

ARE REPLICAS OF NICOLÁS DEL VALLE'S PEAR-SHAPED GUITAR FROM 1850 ACOUSTICALLY MATCHING THE ORIGINAL?

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Abstract:

Replicas of musical instruments typically intend to preserve cultural heritage or to allow people to have a share in instruments with desirable historical or performance properties, such as rare instruments. Three physical copies of a pear-shaped guitar from Nicolás del Valle have been built in 2019, and these are briefly investigated in terms of some main acoustical properties. This short letter briefly reviews the issue of geometric versus tonal copies in the context of plate and instrument tuning, and the achievements in tonal copies, in particular in the market of violins. The three guitar copies are then evaluated. While metrics accuracy in the reproduction process seems to play a role, accuracy in the determination of wood properties and their impact to sound seems to play a less important role. However, these properties can cause noticeable acoustical differences.

Key words:

guitar, replica, acoustics

Resumen:

Las réplicas de instrumentos musicales buscan preservar el patrimonio cultural y permitir que las personas conozcan y puedan escuchar instrumentos de alta calidad con historia, como por ejemplo instrumentos únicos. Tres copias físicas de una guitarra con forma de pera de Nicolás del Valle se construyeron en 2019, las cuales se investigan brevemente en términos de algunas propiedades acústicas básicas. Este breve ensayo sobrevuela el tema de las copias geométricas versus tonales en el contexto de la afinación de placa e instrumento en conjunto con el alcance de copias tonales, particularmente para el mercado de los violines. Se continua con una evaluación de las tres copias de guitarras. Si bien la precisión de las métricas en el proceso de reproducción parece jugar un papel; la precisión en la determinación de las propiedades de la madera y su impacto en el sonido parece tener menor importancia. Sin embargo, estas propiedades pueden causar diferencias acústicas notables.

Palabras clave:

guitarra, replicar, acústica

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INTRODUCTION

Replicas of musical instruments are often motivated to allow a larger multitude of musicians to participate in using high-level musical instruments while they learn and perform with instruments having desired features. While the number or the availability of original instruments is often limited, an appropriate replica allows affordable participation. The level of perfection of copying originals reaches from approximate imitations of models in mass markets to perfect replicas of specific instruments for individual customers. In terms of mass market, even a poor copy of a dreadnought guitar will sound more or less like a dreadnought guitar, and will clearly differ from a mediaeval lute and its copy or from a modern jazz guitar and its cheap factory made copy. At the top end of the market, a knowledgeable and hand made master piece might get very close to an original model and might at the same time reveal minor deviations as well as interesting and desirable sound features on its own, as a result of a months-long piece of work. While judging the perfection of matching an original, inspection of metrics and visual features is objective and seems to be the easy part. Exploring the match of sound and playability features is typically subjective and much more difficult.

In the context of the 2019 temporal exhibition 'PLAY. Ciencia y Música' in the Science Park in Granada, the Granadian guitar makers Aarón García Ruiz and Oscar Muñoz manufactured three replicas of a pear-shaped guitar from Nicolás del Valle, built in 1850. While the motivation of the project was educational in the Science Park - showing the process of manufacturing a guitar in a display workshop - the two guitar makers followed their tradition of craftsmanship. This means that they built the guitars along the technical drawing previously taken from the original and at the same time incorporate their knowledge and experience. For example, crafting the top would be ruled by a given measure for the plate strength, but still the luthiers would deviate slightly from this measure here and there to achieve a uniform stiffness across the top. The two guitar makers worked together on each of the three models, effectively aggregating their knowledge and experience.

The question raises whether the beautifully manufactured guitars are appropriate copies in terms of sound. This is interesting here because there are three copies in place, representing the aggregated experience of two guitar makers. How the resulting sound relates to the sound of the original instrument will be evaluated by some objective acoustical measures.

The guitar makers' objective target

The guitar maker Aarón García Ruiz believes that the original guitar from del Valle is not any longer in its original condition and that the sound, as a consequence, is not any longer the same as intended by the creator. He reports:

“The guitar Nicolás del Valle subject of copy has not arrived to the present intact. In more than one occasion it has been restored and, what is more important, it has been "scraped" (eliminated the varnish with a cabinetmaker blade), and the shellac film has been changed after some of the restorations. This implies a reduction in the thicknesses of the boards that make up the instrument, which undoubtedly were somewhat thicker when it was manufactured. But this original thickness is not already measurable, so we had to stick to a hypothetical proposal.”

There are good examples of restoration, where removing the shellac does not necessarily mean a thinning of the top. But the above statement is grounded on many years of experience in restoring musical instruments. Therefore, Aarón García Ruiz intends to trace back to the original, saying:

“The intention of the project has been to recreate the work, the systems of elaboration of the pieces and the use of materials and techniques that were used in Granada 170 years ago in the construction of guitars. ... We wanted to get instruments that look like Nicolás del Valle's guitar when it was built, not as it is today. We know that it is always a future to carry out this type of approach to the knowledge of ancient instruments, but in any case, it is a proposal as valid and objective as others. The pieces have been worked with hand tools, using the same types of saws, chisels and planes that Nicolás del Valle could use; French polishing has been applied, filling the pore with pumice, in a completely traditional way. The instruments have been tested with nylon strings and alternatively also with gut strings, which were used in the middle of the 19th century in all the instruments of the guitar family.”

And furthermore, in terms of trading between sound and the geometric accuracy of a copy, he states:

“The copies have been made without subjecting us to the slavery of the caliber; in each moment we have worked with the desire to make a theoretical model rather than an exact copy. The boards with which the guitars have been built have been thinned to the thicknesses that we have considered, the two makers, which were adequate according to our extensive experience with materials and guitar construction techniques, thinking about the tuning and type of guitars, and the strings that I should have. Knowing the tradition of the Granadian School, and its way of working pushing the materials to the limit to achieve a good acoustic response, we have used more intuition and testing while manually bending the plates with the hands and thumbs (technique described by Antonio de Torres as his only secret), always taking into account the materials used that have been relatively heterogeneous in their origin. But we have been very conscientious in this aspect, taking into account each plate and its characteristics to assign the thicknesses, alignment of veins

and work of roughing. The only variant that we have not analyzed has been the age of the plates, which reaches differences of more than forty years. This we have noticed extensively when working since very dry wood, crystallized over the years, has completely different characteristics than the recently cut, which is softer and easier to work and bend.”

And in terms of wood selection, he reports:

“In two of the guitars (the B and the C) we have used for the top and spruce *Picea abies* for the box cypress *Cupressus sempervirens* with more than fifty years of drying in both cases (bought from the heirs of Antonio Ariza), while that in the other (copy A) has been used wood with approximately five years of drying. ... in this case the cypress was cut by me in the Albaicin neighbourhood of Granada. For the rest of the woods (Spanish cedar *Cedrela odorata*, walnut *Juglans regia*, Indian rosewood *Dalbergia latifolia*) some material from diverse origins has been used, considering that it has less acoustic importance than the top and the body of the instrument.”

Finally, about the results, he states:

“For us, the construction process of the three instruments has been so important, how it has been developed, and the final visible result, with which we are fully satisfied; to the point where we propose that these copies may be more similar to Valle's guitar in its initial state than it is today, after being restored and modified.”

REVIEW

A recent project aimed at restoring a historical guitar, made by the Casella brothers, Catania, around 1849 (Andreou, et al., 2018). The restorers scanned the geometry and explored the applied materials not only for restoration but also for manufacturing a physical copy of the instrument. After restoration and manufacturing they investigated the acoustical identity between the two instruments using the impulse response method. The response of a structure to a very short impulse reveals enough temporal and spectral features to predict similarities not only of structure borne sound but also of radiated and perceived sound. As a result, the two guitars “have almost similar admittance curves at the range of 200 to 700Hz”, as shown by a frequency plot. Unfortunately, the important range below 130 Hz is not shown or documented in the mentioned publication. This range covers the fundamental air mode and some longitudinal modes across the guitar. Still, the result is impressive, as the copy gains from the diligence of careful restoration rather than from the experience of guitar makers. It is also impressive since the test was conducted after the work has been finished, and the restorers did not seem to take intermediate acoustical measures, nor means or action to finally achieve acoustical identity.

Are “accurate” metrics and material propositions enough to manufacture an acoustical twin? One puzzling observation is that two plates of same measures and thickness coming from the same tree do sound different when knocked at appropriate spots on the plate. This

is even true when the plates come from the same wedge, i.e. they grew side-by-side in the same location within the same log of wood, have the same pattern of annual rings, and have had the same drying process. This is a commonly agreed upon observation, and the mentioned guitar makers and the author observed this again for the pieces prepared for further copies of the del Valle guitar, in the workshop.

This observation explains why the guitar makers, even in this project, incorporated their experience when they smoothen the plate stiffness while taking the given target plate strength of the original del Valle guitar only as an indicator for the general target stiffness of the plate. Smoothen the plate stiffness seems to be important, as wooden plates of “exact” homogenous thickness reveal inhomogeneous stiffness.

This observation is more delicate in violin making as there are, compared to guitar making, far more issues of mutual acoustical coupling of the various components in the instrument. In other words, violin making implies a long list of tuning tasks involving issues of mutual coupling. And the effects of mutual coupling are sensitive to slight variations of modal frequencies. So violin acoustics is a good field to learn from and to derive some benchmarking for making acoustical twins.

A lot of these tuning issues have been researched in the 80ties and 90ties of last century, and important papers are collected in (Hutchins, 1997). To briefly outline a few basics, modal coupling begins within each plate. Fig. 1 shows some fundamental modes of a free rectangular plate. Modes (0,2) and (2,0) will couple due to shear effects that come with bending, effectively resulting in the (0,2) - (2,0) and the (0,2) + (2,0) mode, or X- and O-mode, or #2 and #5 modes, as different researchers and luthiers would call it. This coupling in plates will become more and more prominent as the respective frequencies of the individual modes approach each other. For the shown Sitka spruce plate, the frequencies shifted from 120 Hz (2,0) and 123 Hz (0,2) to 117 Hz (X) and 128 Hz (O), due to coupling. For extensive studies see Caldersmith (1984) among others.

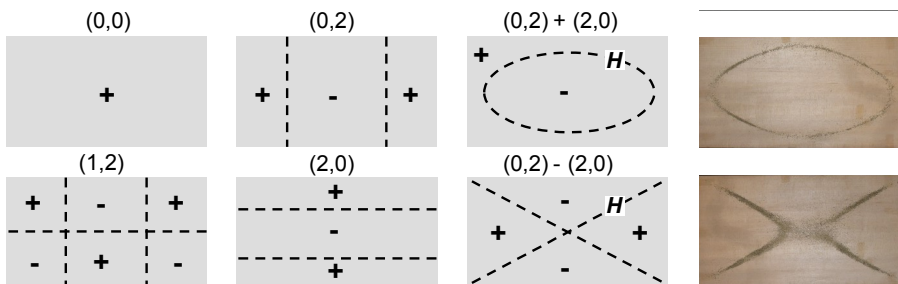


Figure 1. Fundamental modes in rectangular plates, assuming different sound velocities along length and width. Fundamental modes coupling to establish X- and O-modes, and respective Chladni figures in a rectangular spruce plate.

To broaden the spectral response of an instrument, the target is a slight mis-tuning between the initial frequencies, anticipating the shift due to coupling. In violin making, the tuning and coupling is considered for the top and back each on their own, and then additionally between the plates. This is similar in guitar making, as most guitars reveal a somewhat higher knocking tone, when knocking to the back as compared to when knocking at the top. In the assembled violin, the breathing and bending modes of the corpus will again couple, effectively resulting in the so-called B1+ and B1- mode. These two modes are again related to the plate modes, as the breathing comes from the fundamental plate mode. The list of tuning tasks continues with the B1+ or B1- coupling with air modes, and with the finger board coupling with air modes, and many more.

A brief look at some analyses reveals some physics behind the tuning in violin making. Fig. 2 represents one of the many results in the work of Bissinger (2012). The X-mode (#2) and O-mode (#5) of the free top plate predict the B1+ and B1- modes of the assembled violin. In other words, while working on the free plate, the luthier can predict the outcome of the assembled violin. More interesting, different luthiers experience two things while working in their workshop: (i) there are common physical boundary conditions, as the prediction from plate to violin obviously follows some conditions ruled by plate stiffness, and (ii) the different luthiers seem to aim at similar sound targets.

Such aiming at a sound target can be referenced to the long term auditory memory of the luthier, or to reference instruments in the workshop, or to measurements and recordings. An example of sophisticated workmanship is reported by Schleske. Measurements are taken from original instruments, and again during the working process, and also for final documentation, for both structural acoustics and radiated sound (Schleske, 1996). The “tonal copies”, how he calls it, reveal the same modes at the same intensity for the deterministic frequency range up to 700 Hz, as demonstrated for a Domenico Montagnana violin from 1740 (Schleske, 2002). In terms of measures, the Montagnana copy does not really deviate from the original, however, Schleske would have varied for instance plate strength here and there to approach the acoustical target.

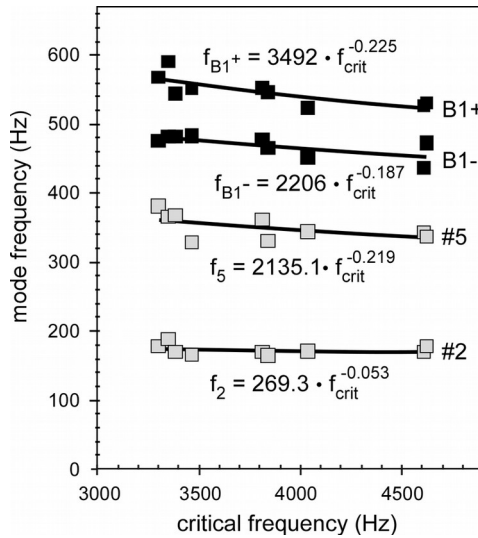


Figure 2. Violin tuning issues summarized for 9 violins. X-mode (#2) and O-mode (#5) of the free top plate predict the B1+ and B1- modes of the assembled violin. The regression with just one parameter, f_{crit} , is possible. The critical frequency f_{crit} also represents plate stiffness. The Figure is taken from the publication (Bissinger, 2012, Fig. 6).

This brief review reveals the different concepts of making a “tonal copy”. Bhatnagar (2009) believes he can achieve the perfect acoustical copy by the perfection of computer tomography (CT) combined with computer aided machine cutting (CMC). Both technologies, when combined, translate metrics of an original to a copy, achieving impressive geometric accuracy. And there are others believing in this method (Stoel and Bormann, 2008; Skollnick, 1997), and there are more projects of this kind out there, some of them documenting valuable old violins, for instance the Violin Project done on three old violins (Zygmuntowicz, 2010). However, with the same CT technology, scientists revealed considerable density differences between violins, even for violins made by the same maker in the same epoch (Borman and Stoel, 2011).

These differences of density directly leads to the question of differences of physical properties in wood in general. Even two pieces of Sitka spruce of same density may still vary in terms of elasticity in longitudinal or radial direction, E_l or E_r . Elasticity is relevant to sound velocity.

$$c_r = \sqrt{E_r / \rho \cdot (1 - \nu_{rl} \cdot \nu_{lr})} \quad c_l = \sqrt{E_l / \rho \cdot (1 - \nu_{lr} \cdot \nu_{rl})}$$

for the longitudinal and radial velocity, c_l and c_r , of sound in a plate, given the density ρ and the Poisson coefficients ν_{rl} and ν_{lr} . For example, the sound velocity measured for two pieces of spruce in the workshop of Licari in Granada varied strongly in the radial direction, see Table 1.

| | c_l in m/s | c_r in m/s | f_{20} in Hz | f_{02} in Hz |
|----------------------|--------------|--------------|----------------|----------------|
| Spruce Val de Fiemme | ~5100 | 1233 | 217 | 102 |
| German spruce | ~5100 | 1570 | 219 | 123 |

Table 1. Examples of measured velocity for two individual samples of spruce in a guitar workshop in Granada, and frequencies for (0,2) and (2,0) modes, when assuming $h = 2.5$ mm thickness in plates of size 0.4×0.5 m. While the frequency for longitudinal bending is almost the same for both wood samples, it differs strongly for bending in radial direction.

Such differences are not surprising, as the Wood Handbook reports differences for different types of spruce (Ross, 2004, chapter 4), as listed in Table 2.

| | E_t / E_l | E_r / E_l |
|-------------------|-------------|-------------|
| Spruce, Sitka | 0.043 | 0.078 |
| Spruce, Engelmann | 0.059 | 0.128 |

Table 2. Ratio of elasticity for different directions in two samples of spruce, according to the Wood Handbook (Ross, 2004).

The difference of 39 % in elasticity ($0.078 / 0.128 = 0.609$) translates to a difference of 22 % in velocity. This means that plates of otherwise same dimensions would also differ significantly in terms of frequency, while taking (Fletcher and Rossing, 1998)

$$f_{mn} = 0,453 \cdot h \cdot \left[c_l \cdot \left(\frac{m+1}{L_l} \right)^2 + c_r \cdot \left(\frac{n+1}{L_r} \right)^2 \right]$$

as a reference to calculate the frequency of (m,n) modes in plates of dimensions L_r and L_l and strength h . For example, the two plates in Licari's workshop, when assuming $h = 2.5$ mm, $L_r = 0.4$ m and $L_l = 0.5$ m, reveal differences of only 4 Hz for f_{20} , but differences of 21 Hz for f_{02} , or 19%, see Table 1. This will certainly mean a difference in terms of coupling, and it will very likely mean a difference in terms of perceived sound. The same difference, provoked by differences in velocity, can also be provoked by changing plate strength h . With the same model, the difference of 21 Hz for f_{02} can be achieved when increasing the strength of the plate coming from Val de Fiemme by a little more than 0.5 mm, from 2.5 mm to 3.03 mm. This is a considerable addition. Of course, the bracing will again change the stiffness and therefore the frequency of fundamental plate modes. However, any initial difference will be carried forward along further assemblage.

Following these arguments, some people might trust in the fidelity of metrics, but there should be an awareness of wood properties at the same time. A guitar maker would probably be very careful claiming that an instrument is a specific replica when the strength of the top plate deviates from the original by more than 0.5 mm, but little measurement is done in the wood selection process. Given these arguments, the working process of Schleske seems to be the most rational approach to achieve both, visual and acoustical twins, at the same time.

Guitar tuning

Some of the tuning issues in a guitar are outlined in the accompanying paper in this issue (Mores, 2019). To summarize: (i) coupling within a plate, either top or back, is similar to violins, achieving coupling between (2,0) and (0,2) modes to yield X- and O-modes. Guitar makers in Granada reported not to listen to a particular tone, or its height, but to the “quality of tone”. This is similar to violin making, as violin makers search for a strongly “ringing” knocking tone. (ii) The back plate has a somewhat higher knocking tone. (iii) The fundamental air mode and the main top mode couple with each other, and again the frequencies shift apart. The air mode around 130 Hz in modern guitars shifts down to about 90 Hz, due to the box flexibility that comes with a somewhat soft top, and the main top mode shifts up to about 200 Hz due to the air compression effect in the cavity (Firth, 1977; Meyer, 1985; Elejabarrieta, 2002). While guitar makers seek to support the lowest open bass string they have to anticipate the result of coupling that results from assembly.

Replicas of del Valle’s guitar

The original guitar is shown in Fig. 3 and the picture to the left in Fig. 4. The three replicas were manufactured by two guitar makers. More precisely, the two guitar makers were alternately on duty in a display workshop in the PLAY exhibition in the Granada Science Park. During their duty time, they did not work for themselves, everyone on his own replica, but they worked together, and both worked on each production step of each replica, Fig. 4, picture to the right.

For the assessment of the vibrational characteristics of the guitars, impulse response measurements were done on the replicas, but also on the original guitar from del Valle. Impulses are introduced by a light-weight hammer (9 grams) on the bone inlay at the bridge, on the bass side between E and A string, and on the treble side between B and E string. The response to these impulses is sensed by light-weight accelerometers (1 gram) at the bridge, in close proximity to the impulse insertion spots. The response in relation to the input force delivers the mobility. Mobility expresses the willingness of a structure to move when exposed to force. Mobility is displayed versus frequency, and therefore reveals mode density and intensity. Fig. 5 captures the response for the original and its three replicas.

From the mobility plot, one can read the main structurally determined modes, most of them in the frequency range below 600 Hz for this guitar. In general, reading across all four plots, reveals the structural similarity. On one hand there is a signature in the graphs that is more or less the same for all four guitars, and this comes from the “identical” geometry in terms of plate size, cavity, bracing, etc. On the other hand this signature seems to be scaled up for the replicas. This comes from stiffness of plates, whether caused by thicker plates of stiffer material.



Figure 3. Top, side, and back view of the pear-shaped guitar, made by Nicolás del Valle in 1850.

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Figure 4. (left) Label of the original, pear-shaped guitar, made by Nicolás del Valle in 1850, and (right) two replicas under construction in the display workshop in the Science Park in Granada.

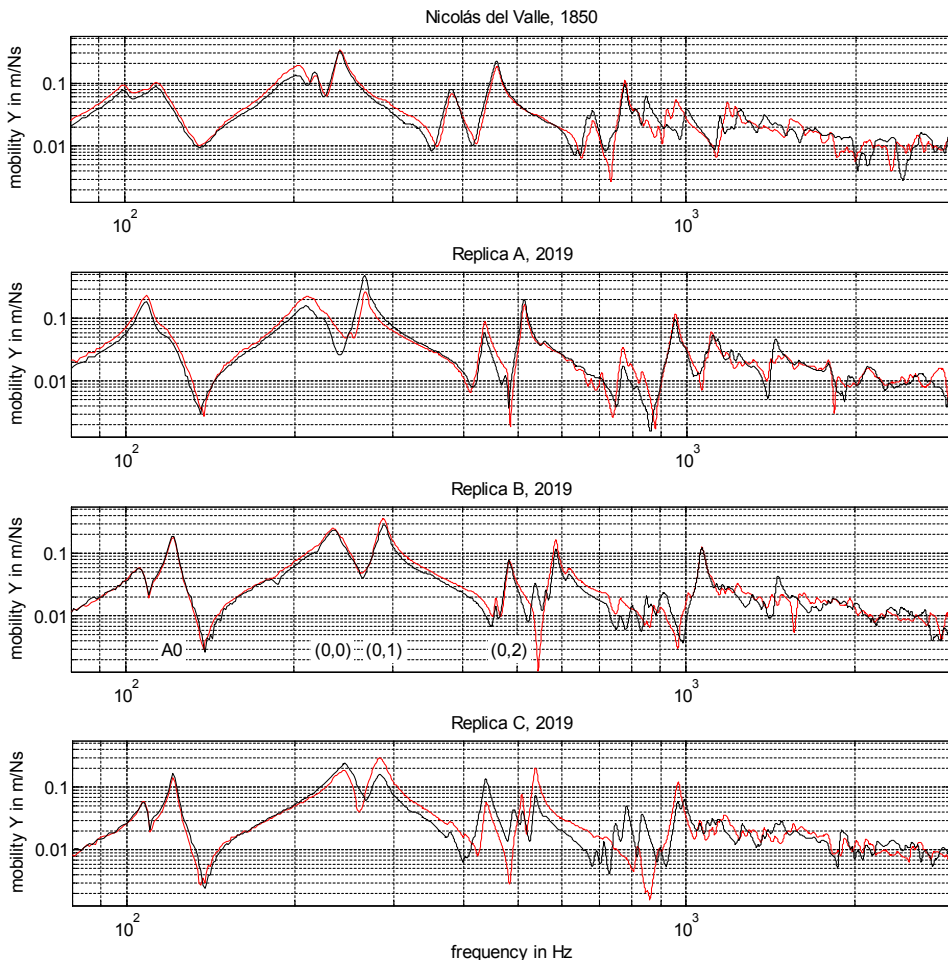


Figure 5. Mobility of the original pear-shaped guitar from Nicolás del Valle, and of its three replica. Mobility measured at the bass side (red) and the treble side (black) of the bridge. Fundamental air mode A_0 , main top mode (0,0), first cross mode (0,1), and the (0,2) mode indicated for replica B.

More specifically, for the range of structurally determined modes, the main modes are indicated in the plot of replica B: fundamental air mode A_0 , main top mode (0,0), first cross

mode (0,1), and one higher order radial mode (0,2). For the cross mode, the modal line crosses the bridge at its center and the bridge is rotating like a seesaw, with the plane of motion perpendicular to the strings. Therefore, with the cross mode, the treble and the bass side are in anti-phase, while with the (0,0) and the (0,2) modes the treble and the bass side are in phase. Table 3 summarizes the frequencies of the main structural modes.

| | f_{A0} in Hz | f_{00} in Hz | f_{01} in Hz | f_{02} in Hz |
|-------------------|----------------|----------------|----------------|----------------|
| Nicolás del Valle | 114 | 203 | 242 | 383 |
| replica A | 109 | 210 | 267 | 436 |
| replica B | 121 | 235 | 290 | 483 |
| replica C | 121 | 246 | 283 | 439 |

Table 3. Frequencies of fundamental modes in the four guitars, as extracted from mobility measurements, see Fig. 5.

A_0 is shifted down for replica A, and seems to merge with the longitudinal mode of the neck, which is clearly separated in B and C, for instance at 106 Hz in B. On the other hand, A_0 is shifted up for replicas B and C, by 7 Hz compared to the original. The cross mode is shifted up by 25, 48, and 41 Hz for replicas A, B, and C. And the shift at (0,2) is even stronger, 53, 100, and 56 Hz. In the plots, one can read the similarity of the structure between original and replica, however, all modes are strongly shifted to higher frequencies in all replica. For instance, another peak at 777 Hz in the original is then found at 956, 1056, and 967 Hz, shifted by 180 to 280 Hz. This shift brings along a change in the spectral distribution of the response.

Coming back to the question of geometric accuracy of a copy and its acoustical consequence, the differences cannot easily be explained by deviations from original geometry. As outlined in the section above, a 0.5 mm increase in plate strength translates to an increase of the (0,2) mode frequency by some 21 Hz for the free plate. Taking such measure as a rough indication also for the assembled guitar, the difference of 43 Hz between original and replica C for the fundamental (0,0) top mode would argue for larger geometric difference than anticipating for replica reproduction. And the manual manufacturing process is far more accurate than necessary. For example, the measures of top plate strength taken in the workshop was 2.270 ± 0.054 mm across the replica. So the standard deviation is one order of magnitude smaller than the estimated difference necessary to explain frequency differences by metrics. Bracings were likewise accurate, for instance the top middle brace has a height of 18.2 ± 0.9 mm.

The guitar makers report that the wood for replica B and C may come from a different pile than for replica A. In the workshop, stiffness was measured in a very simple approach to explore the differences. The bridge of replica A dipped by 0.56 mm under a load of 2 kg while it only dipped by 0.23 mm in replica B. This clearly softer top explains the rather low f_{A0} and f_{00} in replica A. An additional measurement on the original guitar would support the

argument, however, such measurement was too delicate to be executed on the original instrument.

In general it seems that replica A is closer to the original than are replica B or C. And replica B and C are rather acoustical twins to each other than to A or the original, due to stiffer material, probably a stiffer top plate.

To summarize, a good part of the achieved similarity comes from the macro-dimensions of the instrument. The scaling comes from the stiffness. And whether the A_0 splits into two modes in combination with the neck, replica B and C, or into one mode, replica A, is a question of tuning.

Another observation in the mobility plots is the perfection in symmetry while comparing the two responses on the treble and on the bass side this can be read from whether the red and the black traces in each graph of Fig. 5 match with each other. If symmetry was a target for the guitar maker, this symmetry is achieved in the instrument more or less perfectly, most perfect for replica B.

CONCLUSION

A good part of the given structural similarity comes from the geometric macro-parameters, such as size. The scaling of the signature modes comes from the plate stiffness. That means, the given signature modes scale up or down along the frequency axis depending on stiffness. While reasoning the frequency shifts, there are three sources of uncertainty and determination. In the model, a 0.5 mm stronger plate will vibrate with its (0,2) mode at a 21 Hz frequency. The same shift may come from wood selection, as German spruce and spruce from Val de Fiemme might differ by 39 % for the elasticity, translating to a difference of 22 % for the velocity, and 21 Hz, or 19%, for the frequency of the (0,2) mode. Third, the guitar maker targets at homogenous stiffness while sensing local stiffness between the fingers during the manufacturing process.

For the replica, the target was a sound that del Valle might have indented originally, anticipating the assumed thickness reduction that came along with intermediate restoration. So the plate thickness and stiffness results from a replica production based on both, the assumptions about the condition of the original del Valle guitar, and the experience of two guitar makers in restoring and manufacturing guitars. The frequency deviations in the replicas are about 20% and more, see Table 3, and these can be explained by the somewhat thicker plates, fully in line with the anticipations of the guitar makers. At the same time, the guitar makers report that the wood for replicas B and C was more than 40 years older than the wood for replica A, and also somewhat stiffer from the beginning. This also explains the shift to higher frequencies for these replicas as compared to replica A.

In summary, acoustical twins can be build when accurately following the geometries and when using plates with the same material parameters. Deviating material parameters can be compensated for by geometric measures. But even then there will be final deviations, as wood remains inhomogeneous and the guitar makers are challenged by adjusting more than just a few mutually interdependent parameters during their working process.

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