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VIBRATION ANALYSIS OF A PROTOTYPE GUITAR WITH A DOUBLE PLATE SOUNDBOARD COUPLED BY A SOUNDPOST

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RESUMEN

La guitarra es un instrumento musical que produce su sonido a través de la vibración de sus cuerdas, que es amplificada por la caja de resonancia. Parte de esta vibración se transmite a la tapa superior a través del puente, aunque no contribuye excesivamente a esta producción de sonido. A pesar de que, a lo largo de los años, los lutieres han experimentado con diferentes diseños para mejorar sus cualidades sonoras, en comparación con otros instrumentos de la familia de los cordófonos, se puede observar que la guitarra presenta un poder de radiación relativamente débil. A partir de las ideas de un lutier y guitarrista (PVC), se presenta una posible solución a este problema que consiste en dividir la tapa superior de la caja de resonancia en dos tapas de diferentes tamaños que interactuarían dinámicamente mediante la acción de un alma. En este trabajo exploramos esta idea. Se realizan medidas de vibración de ésta nueva guitarra, tanto sin alma como con alma, y se compara con el comportamiento de la guitarra clásica usual.

ABSTRACT

The guitar is a stringed instrument that radiates sound through the vibratory motions of its body and the air inside the cavity. Over the years, luthiers have experimented with different designs to improve its sound qualities but musicians still commonly complain about the rather weak radiation of the instrument. Stemming from the shared ideas of a luthier and a guitar player (PVC), a potential solution to this issue would consist of splitting the soundboard into two plates of different sizes that would dynamically interact through the action of a soundpost. In this work, we explore this idea. Experimental modal analysis of a prototype guitar is pursued, focusing on both configurations, i.e. with and without the soundpost, in order to shed light on the singularities of its dynamical behaviour with comparison to conventional classical guitars.

Keywords: guitar, split-soundboard, soundpost, experimental modal analysis, music acoustic.

1. INTRODUCTION

The guitar is a musical instrument that produces sound by plucking strings that are structurally coupled to the instrument body for efficient radiation [1]. This occurs via the bridge that receives the string vibrational energy and in turns excite the soundboard and the other components parts. When comparing the acoustic properties of guitars to instruments from the violin family, it becomes evident that guitars produce only a rather small amount of sound. Aside a number of subjective factors [2], this lack of radiation efficiency is certainly the results of a combination of complex physical factors including namely the shapes of the body modes or their small number in the high frequency range [3]. The choice of a particular bracing in the top plate as well as the existence of other internal reinforcements such as the waist bar [4] localize the whole vibration to specific areas of the soundboard and could thus reduce the effective radiating surface drastically. To overcome this issue, we study here the vibrational behaviour of a new soundboard design proposed by a luthier and a guitarist (PVC). This design involves to split the top plate into two plates of different sizes that interact dynamically through the action of a soundpost, as found in the violin. It is important to note that the soundpost is *not* inserted between the top and back plates as in [5] but that the top plate is here divided into two parts connected by the soundpost. This arrangement would allow to distribute the string energy into two different top plates, with different mechanical and radiation properties, and could result in more effective radiation, in particular from the region above the waist. Other motivation behind this particular design is to break tradition rules in instrument making and extend the sonic possibilities of classical guitars. By adjusting the position of the soundpost, this new guitar could offer a variety of different musically interesting timbre where the soundpost would

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act as the control parameters, changing the natural frequencies, modal damping and mode shapes of the guitar box.

One can find a large number of work dealing with the influence of the soundpost in the literature of violin research [6–9]. Aside the structural reinforcement that offers its insertion between the top and back plates, its essential acoustic purpose is to introduce distortion in the mode shapes, thus transforming initially non-radiating symetric modes into efficient sound radiators [6]. Its role in defining the overall sound character of the instrument is well known by musicians and luthiers, who take great care in its set-up, specifically adjusting its placement, tightness and fit [9–12]. One of the consequence of a good adjustement is an overall increase of the sound radiation, mainly in the low frequency range, which could benefit to previously mentioned issues of the guitars.

Based on a collaboration with a musician and an instrument maker, the main purpose of this work is to explore this new guitar design and discuss its vibrational characteristics from experimental techniques of vibration analysis. Both configurations without and with the soundpost are studied and compared to modal data of a classical guitar. We also conduct a parametric study involving variations to the location of the soundpost that aims at giving a feel of its effect on the vibrational behaviour of the instrument body.

2. EXPERIMENTAL PROCEDURE

The studied guitar is a concert instrument built with typical materials and dimensions of a classical guitar. The soundboard is crafted from pine wood, includes a traditional bracing but differs in design: it is actually divided into two plates that are separated by a vertical distance of about 3 cm and that overlap in a limited region where the soundpost can be fitted. The "soundhole" has a rectangular shape of about 73.5 cm^2, which is slightly larger than the area of traditional circular soundholes, which are typically of about 50 cm^2 [13].

During measurements, the guitar was freely suspended via two elastic bands stretched between the ceiling and the headstock as seen in Figure 1. As usual in measuring input admittance of string instruments [14], the strings were muted to prevent any string vibration residue in the instrument body response. Also the instrument was put under normal playing constraints by tuning the strings to their nominal values.

To study the vibrational performance of the instrument, we consider measuring the body admittance, which is the vibrational response of the guitar body to an impulse excitation. The force input is generated and measured using a small instrumented hammer (PCB 084A17) while two accelerometers (B&K type 4375) are used to capture the body response: one mounted on the first top plate, close to the bridge saddle, and the second mounted on the second top plate, in the middle right side. Both sensors were fixed using a thin layer of bees-wax. Each signal captured by the accelerometers is amplified using a charge amplifier (B&K 2635) and then connected to a signal analyzer (B&K Photon+), where post-processing based on Fourier transform techniques is performed for calculating the transfer functions. A schematic diagram of the measurement instrumentation is given in Figure 1.

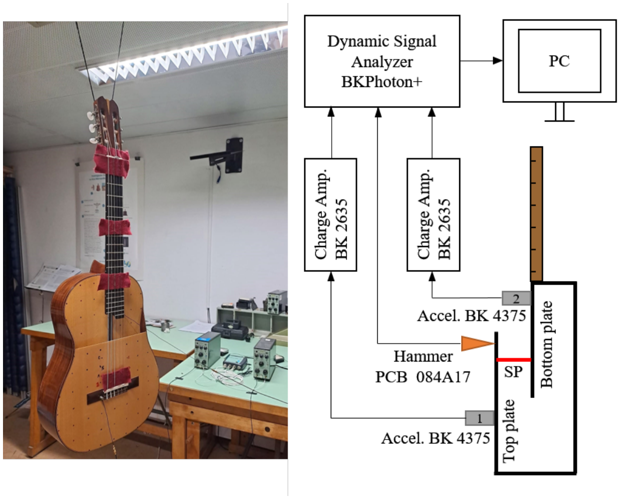

Figure 1: Left: prototype guitar under test. Right: diagram of the apparatus used during measurements.

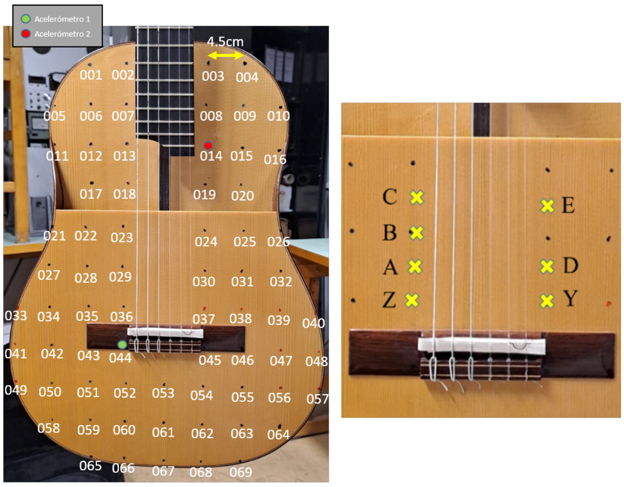

Figure 2: Left: experimental mesh for the full modal identification. Right: positions of the soundpost for the parametric study.

3. MODAL IDENTIFICATION

For modal identification, an implementation of the Eigensystem Realization Algorithm [15] was used, fed by a set of impulses response functions expressed in terms of velocity, calculated after integration of the measured accelerometer signals. The algorithm is based on a state-space formulation of the system dynamics and attempts to identify a linear mathematical model to match the impulse responses of the structure. It combines the set of free decay responses to build a generalized Hankel matrix and then estimate the order of the model by using singular value decomposition. The last step of the algorithm consists of computing the eigenvalues of the chosen minimum model from which the modal parameters are extracted. This algorirthm has been recognized as being very effective for the modal identification of complex systems.

Two series of measurements were conducted. The first measurements concerned a full modal identification of the guitar in both configuration, without and with the soundpost. To that end, a mesh of 69 test locations regularly spaced on the two top plates was defined and impact excitation was performed on all of the points (see Figure 2). A total of 276 impulse responses was recorded. The modal identification then provides the modal frequencies and modal damping values of the top plates, as well as the corresponding mode shapes. The second series of measurements aimed at investigating the influence of the soundpost position on the vibrational behaviour of the guitar. Seven arbitrary positions were considered, all between the bridge and the soundhole as shown in Figure 2. For each soundpost location, two impact excitations were given at the sensors locations, resulting in four response signals. In that case, the modal identification provides estimates of the modal frequencies and modal damping values only.

For illustration, Figure 3 presents an example of a measured impulse response and its corresponding transfer function together with the reconstructed signals synthetized from the identified modal parameters. As seen, the global fit performed over the entire bandwith is not perfect as some modes are actually missing in the identification. This comes from a by-product of modes that do not respond strongly (modes with a node close to sensor and/or excitation positions or modes of the back plate for instance) and the low-order of the model that is chosen. However, the fit seems good enough for identifying the dominant modes as it reproduces the main dynamics observed in the time-domain impulse response.

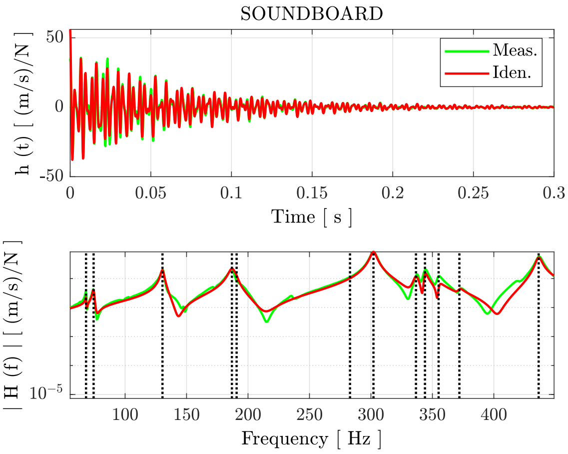

Figure 3: Measured (green) and identified (red) impulse responses (top) and transfer functions (bottom) of the guitar with soundpost. Soundpost positioned at point A ; excitation: point 55; response: point 14. The vertical dashed lines indicate the identified modal frequencies .

4. MODAL DATA ANALYSIS

4.1. Guitar without and with soundpost

Before discussing the identified modal data, a global view of the influence of the soundpost on the distribution of the vibrational energy is given in Figure 4. It is a plot of the average power spectrum defined as:

$$APS(f) = \frac{1}{N} \sum_{n=1}^{N} |H_n(f)|^2 \qquad (1)$$

where N is the total number of measured transfer functions. This is a simple quantity that evidences the relative strength of the mode and here gives a direct visualization of the frequency region where the soundpost affects the behaviour of the guitar body. Figure 4 shows the average power spectrum calculated from the full set of transfer functions, for the two studied configuratons. Large differences, both in terms of amplitude level and peak localization, can be seen until 450 Hz while above that, the two curves remain closer. On the whole, this indicates that the soundpost has little effect at high frequencies and suggests to focus on the low-frequency body behaviour.

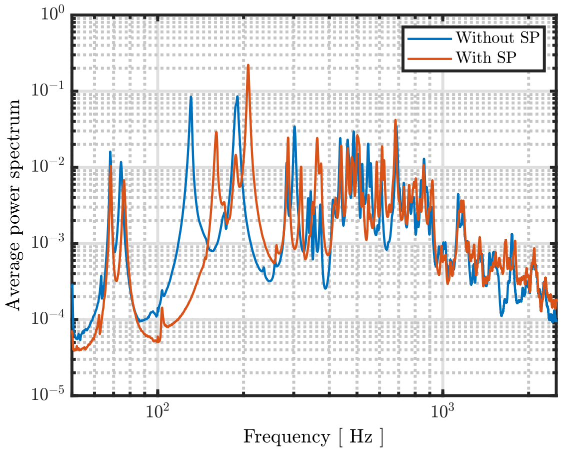

Figure 4: Average power spectrum calculated for the configuration with and without soundpost (SP). Soundpost position: A.

A more detailed analysis of our results is then pursued by comparing the modal parameters identified for the two configurations, without and with the soundpost. Figure 5 presents the mode shapes, together with the modal frequency and modal damping values, identified in the low-frequency range. Surprisingly, it does not seem likely from Figure 5 that the soundpost has a strong effect on the mode shapes, except for the third mode for which the soundpost introduces a node and creates a strong asymetry. This occurs because of the relative motion between the plates before the soundpost is added. Indeed, in the low-frequency range, the soundpost behaves like a rigid body [8] and one expects that modes involving out-of phase plates motions before introducing the soundpost would be strongly disturbed. For instance, it seems that the third mode can be interpreted as the in-phase combinaison of modes 3 and 4 of the uncoupled configuration.

Focusing on the configuration without soundpost, one understands that the lower modes actually involve motions of both top plates. This means that, even with no soundpost, coupling exists between the plates and this can only occur through structural components, namely the ribs, and the air inside the cavity. Conversely, at high frequency, the vibratory energy becomes more localized in one of the two plates. Interestingly, this confirms that the tested guitar includes two main radiating components that could act in different frequency ranges, similarly to what is found in a loudspeaker, where woofers and speakers are used to radiate different frequencies. However, it is worth noting that this configuration, i.e. without the soundpost, is clearly not efficient since the second radiator can only be weakly excited due to the lack of an efficient coupling.

While it was pointed out that the differences between the two configurations remain small globally, the insertion of the soundpost however introduces local differences that could have large influence on the radiated sound. For instance, the fifth mode becomes slightly distorded by the insertion of the soundpost, with a node created at its location, and is no longer a pure dipole. Moreover, the soundpost seems to reinforce the already-existing small coupling in some modes - see modes 4, 6 and 7, and slightly increases the vibrating area. Interestingly, the introduction of the soundpost also makes likely that the lower top plate receives more vibrational energy from the strings, and this could change and/or enhance the overall sound radiation and character of the instrument. Finally, note that some modes certainly remain almost unaffected by the soundpost, which can occur if the sounpost is located at a nodal point of the mode shape.

As seen in Figure 4, the introduction of the soundpost is also accompanied by a rise in frequency for some of the lower modes, a fact that is consistent with studies on the violin [7, 8]. The comparison of modal damping values is not obvious and there seems to be no clear trend in the observed changes. As for any coupled structures, changes do occur when inserting the soundpost but the effect certainly depends on other details, in particular the way the soundpost is fitted.

To have a clearer view of the unique features of the test guitar, it seems interesting to compare our results with modal data obtained on a classical guitar. By looking at the mode shapes presented by Richardson in [16], it is first straightforward to understand that the low-frequency modes are very similar for both guitars. Not surprisingly, new modes are also brought out by the new degree of freedom offered by the soundpost. Overall, it seems that the soundpost retains the modes of the classical guitars but brings new coupled modes that are dominated by motions of the individual plates as if they were uncoupled. Notably, for sufficient string/body strength, these new modes could lead to perceived musical qualities in the sound radiated.

Looking at Figure 6, our results are now compared to guitar data obtained by one of the authors using a similar set-up [17]. In addition to the new mode, which becomes apparent at around 160 Hz, differences in the response amplitude of the instrument body are pronounced in the low-frequency region, while the two curves remain closely aligned in the high-frequency range, when modes overlap. To see what differ between the instruments in this frequency range, we perform a simple average of the measured transfer functions. Averaging is calculated using a bandwith of 1000 Hz. The results in the lower plot of Figure 6 show an interesting structure. Although the two instruments show similar amplitude response, the general trend obtained by averaging slightly differs. In particular, the magnitudes for the test guitar remain higher up to about 1000 Hz, and then decrease above that value. Whether the differences are significant from a musical standpoints remains an open question and certainly deserves further investigation, in particular by studying the radiating properties of the instrument.

4.2. Influence of the location of the soundpost

Finally, other aspect studied in this work is the influence of the soundpost location on the vibrational behaviour of the test guitar. Figure 7 presents the set of transfer functions measured in the different positions shown in Figure 2, which were arbitrarily defined. Globally, it is no surprise that the location of the soundpost has a small influence at high frequencies while it has a profound influence on the low-frequency mode. From a closer view of the transfer function, it is actually apparent that moving the soundpost is

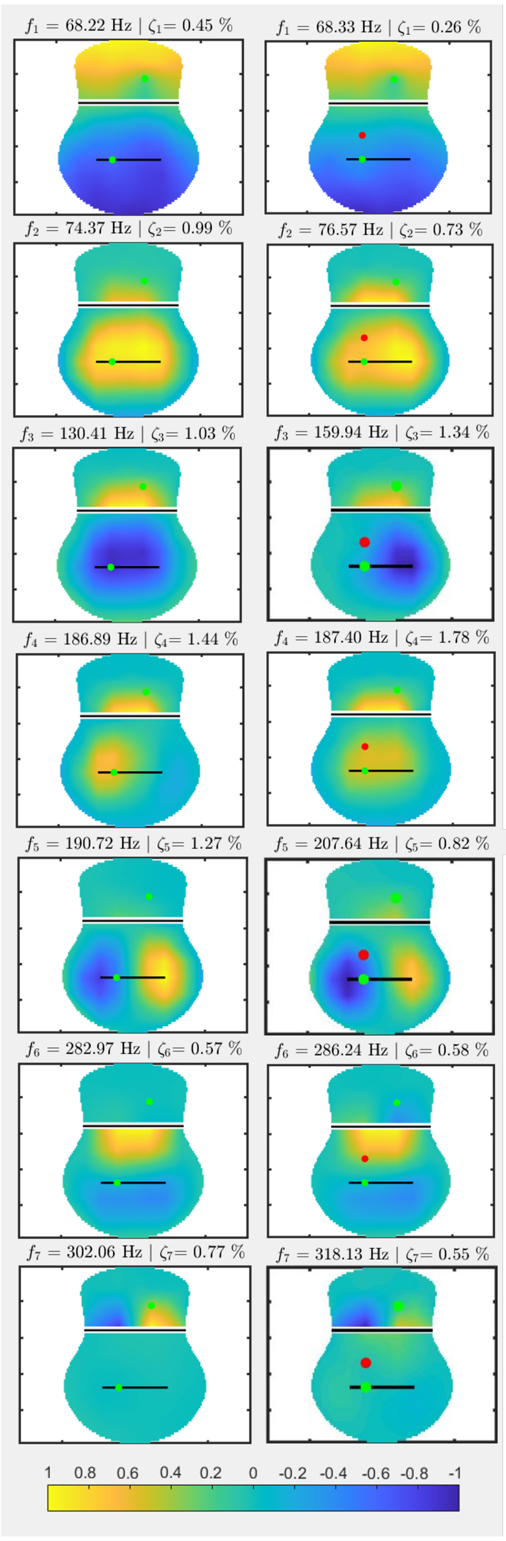

Figure 5: Real part of the first experimentally identified mode shapes with (right) and without (left) soundpost. Green and red dots are the positions of the accelerometers and soundpost respectively. Mode shapes normalization such as: $\max(|\varphi(x, y)|) = 1$.

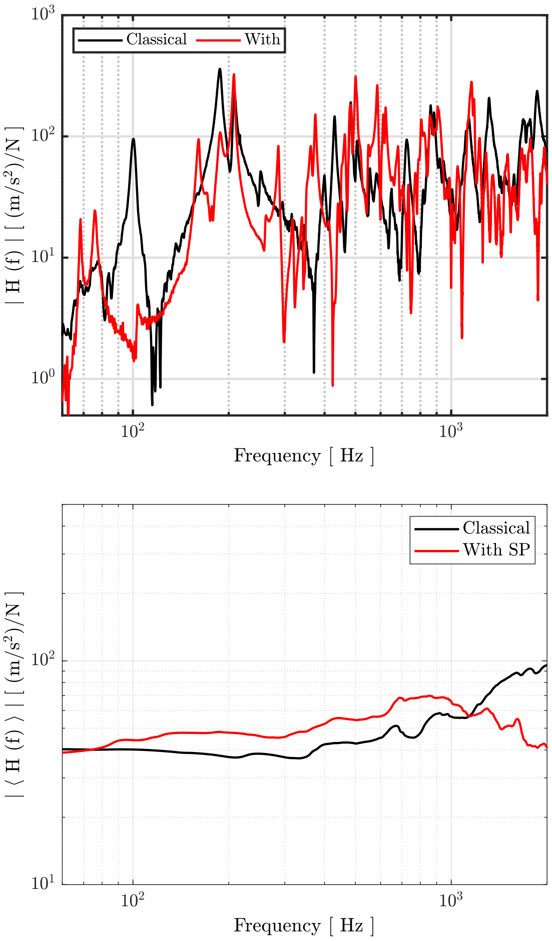

Figure 6: Top: magnitude of measured transfer functions. Bottom: band-averaged transfer function. Black: classical guitar ; red: tested guitar with soundpost

accompanied by changes in both the frequencies and the amplitude responses of the first modes. For instance, the amplitude response of the third mode around 160 Hz reduces of about 20 dB when moving the soundpost from location Y to Z.

Figure 8 is an attempt to quantify the changes in modal parameters statistically. As can be seen, there is a noticeable change in the frequency of the fourth mode with the soundpost location, of about 10 Hz. Regarding modal damping values, the variations remain rather small, except for the third mode. If these modes play a significant role in the radiated sound, then alterations in their frequency and damping values are likely to have audible consequences, and this is of direct interest for musicians since the tonal character of the instrument would be somehow adjustable.

5. CONCLUSIONS

Based on modal analysis, this works explored the features of a new design of guitar, for which the soundboard consists of two separated plates coupled through a soundpost. Two important questions were addressed: (i) how does the new guitar differ from other guitars, and (ii) how does the soundpost influence the dynamics of the

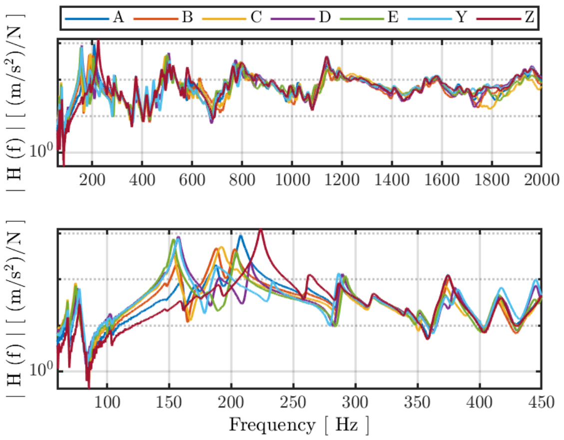

Figure 7: Magnitude of the measured transfer functions as the location of the soundpost is varied. Input accelerance measured close to the bridge.

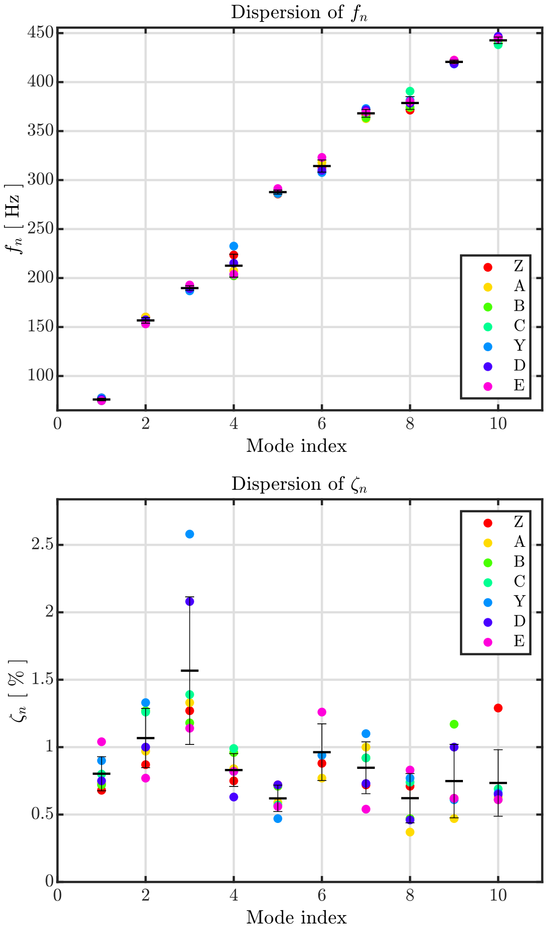

Figure 8: Influence of the soundpost location. Top: identified modal frequencies ; below : identified modal damping. Each color stands for one position. For each mode, the horizontal black line is the average and the error bar represents the standard deviation.

instrument? From our analysis, it appears that the tested guitar shares modal features with a conventional classical guitar. The principal lower-order modes are actually spread across the same frequency range, follow the same order and present similar modal shapes. The soundpost however introduces new modes that involves motions controlled by one of the top plates mainly, as if they were isolated. Regarding the influence of the soundpost, the most noticeable differences are seen in the low frequency range, below 450 Hz. Changes in the modal frequencies, the modal shapes as well as the modal amplitude responses are clearly evidenced. Notably, this could provide a variety of tonal qualities to the instrument but most importantly, it remains to be analyzed whether these modes are efficient radiators.

It seems evident that further work is needed to establish the full character of the new guitar. A vibrational approach, as devised in this work, is certainly useful for understanding the acoustical performance of an instrument; however, its capacity to interpret the full range of musical effects remains limited. Finally, it seems important to stress that this new guitar opens up a new frontier in acoustic guitar design while it has been steeped in tradition for centuries. This project offers a realm to explore new dynamics and new shapes of instruments with perhaps, new musical possibilities.

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