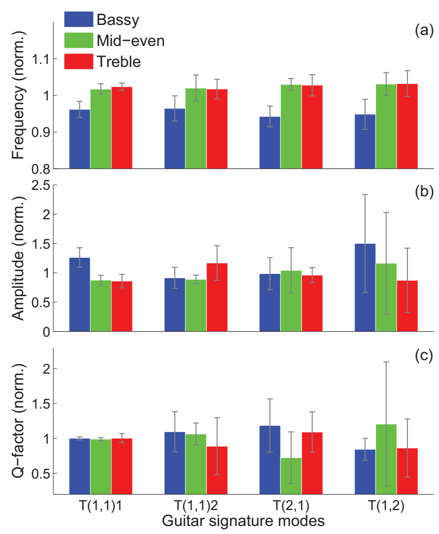

Figure 2: Normalized average frequency (a), amplitude (b), and Q factor (c) for the first four signature modes for *bassy* guitars (blue bars), *mid-even* guitars (green bars), and *treble* guitars (red bars). The error bars show one standard deviation on each side.

As a first estimate of the variability observed within the pool of guitars involved in this study, the standard deviation (STD) of the magnitude of the input admittance calculated across all instruments was calculated and found to be 2.75 dB in the range 70Hz - 6 kHz and at a slightly higher level (3.79 dB) in the 70 Hz - 1 kHz interval. Although these values seem relatively small, they are still in the range of just-noticeable-difference (JND) for human perception [6]. Calculated across each categories, the STD of the admittance in dB is found to be 2.63 dB, 2.36 dB and 2.15 dB in the 70 Hz - 6 kHz range for the *bassy*, *mid-even* and *treble* groups respectively. These values, slightly lower than the STD calculated over all instruments despite an obviously lower number of samples within each category, lend support to the subjective tonal classification proposed by the manufacturer.

Figure 2 presents the normalized average frequency, amplitude and Q-factor of the 4 first "signature" modes extracted from the modal fitting procedure for each tonal category. The frequencies of the four modes are systematically lower for the *bassy* category, while no significant differences are observed between the *mid-even* and *treble* groups. These lower-frequency modes are accompanied by a larger amplitude of $T(1,1)_1$ and T(1,2) for the *bassy* group.

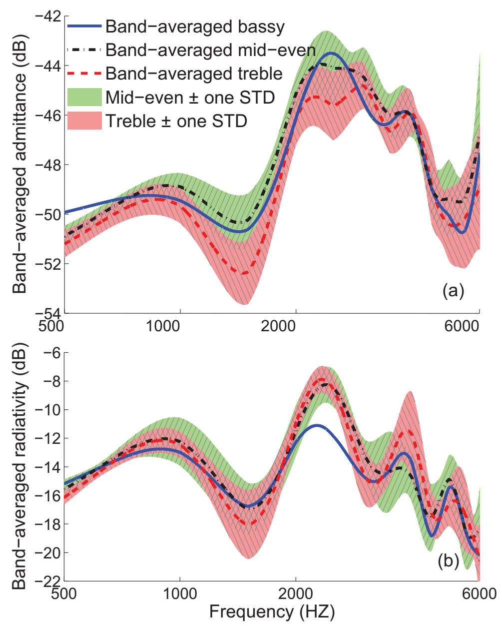

Figure 3: Averaged admittance (a) and radiativity (b) taken over *bassy* instruments (blue solid), *mid-even* instruments (black dash-dot) plus/minus one standard deviation (green shade), and *treble* instruments (red dashed) plus/minus one standard deviation (red shade).

In order to investigate additional differences in the acoustic response of the three perceptual categories, the admittance and radiativity were smoothed in the statistical range (i.e. at higher frequencies) by means of a 500 Hz sliding window and then averaged within each category (Fig. 3). The band-averaged admittance for the *mid-even* instruments is found to be greater than or equal to that of the *treble* instruments over a wide range of frequencies, particularly from 600 Hz to 2 kHz. This further indicates that the mean level of mobility (mean input admittance) in the 600 Hz - 2 kHz range may be a relevant criteria to differentiate between the *mid-even* and *treble* categories. Nevertheless, the band-averaged radiativity does not reveal any significant difference between the categories. However, this result should be interpreted with care as the sound measurements were only performed at a single location, and may thus be significantly influenced by the radiativity pattern of the instrument.

3.2 LTAS

LTAS results averaged over the different categories are presented in Fig. 4a. The sound level in dB produced by *mid-even* instruments is clearly above the sound level of the two other groups at almost all frequencies. When normalizing

LTAS results by their area before further processing, all categories behave quite similarly across frequencies. This further suggests that *mid-even* instruments were simply louder than other instruments rather than emphasizing certain frequency regions.

Although the averaged admittance of *mid-even* instruments is slightly higher than for *treble* instruments (see Fig. 3), linking this observation with the observed louder response of *mid-even* instruments (particularly above 3 kHz) might not be that straight forward. Indeed, it is possible that the *mid-even* instruments were systematically played harder than *treble* guitars as they were played last during the recording session, possibly when the player was most comfortable with the playing task. Another hypothesis is that *mid-even* instruments allowed the performer to play more "freely", as the manufacturer described this category as having a more "stable" sound than the *treble* group.

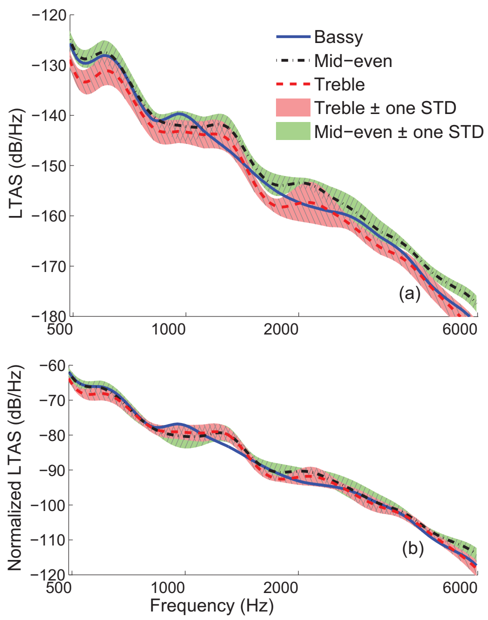

Figure 4: Non-normalized LTAS (a) and normalized LTAS (b) averaged for the guitars of different categories plus/minus one standard deviation (solid blue line for *bassy*, dash-dot black line and green shade for *mid-even*, and dashed red line and red shade for *treble*).

3.3 Classification

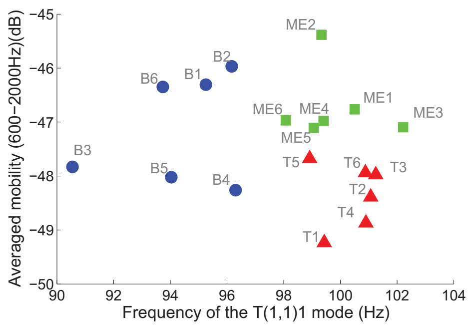

Figure 5: Classification of the acoustic guitars by the frequency of their first signature mode $T(1,1)_1$ and their averaged mobility from 600 Hz to 2 kHz (B = *bassy*, ME = *mid-even*, T = *treble*).

Based on the analysis of input admittance measurements provided in Section 3, a two-dimensional clustering is proposed in Fig. 5 in accordance with the subjective categories, and based on two objective parameters derived from the measurements: the frequency of the $T(1,1)_1$ mode and the average level of mobility in the 600 Hz - 2 kHz region. This 2D classification allows to cluster the three guitar groups in three non-overlapping areas in the 2D space. Furthermore, it should be noted that guitar B3, which presents the lowest breathing mode ($T(1,1)_1$=91 Hz) was classified by the manufacturer as *extra-bassy*, hence further supporting the choice of $T(1,1)_1$ frequency as an indicator of *bassy* instruments.

This shift in the frequency of $T(1,1)_1$ (about 5% lower for *bassy* instruments) may be attributed to the combination of variations in the thickness and/or equivalent stiffness of the sound board compared to the two other groups. Given the tight manufacturing constraints and tolerances in cutting the plates, it is most likely that variations of the equivalent stiffness are primarily responsible for the *bassy* character of these instruments.

Regarding the vertical dimension of the 2D plane shown in Fig. 5, the average mobility in the high frequency region differs between the *mid-even* and *treble* by about 2 dB. This suggests that the weaker admittance of *treble* instruments in the high range contributes to a longer sustain for the higher partials. This may provide a sharper after-sound to the *treble* instruments that is known to allow them to cut through the band more effectively.

4 Perceptual study

In order to investigate the level of agreement among guitar players in classifying the guitars into the categories proposed by the manufacturer, a perceptual experiment was conducted on a pool of guitar players of varying experience and musical background.

This experiment was conducted in a diffuse room with a reverberation time of about 0.3 s and involved thirteen guitar players of at least 6 years of acoustic guitar experience. The experimental session was organized in two phases: In the first phase, participants were presented with the guitars randomly ordered on the floor. They were asked to play all instruments for up to 20 minutes in order to familiarize themselves with the set and use this time to tune the guitars as needed. In the second phase, participants were given up to 20 minutes to classify each of the guitars as either *bassy*, *mid-even* or *treble* by placing them in specially marked areas of the room. Within each class, they were asked to place the guitars they were more confident about on the left and the ones they were less certain about towards the right. At the end of the second phase, participants were given the opportunity to revise their initial judgments if they so wanted, until they were satisfied with their classification. No playing constraints were imposed in terms of repertoire, but the participants were asked to use both strumming-oriented songs (e.g., *Sitting, Waiting, Wishing by Jack Johnson*) and fingerpicking-oriented pieces (e.g., *Dust in the Wind by Kansas*) for the evaluation.

The percentage of times a guitar was classified as either *bassy*, *mid-even* or *treble* is presented in Fig. 6. Although a relatively good agreement with the *bassy* category

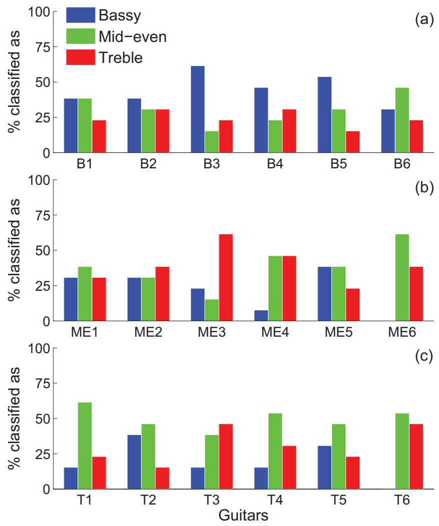

Figure 6: Perceptual evaluation: Proportion of times a guitar was classified into one of the categories by the participants. Guitars are labeled and grouped according to the factory classification (B = *bassy*, ME = *mid-even*, T = *treble*). The color scheme corresponds to the classifications provided by the guitar players.

is observed (the *extra-bassy* guitar B3 was most often classified as *bassy*), the perception of the two other classes significantly differs across musicians. Particularly, many guitars labeled as *treble* by the manufacturer were classified as *mid-even* by the guitar players. This observation, together with the small differences observed from the input admittance of the *mid-even* and *treble* instruments, calls into question the potential relevance of the two latter categories. It further suggests that the guitar players involved in the perceptual experiments are listening to different aspects of the instruments and not necessarily attending to the same features.

5 Conclusions

Various measurable features derived from bridge admittance measurements were investigated in an effort to differentiate 18 steel string guitars from the same production line and postclassified by the manufacturer as either *bassy*, *mid-even* or *treble*. A two-dimensional space (consisting of: 1. the frequency of the breathing mode; and 2. the averaged mobility in the frequency range 600 Hz to 2 kHz) was found to support the classification proposed by the manufacturer. However, while the first dimension (breathing mode frequency) was found to effectively identify *bassy* instruments, differentiations using the second dimension (averaged mobility in the high frequency range) were less robust.

Results from a perceptual experiment showed very low agreement between guitarists in their evaluation, as well as with the classification proposed by the manufacturer. However, despite the overall lack of consensus, guitar players tended to agree more on the *bassy* instruments rather than on the two other categories.

In sum, one can conclude that our attempt to find objective features allowing to predict the tonal characteristics of a group of guitars was relatively successful with respect to the judgment of one player (the employee who classified the guitars at the factory). The issue of generalizing these findings to a larger pool of players is more critical and should be the object of further effort. To this end, different directions may be undertaken: a more careful analysis of the perceptual definition of *mid-even* versus *treble*, an analysis of decay rates of the partials of plucked sounds to see how they correlate with the admittance, an analysis of transients of plucked sounds that may importantly participate to the perceptual evaluation of the guitars, and their relation to the measured input admittance.

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