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 radiada por la caja de resonancia. Parte de esta vibración se transmite a la tapa superior a través del puente. 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 un protótipo fabricado por un guitarrista y lutier (PVC), se presenta una posible solución para el aumento de variedadade tímbrica e, eventual aumento de la projecion sonora, que consiste substituir la tapa superior de la caja de resonancia por dos tapas de diferentes tamaños y respostas vibratórias, situadas em planos diferentes, com uma zona de sobreposição em que se coloca uma alma que garante la interaccion de las dos tapas. En este trabajo exploramos esta idea. Se realizan medidas de vibración de ésta protótipo, 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 body of the instrument for efficient radiation [1]. This occurs via the bridge that receives the vibrational energy of the strings and in turn excites the soundboard and the other parts of the instrument. When comparing the acoustic properties of guitars to instruments from the violin family, it becomes clear that guitars produce only a rather small amount of sound. Apart from a number of subjective factors [2], this lack of radiation efficiency is certainly the results of a combination of complex physical factors, including in particular the shapes of the body modes or their low 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 all the vibration to specific areas of the soundboard and could thus reduce the effective radiating surface drastically. To address this problem, here we study the vibration behaviour of a new soundboard design proposed by a luthier and a guitarist (PVC). In this design, the top plate is divided into two different sized plates that interact dynamically through the action of a soundpost, as it is the case in a violin. It is important to note that the soundpost is *not* inserted between the top and back plates as in [5], but here 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. Another motivation behind this particular design is to break with traditional rules in instrument making and extend the acoustic possibilities of classical guitars. By adjusting the position of the soundpost, this new guitar could offer a variety of different musically interesting timbre, with the soundpost

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acting as a control parameter, 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 provided by 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 symetrical modes into efficient sound radiators [6]. Its role in defining the overall sound character of the instrument is well known to musicians and luthiers, who take great care in its set-up, especifically adjusting its placement, tightness and fit [9–12]. One of the consequence of a good adjustement is an overall increase in 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 instrument maker, the main purpose of this work is to explore this new guitar design and discuss its vibration characteristics from vibration analysis techniques. The two configurations without and with the soundpost are studied and compared with modal data of a classical guitar. We also perform a parametric study varying the position of the soundpost to get a feel of its effect on the vibration behaviour of the instrument body.

2. EXPERIMENTAL PROCEDURE

The studied guitar is a concert instrument built with the 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 divided into two plates separated by a vertical gap of about 3 cm and that overlap in a limited area where the soundpost can be fitted with specific setter (see Figure 1). 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 the measurements, the guitar was freely suspended via two elastic bands stretched between the ceiling and the headstock as seen in Figure 2. As is usual when measuring the input admittance of string instruments [14], the strings were to avoid residues of string vibrations in the response of the instrument body. Furthermore, the instrument was played under normal conditions by tuning the strings to their nominal values.

To study the vibrational performance of the instrument, we measure the body admittance, i.e. the vibrational response of the guitar body to an impulse excitation. The force input is generated and measured with a small instrumented hammer (PCB 084A17) while two accelerometers (B&K type 4375) are used to capture the body response: one is mounted on the first top plate, close to the bridge saddle, the second on the second top plate, in the middle of the right side. Both sensors were fixed using a thin layer of beeswax. 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 to calculate the transfer functions. A schematic representation of the measurement instrumentation is given in Figure 2.

3. MODAL IDENTIFICATION

For the 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

Figure 1: Soundpost mounted between the two top plates with its setter tool.

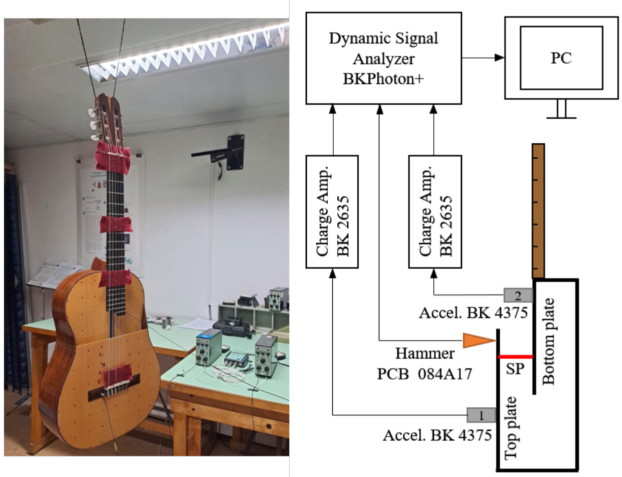

Figure 2: Left: Prototype of the guitar tested. Right: Diagram of the apparatus used during measurements.

according to 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 estimates the order of the model by using singular value decomposition. The final step in the algorithm is to calculate the eigenvalues of the selected minimal model, from which the modal parameters are extracted. This algorithm has proven to be highly effective for the modal identification in complex systems.

Two series of measurements were performed. The first measurements concerned a full modal identification of the guitar in both configurations, without and with the soundpost. To that end, a mesh of 69 test points was defined, evenly spaced on the two top plates, and impact excitation was applied at all of these points (see Fig. 3). A total of 276 impulse responses were 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 vibration behaviour of the guitar. Seven arbitrary positions were considered, all located

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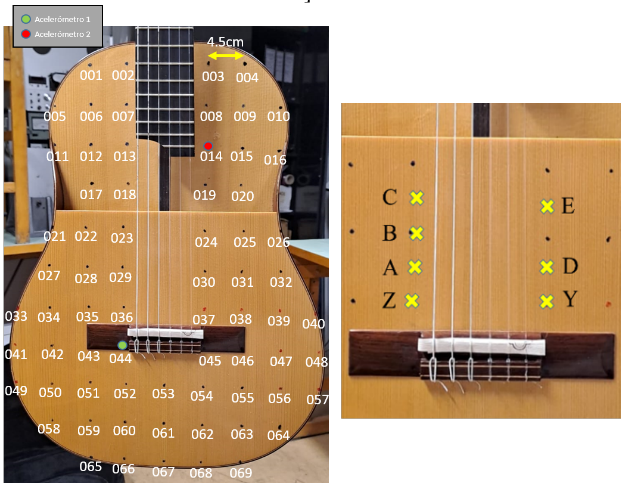

Figure 3: Left: Experimental mesh for full modal identification. Right: positions of the soundpost for the parametric study.

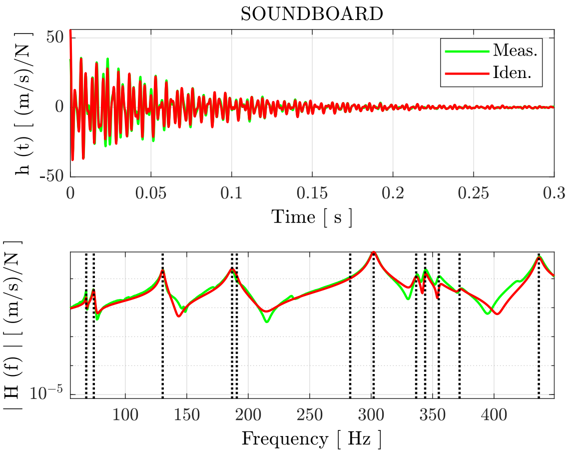

Figure 4: Measured (green) and identified (red) impulse responses (top) and transfer functions (bottom) of the guitar with soundpost. Soundpost positioned at point A ; excitation: point 55; response: point 14. The vertical dashed lines indicate the identified modal frequencies.

between the bridge and the soundhole as shown in Fig. 3. For each soundpost position, two impact excitations were applied at the sensors positions, resulting in four response signals. In this case, the modal identification only provides estimates of the modal frequencies and modal damping values.

For illustration, Figure 4 shows 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 (e.g. modes with a node close to sensor and/or excitation positions or modes of the back plate) and the chosen low-order of the model. However, the fit appears to be good enough to identify the dominant modes as it reproduces the main dynamics observed in the time-domain impulse response.

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 Fig. 5. This is a plot of the average power spectrum defined as:

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

where N is the total number of measured transfer functions. This is a simple quantity that proves the relative strength of the mode and here provides a direct visualization of the frequency range in which the soundpost affects the behaviour of the guitar body. Figure 5 shows the average power spectrum calculated from the full set of transfer functions, for the two configuratons studied. Significant differences, both in terms of amplitude level and peak localization, are noticeable up to 450 Hz, with the two curves continuing to converge beyond this frequency. On the whole, this indicates that the soundpost has little effect at high frequencies, so we should focus on the body's behaviour at low frequencies.

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 6 shows the mode shapes, together with the modal frequency and modal damping values, identified in the low-frequency range. Surprisingly, Fig. 5 does not show 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 asymmetry. This is due to 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 modes in which the plates move out of phase before the soundpost is introduced are expected to be strongly perturbed. For example, it seems that the third mode can be interpreted as the in-phase combination of modes 3 and 4 in the uncoupled configuration.

Focusing on the configuration without soundpost, one understands that the lower modes actually involve motions of the two top plates. This means that, even without soundpost, there is a coupling between the plates that can only occur through structural components, namely the ribs, and the air inside the cavity. Conversely, at high frequencies, the vibrational energy is 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, similar to 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 as the second radiator can only be weakly excited due to the lack of efficient coupling.

While it has been pointed out that the differences between the two configurations remain small globally, the insertion of the soundpost leads to local differences that could have a great influence on the radiated sound. For example, the fifth mode is slightly distorded by the insertion of the soundpost, with a node created at its position, and is no longer a pure dipole. Moreover, the soundpost

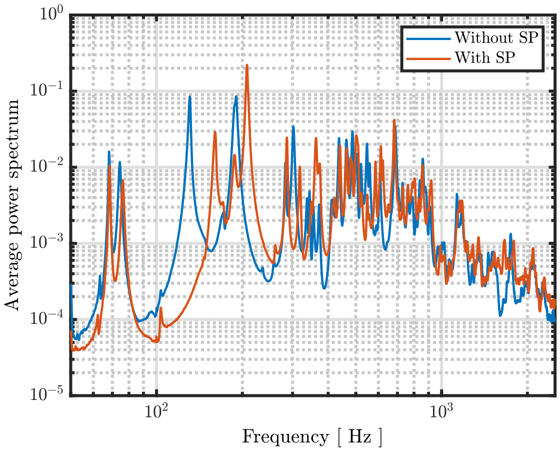

Figure 5: Average power spectrum calculated for the configuration with and without soundpost (SP). Soundpost position: A.

seems to reinforce the already-existing low coupling in some modes - see modes 4, 6 and 7 -, and slightly increases the vibrating area. Interestingly, the introduction of the soundpost also causes the lower top plate to receive more vibrational energy from the strings, which 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 at a nodal point of the mode shape.

As can be seen in Figure 5, the introduction of the soundpost is also followed by a frequency increase in 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 with all coupled structures, changes occur when the soundpost is inserted but the effect certainly depends on other details, especially 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. A look at the mode shapes presented by Richardson in [16], it is initially easy to understand that the low-frequency modes are very similar on both guitars.Unsurprisingly, 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. With sufficient string/body strength, these new modes could lead to perceived musical qualities in the radiated sound.

Figure 7 compares our results with guita data obtained by one of the authors with 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, where the modes overlap. To see how the instruments differ in this frequency range, we perform a simple averaging of the measured transfer functions. The averaging is calculated using a bandwidth of 1000 Hz. The results in the lower graph of Fig. 7 show an interesting structure. Although the two instruments show a similar amplitude response, the general trend

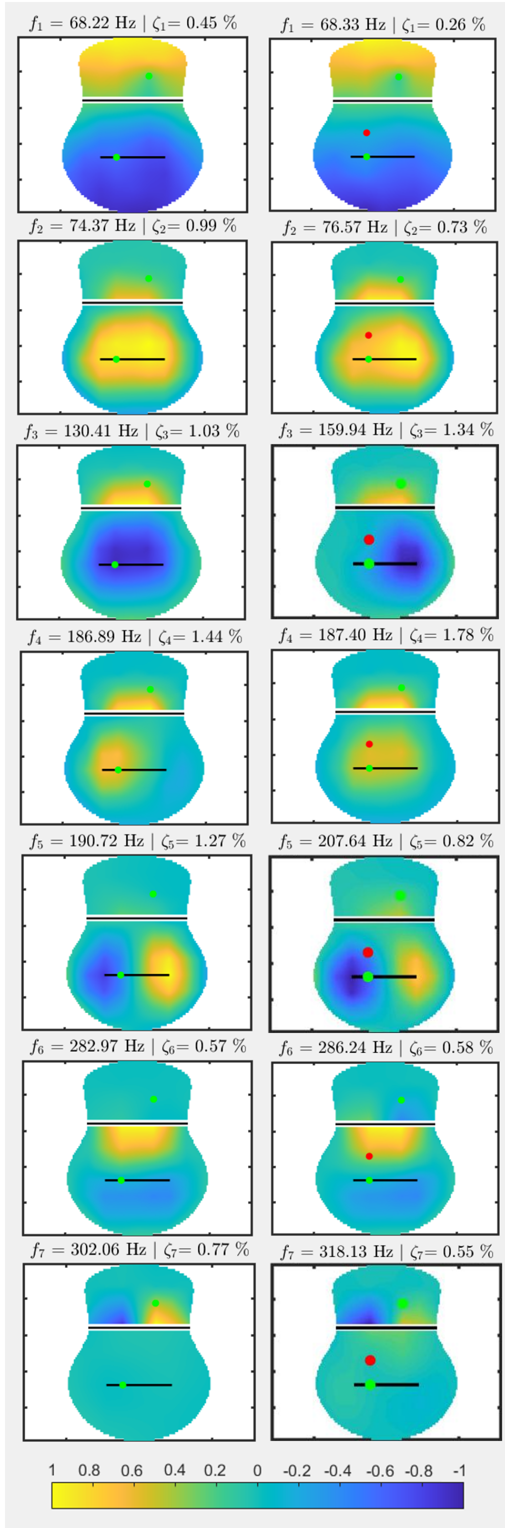

Figure 6: Real part of the first experimentally identified mode shapes with (right) and without (left) soundpost. Green and red dots are the positions of the accelerometers and the soundpost, respectively. Mode shapes normalization according to: $\max(|\varphi(x, y)|) = 1$.

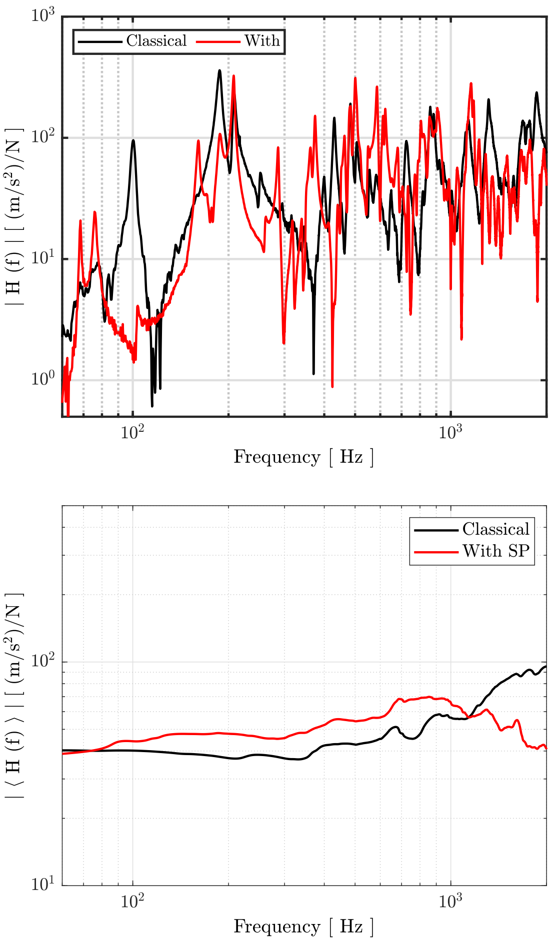

Figure 7: Top: Amplitude of the measured transfer functions. Bottom: band-averaged transfer function. Black: classical guitar ; red: tested guitar with soundpost.

resulting from the averaging deviates slightly. In particular, the amplitudes for the test guitar remain higher up to about 1000 Hz, and then decrease above this value. Whether these differences are significant from a musical perspective remains an open question and certainly warrants further investigation, especially by studying the radiating properties of the instrument.

4.2. Influence of the location of the soundpost

Another aspect studied in this work is the influence of the position of the soundpost on the vibrational behaviour of the test guitar. Figure 8 shows a series of transfer functions measured at the various arbitrary positions shown in Fig. 3. It is no surprising that the position of the soundpost has a small influence at high frequencies, while it has a large influence on the low-frequency mode. A closer look at the transfer function reveals that moving the soundpost is 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 decreases by about 20 dB as the soundpost is moved from position Y to Z.

Figure 9 is an attempt to statistically quantify the changes in modal parameters. As can be seen, there is a noticeable change

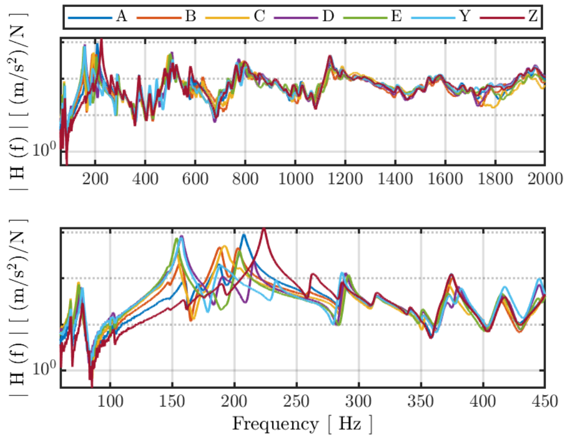

Figure 8: Amplitude of the measured transfer functions at different positions of the soundpost. The input acceleration was measured near the bridge.

in the frequency of the fourth mode with the soundpost location, by about 10 Hz. As for the modal damping values, the variations are rather small, except for the third mode. If these modes play an important role in the radiated sound, then changes in their frequency and damping values are likely to have audible consequences, and this is of direct interest to musicians, as the tonal character of the instrument would be adjustable to some extent.

5. CONCLUSIONS

Based on modal analysis, this works explored the features of a new design of guitar, in 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 affect the dynamics of the instrument? From our analysis, it appears that the tested guitar shares modal features with a conventional classical guitar. The principal lower-order modes are distributed over the same frequency range, follow the same order and present similar modal shapes. However, the soundpost introduces new modes that involves motions controlled mainly by one of the top plates, as if they were isolated. Regarding the influence of the soundpost, the most noticeable differences are observed in the low frequency range, below 450 Hz. Changes in the modal frequencies, the modal shapes and the modal amplitude responses are clearly evidenced. 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 obvious that further work is needed to establish the full character of the new guitar. A vibrational approach, such as that developed in this work, is certainly useful in understanding the acoustic 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 a new frontier in acoustic guitar design, while being rooted in tradition for centuries. This work offers a realm to explore new dynamics and new shapes of instruments with perhaps, new musical possibilities.

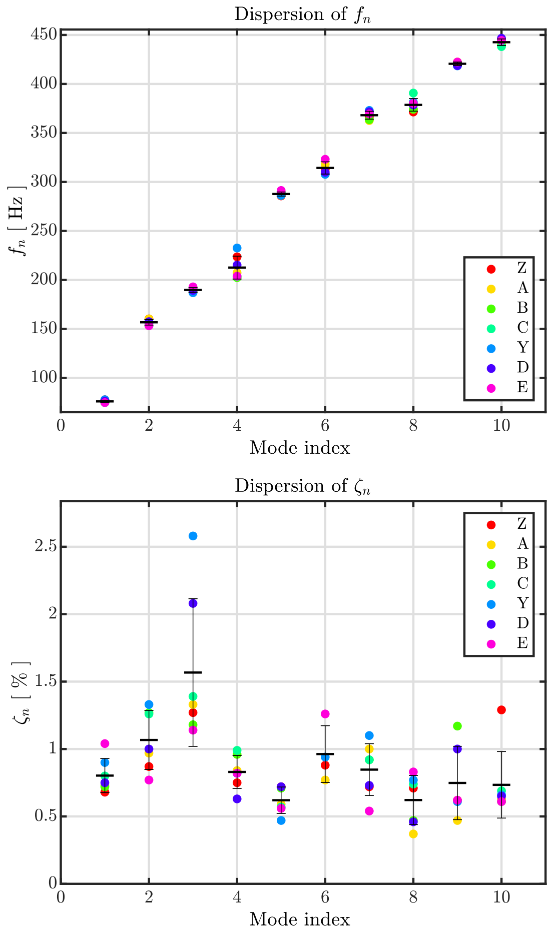

Figure 9: Influence of the position of the soundpost. Top: identified modal frequencies ; Bottom: identified modal damping. Each color represents a position for one position. For each mode, the horizontal black line is the average and the error bar represents the standard deviation.

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