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Evaluation of Guitars and Violins Made using Alternative Woods through Mobility Measurements

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The feasibility of substituting the types of wood usually employed in the making of guitars and violins was analyzed, but without comparing the properties of involved materials as it is often reported; in this work, the vibrational behavior of twelve guitars and three violins built with alternative types of woods was compared to data of classical instruments available in the literature. In the guitars here measured, the back plate and ribs were not made from traditional woods; while in the violins, only the top plate was made from an alternative type of wood. The results showed that changing the wood of back plate and ribs does not radically affect the typical mobility of a guitar; however, the expected mobility for a violin was not clearly obtained substituting the wood of the top plate. Thus it seems feasible to substitute the wood of back plate and ribs in guitars without causing dramatic changes in their performance; in contrast, a change of the wood type for top plate in violins seems inadvisable unless the design of the top plate is modified to compensate the differences between the woods.

Keywords: mobility, violin, guitar, luthier, Stradivari.

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1. Introduction

The woods used to build string instruments are pre-established, and it is uncommon for makers to take the risk of trying the use of alternative woods. Traditionally, violins are built using spruce for the top plate and maple for the back plate and ribs; while guitar top plates are also built with spruce (Wegst, 2006), and there is historical evidence that Brazilian rosewood is suitable to build their back plates and ribs (Yano *et al.*, 1997). Unfortunately, these woods are in short supply and expensive.

Some papers have been focused on studying alternative materials for the making of musical instruments; e.g. (Sedik *et al.*, 2010; Yano *et al.*, 1997; Orduña, Quintanar Isaías, 1992) analyzed the behavior of other woods, while (Holz, 1979) employed synthetic materials. Typically, in this kind of studies some properties of the analyzed materials are compared to those of the traditional woods because the acoustical behavior can be estimated from the density ρ, and the propagation velocity c (both related in the *sound radiation coefficient* $R = c/\rho$), as well as knowing the damping coefficient of the materials (Wegst, 2006). Exceptionally, the work of Yano *et al.* (1997) includes construction of a guitar with a substitute material instead of Brazilian rosewood; however, no measurements of the finished guitar were reported beyond informal comments of musicians and guitar makers.

Comparing the vibrational response of musical instruments made of alternative woods against other ones built using the traditional woods could help to evaluate, objectively, the performance achieved by the instruments constructed with the alternative woods. Such comparisons should be viable, considering that there are many studies on the vibrational response of classical guitars and violins, both in books (Fletcher, Rossing, 1991; Rossing, 2010) and in papers (Hill *et al.*, 2004; Jansson, 2004; Bissinger, Gregorian, 2003; Roberts, Rossing, 1998).

In fact, vibrational measurements of slightly different stringed instruments have been compared in some cases; e.g. Skrodzka *et al.* (2009) compared two identical violins but with a difference of 0.5 mm of thickness in the back plate; and later Skrodzka *et al.* (2013) analyzed two replicas of a Guarneri violin built by a professional violin maker but using different varnishes. Moreover, measurements on guitars with different design have been compared (Skrodzka *et al.*, 2005; 2011). Unfortunately, finding evaluations of the performance of stringed instruments built of alternative woods is a hard task.

Waltham (2009) reported the response of a violin constructed with balsa wood compared with the response of a factory violin; however, he clearly stated that his aim was only for educational purposes but not for evaluating the performance of the balsa violin, which is obvious because Balsa wood is too light (Wegst, 2006) to obtain a functional violin.

For these reasons, in the present work the mobility was measured on fifteen musical instruments built of alternative woods: twelve guitars and three violins. The data obtained for the guitars were compared against experimental data of a typical classical guitar (Hill *et al.*, 2004), while the violin data were compared with those of a Stradivari violin (Jansson, 2004).

2. The instruments

The construction specifications for the fifteen instruments tested in this work are shown in detail in Table 1. The names assigned to the three violins begin with “v” followed by the number of internal control of the Violin Making School of Mexico, while the names assigned to the twelve guitars begin with “g” followed by the first three letters of the common name of the alternative wood used for their construction. The employed woods are listed in Table 1 by their common name and, in parentheses, their scientific name. The woods produced in Mexico are identified by an asterisk.

The dimensions of the violin known as *Mediceo*, built by Antonio Stradivari in 1716, were strictly followed for the construction of the three violins; but each violin was built by a different student of the Violin Making School, in different years. The twelve guitars tested in this work were built by the renowned Mexican guitar maker Abel García with the aid of his brother Benjamín, as part of a project to test Mexican woods in guitar making (García, 2010). As a basis for the design of the twelve guitars, Abel chose the shape of a historical guitar built by the German guitar maker Hermann Hauser in 1927, which is part of the collection of the acclaimed guitarist Pepe Romero.

Table 1. Specifications of the measured instruments. Names started with ‘v’ indicate violin, while ‘g’ indicates guitar. All the alternative woods are Mexicans and they are marked with *. The scientific name of each wood is given using parenthesis.

Name	Weight [g]	Wood for back and ribs	Wood for soundboard
v247	441	Hard maple (*Acer sp*)	Oyamel (*Abies religiosa*)*
v133	460	Hard maple (*Acer sp*)	Oyamel (*Abies religiosa*)*
v004	460	Hard maple (*Acer sp*)	Oyamel (*Abies religiosa*)*
gNog	1358	Nogal (*Juglans pyriformis Lieb*)*	Western red cedar (*Thuja plicata*)
gHay	1402	Haya (*Fagus mexicana*)*	Western red cedar (*Thuja plicata*)
gCue	1588	Cueramo (*Cordia eleagnoides DC*)*	Western red cedar (*Thuja plicata*)
gGra	1594	Granadillo (*Platymiscium lasciocarpum Sandw*)*	Western red cedar (*Thuja plicata*)
gBal	1628	Bálsamo (*Myroxylon balsamum L Harms*)*	Western red cedar (*Thuja plicata*)
gCam	1639	Campincerán (*Platymiscium lasciocarpum Sandw*)*	Western red cedar (*Thuja plicata*)
gCed	1368	Cedro Blanco (*Cupressus lindleyi*)*	Spruce (*Picea abies*)
gPal	1402	Palo escrito (*Dalbergia paloescrito*)*	Spruce (*Picea abies*)
gMor	1442	Mora (*Morus sp*)*	Spruce (*Picea abies*)
gZop	1467	Zopilote (*Dalbergia granadillo Pittier*)*	Spruce (*Picea abies*)
gSir	1493	Siricote (*Cordia dodecandra DC.*)*	Spruce (*Picea abies*)
gMam	1520	Mamey (*Dalbergia paloescrito*)*	Spruce (*Picea abies*)

3. Mobility of stringed instruments

Modal testing techniques have been effectively applied to analyze the vibrational behavior of guitars and violins (Rossing, 2010), because their responses have been shown to be proportional to excitation, e.g. see (Skrodzka *et al.*, 2009). In other words, guitars and violins can be considered as linear systems, which is the main requirement to perform these techniques.

One of these modal testing techniques, the mobility, was used to evaluate the fifteen instruments of this work. Mobility is a transfer function (Ewins, 1984), in which a proportional relationship between an input signal and an output signal is represented using two linked plots: magnitude and phase, or real and imaginary part.

A force driving a single point of the instrument is measured as input signal, while the structural velocity (measured in the same driving point or any other) is taken as an output signal. The reason to choose the velocity as output signal (instead of displacement or acceleration) is that the sound pressure radiated by the instrument will be nearly proportional to its structural velocity (Fletcher, Rossing, 1991). If the driving force and the structural velocity are measured at the same point, the obtained measurement is called *point* mobility; if both signals are measured in different points, the obtained response is called *transfer* mobility. Usually the force is applied and measured on the bridge, while the velocity is also measured on the bridge; this part of the instrument is chosen because the vibrational energy of the strings is transferred to the soundbox via the bridge.

Then, the mobility measured at the bridge (given as the ratio of velocity per unit of force) allows having a good estimation of the sound radiated by guitars and violins. For both instruments, the magnitude of the mobility exhibits several peaks (corresponding to resonances when the phase plot goes to zero), and several valleys that show antirresonances. For practical purposes, the mobility measured on each instrument will be unrepeatable in another.

However, a proof that an experimental guitar *works* as a typical guitar is that its mobility is similar to the mobility of other guitars; likewise, the mobility of one instrument which *works* as a violin must be similar to the mobility of other violins. With that in mind, reported mobilities by other authors (Hill *et al.*, 2004; Jansson, 2004) were used to evaluate the behavior of the guitars and the violins measured in this work.

3.1. Guitar mobility

The dotted lines of Fig. 2 and Fig. 3 show the magnitude and phase of the point mobility of a classical guitar, which were carefully digitized from the experimental data of Fig. 6 of the paper of Hill *et al.* (2004); they identified this guitar as BR2 and in the present work it also will be referred on this way. It is worth mentioning that magnitudes are here plotted using the same scale that will be imposed for the violins (dB referred to 0.04 s/kg).

The shape of the mobility of BR2 is typical of a classical guitar. In Fig. 2, the mobility of BR2 starts with three low-frequency resonances labeled by Hill *et al.* (2004) as $T(1,1)_1, T(1,1)_2, T(2,1)$. These resonances are also known as *air-pumping modes*, and they are caused by the interaction between the top plate, the back plate, and the enclosed air inside the soundbox. Although the three resonant frequencies and their amplitudes do change slightly from one guitar to another, classical guitars tend to show the air-pumping modes (Hill *et al.*, 2004). For example, these modes can be also detected in the measurements reported by Skrodzka *et al.* (2011), even using different mounting settings to obtain the responses.

Once that the frequency increases beyond 300 Hz, guitar resonances have few hertz of difference and these are mixed; then, the mobility will show particular details for each guitar in the middle-high frequency range. The whole soundbox causes the radiated sound by the instrument, although it is already known that the main radiator in high frequencies is the top plate (Fletcher, Rossing, 1991).

3.2. Violin mobility

Magnitude and phase of a transfer mobility of a 1709 Stradivari violin are included with a dotted line in Fig. 4, which were digitized from the measurements published in Fig. 3 on the paper of Jansson (2004). These data can be considered as a typical mobility of a high quality violin. In comparison with guitar studies, analysis of violin mobility has been more detailed by far.

Still, there is no agreement to label the violin resonances, but the different nomenclatures refer to the same behaviors systematically detected in several violins. In Fig. 4 (of the present paper) appears the four lowest resonances of acoustical relevance for the violin, called *signature modes* (Bissinger, Gregorian, 2003), which are conformed by one resonance with the f-holes as the main radiator (A0); followed by three resonances of the body (C1, C2 and C3). More details about these low modes of a violin can be easily found in literature, e.g. (Skrodzka *et al.*, 2013).

Another strong resonance has been detected in several violins slightly below 1.1 kHz, which has been linked to lateral movement of the enclosed air; for this reason, Roberts and Rossing (1998) labeled this resonance as A3 (while other authors call it *A-formant*). Also, in good violins, the violin mobility ends with a resonance cumulus causing a broad peak in the magnitude plot centered between 2 and 3 kHz; this cumulus is called *bridge hill* (Jansson, 2004), which is characterized also by a dramatic decrease in the phase plot. Finally, it is noteworthy that the maximum amplitudes of the magnitude plot of a good violin usually occur for signature modes and/or bridge hill, but not for A3.

4. Experimental set-up

Figure 1 shows details of the experimental set-up used here for the mobility measurements of the instruments. These experiments are based on typical settings applied in specific reports of the literature; with the aim to compare the measurements here obtained against those reports in the same frequency ranges. The procedure to measure the twelve guitars is based in the settings reported by Hill*et al.* (2004); for the three violins, the experimental set-up is similar to the typical measurement proposed by Jansson (2004).

Fig. 1. Experimental set-up.

The mobilities were obtained using a dual IEPE channel spectrum analyzer. First, a pendulum was made to impinge on the bridge on the musical instrument and the impact was measured using a IEPE force transducer with an attached polymer tip (Fig. 1 right). An increase in the signal of this transducer, caused by the impact, triggered the capture on both channels during an instant. The vibration of the structure was measured through an ultra-miniature (0.4 g) IEPE accelerometer attached with wax, and its signal was digitally integrated to calculate the velocity. Each mobility was obtained averaging sixteen impacts, although the first four or five hits were enough to clean the obtained plots from noise.

Each guitar was vertically suspended from the neck, fastened with a rubber band. A soft fabric was placed under the instrument, and the six strings were damped using a piece of fabric fastened to the fretboard (Fig. 1 left). Point mobility in the bridge was measured in a direction perpendicular to the plane of the top plate, close to the first string E4. The frequency span of the obtained spectrum ranged from 70 Hz to 2 kHz, spaced by 5 Hz of resolution.

The mounting settings to test the violins was slightly different from the one used for the guitars. Figure 1 (right) shows one of the violins (v133) mounted on a structure built for this application. The instrument rested horizontally on two low impedance supports: one under the end button and other one under the button on the back. The strings were damped inserting a card between them without touching the fretboard, to avoid interfering with the vibrations of this part of the violin.

The experiment was designed in such a way that the excitation of the instrument was in the same direction as the vibrating force exerted by the strings on the bridge as they are bowed. To this end, a 12-cm pendulum was used to hit the violin bridge. The rotation axis of the pendulum was located over the violin contour, at an adequate height to allow hitting the G-string corner of the bridge. The velocity was sensed at the other side of the bridge, in the E-string corner. For the case of the violins, the frequency span reached 5 kHz with 12.5 Hz of resolution.

It is worth mentioning that when the weight and mobility were measured on the instruments, the value of relative humidity of the air was constantly monitored and it remained at 41% ± 1% for the guitars, and 51% ± 1% for the violins. Therefore, it appears unimportant the variations caused by the influence of this relative humidity on the measured mobilities (Torres *et al.*, 2014).

5. Obtained guitar mobilities

The mobilities of the six guitars with top plates made from western red cedar are shown in Fig. 2, and the corresponding data for the other six guitars, with spruce top plates, are plotted in Fig. 3. BR2 mobility (dotted line) remained unaltered for ordinate values, i.e. the y-scale has the same values as in (Hill *et al.*, 2004); but in order to avoid curves saturation, the graphs of each guitar were sorted by steps of 30 dB for magnitude plots as well as each 200° for the corresponding phase. With the aim to facilitate the comparison of the frequencies of air-pumping modes, thin vertical lines corresponding to 100 and 200 Hz were elongated.

The order of appearance of the mobilities was sorted by the weight of each guitar, starting with the lightest guitars and ending with the heaviest guitars at the bottom of the graph. Considering that the same kind of top plate was employed for each set of six guitars, the difference in weights between guitars of the same set can be mainly attributed to the difference in the wood of back plate and ribs.

The lightest and the heaviest guitar of the twelve are found in the set of Fig. 2, gNog and gCam respectively. It seems that frequencies of air-pumping modes resulted proportional to the total weight of the guitars: on one hand, these modes in gNog seem to be slightly moved to the left with respect to BR2; on the

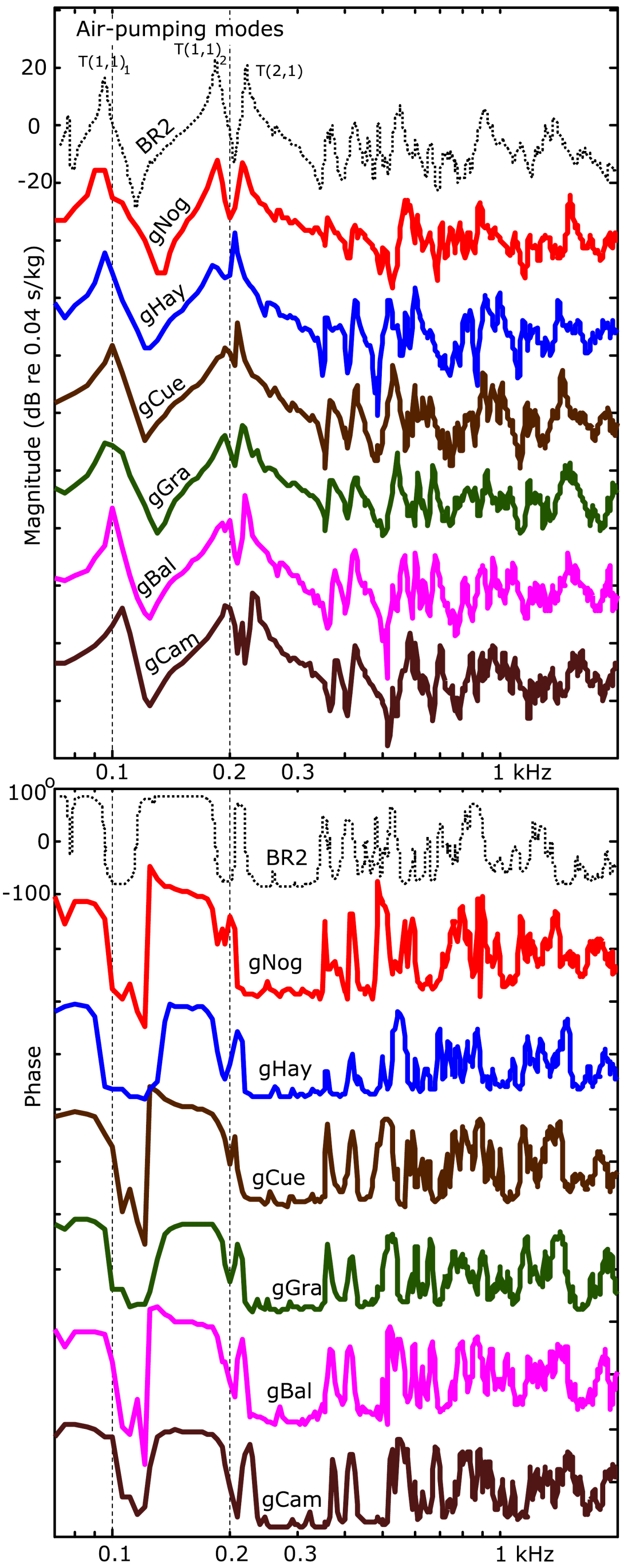

Fig. 2. Bridge mobility of six guitars with top plate of *western red cedar*. Responses were sorted according to the weight of each instrument (see Table 1) in steps of 30 dB in magnitude and 200° in phase. Data of the reference guitar BR2 (Hill *et al.*, 2004) are also included using dotted line, preserving the true values.

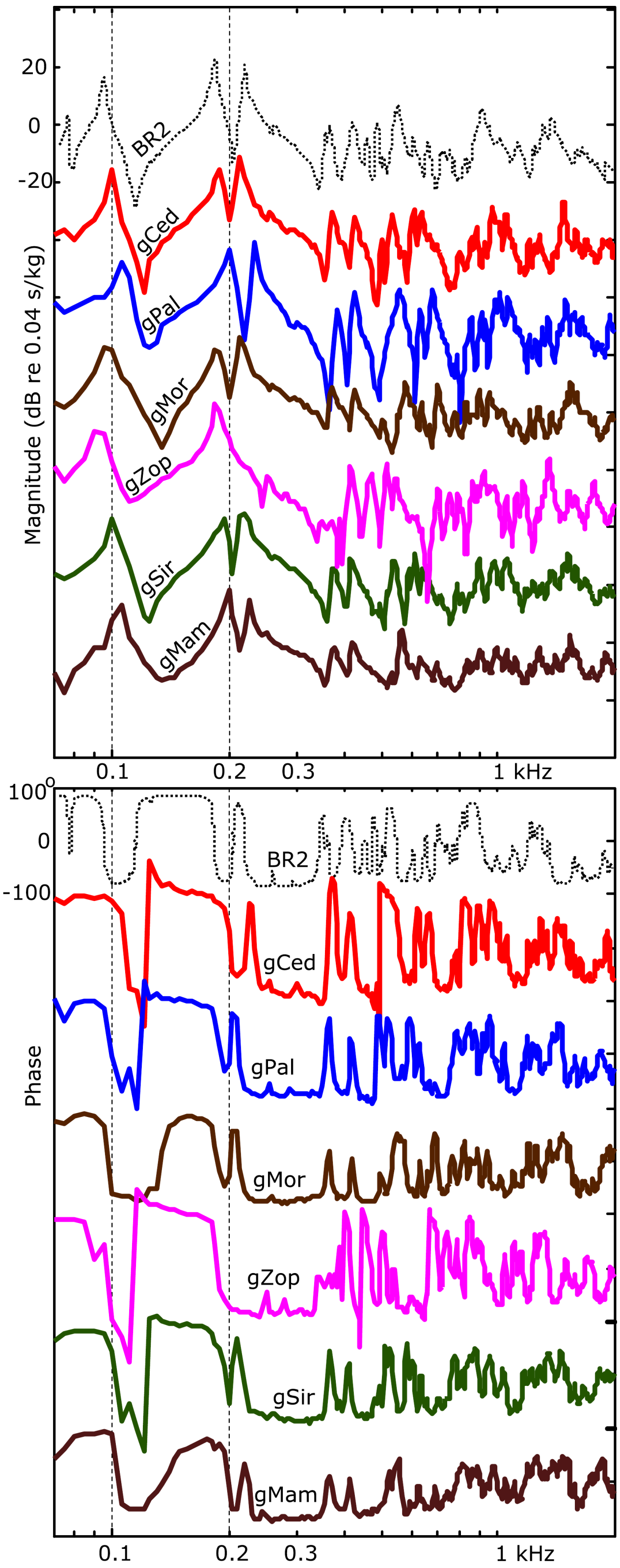

Fig. 3. Bridge mobility of six guitars with top plate of *spruce*. Responses were sorted according to the weight of each instrument (see Table 1) in steps of 30 dB in magnitude and 200° in phase. Data of the reference guitar BR2 (Hill *et al.*, 2004) are also included using dotted line, preserving the true values.

other hand, the graphs of gCam seem to be markedly moved to the right with respect to BR2. Even when the weight difference between guitars was small, as in the case of gGra and gCue (only 6 g of difference), the frequencies of air-pumping modes are very close too.

Certainly, the data for the other six guitars plotted in Fig. 3 exhibited features similar to the ones discussed for the previous set (specifically, the lightest guitar of this set, gCed, has air-pumping modes of lower frequencies than the heaviest guitar, gMam). However, the behavior of the other four guitars of this set does not allow to identify any trend concerning the air-pumping modes.

Nonetheless, it is clear that typical air-pumping modes were present in almost all the twelve guitars (only T(2,1) in gZop was not detected); also, when the mobility of any of the twelve guitars was analyzed for frequencies beyond 300 Hz, substantial consequences of using alternative woods for back plate and ribs on the twelve guitars were not detectable. The resemblance of mobilities of some of these guitars to BR2 mobility is remarkable (e.g. see gMor for both magnitude and phase). Thus, in general, the typical vibrational behavior of a guitar can be obtained using alternative wood in back plate and ribs. In fact, the twelve guitars have been subjectively judged by renowned musicians, including Pepe Romero, as instruments of high quality (García, 2010).

6. Obtained violin mobilities

In contrast to what we observed for the guitars, using a different type of wood as substitute for spruce for the top plate of violins brings about noticeable vibrational differences, even using a type of wood with a considerable high value for the sound radiation coefficient R, considering that R_{spruce} falls from 12 to 16 (Wegst, 2006) and $R_{\text{oyamel}} \approx 16$. Figure 4 shows the mobility of the three violins tested in this work (continuous lines) intentionally stepped by 30 dB in magnitude and 200° in phase; the mobility of a 1709 Stradivari violin (dotted lines) was also included preserving the true values reported by Jansson (2004).

Signature modes and A3 are clearly identified in the mobilities of the violins made using oyamel wood, at least more clearly than in the mobility of the balsa violin reported by Waltham (2009) (here not shown); to a lesser extent, bridge hill can be also detected. The mobilities of the three oyamel violins are quite similar between them, implying good repeatability in the construction process; however, a detailed analysis reveals significant differences when they are compared with the plots of the Stradivari violin.

The only resonance of similar frequency in the four violins was A0 (see elongated line at 300 Hz as reference), although this is not surprising considering that this frequency majorly depends on the dimensions of

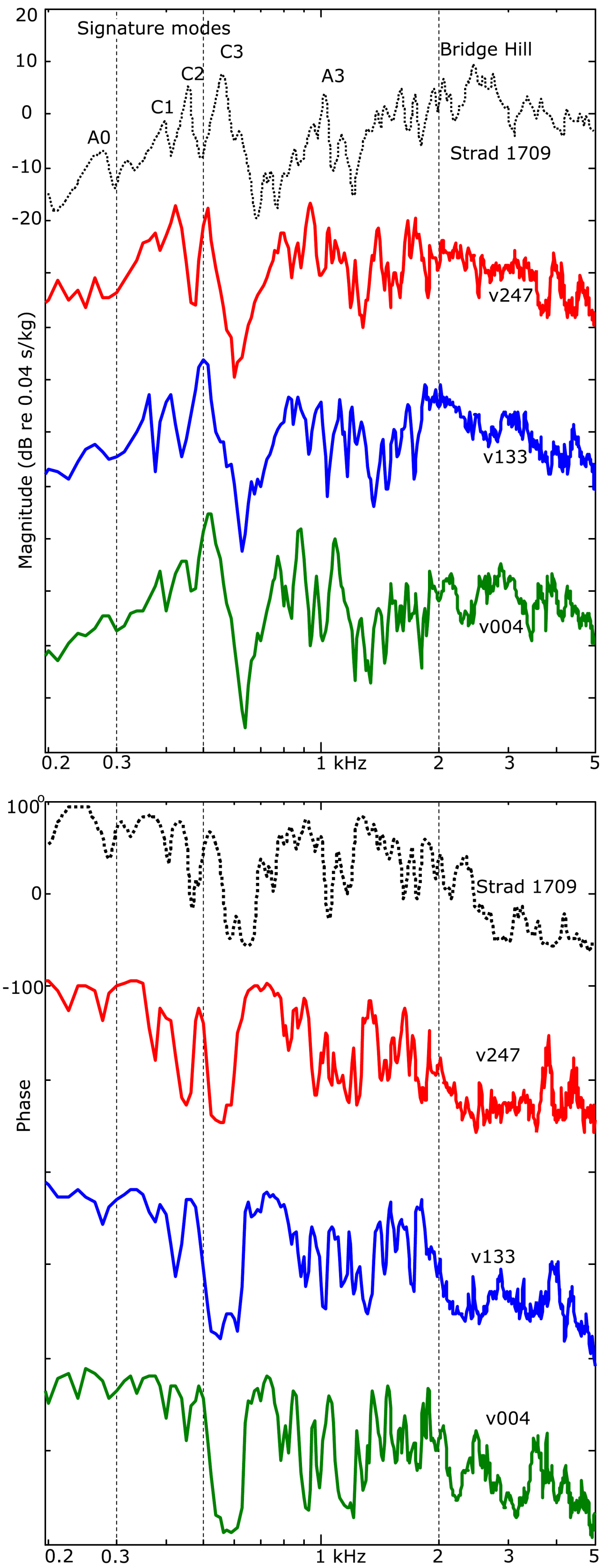

Fig. 4. Bridge mobility of four violins. Continuous lines: oyamel violins. Dotted line: 1709 Stradivari violin (Jansson, 2004) preserving the true values (the other plots are offset towards down in steps of 30 dB in magnitude and 200° in phase).

the enclosed air and of the f-holes. Conversely, for higher frequencies, where the wood behavior is crucial, mobilities of oyamel violins seem to be displaced towards the left in comparison with Strad data. For example C1, C2 and C3 appeared at lower frequencies for the oyamel violins, but A3 and bridge hill (see phase shift) had lower frequency values too. Once signature modes were found to exhibit lower frequencies, it was reasonable to expect lower frequencies in higher modes; but it was here highlighted because finding papers reporting a group of violin responses clearly showing this feature had been a hard task.

Some undesirable features were found when amplitudes of peaks and valleys were analyzed in the magnitude curves of the oyamel violins. The amplitudes for A3 are abnormally higher than their corresponding bridge hill or signature-mode amplitudes (especially for v247); even the bridge hill for v004 had the lowest amplitudes of the curve. Moreover, the valley between C3 and A3 seemed too deep in the three oyamel violins.

Thus, it is clear that the vibrational response of a violin built using an alternative wood for the top plate will tend to be noticeably different from the response of a typical violin. Nevertheless, it may be feasible to adjust the design of the violin built with an alternative wood to improve its vibrational response, though this last topic is beyond the scope of the present work.

7. Conclusions

Research about alternative materials to make stringed instruments, which are typically built using woods in short supply and expensive, used to be focused on analyzing bulk properties of the proposed materials. However, research about the performance of alternative materials evaluated on a *finished* instrument was hard to find (if any). With the present paper, an evaluation of guitars and violins made from alternative woods is now available, comparing their mobilities against the typical data of a classical guitar and a Stradivari violin.

The use of alternative woods for back plate and ribs of a guitar does not cause considerable variations in the middle and high-frequency ranges of its vibratory response, according to our evaluation of twelve guitars. Thus, this work factually shows that substituting materials in back plate and ribs of the guitar does not compromise the quality of the finished instrument. This is encouraging because the guitarists (who are the final consumers) are hard to convince to trust instruments not built in the traditional way.

In contrast, the evaluation of the three violins with top plates made from oyamel wood revealed noticeable differences in comparison with the response of a traditional violin. This implies that substituting the spruce of the violin top plate by another kind of wood is not advisable, at least at a first look. Nevertheless, changes in the design of a top plate of an alternative wood type could be tried in order to approach a desirable vibrational behavior of the finished violin; and this would be a topic of interest for future work.

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