PROCEEDINGS of ISMA 2019
International Symposium on Music Acoustics

13 - 17 September 2019 in Detmold, Germany

Temporal acuity - flamenco guitar versus classical Spanish guitar

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Abstract

Other than classical Spanish guitars, flamenco guitars are capable of projecting rapid beat sequences in pronounced clarity. This relates to what musicians call a fast guitar. This asks for fast attack but also for some kind of damping in between beats, which may follow each other densely by some ten milliseconds in a rasgueado. Temporal features are investigated across guitars of both types to understand whether the flamenco guitar differs from the classical guitar in these aspects. The full data corpus contains impulse responses from more than 60 valuable reference guitars. Attack and decay are extracted from bridge impulse responses and from playing open strings. Additionally, a simple measure represents the speed of sound development across the soundboard. Populations of both types of guitars strongly overlap in these temporal maps and the physics seem to provide only part of the answer, auditory physiology may provide the other part of the answer.

Keywords: flamenco guitar, temporal features

1 INTRODUCTION

Contemporary flamenco and classical Spanish guitars appear to be similar on the first sight, without typical differences for the scale, the plantilla, the volume of the enclosed air, or the strings used. On the contrary, in the times of Torres, the plantillas differed very much from guitar to guitar, and guitars were not necessarily classified flamenco or classical guitars, but rather professional or cheap guitars (1). And even though flamenco *(FG)* and classical Spanish guitars *(CG)* are much more similar today than ever, most of the Andalusian contemporary guitars makers offer them as specific *FG* or *CG* (2). While interviewing some ten different Granadian guitar makers about the differences most of them claim that there is no difference but the action. The action should allow for easy play in both hands: the lasting play of fast pieces should not tire the left hand, and the striking/plugging combined with the golpe should be ergonomically convenient for the right hand. A few guitar makers claim, that the action also determines the sustain and the modulation of tone, i.e. a higher bridge would cause the modulation and sustain that you want for a *CG*. Another difference is the wood used for the ribs and the bottom. While palisander is the typical wood used for *CG*, the much lighter cypress is the typical wood used for *FG*. Some guitar makers say they would even refuse to build a *FG* with palisandro or a *CG* with cypress, some other guitar makers claim that they can use either wood and tune the sound towards either direction.

This brings up the question about desired sound features for *FG* versus *CG*. Interviewing not only guitar makers but also musicians and in particular professional flamenco musicians in Granada, the desired sound features can be summarized in its most simple form as shown in Table 1.

Table 1**.** Some basic sound features in flamenco versus classical guitars.

guitar	classical *(CG)*	flamenco *(FG)*
main focus	melodic sound	percussive sound
sustain	long	short
sound	rich, full	clear
modulation	strong	no
bass	strong	dry

Apart from that, the *FG* has its own typical sound character that cannot easily be described in words, but can be recognized by many players and listeners. A typical element for the percussive play in flamenco is the rasgueado, that is striking the four fingers in a rapid sequence, with as little as some 20 ms between strokes. A *FG* is expected to project such fast sequence with acuity while a *CG* is not. With a *CG*, the four strokes usually kind of merge to

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just one sound comparable to what a bell does when being hit rapidly. On the other hand, a *CG* can develop a beautiful, modulated and rich tone even while playing only simple melodies or even single notes, whereas a *FG* will not necessarily. And even more, a good *CG* provides a range of voices, or registers, that is, the guitar translates variations of manual action into variations of sound. And while there is an even more differentiated expectation of what a *CG* should provide for different epochs of composition, there is a likewise differentiated view on what a *FG* should do for the three main different flamenco performances: accompanying a singer, playing for dance, and playing solo. There are some 30 to 40 styles of singing and some 200 styles of dancing (3). Some professional musicians claim that these even require three different types of flamenco guitars.

All flamenco musicians interviewed in Spain and in Germany agree that accompanying a singer or playing for dance requires a traditional *FG* made of cypress, whereas the solo play benefits from using palisander wood, referring to the skilled solo play of Paco de Lucia, who strongly developed the solo play and is still a reference for virtuous flamenco. The musicians also agree that the *FG* approaches the *CG* in terms of sound features since the days of Paco. This is where the larger question of this research begins: how did the *FG* evolve over the last 100 years? This raises not only ethnological questions (4) but also acoustical ones. Measurements were taken from more than 60 very good to excellent instruments, including reference instruments of history such as guitars from Barranco, Fleta, Pages, Torres, Simplicio, but also best vintage and contemporary guitars from Barber, Bellido, Conde, Contreras, Devoe, Marin, Reyes, and Wiechmann. In this study, six classical guitars and six flamenco guitars are evaluated, three of each from a Hamburg vintage collection of Andalusian guitars, and three of each from contemporary Granadian guitar makers. For a brief spectral evaluation, these will be referenced against Romantic guitars, early romantic guitars, and Torres' guitars. For temporal discussions, mentioned guitars will be referenced against a vintage guitar from Faustino Conde (Madrid), which reveals features of both types of guitars.

2 MEASUREMENT METHOD AND DATA CORPUS

2.1 Measurement matrix

Acceleration sensors (Kistler Type 8778A500, 0.4 grams) are placed at the bass side and the treble side of the bridge, red marks in Fig. 1. The bridge is driven with an impulse hammer (DYTRAN 5800SL, 9.8 grams) between pairs of string attachment locations, on top of the bone inlay, see blue marks. Radiation is measured by pressure microphones located at the far end of the bridge, see green marks, but 10 ± 0.1 cm above the top. For additional temporal features, the top is excited at 13 different locations and the response measured at the bridge.

Figure 1. Setup with positions for hammer excitation (blue), acceleration sensors (red), and microphones (10 cm above green marks), for structural and radiation response from the bridge (left) and for temporal responses of the top (right).

In order to prevent room acoustics to interfere in radiation responses, a dedicated mobile absorber was used on the ground underneath the guitars, featuring 50% absorption at 100 Hz and close to 100% absorption from 200 Hz (5). Measured guitars were placed in the middle of larger rooms, yielding some 20 ms of reflection-free responses.

2.2 Guitar selection

The various guitars from various collections and museums are listed in Table 2.

Table 2. Investigated guitars and some of their features. All guitars made by Andalusian guitar makers if not noted otherwise. All *FGs* have cypress ribs and back, whereas all *CGs* have palisander ribs and back. The only exception is FC64 with palisander ribs and back while build as a *FG* using golpe plate, low action.

acronym	maker / model [location]	year	epoch	type	remark
JB18	Jesus Bellido	2018	contemporary & vintage	*FG*	workshop products 2018
McB18	Mauricio Bellido	2018		*FG*	
MB18	Manuel Bellido	2018		*FG*	
MB18c	Manuel Bellido /Aurea closed hd.	2018		*CG*	
MB18o	Manuel Bellido /Aurea open head	2018		*CG*	
MB99	Manuel Bellido	1999		*CG*	workshop reference guitar
JLB01	Jose Lopez Bellido	2001		*CG*	private vintage collection, Hamburg
MC71	Manuel Contreras [Madrid]	1971		*CG*	
MLB78	Manuel Lopez Bellido	1978		*CG*	
MC81	Manuel Contreras [Madrid]	1981		*FG*	
GPB71	Germán Pérez Barranco	1971		*FG*	
JLB70	Jose Lopez Bellido	1970		*FG*	
FC64	Faustino Conde [Madrid]	1964		*(FG)*	private collection, Hamburg
T89	Antonio de Torres	1889	Torres, 2nd epoch		Museo Barcelona #12107
T83	Antonio de Torres	1883			Centro Doc. Mus. Andalusia
O78	Francisco Ortega	1878	romantic		collect. Daniel Gil de Avalle
T67	Antonio de Torres	1867	Torres, 1st epoch		collect. Daniel Gil de Avalle
T62	Antonio de Torres	1862			Museo Barcelona #625, paper
T59	Antonio de Torres	1859			Museo Barcelona #626
C40	Benito Campo	1840	romantic		collect. Daniel Gil de Avalle
P37	Francisco Pagés	1837			Museo Barcelona
P06	José Pagés	1806			Museo Barcelona #452
M05	Francisco Martinez	1805	early romantic		12 strings, collect. Romanillos
M03	Manuel Munoa	1803			12 strings, collect. Romanillos

3 META-LEVEL SPECTRAL FINDINGS

The structural response of the guitars in Table 2 is documented and discussed in detail by means of mobility plots for the contemporary and vintage guitars (6), and for the Torres, the Romantic and the early romantic guitars (7). One of the major findings of the study on the vintage and contemporary guitars is, that all but one *FGs* have a systematically wider bandwidth at the air mode A_0 compared to *CGs*, and all but one *FGs* have a systematically narrower bandwidth across the (0,0) top mode and the (0,1) cross mode, compared to *CGs*. This answers, in part, the feature of modulation for the *CG*.

From the mobility plots, tuning parameters can be derived. In the context of mutual coupling between top mode and air mode (8, 9, 10, 11) and the guitar makers' desire to support the lowest E string at 82.4 Hz, the mapping of the (0,0) top mode versus the fundamental air mode A_0 is revealing. Regressions across these major tuning parameters suggest a classification of epochs. The plantilla size for Spanish guitars increased steadily until today, left graph in Fig. 2, and the Helmholtz resonance frequency f_0 of the enclosed cavity, calculated for the rigid, non-flexible box, accordingly declined until today, left graph in Fig. 2. Surprisingly, the fundamental air mode A_0 for the assembled, flexible-plates in contemporary guitars does *not* further tend to even lower frequencies when compared to Torres, as could be assumed from the plantilla size and the 'rigid-body' air cavity frequency f_0. Even though Torres' guitar bodies are small in the light of contemporary guitars, their A_0 their reaches further down. This can be explained by the rather large flexibility of Torres' rather thin tops. Contemporary guitar makers returned to thicker tops in favour of the projection potential. This comes from factors of radiation derived from plate thickness as explained in (7).

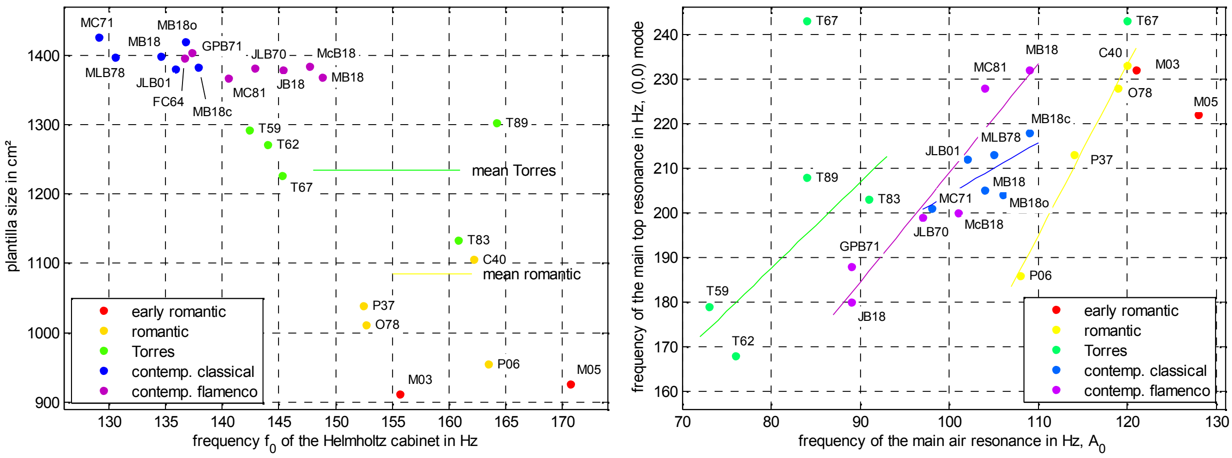

Figure 2. Plantilla size versus frequency f_0 of the 'rigid-body' air cavity for different epochs (left), and frequency of the main top resonance (0,0) versus frequency of the main air resonance A_0 for different epochs. The regression for Torres does not include T67 as there are two very strong peaks in the typical region. Values for mean size of Torres plantillas from (1) for Romantic plantillas from (12).

This brief discussion on meta-level spectral findings has a purpose. As the question is about the evolution of flamenco guitars over the last century, this perspective helps to recognize some fundamental trends. Contemporary flamenco guitars are conceptually very close to contemporary classical guitars. And both are conceptually well distinguishable from guitars of other epochs. So flamenco and classical guitars evolved both into similar directions for the similar reasons, such as bass support or projection. Unfortunately, the author did not find flamenco guitars of the early 20th century in any good condition. The reason is that these guitars initially were cheap guitars for ordinary people; these simple guitars were played extensively with heavy percussive strokes and golpe, and the top was usually typically thinner than that of classical guitars, as it is still the case today. So these guitars had no long future anyway. In lack of reference guitars the discussion about the evolution and the context of the flamenco guitar reduces to a comparison between contemporary classical and flamenco guitars, and only vague trends from vintage to today.

4 TEMPORAL FATURES

From the impulse responses three different temporal features are derived.

4.1 Attack and decay in the radiation impulse response

As outlined in the introduction, the impulses of a fast rasgueado come along in intervals of few 10 ms. In order to expose the distinct impulses, a fast attack and some decay between impulses is assumed to foster temporal acuity. Guitars are now compared along this feature. The attack time is extracted along the conditions of measurement. With few exceptions, there was no way to bring the instruments into free-field conditions. That means that most guitars were measured under semi-reverberant conditions. In most cases, walls and the ceiling were at least somewhat more than 3 m away from the guitar so the first echo is expected around 20 ms after impulse strokes. Reflections from the near-by ground were absorbed by a mobile absorber. While the radiation impulse response lasts longer than 100 ms, the ambient noise floor became the strongest component after some 50 to 100 ms. But after some 50 ms, most of the energy is already radiated. As a measure for the attack time, $T_{r,a}$ represents the time when 50% of the energy is radiated with reference to the total energy radiated over the first 50 ms after strokes. As decay relates to the damping of a signal, the damping of the radiated response is measured. The damping after 20 ms appears to be a telling feature when referencing against the temporal conditions of a rasgueado. The damping is extracted via a 5th order fitting to the logarithm of the envelope. Figure 3 shows attack times versus damping after 20 ms, for the vintage and the contemporary guitars, for both ends of the bridge, bass side and treble side.

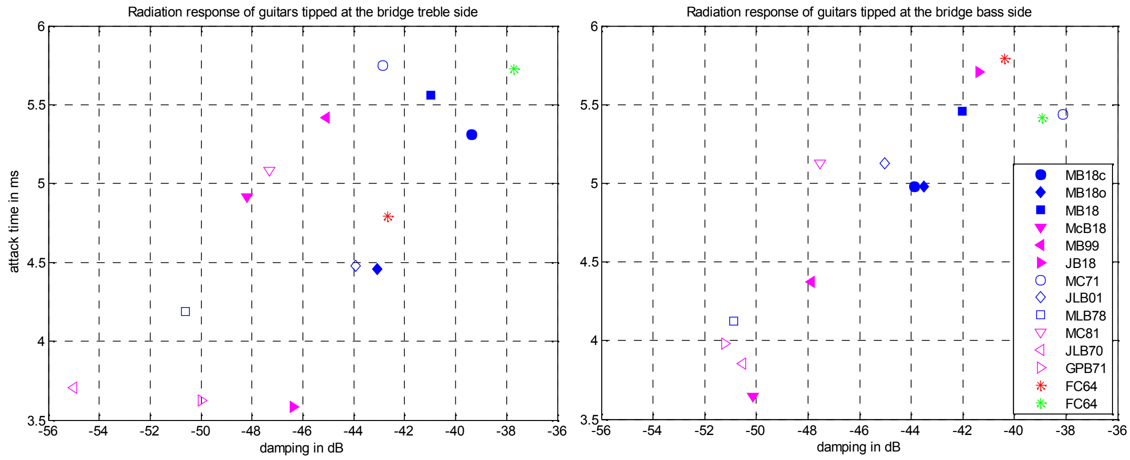

Figure 3. Attack time, i.e. 50% of total energy radiated, versus damping after 20 ms for vintage (non-filled marks) and contemporary guitars (filled marks), classical guitars (blue), and flamenco guitars (purple). The reference guitar FC64 was measured along with other guitars in the various measurement environments, and differences are likely to represent the influence of ambient acoustical conditions.

There are several observations concerning the attack versus damping populations:

(i) Fast attack correlates with damping in a plausible way. The faster the guitar, the more likely the main energy is dissipated early, the larger is the damping. In fact, all guitars rank along the same trend line, well observable in the right graph of Fig. 3.

(ii) There are significant differences between guitars, some radiate 50% of their energy within 3.7 ms others within 5.7 ms. This difference is relevant for the question here, as the rasgueado leaves only some 20 ms between strokes, and a fast attack combined with a fast declining between individual attacks is assumed to sharpen the impulse pattern.

(iii) Populations of *FGs* and *CGs* overlap. There is only a minor tendency to faster *FGs* as compared to *CGs*. In the right graph of Fig. 3, there are four *FGs* clearly faster than five *CGs*. But there is also a rather fast *CG* (MLB78), and there are also two rather slow *FGs* (JB18, MC81).

(iv) Regarding the reproducibility of measurements, the FC64 guitar is a good indicator. This guitar served as reference instrument in a semi-reverberant room (red asterisk in Fig. 3) and in a free-field (green asterisk).

(v) Mentioned tendency for *FGs* is less clear in the left graph of Figure 3, and even less clear when taking the uncertainty of (iv) into account.

(vi) There is likewise no clear tendency whether vintage guitars or contemporary guitars are faster. The populations overlap with the vintage guitars at the faster end and the contemporary guitars at the slower end.

(vii) The FC64, in this representation, is a slow guitar. Interesting to note here, because the same guitar will be at the fast end in another temporal representation.

In conclusion, there is a tendency that *FGs* are somewhat faster than *CGs*, but the employed features are not good enough to clearly separate classes of guitars.

4.2 Spacial coincidence of attack across the top plate

The attack coincidence across the top plate seeks to represent the time it takes to develop the acoustical radiation from the entire top. One would think that the sound velocity of typically more than 5000 m/s in spruce does not leave much room for such a question. Indeed, such speed would imply, that a wave originating from the bridge would reach the far end of the top in less than 0.0001 seconds, which is 2 orders of magnitude smaller than the timelines considered here for musical temporal acuity. However, as has been shown by Bader (13), the waves that travel across the top surrender part of their energy to the ribs, and further on to the back plate. The systemic approach considers an initial phase until the energy is distributed more or less well across the guitar components. The climax of vibration obviously cannot be reached across the entire top at the instant of releasing a string. Indeed, the measurements show that it takes a few milliseconds rather than 100 microseconds to develop the vibrational response at the far end of the top.

This translates to a relevant acoustical cue. The principles of projection suggest that spacial focus grows with the size of a sound source. Of course this is frequency dependent. Secondly, the attack is likely to be more distinct, if the radiation impulse starts concurrently across the entire top. So the size of a guitar top and the concurrency together could be a reasonable temporal feature.

This feature differs from the attack and decay in the radiation impulse response. Of course, the principle of loading a structure with vibrational energy is still the same and the attack and decay should also hold this aspect. However, the bridge impulse response has little chance to represent the concurrency of energy flow and dissipation across a guitar's components.

To derive a useful measure, the vibrational response across the top plate is taken. Assuming that the principle of reciprocal transfer functions applies also for guitar tops, the mechanical impulses are inserted at the various positions across the top while the response is measured at the two positions at the bridge, see the right picture in Figure 1. This measurement approach seemed reasonable, as otherwise the 1 gram heavy sensor on the thin top would impair the results more than applying the same sensor at the rather heavy bridge. The measurement with an acoustical array would be the perfect approach. However, this is impractical: the guitars usually had to stay at the collector's or at the museum's space, and the transport of an entire 100 channel array is more than difficult.

Figure 4 shows the response what is now called local rise time for each of the 13 locations across the top plate. This time is measured beginning with the rising edge of the inserted impulse (50 %), while the impulse is typically 600 to 900 microseconds wide, ending with the peak of the envelope function of the signal measured at the bridge, on either side, bass or treble.

The observations concerning the maps of local rise times are:

(i) The differences between measurements of the FC64 in the semi-reverberant and in the free-field are little. The mean difference across all measurements between semi-reverberant and free-field is 0.21 ms for the FC64.

(ii) The rise time across positions on the soundboard and across guitars ranges from 0.4 to almost 7 ms. Most of the entries are in the range of 2 to 3 ms. Note that even positions 5 and 9 very close to the bridge peak after some 2 ms, for most of the guitars, see brown area rectangles in Fig. 4.

(iii) Propagation is faster along the grain direction / along the direction of bars. This can well be seen with the fast response indicated by entries within black boxes. It is apparent that there is a fast response at the side of the impulse insertion. Positions 3, 4, 6, and 7 for the treble side of the bridge, and positions 7, 8, 10, and 11 for the bass side. It is surprising that even the remote positions 3 and 11 have a shorter rise time than the close-by positions 5 and 9. Note the typical effect of the top plate responding fast in one half and slow in the other half.

(iv) Even the remote positions 2 and 12 show short rise times, see green rectangles in Figure 4. This can be explained by the bars which roughly point in the same direction as the grain of the top plate. The bars act as fast wave guides while vibrations spread through a soundboard.

(v) There is only a slight tendency that *FGs* are faster than *CGs*. For instance, vintage *FGs* in positions 3, 4, 7, and 8 on the bass side are faster than vintage *CGs*. Contemporary *FGs* are faster than contemporary *CGs* only on positions 2 and 4 on the bass side.

(vi) The FC64 is surprisingly fast on both halves, whether the impulse insertion is on the treble side or the bass side. Among all guitars, the FC64 seems to be the fastest. This is evident when checking whether the respective other half is fast as well, e.g. positions 2 and 4 when inserting an impulse at the bass side, or positions 10 or 11 when striking the treble side. Even the remote positions 1 and 13 are surprisingly fast with the FC64. This speed is also very striking when playing the guitar. It is much faster than the other guitars investigated. The fast rise time can be explained by the inverted bracing: the bars of all other guitars are directed towards a crossing point somewhere between the 7th and the 19th fret, the bars of the FC64 are directed towards a crossing point in opposite direction outside the guitar. This means that a bar reaches from a position somewhere between 6 and 7 directly to position 3, and from a position somewhere between 7 and 8 directly to position 11.

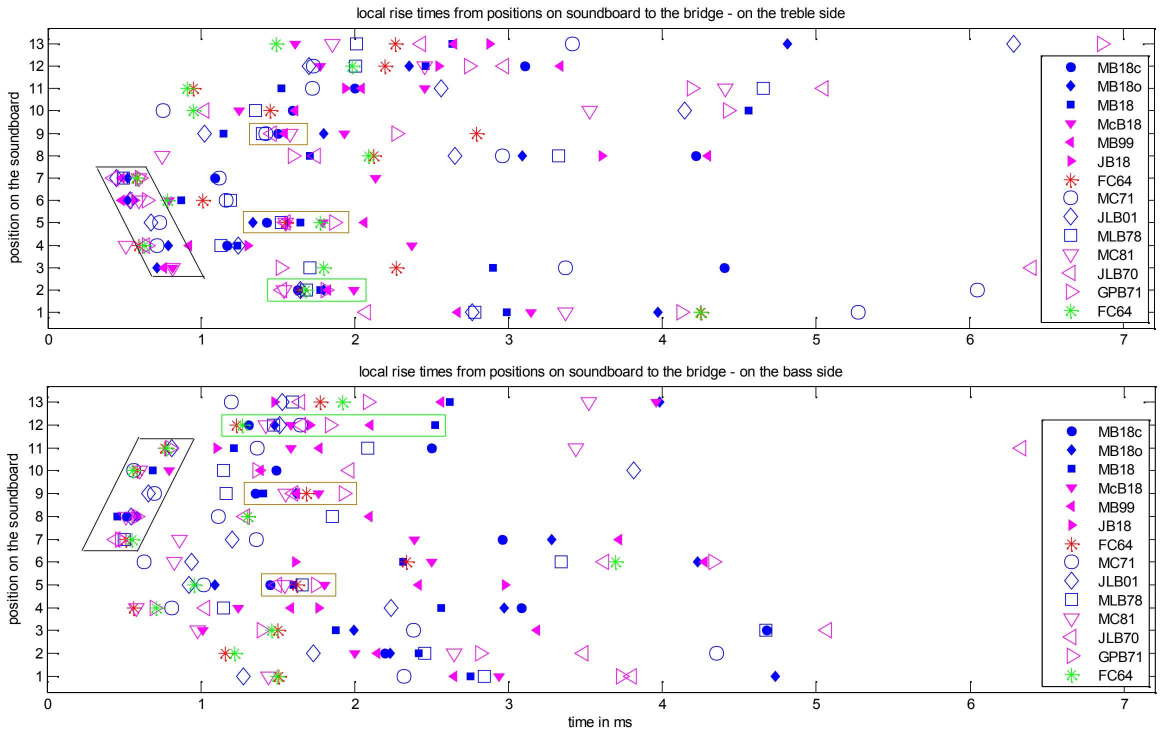

Figure 4. Local rise time for 13 positions across the top plate, or soundboard, for guitars listed in Table 2. Rise time measured from the beginning of the hammer impulse at the specific position to the time of a peaking envelope at the bridge, on either side, bass or treble, see Fig. 1 For details see text. Vintage (non-filled marks) and contemporary guitars (filled marks), *CGs* (blue), and *FGs* (purple). The reference guitar FC64 was measured along with other guitars in the various measurement environments, and differences are likely to represent the influence of ambient acoustical conditions. For rectangles see text.

4.3 Attack and decay in the radiation response to plucked strings

Using the plucked open strings instead of the impulse hammer relates well to the use case of having various impedance matching across strings and guitar bridges. Fig. 5 shows the attack and decay for the contemporary guitars. A comparison with the vintage guitars is not credible due to the strong influence of the room acoustics after 20 ms. All six contemporary guitars were furnished with the same type of new strings on the day of measurement, so the string impedance is the same across guitars. The damping after one second is extracted via a 5th order fitting to the logarithm of the envelope.

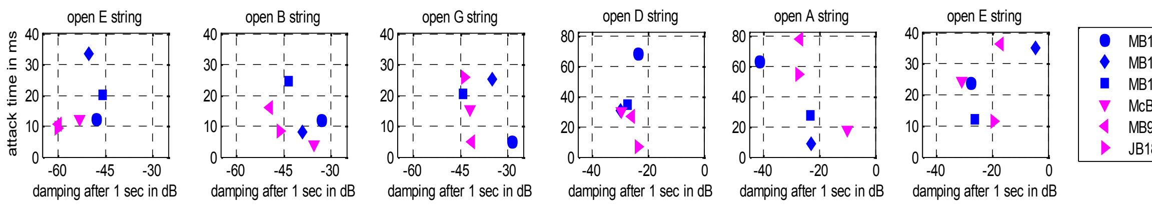

Figure 5. Attack time, maximum of the envelope after releasing open strings at the sound hole, versus damping after 1 sec. for classical guitars (blue) and flamenco guitars (purple).

The *FGs* are clearly faster than the *CGs*, on the treble strings. This can be explained by the somewhat lighter top soundboard in *FGs*. *FG* soundboards are typically some two to four tens of a mm thinner. This difference is more apparent for the treble strings with their lower impedance. The small time advantage may be enough for the ears to perceive the brightness of a *FG*. Reutter (14) studied onset perception and he claims that even tiny temporal advantages in the range of few ms of one spectral band against another one will condition the hearing process such that an advantageous band will dominate even if it is not provided with superior energy.

5 SUMMARY

The meta-level spectral findings suggest that the discussion of flamenco guitars *(FG)* versus classical guitars *(CG)* is a discussion limited to contemporary and vintage guitars, and not to historical guitars from 1900 and before. Three different temporal features lead to various findings: Attack and decay of the bridge impulse radiation responses suggest that *FGs* are somewhat fast than *CGs*, however a clear classification is not supported. Second, the attack in terms of coincidence across the soundboard helps even less in terms of classification. However, this attack measure reveals the function of bracing and it does relate to the guitar's ability to instantaneously translate action into sound. This result relates well to what can be heard across the guitars. Third, attack and decay of plucked open strings support a clear classification. Treble strings on *FGs* have some time advantage. This small advantage may be enough for the ears to perceive the brightness and acuity of a *FG* when taking psychophysics into consideration.

ACKNOWLEDGEMENTS

Guitars were measured from various collections in Spain and Germany. I want to express my honest gratitude to José Luis Romanillos and Marian Harris, to Daniel Gil de Avalle in Granada, to the Museu de la Música de Barcelona, and in particular to Soledad Sánchez Bueno and to Manel Barcons, to the Centro de Documentación Musical de Andalucía in Granada, and in particular to Antonia Riquelme Gómez, for allowing me to measure their Torres guitars and the early romantic guitars. I also thank Hakan Hatay in Hamburg, and Jésus, Mauricio and Manuel Bellido in Granada for allowing me to measure contemporary guitars.

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