Ebony vs. rosewood: experimental investigation about the influence of the fingerboard on the sound of a solid body electric guitar

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ABSTRACT

Beyond electronics, lutherie also has something to do with the sound of the solid body electric guitar. The basis of its sound is indeed the conversion of the string vibration to an electrical signal. The string vibration is altered by coupling with the guitar at the neck. Electric guitar lutherie being a huge topic, this paper focuses on the influence of the fingerboard on the string vibration. An experimental study is carried out on two guitars whose only intentional difference is the fingerboard wood: ebony or rosewood. The well-known "dead spot" phenomenon is observed, where a frequency coincidence of string and structure at the coupling point leads to an abnormal damping of the note. Striking is the different behaviour of each fingerboard wood about dead spots: affected notes, as well as how much they are affected, differ with the wood.

1. INTRODUCTION

Physical studies about the solid body (without soundbox) electric guitar have been mainly focused on electronics, whether it is on the string transduction by the pickup [1,2], the effects and processing chain [3] or the amplifier [4], often with the purpose of doing numerical synthesis. The characteristics of the pickup (transducing the velocity of the string into an electrical signal), effect pedals (transforming this signal with endless possibilities), amplifier (far away from high-fidelity), loudspeakers (reproducing and distorting the final sound) are of course of significant importance. But lutherie is at least partially responsible for the sound. The vibration of the string is altered by the coupling to a moving structure (the guitar) at its ends. The structure may vibrate and exchange energy with the string, like it is the case for e.g. the classical guitar [5] or the harpsichord [6].

The coupling of a string to a structure is described in [7]. The admittance of the structure at the coupling point causes the frequencies and dampings of the coupled-string partials to differ from those in the uncoupled case (string with two rigid ends). This admittance at the coupling point is known as the "driving-point admittance". It is defined by the ratio in the frequency domain between the velocity $V(\omega)$ of the structure at the coupling-point and the force $F(\omega)$ applied on the same point. Driving-point admittance can be obtained by classical measurements on relevant coupling points between the string and the structure, typically on the neck [8,9]. The real part of this driving-point admittance is called the driving-point conductance. It provides additionnal damping to the string [7]. Measurements in [9] qualitatively link a measured high conductance value at a specific frequency with the fast decay of the note at the same frequency, when fretting point and measurement point are the same. Notes affected by an abnormally big damping are known as "dead spots". Damping inhomogeneity among notes is known to be disturbing for the players.

The vibrational behaviour of the structure, seen by the string as end conditions, is influenced by many parameters. Electric guitars can differ in many things [10]: shape of the body and headstock, wood used for body, fingerboard or neck, bridge type, nut material, size and material of the frets, neck profile... Each of these lutherie parts changes the vibrational behaviour of the structure and then may alter the sound.

Fleischer and Zwicker [8] studied a *Gibson Les Paul* and a *Fender Stratocaster*, which have been the two reference models in the electric guitar industry [10]. Differences in modal behaviour are found and are attributed to the symmetry of the headstock. However, these two guitars differ not only in the headstock shape, but also in the wood species, the body shape, ...

In order to draw conclusions about the influence of a lutherie parameter, this parameter should be the only varying one. This paper is part of a broader project [11, 12] aiming at studying the influence of each lutherie parameter taken separately. Here the spotlight is on the study of the fingerboard wood on the sound. An experimental investigation of ebony and rosewood fingerboards is presented. These are two out of three (the other one being maple) typical woods used for solid body fingerboards.

Section 2 gives a simple model of string-structure coupling and its consequences on string frequency and damping. Section 3 describes the experimental protocol, and quantitatively checks the model of section 2: the string damping value can be predicted from the conductance value. Section 4 discusses the change in sound induced by the change in fingerboard wood.

2. MODEL

A simple model of a stiff lossy string connected at one end to a moving body is proposed. The moving-end string model is derived as small perturbations of the stiff string model simply-supported at its two ends. The theory has already been detailed by [7] and it is briefly described here.

Let x be the axis of the string at rest position and y its motion normal to the fingerboard plane. The string is simply-supported at $x = 0$ and $x = L$. It is stretched with tension T. The string is also characterised by its mass per unit length ρ_L, second moment of area I and Young's Modulus E. The dispersion relation is:

$$\omega_n^0 = ck_n^0 \left(1 + (k_n^0)^2 \frac{EI}{2T}\right) \quad (1)$$

where $c = \sqrt{\frac{T}{\rho_L}}$ is the wave velocity, $\kappa = \sqrt{\frac{T}{EI}}$ is the stiffness term and $k_n^0 = \frac{n\pi}{L}$ is the quantized (n is a positive integer) wavenumber for simply-supported end conditions.

The string loses energy through three damping mechanisms: visco-elasticity, thermo-elasticity and air damping. Let ξ_n^0 be a damping coefficient taking into account those three damping mechanisms. It is frequency-dependent because it depends on the partial number n. The damping ξ_n^0 is generally added as the imaginary part of the complex angular frequency, so that the dispersion relation becomes:

$$\omega_n^0 = ck_n^0 \left(1 + (k_n^0)^2 \frac{EI}{2T} - 2j\xi_n^0\right) \quad (2)$$

Yet the string is not simply-supported at its ends. One end is connected to the bridge and the other end is connected at the neck to a fret or to the nut. What [8, 9] showed was checked: most of the time the motion of the end connected to the bridge is small compared to the motion of the end connected to the neck. The bridge end (at $x = 0$) is still assumed to be rigid whereas the other end (at $x = L$) is connected at the neck to the admittance of the moving guitar. The moving end at $x = L$ only causes small perturbation $\delta k_n \ll 1$ to the wavenumber k_n^0, so that the corrected wavenumbers $k_n = k_n^0 + \delta k_n$ are used.

At $x = L$, the string's admittance is defined as the ratio between its velocity and the force being applied on it:

$$Y_{string}(L, \omega_n) = \frac{\frac{\partial y}{\partial t}(L, t)}{-T\frac{\partial y}{\partial x}(L, t)} = j\frac{tan(k_n L)}{Z_c} \quad (3)$$

where $Z_c = \sqrt{\rho_L T}$ is the characteristic impedance of the string. At $x = L$, the string and the structure are connected and must have the same admittance. Letting $Y(L, \omega)$ be the admittance of the structure at the connection point, one has :

$$Y(L, \omega) = Y_{string}(L, \omega) \quad (4)$$

Remembering that $tan(k_n^0 L) = 0$ [1] and assuming that $Z_c Y(L, \omega_n) \ll 1$ [2], equation 3 leads to the expression of k_n:

$$k_n = k_n^0 + \delta k_n = \frac{n\pi}{L} - j\frac{Y(L, \omega_n)Z_c}{L} \quad (5)$$

with which equation 1 becomes:

$$\omega_n = \frac{n\pi c}{L}\left[1 + \frac{n^2\pi^2 EI}{2TL^2} - 2j\xi_n^0 - j\frac{Y(L, \omega_n)Z_c}{n\pi}\right] \quad (6)$$

ω_n are the complex angular frequencies of a stiff lossy string having a moving end. Modal frequency is defined as :

$$f_n = \frac{\mathrm{Re}(\omega_n)}{2\pi} = \frac{nc}{2L}\left[1 + \frac{n^2\pi^2}{L^2}\frac{EI}{2T} + \frac{Z_c}{n\pi}\mathrm{Im}(Y(L, \omega_n))\right] \quad (7)$$

and modal damping as:

$$\xi_n = \frac{-\mathrm{Im}(\omega_n)}{2k_n c} = \xi_n^0 + \frac{Z_c}{2n\pi}\mathrm{Re}(Y(L, \omega_n)) \quad (8)$$

The imaginary part of the body admittance implies a shift in the simply-supported string frequencies, affecting the inharmonicity [13]. Nevertheless, measured admittance imaginary parts on the tested guitars never lead to a frequency shift larger than 1Hz. For this reason this paper only discusses the influence of the real part of the admittance, the conductance.

3. EXPERIMENTAL STUDY

The main effect of string-structure coupling is the damping due to the conductance. The experimental study identifies the conductance terms $C(\omega) = \mathrm{Re}(Y(\omega))$ at the points where the strings couple to the structure [3], that is on the fingerboard.

3.1 The two guitars of the study

This experimental study is intended to determine what differs in the sound when changing the fingerboard wood. The fingerboard should therefore be the only varying lutherie parameter. In order to fulfil this recommendation, a collaboration with instrument-makers was developped. Two guitars were made by luthiers from Itemm [4], a french leading lutherie training-center. The two guitars follow the specifications of the *Gibson Les Paul Junior DC*, a version of one of the two most important solid body electric guitars in history [10]: original shape, quartersawn mahogany for body, neck and head, set-in neck, same equipment (bridge, bone nut, *P-90* pickup). The only intentional difference between the two guitars is the fingerboard wood. One guitar has an ebony fingerboard (E) and the other one a rosewood fingerboard (R). It should be kept in mind that other parameters may differ between the two guitars, mainly because of the wood variability and the handmade process. For schedule reasons, the guitars could not be measured prior to the gluing of the fingerboard.

[1] k_n^0 is the the simply-supported end solution for the wavenumber

[2] The impedance of the structure is much greater than the characteristic impedance of the string, resulting in a reflection of travelling waves in the string at the connection point

[3] Measurements of this section are made at the connected end of the string, so the dependence in L of $Y(L, \omega)$ is no longer specified.

[4] http://www.itemm.fr

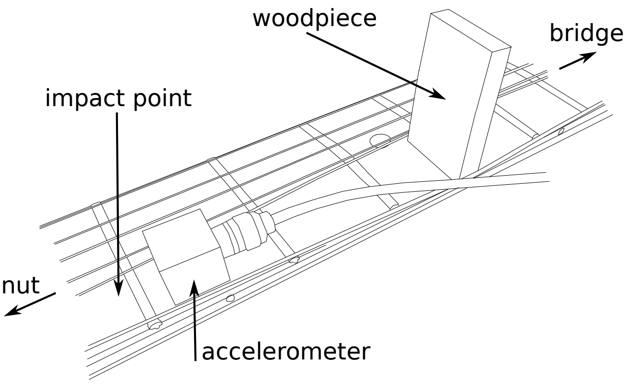

Figure 1. Setup for driving-point conductance measurement along the 5th string's axis, at a particular fret. An accelerometer is put on the one side of the fret. The hammer strikes at the other side of the fret. A very light piece of wood moves aside the strings and allows the accelerometer to stay between the two strings.

Samples of the woods used for the fingerboards were provided. Ebony density ρ_E =1180kg.m^{-1} and rosewood density ρ_R =751kg.m^{-1} are simply measured. Longitudinal Young's moduli $E_E = 3.02\ 10^{10}$Pa and $E_R = 2.30\ 10^{10}$Pa are identified with simple bending test. The two fingerboard woods have different characteristics: fitting the neck with one or another fingerboard wood may then change the vibrational behaviour of the instrument.

3.2 Experimental setup

The experimental setup is sketched in figure 1. The conductance is measured at every potential coupling point between string and structure, that is at every fret-string crossing on the neck. As in [9], only the conductance normal to the plane of the fingerboard is studied. Only the coupling of the string polarisation in this direction is studied in this paper. As usual, force $F(\omega)$ is applied with an impact hammer equipped with a force sensor, and velocity $V(\omega)$ is measured with an accelerometer. Impact and measurement points must be as close as possible in order to obtain actual driving-point conductance. The modal domain (where peaks and modes are well identified) is from 20Hz to 700Hz. The useful impact bandwidth is from 20Hz to 2000Hz. It is decided to consider the coupling of only the fundamental frequency with the structure, so that $n = 1$ in all equations of the section 2. The guitar is laid on elastic straps supported by a frame. Resonant frequencies of the system {frame-straps} is below the resonant frequencies of the guitars, so that this setup provides a good approximation for free boundary conditions. Modeling clay is put on the pegs and on the screw of the truss rod to prevent them from vibrating. Paper is used to avoid string vibrations, which are unwanted here for the study of the guitar only.

Section 3.3 experimentally checks the model of section 2.

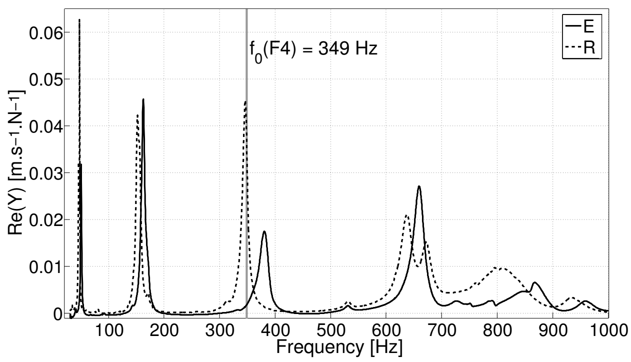

Figure 2. Driving-point conductance at the 6th fret along the 2nd string's axis. Solid line is used for the guitar E and dashed line for the guitar R. Gray line highlights the fundamental frequency of the F4 played at this place.

3.3 Validation of the model

In order to validate the model of section 2, a simple check is done. Figure 2 is an example (further discussed in section 3.4) of measured driving-point conductance: here at the 6th fret along the 2nd string for both guitars. The corresponding note is F4 with fundamental frequency f$_{F4}$ = 349Hz. This note is also recorded by picking the string with a guitar pick, fretting the 6th fret with a capo and taking the output signal of the guitar pickup. Figure 3 shows the temporal evolution of the fundamental of this note. This temporal evolution is extracted from the recorded signal. It is obtained by computing a short-time Fourier transform of the signal and determining the envelope of the bin centered on the fundamental frequency. The time constant τ, defined as the time needed for the amplitude to get divided by Euler's number e, can be estimated from the fundamental envelope signals for guitars E and R. The estimation of the global damping terms $\xi^E_{F4} = (2\pi f_{F4}\tau^E_{F4})^{-1} = 2.8\,10^{-4}$ and $\xi^R_{F4} = (2\pi f_{F4}\tau^R_{F4})^{-1} = 1.4\,10^{-3}$ is straightforward. Superscripts "R" and "E" refer to guitar R and E respectively. Subscript refers to the note.

Identical string sets provided the string for both guitars. String damping ξ^0_{F4} is then assumed to be the same for both guitars. The magnetic pickup could be a cause of string damping as well. Since the guitars are equipped with pickups of the same model series, the magnetic damping is assumed to be the same for both guitars. This magnetic damping can be included in ξ^0_{F4}. According to equation 8 with $C(\omega) = \mathrm{Re}(Y(\omega))$, one expects :

$$\xi^R_{F4} - \xi^E_{F4} = \frac{Z_c}{2\pi}\left[C^R(2\pi f_{F4}) - C^E(2\pi f_{F4})\right] \quad (9)$$

Estimating the conductance values from measurements presented in figure 2 ($C^E(2\pi f_{F4}) = 1.9\,10^{-3}$m.s^{-1}.N^{-1} and $C^R(2\pi f_{F4}) = 3.2\,10^{-2}$m.s^{-1}.N^{-1}) leads to:

$$\xi^R_{F4} - \xi^E_{F4} = 1.1\,10^{-3} \quad (10)$$
$$\frac{Z_c}{2\pi}\left[C^R(2\pi f_{F4}) - C^E(2\pi f_{F4})\right] = 1.0\,10^{-3}$$

ξ^0_{F4} can be identified by subtracting the term $\frac{Z_c}{2\pi}C(2\pi f_{F4})$ from the experimental ξ_{F4}. The line with crosses in figure

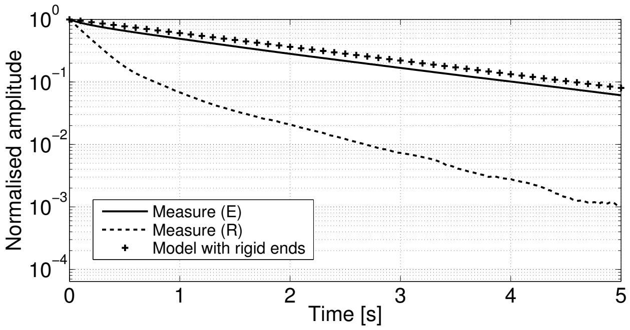

Figure 3. Temporal evolution of the fundamental frequency of the F4 (6th fret and 2nd string) played on both guitars. Solid line is for guitar E, dashed line is for guitar R, crosses show the computed decay of the same string with rigid ends.

3 is the decay curve with identified $\xi^0_{F4} = 2.3\ 10^{-4}$.

The small difference between the two lines of equation 10 can be explained by our estimation of τ, and by the accuracy of our measurements. Nevertheless, the two values are quite close and the model of section 2 is validated.

3.4 Observation of dead spots

Figure 2 shows that at the fundamental frequency of the note, the conductance takes a low value for the guitar E. Thus the factor $\mathrm{Re}(Y)$ in equation 8 is small and so should be the string damping due to coupling with support. This is checked in figure 3 and in the calculations of section 3.3: the experimental computed decay is close to the intrinsic decay (i.e. the rigid-ends case).

On the other hand, figure 2 shows a high conductance value for the guitar R. Figure 3 and calculations of section 3.3 confirm the "abnormal" damping of the fundamental. This damping is indeed higher for the guitar R, and the decay curve exhibits two slopes instead of the single slope decay for "normal" cases.

These two phenomena are consistently checked on the two guitars: a low conductance value leaves the note's decay unperturbed (live spot), a high conductance value makes the decay of the note shorter (dead spot).

When looking at other notes, it is found that both fingerboards exhibit dead spots. However, the note studied in this section showed a difference between the two fingerboard woods: for the same note at the same place on the neck, a guitar exhibited a live spot whereas the other exhibited a dead spot. Section 4 deals with the differences in sound that may appear between the two guitars.

4. SOUND DIFFERENCES BETWEEN THE TWO FINGERBOARDS

The two fingerboard woods lead to the same dead/live spot phenomenon. However, it does not break out the same way depending on the instrument.

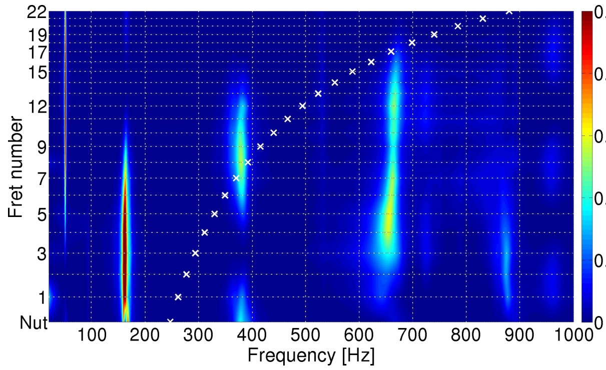

Figure 4. Guitar E: driving-point conductance values in the frequency range [20Hz–1000Hz] for all frets along the 2nd string. White crosses spot the fundamental frequencies of the notes played at each fret of the 2nd string. Unit of conductance is $m.s^{-1}.N^{-1}$.

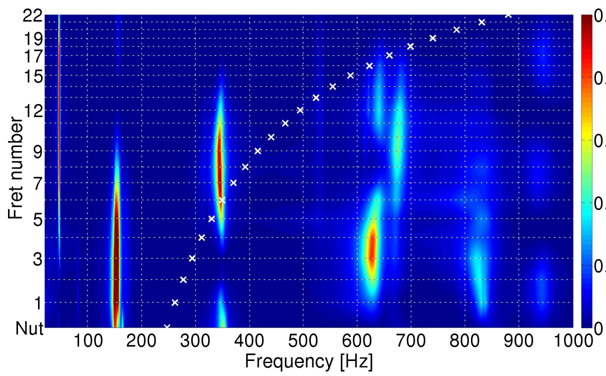

Figure 5. Rosewood-fingerboard guitar: driving-point conductance values in the frequency range [20Hz–1000Hz] for all frets along the 2nd string. White crosses spot the fundamental frequencies of the notes played at each fret of the 2nd string. Unit of conductance is $m.s^{-1}.N^{-1}$.

4.1 Dead spot location

Section 3.4 indicates that a difference between the two guitars is the places where dead spots occur. Since the representation of figure 2 is hard to handle if one wants to have an overview of every fret of one string, figures 4 and 5 propose a synthetic view of the string-structure frequency coincidences, a "dead spot map". The frequency-dependant driving-point conductance values at every fret along one string are represented on the same plot. Conductance value is transcribed as a continuous color coding from blue (very low conductance) to red (conductance peak). For each fret, the fundamental frequency of the note is plotted with a white cross. Hence, whenever a white cross gets close enough to a red spot, a dead spot is reached.

Figures 4 and 5 can be used to quantify the number of dead spots of a guitar. Here on the 2nd string, the rosewood-fingerboard guitar has one dead spot (6th fret) and none at any other place. "Corresponding" dead spot for the guitar E is moved to the 7th and 8th frets. A first remark can be done, when looking at the "dead spot maps" for all six strings (five are not showed in this paper): the number of

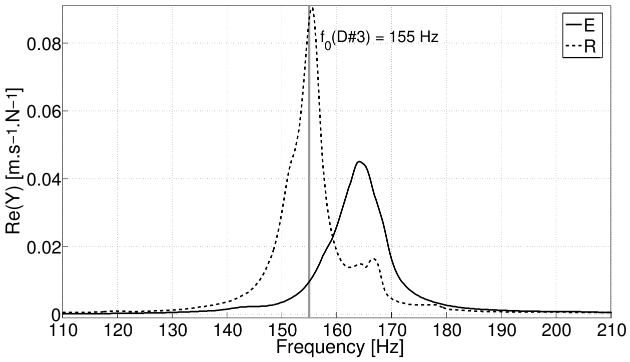

Figure 6. Driving-point conductance at the 1st fret along the 4th string's axis. Solid line is used for the guitar E and dashed line for guitar R. Gray line highlights the fundamental frequency of the D#3 played at this place.

dead spots is roughly the same between the two guitars, but their locations often slightly (one or two frets) differ.

A second remark is that the conductance peaks (for example figures 4 and 5 around 400Hz and between 600Hz and 700Hz) seem to be higher for the guitar R than for the guitar E. This is the purpose of section 4.2.

4.2 Dead spot dangerousness

Another kind of difference between the two fingerboard woods is the amplitude of conductance peaks, that is the potentially high damping of the note. That is what we call the "dangerousness" of a dead spot. Most of the measurements show that higher values of driving-point conductance are reached for the rosewood-fingerboard guitar. Figure 6 illustrates this tendency. It shows the measurement at 1st fret along the 4th string for both guitars. The conductance at the frequency of the note (D#3,155Hz) is high for both guitars. Estimation of experimental damping coefficient ξ as in section 3.3 leads to $\xi^E_{D\#3} = 1.0\ 10^{-3}$ and $\xi^R_{D\#3} = 2.4\ 10^{-3}$ in this case. $\xi^0_{D\#3}$ is estimated as in section 3.3: $\xi^0_{D\#3} = 3.0\ 10^{-4}$. For both guitars, $\xi_{D\#3}$ is much higher than $\xi^0_{D\#3}$: this clearly reveals a common dead spot. However, the dead spot is more pronounced for the guitar R than for the guitar E. Guitar R's conductance peak is closer to the frequency of the note than guitar E's one, and guitar R also has a higher peak guitar E's one.

Whatever the tuning (determining the frequencies of the notes) is, the string-structure coupling still occurs because the neck conductance still takes non-zero values. In order to characterise this conductance amplitude difference tendency between guitars E and R in a more tuning-independent way, a mean conductance value is computed. For each measurement (each fret) along a string, the mean of the conductance is computed in the frequency range [20Hz–2000Hz]. Figure 7 presents these computed mean conductance values as a function of the place on the neck along the 2nd string. For every fret the guitar R clearly stands out from the guitar E with systematically higher mean conductance. This would mean that whatever the tuning is, the rosewood-fingerboard guitar is likely to grasp more vibrating energy from the string.

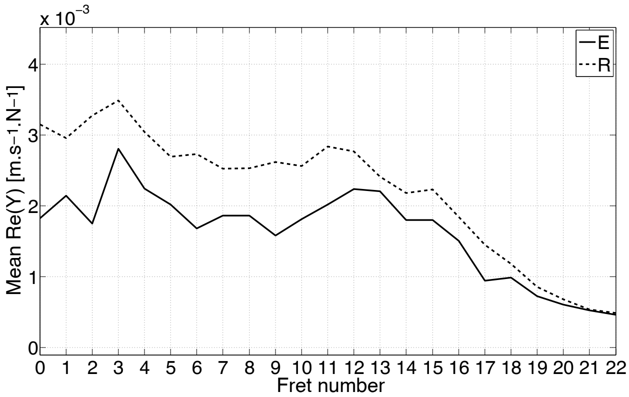

Figure 7. Mean value of conductance in the frequency range [20Hz–2000Hz] as a function of fret number/measurement place along the 2nd string. Solid line is used for the guitar E and dashed line for the guitar R.

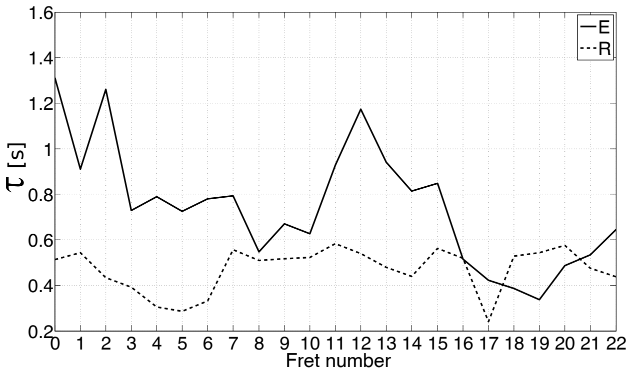

Figure 8. Computed time constants τ for each note of the 2nd string. A bandpass filter ([20Hz-2000Hz]) was applied to each note. Solid line is used for the guitar E and dashed line for the guitar R.

In figure 7 it can be seen that above 15th fret, the two curves become closer and the mean conductance tends to become smaller. This is because 15th fret and upper frets are close to the neck-body junction, an area where the neck motion is smaller.

These mean conductances can be linked to the computed time constants τ for each note along the 2nd string showed in figure 8. This computation is slightly different from section 3.3: a bandpass-filter (20Hz to 2000Hz) is applied to the pickup signal and τ is computed from this filtered signal. Guitar E almost always has a higher time constant. The smaller damping (for every partial in the frequency range [20Hz-2000Hz]) due to the smaller mean conductance for guitar E results in a higher time constant τ.

The mean conductances and the time constants are computed along the five other strings. The tendency is confirmed: the guitar E almost always has a lower mean conductance value and a higher time constant. Rosewood might then perturb the string more than ebony.

5. CONCLUSION

Previous results on the influence of the structure on the vibration of the string have been confirmed. Because the vibrational behaviour of the electric guitar is highly dependent on the lutherie parts, which are numerous, it was decided to focus on the influence of a single lutherie parameter: the most prominent difference between the two guitars of the study was the wood of the fingerboard (ebony or rosewood). Comparative study of sound and driving-point conductance on these two guitars indicate that the wood of the fingerboard may have an influence upon the:

- **dead spot location:** the spatial and frequency coincidence of string and guitar resonances happens at different places depending on the fingerboard wood
- **dead spot dangerousness:** when this coincidence happens, the string damping may be bigger for rosewood-fingerboard guitar

Experimental investigation about dead spots and the related discussion are naturally not only valid for the fundamental of the string but also for partials. As equation 8 shows, each string partial may couple with higher structure modes. Hence the timbre is affected by the fingerboard.

The sound differences that may be induced by the change of fingerboard wood can then have consequences in:

- **instrument-making:** the guitar maker could attempt to change the resonance coincidences: for example fingerboard thickness, shape (the so-called "slim" and "slapboard" fingerboards by Fender) or sawing angle are parameters changing the modes of the structure. Hence the instrument-maker can reduce the differences between the woods or on the contrary increase them.
- **playing:** the same note can be played at different places on the neck. Depending on the location and dangerousness of the dead spots, the player may be forced to avoid certain places on the neck and to conform his playing to the guitars' sound.
- **tuning:** actually, the frequency coincidence between the string and the structure depends on the tuning of the string. In order to avoid a too strong coupling, the guitar player can slightly change the tuning of the strings. This could be an explanation to the fact that some guitar players say that a guitar sounds better with a special tuning (e.g. all the strings a whole-tone lower) than with the standard tuning A-440Hz.

A perceptual study involving the two guitars of this paper has been carried out. The analysis is in progress and is expected to tell us to what extent the differences found here are perceptible for the guitar player.

Acknowledgments

The authors pay a special tribute to the luthiers Vincent Charrier, Loïc Keranforn, Lisa Marchand, Bela Pari, Alexandre Paul and Julien Simon and warmly thank as well Yann-David Esmans, Fred Pons and Pierre Terrien from Itemm. The efficient mediation of Vincent Doutaut made the collaboration with instrument-makers possible.

The authors also thank Rémi Blandin for his helpful contribution to the measurements on the guitars, and Benoît Navarret for fruitful discussion.

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