Akustik

Vasileios Chatziioannou/Alexander Mayer

An Analysis of Reconstructed Rababs Based on Physical Principles, Experimental Measurements and Numerical Simulations

In this essay, the reconstruction of early rabāb *instruments is supported by experimental measurements and physical modelling. In contrast to arched wooden top plates that are commonly used in Western bowed string instruments, the* rabāb *top consists of natural skin. This results in different acoustical properties for the instrument. While violin-like instruments have been thoroughly studied in the past from the perspective of both acoustics and material science, the same is not true for* rabāb*-like instruments. Of particular interest in this study is the placement of sound holes on the body of the instrument, and how this practice influences its acoustic properties. In fact, the air-cavity resonance of the* rabāb, *also known as the Helmholtz resonance, appears to lie above the common playing range of the instrument, thus amplifying the overtones of the sounds produced.*

Introduction

The reconstruction of early musical instruments based on historical pictorial, textual and musical sources has been discussed extensively in relation to early viola da gamba designs.[1] The present study aims at following a similar approach to the reconstruction of early European rababs and their subsequent acoustic analysis. A major difference between these two types of instruments lies in the instrument top, which is responsible for the greater part of the sound radiated by the instrument. Unlike the typical practice of arched wooden top plates on bowed-string instruments like the viola da gamba, the rabab uses a natural skin.

The mechanical properties of these designs vary significantly. Wooden top plates have been studied in tremendous detail as a result of the interest of acousticians, instrument makers and musicians in traditional, violin-like instruments.[2] However, rabab-like instruments have received less attention from researchers. This essay uses physical modelling and experimental measurements in order to acquire useful information that can enhance our understanding of the building principles that have an impact on how the instrument functions. Of particular interest is the effect of the sound holes in the instrument body and their possible influence on the acoustical behaviour of the instrument. In the following section, we present a numerical model based on a Moroccan *rabāb* built in Fez in 2015 by Abdessalam Chiki[3] and discuss the acoustic effects of the bridge position and the presence or absence of sound holes.

1 Hirsch 2018.
2 A vast bibliography exists on this subject, see Woodhouse 2014 and the sources given there.
3 The template for the numerical model was created on the basis of 360° photos of the instrument using photogrammetry. The original photos by Thilo Hirsch are available on open access (Hirsch 2023a).

A physics-based analysis of a Moroccan *rabāb*

If we know the geometry and the material properties of a musical instrument, we can solve the equations describing the underlying physics that determine the acoustical properties of the instrument. The Finite Element Method is employed in this study, both because of its ability to simulate complex geometries and because of its accuracy in handling the coupling between mechanical elements (body parts) and acoustic elements (the air both in the instrument and surrounding it).[4] For this investigation, the geometry of the virtual instrument was based on a simplified 3D scan (Fig. 1).

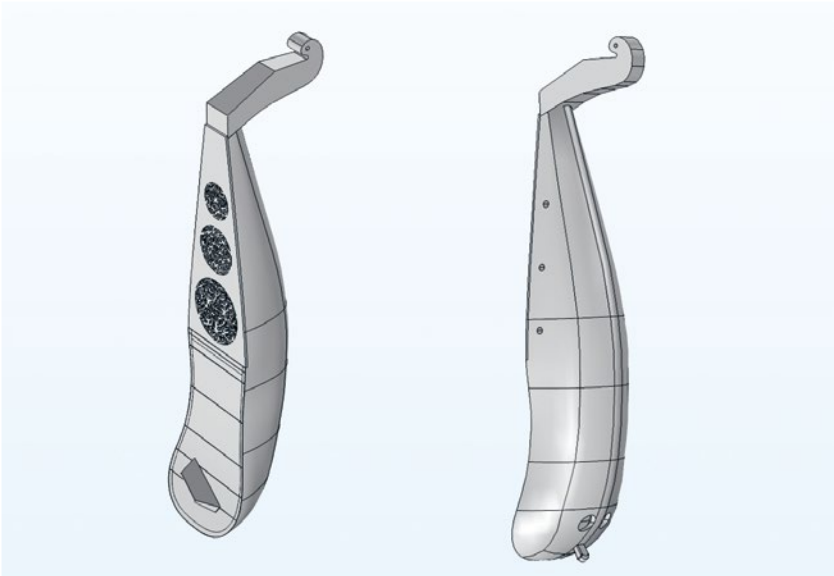

Fig. 1 The three-dimensional computer model of a Moroccan *rabāb* used for simulation. For the vibrational analysis the strings and tuners are not included, as only the vibrational characteristics of the instrument body are of interest. String tension is still taken into account.

Following well-established experimental measurement techniques, the virtual instrument is excited by a force at the bass side of the bridge. This corresponds to a sinusoidal excitation at every frequency of interest. The model is used to calculate the 'response' of the instrument in two ways:

1. the velocity of the bridge at each frequency of excitation;
2. the sound pressure at each frequency, 1 metre in front of the instrument.

The former constitutes a bridge admittance (or bridge mobility) measurement. The bridge admittance can yield useful information regarding the structural characteristics of the system. As outlined later in this article, it is possible to obtain the bridge admittance of an existing instrument experimentally. This allows us to compare the numerical model predictions with experimental observations. Similarly, the sound in front of the instrument shows how well sound may be radiated (in that direction) for different frequencies, something that is directly linked to the bridge admittance.

In the latter quantity (often termed 'acoustic transfer function'), one is also able to observe the effect of the lowest air-resonance of the instrument's cavity. This so-called Helmholtz resonance corresponds to the whole volume of air inside the instrument vibrating, similar to a

4 See, for example, Tahvanainen et al. 2013.

breathing element.[5] It can be tuned by violin makers in order to support the low frequency range, where the instrument's bridge admittance is relatively low. This is possible using the theoretical formula[6] for a Helmholtz resonator with a single opening:

$$2\pi f = c\sqrt{\frac{S}{VL}} \qquad (1)$$

where f is the frequency of oscillation, c the speed of sound in air, S the cross-sectional area of the sound hole openings, V the cavity volume and L the height of the cavity opening (in this case the thickness of the top plate). One of the simplest possible modifications is to alter the opening area S, thus increasing or decreasing the air resonance. In the case of the *rabāb* under study here, this is achieved by including additional holes in the body of the instrument, thereby gradually shifting the Helmholtz resonance to higher frequencies.

Before investigating this phenomenon, the model assesses the contrast in radiated sound between a perpendicular and a tilted bridge (as is used today on the Moroccan *rabāb*). Figure 2 (top plots) shows the two different bridge configurations along with the instrument's membrane deformation when excited at 250 Hz. It can be observed that different regions of the membrane are vibrating, depending on the orientation of the bridge. This appears to have a significant impact on the radiated sound pattern. In fact, for the case of the angled bridge, the sound is radiated in a more uniform way around the instrument for most frequencies (see Figure 2, bottom; instrument facing to the left, towards 180°). On the other hand, in the case of the straight bridge, less circular radiation patterns are observed, whereas the sound pressure intensity is considerably lower compared to the case of the oblique bridge. This may be attributed to the asymmetry that the oblique bridge imposes on the system, which is known to enhance the radiation of bowed-string instruments at the lower frequencies.[7]

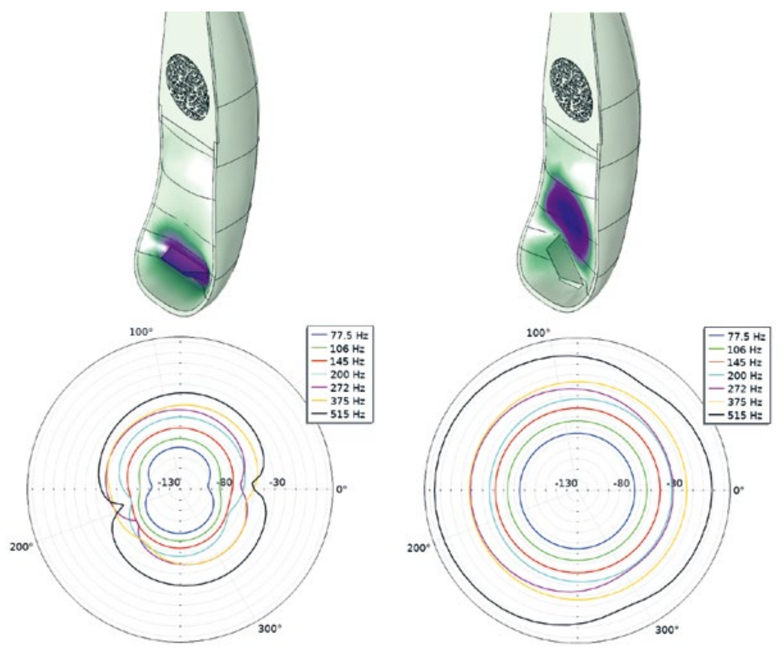

Fig. 2 Top: exaggerated displacement of the *rabāb* membrane when the bridge is excited at 250 Hz in the case of a perpendicular and an angled bridge. Bottom: Radiation characteristics calculated for both bridge settings.

5 See Woodhouse n.d., Chapter 5.3.0.
6 See Fletcher/Rossing 2012, Chapter 1.6.2, pp. 13f.
7 See Chatziioannou 2019.

This is also verified by the acoustic transfer function plotted as a function of frequency for both instrument configurations in Figure 3 (right). The left plot shows the simulated bridge admittance in both cases, where the measured bridge admittance of the Moroccan *rabāb* is also given for comparison. The modal shapes are shown for four peaks of the simulated curve in the case of the oblique bridge. Given the better radiation characteristics, all further simulations are assuming an oblique bridge.

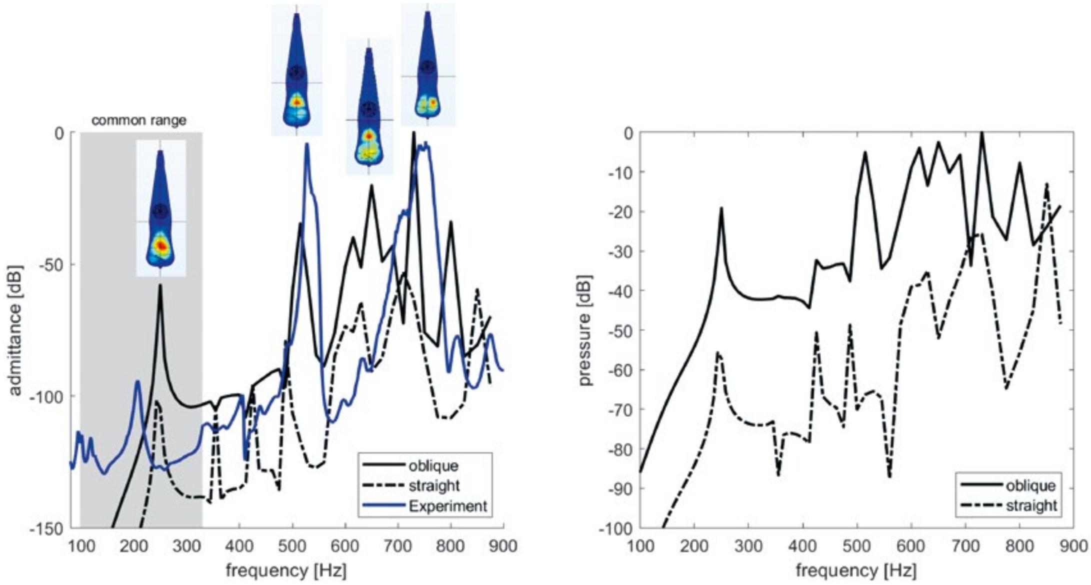

Fig. 3 Bridge admittance (left) and acoustic transfer function (right) plotted as function of frequency for both bridge settings. The measured bridge admittance of the Moroccan *rabāb* is also plotted (blue curve). Modal shapes (for the oblique-bridge case) are shown for the simulated admittance peaks. The grey-shaded area depicts the frequency region where the instrument is commonly played (with respect to the fundamental frequency of the played notes).

Modified instruments

Modifications to the instrument design, focusing on opening holes, are hereby analysed with the aid of the above numerical model. Two types of modifications are considered, also visible in Figure 1: the inclusion (or not) of two additional rosettes, and the inclusion (or not) of sound holes at the side and lower end of the instrument. The effect of such additional holes mainly manifests itself in the frequency location of the Helmholtz resonance, roughly following the theoretical formulation in equation (1) for a simplified case. This predicts that adding more holes to the instrument body should shift this resonance frequency to a higher value. As a default design, the only opening is the lower rosette. This is compared to such cases where, in addition to the lower rosette,

a. two more rosettes in the wooden top part are included (see Figure 1, where all three rosettes are shown);
b. side holes in the body are included (see Fig. 1);
c. holes are included on the lower end of the back of the instrument body (see Fig. 1).

The results obtained from the simulations are again analysed with respect to the bridge admittance and the radiated sound pressure. When the data from all simulated instrument versions are plotted on a single graph, three distinct clusters can be observed, based on the frequency location of the first air mode (Helmholtz resonance). These clusters depend on the presence of holes in the sides and the lower end of the instrument body (Fig. 4). The radiated sound pressure exhibits behaviour comparable to that observed for the associated admittance curves. It appears that in the presence of holes in the lower end of the back of the instrument body, additional side holes or rosettes do not have a significant effect on the Helmholtz resonance. Similarly, in the presence of side holes, opening additional rosettes also only has a minor impact.

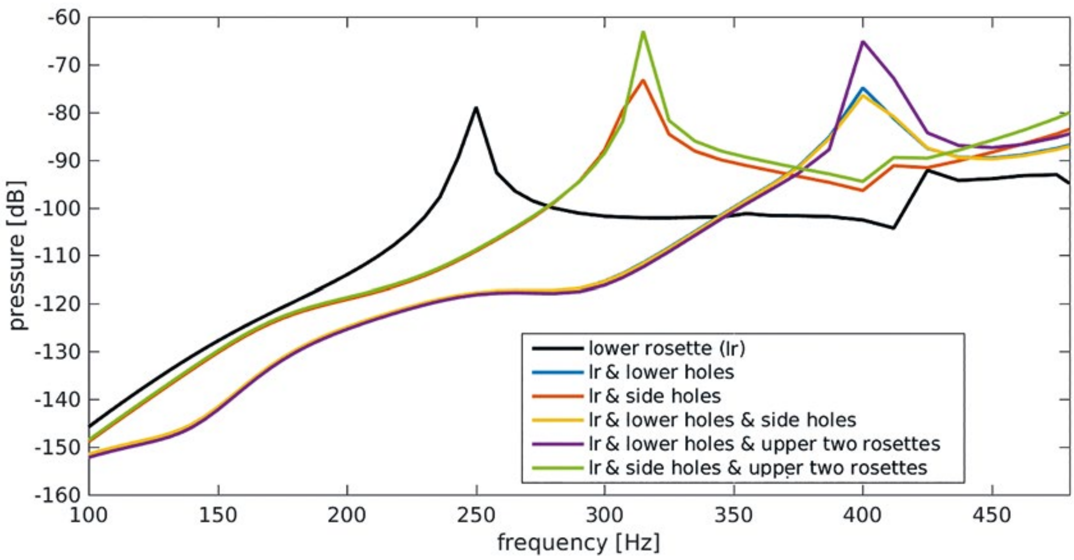

Fig. 4 Comparison of radiated sound pressure depending on the presence of different types of openings (sound holes).

Two of these simulated cases are shown in detail in Figure 5, where both the bridge admittance and the radiated sound are plotted in the case of side holes and lower holes.

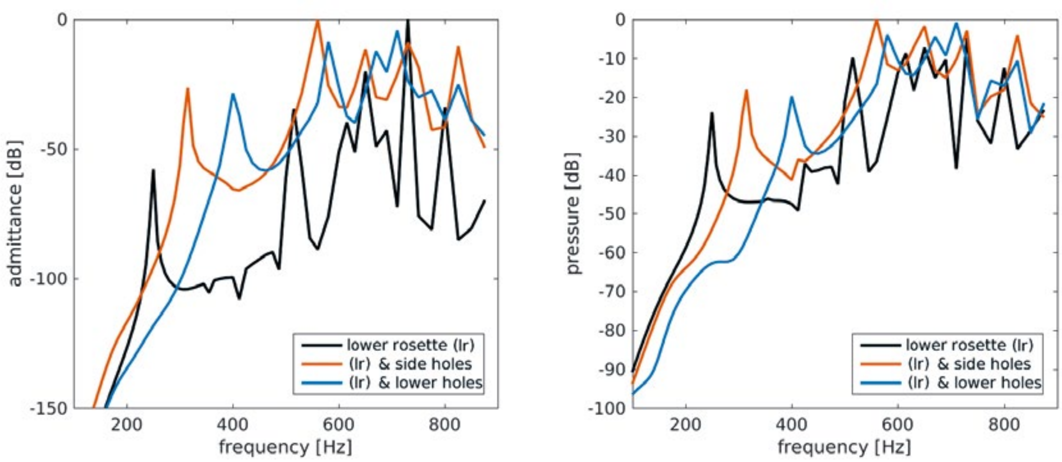

Fig. 5 Simulated bridge admittance and sound pressure depending on sound holes and rosettes.

Acoustic measurement method

In contrast to the simulation, the so-called impulse hammer method was chosen to measure the vibration characteristics of the real instruments. This method is widely recognised[8] for its ability to assess mechanical vibration characteristics and is not only used in the investigation of musical instruments. In this type of measurement, the instrument is excited with a special

8 Zhang/Woodhouse 2014.

impulse hammer with a broad frequency spectrum. The special feature of these impulse hammers is that a force sensor is integrated, which provides information about the excitation force and the distribution within the excitation spectrum. An acceleration sensor attached to the instrument then provides the so-called impulse response. The acceleration signal is converted into a velocity measure by integration. By setting the spectral data of the two signals in relation to each other, the frequency-dependent mechanical admittance is obtained. In addition to measuring the mechanical vibration characteristics, the radiated sound pressure is also recorded. The sound pressure has also been mathematically normalised to the impulse hammer signal. This is known as the acoustic transfer function (see Fig. 6).

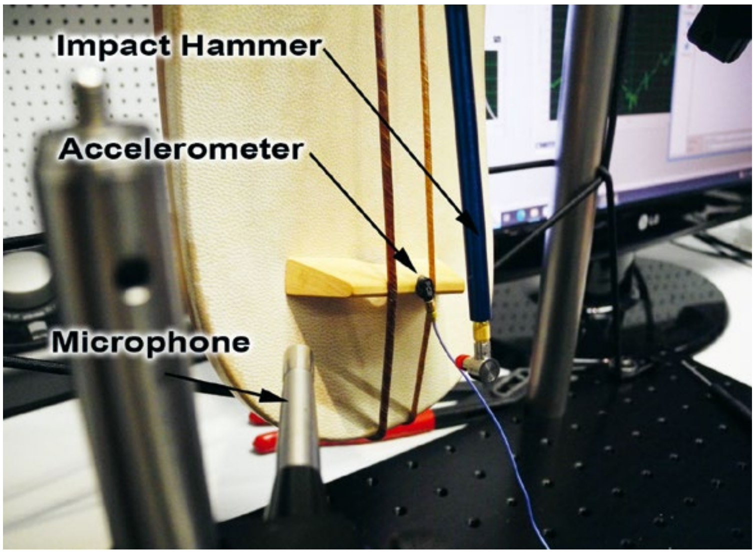

Fig. 6 Detail of the measurement setup: here the accelerometer is placed in the centre of the bridge so that it can also capture the amplitude of a vertical vibration pattern. Photo: Thilo Hirsch

In a computer simulation, the test specimen can be freely suspended in space, so in general there is no influence from the environment. In practice, this is only possible to a limited extent. A proven method is to mount the instrument on rubber cords in a flexible but stable, torsion-proof arrangement on a measuring frame (see Fig. 7). The tension of the rubber cords together with the weight of the instrument result in a very low natural frequency (far below the playing range) and extensive decoupling from structure-borne noise.

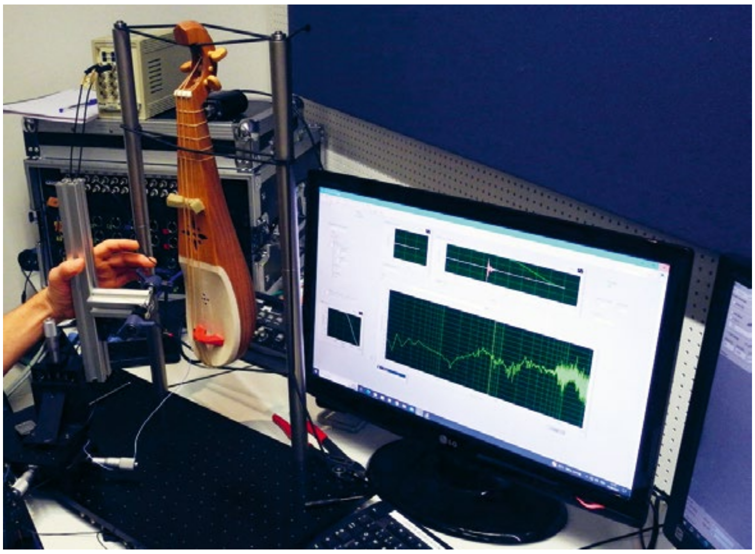

Fig. 7 The measurement setup: the instrument is flexibly mounted on a stand; the impact hammer can be adjusted in angle and three-dimensional position. For excitation, one degree of freedom is provided by a guide bearing (Photo: Thilo Hirsch).

Reconstructed instruments

The behaviour predicted via numerical simulations has been contrasted with the experimental measurements on three instruments that were reconstructed by Thilo Hirsch based on historical pictorial sources (Fig. 8). The models for this were, from left to right, a painting attributed to Jorge Affonso (1515),[9] an anonymous book illustration in the *Cantigas de Santa María* (approx. 1284)[10] and a painting by Francesc Comes (1394).[11] The Affonso rabab features a single rosette but includes bottom holes that can be closed with well-fitted pieces of wood to enable monitoring of the resulting effects. The Cantigas rabab is crafted with two rosettes but without additional holes, and was therefore subject only to bridge admittance measurements. The Comes rabab also has the possibility of open or closed holes in the bottom of the body. The measured admittance and radiated pressure (when available) for all three instruments is shown in Figures 9–11. These also depict the frequency regions where the instruments are commonly played (with respect to the fundamental frequency or pitch of the played notes).

Fig. 8 The three newly built rababs, from left to right: models after Jorge Affonso, the *Cantigas de Santa María* and Francesc Comes (Photo: Thilo Hirsch).

As already explained, the presence of additional holes shifts the air resonance towards higher frequencies. Dashed lines in Figures 10 and 11 (bottom) indicate this frequency shift. It appears that this is a deliberate strategy in order to prevent this resonance (which is the lowest resonance of the instrument) from lying within the playing range of the instrument, as is also shown in the case of the Moroccan *rabāb* described above. This is in contrast to violin-like instruments, where such support is actually desired. For example, in the Renaissance viola da gamba design mentioned previously, the air resonance is the only support that is offered on the bass end of the spectrum and is especially sought after by instrument makers.

In the case of all the rabab measurements above, limited support appears at the playing frequency, whereas ample resonance peaks can be expected at the location of the overtones of the played notes. This would result in a brighter (more 'nasal') sound, especially when the played notes lie in a 'valley' of the admittance curve (as is the case for the Cantigas and Comes models).

9 Affonso 1515.
10 Anonymous 1284.
11 Comes 1394.

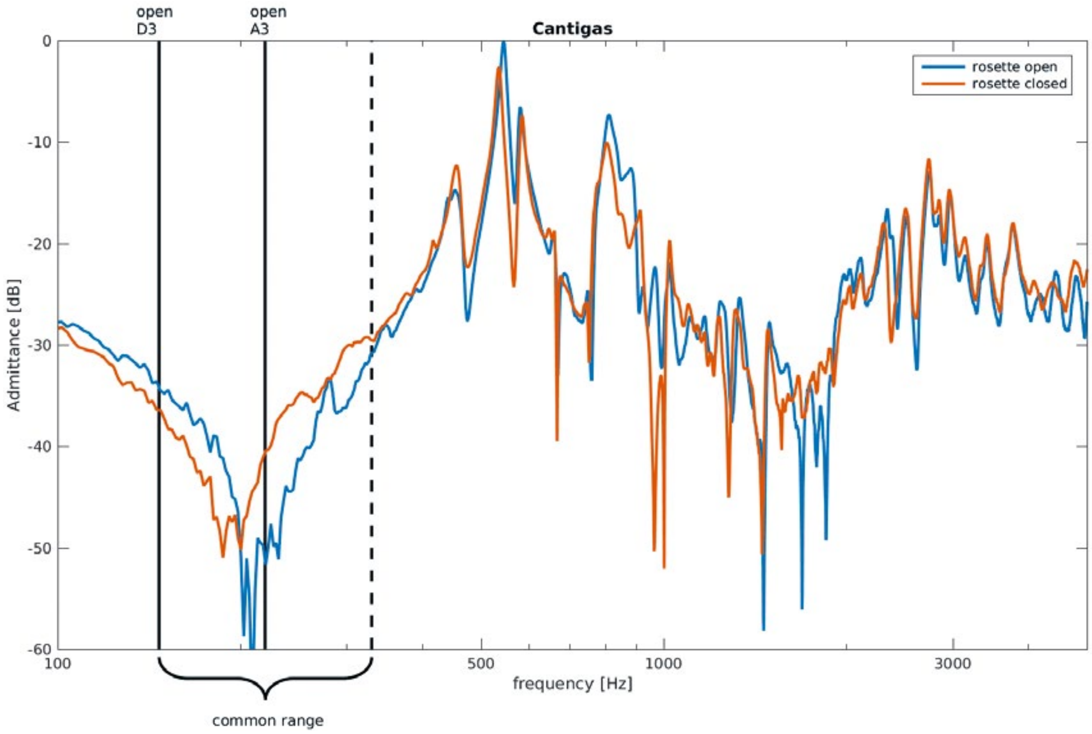

Fig. 9 Comparison of the measured bridge admittance of the Cantigas rabab, blue with open upper rosette, orange with closed rosette.

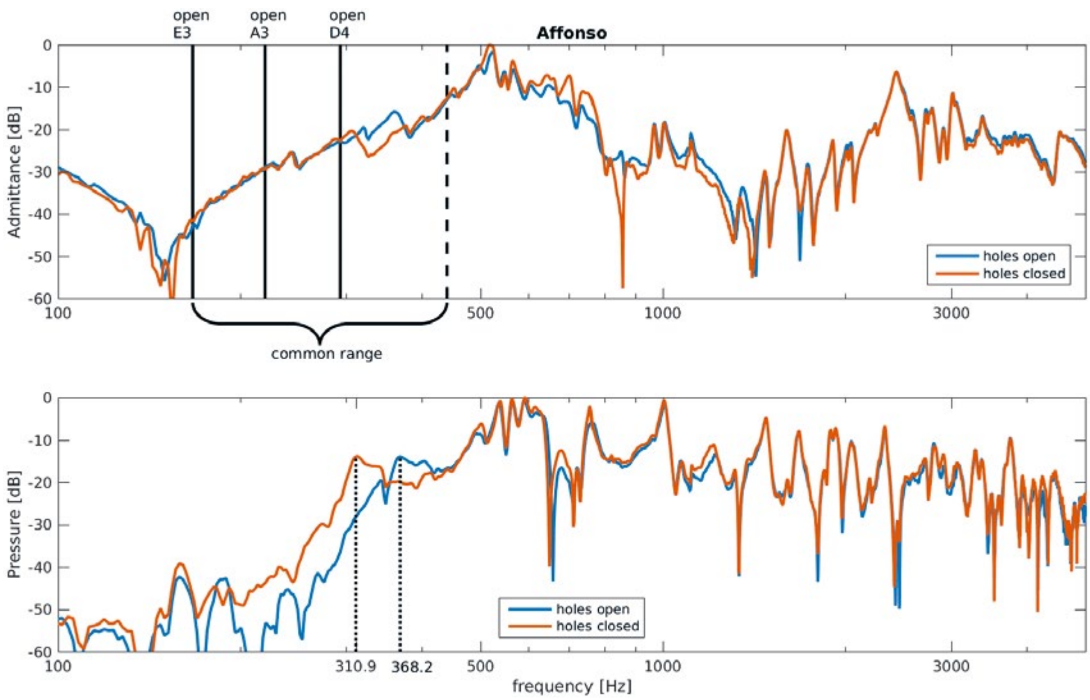

Fig. 10 Comparison of the measured bridge admittance and sound pressure of the Affonso rabab, blue with open bottom holes, orange with closed.

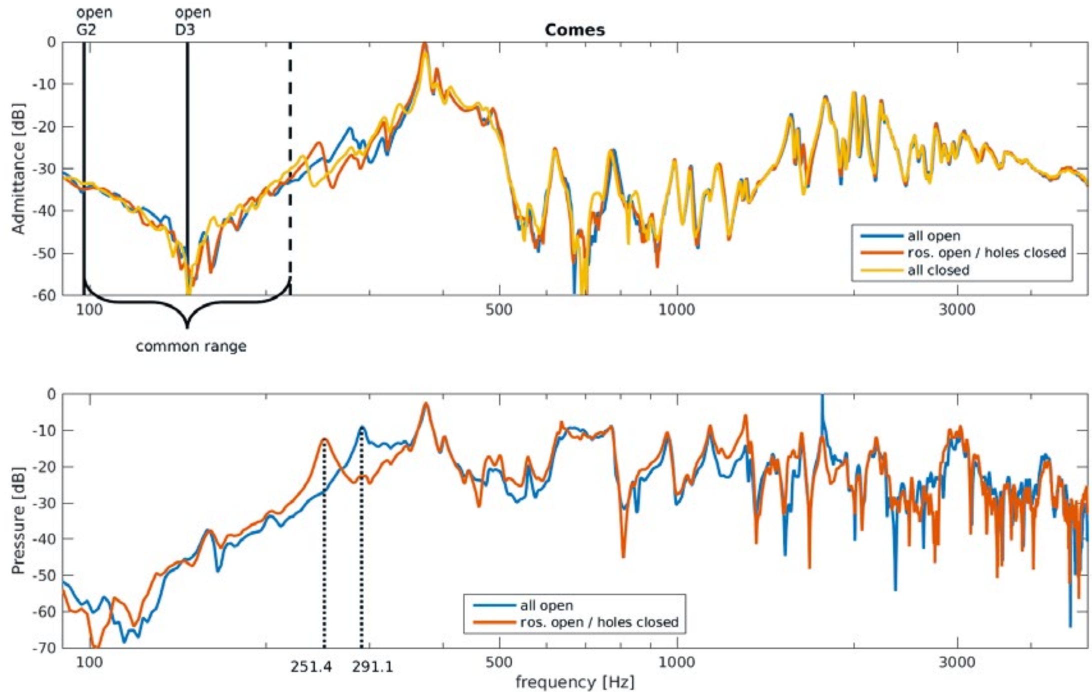

Fig. 11 Comparison of the measured bridge admittance and sound pressure of the Comes rabab for different open-hole configurations (upper rosette and bottom holes).

Discussion

The acoustical properties of rababs have here been investigated using a physical model of a Moroccan *rabāb* design and experimental measurements on three reconstructed historical European rababs. By employing different possible design variants, we focused especially on the effect of additional holes on the instrument's body. These tend to increase the Helmholtz resonance frequency, potentially shifting it to regions above the common playing range of the instrument. This appears to be in contrast to violin-like instruments, where this resonance frequency is deliberately placed close to the frequency of the lowest playable notes.

Contemporary rabab players have reported that, in the absence of holes, a slightly disturbing 'resistance' was presented by some instruments, which was eventually avoided by opening holes and shifting the air resonance to higher frequencies (outside the playing range).[12] While the 'resistance' effect was deemed similar to the minor presence of a so-called wolf tone, no such evidence appears in the measured admittance curves.

As a result, higher support is offered by the instrument's response to the overtones of the played note, with the instruments potentially sounding brighter and more nasal. While this is suggested by the measurements presented here, a comprehensive perceptual analysis of the sounds of diverse rababs (and *rabābs)* would be required to obtain more conclusive evidence.

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Vasileios Chatziioannou *was born and raised in Thessaloniki, where he obtained his BSc in mathematics. In 2004 he moved to Edinburgh, where he received an MSc with distinction in applied mathematical sciences at Heriot Watt University. In 2010 he was awarded his PhD degree for his work at the Sonic Arts Research Centre, Queen's University Belfast. Since 2010, Vasilis has worked at the Department of Music Acoustics at the mdw – University of Music and Performing Arts Vienna, where he teaches and conducts research into the acoustics of musical instruments. He has led two projects on the physical modelling of musical instruments, funded by the Austrian Science Fund (FWF), and the ITN project VRACE, funded by the Horizon 2020 Framework Programme of the European Union. He is also an associate editor of the* Journal of the Acoustical Society of America *and the chair of the Technical Committee on Musical Acoustics of the European Acoustics Association.*

Alexander Mayer *grew up in Vienna and joined the Department of Music Acoustics – Wiener Klangstil (IWK) team in 1993 after graduating from the Höhere Technische Bundeslehranstalt (HTBLA) Wien X technical college. He soon became involved in the development of measurement techniques and analysis equipment in the field of music acoustics. In 2002, Alexander received a full-time contract as a research assistant at the Department of Music Acoustics at the mdw – University of Music and Performing Arts Vienna. In 2004 he graduated as an engineer. Since 2008 he has lectured in scientific methods and measurement techniques at mdw. Thanks to his many years of expertise and extensive practical experience in the research field of musical acoustics, Alexander is heavily involved in many of the Department's research projects.*