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The influence of plectrum thickness on the radiated sound of the guitar

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It is generally thought that the human ear is very sensitive to subtle changes in sounds. In the context of musical instruments, one important aspect to study is how much the physical attributes of any given instrument have to differ so that a human can perceive a difference in the produced sound. In the case of the guitar, it is unquestionable that when the string is plucked at a particular position, some of the differences on the produced sound of the instrument are introduced by changes in how the player plucks the string (playing technique). However, given the wide variety of plectrum types, materials and thicknesses, it is hypothesised that the player is not the only parameter that influences the sound, but that the plectrum itself plays a significant role in the sound production. This paper presents a study whereby a guitar is played with three plectra of different thicknesses with an artificial plucking machine. The radiated sound is recorded, and subsequently analysed using the program SNDAN. Physical and psychoacoustical attributes of the sound are calculated from the resulting analysis. A thorough comparison of these results obtained for the three different plectra is presented and discussed.

1 Introduction

Musicians are faced again and again with the question of which factors have an influence on the sound they produce with their instrument, and how they can take advantage of them. We bring our attention to an element of the guitar which, although has not received much attention in the literature, we believe is nontheless relevant to the sound production of the instrument: the plectrum. Given the fact that plectra are found to be made in a wide variety of forms, materials and thicknesses, it is easy to speculate that these parameters can indeed influence the way the instrument sounds. This study examines whether plectra of different thicknesses influence the radiated sound of the guitar. The motivation of this work is to find out how a guitarist can influence the sound of the instrument by selecting the right plectrum.

An extensive search in the literature did not reveal any studies that have investigated the role of the plectrum itself in the sound production of the guitar. Two groups of authors (Woodhouse [9, 10], Cuzzucoli and Lombardo [4, 5]) have developed physical models of the guitar that in some extent include the player's gesture, but both assumed that the string would be plucked with the player's finger, and not with a plectrum. However, [5] modeled the finger as having mass, damping and siffness: such model could easily be transfered to a plectrum.

From what is known nowadays of the sound production of the guitar, there are several mechanisms that influence the radiated sound of the instrument:

- the plucking position along the string (see for example [6])
- the initial displacement of the string, which is related to the plucking force ([5])
- the shape of the string deformation before being released, which is related to the characteristics of the plucking object ([2])
- the direction of plucking ([2, 9])

The main objective of this work is to find out how the plectrum thickness can affect one or more of these parameters, and thus resulting in a different sound. If we intend to study the influence that the plectrum has on the sound of the instrument, parameters such as the plucking position, direction and force should be kept constant, and the normal variability that a human player introduces while plucking should be removed as far as possible. This is the reason why we chose to do this study with the aid of an artificial plucking machine [1].

Figure 1: Artificial plucking machine used to record the sound of the guitar plucked with three plectra of different thicknesses

This paper is organised as follows: Section 2 presents the method and equipment used to record the guitar sounds with plectra of three different thicknesses. Section 3 describes the analysis done to the raw recordings. Section 4 explains the calculations that were done based on the previous analysis, that yielded to the results presented in Section 5. Section 6 presents some general conclusions.

2 Recordings of guitar signals with plectra of different thicknesses

The guitar used for this experiment was from the brand Larrivée Model LV-03RE. The strings were from the brand D'Addario, model EJ26 Custom Light, which were fitted new two days before the recording took place. Three plectra from the brand Dunlop, model Derlin 500 Standard No. 410 were selected with the following thicknesses: 0.46 mm, 0.96 mm and 2.00 mm. The open strings E_4 (unwound) and G_3 (wound) were plucked at a distance of approximately 13 cm from the bridge by means of an artificial plucking machine, which is shown in Figure 1. With the aid of the machine, it was ensured that each plectrum was placed on the same position along the string, and that the plucking force was constant. Each plectrum was placed so that its tip was 2 mm below the string. The strings that were not played were damped with a piece of foam.

The radiated sound was recorded through an AKG microphone model C414 B-ULS which was placed beside the guitar (see top of Figure 1). The microphone was then connected to a Phantom preamplifier model MPA 2017. The level of the signals from the preamplifier was adjusted to be as high as possible without saturating. This adjustment was done once at the beginning of the measurement. The output from the preamplifier was then connected to an ADAT HD24 digital recorder, which converted the signals from ana-

[1]Developed by Werner Grolly.

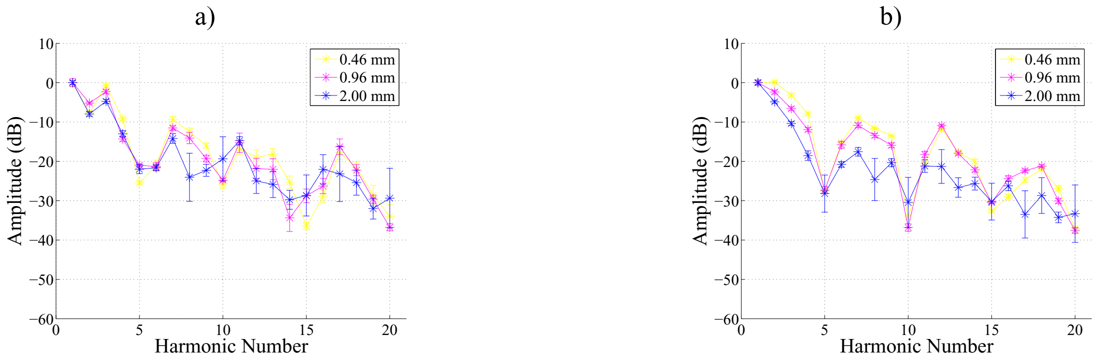

Figure 2: Normalised average spectra for note E_4 from a) microphone and b) pick up

log to digital, and into an optical interface, before being connected to an RME computer sound card model DIGI96/8 PST. The sounds were recorded with the aid of the program Sony Sound Forge v 7.0. Signals from the pick up of the guitar were also recorded in the same way, but the preamplification stage was skipped. The file recorded in Sound Forge was a stereo file, one channel corresponding to the radiated sound recorded via the microphone, and the other to the signal taken from the pick up of the guitar. The sampling frequency was set at 44.1 kHz. Each string was plucked 25 times.

3 Analysis of sounds

The recorded audio files were first split into mono files, one corresponding to the signal from the microphone, and the other to the signal from the pick up. Then each of the 25 notes played was saved in its own .wav file, each with duration of 2 seconds, and analysed using the program SNDAN [1], provided by James Beauchamp from the University of Illinois at Urbana-Champaing. This program performs a pitch-synchronous phase vocoder analysis, i.e. it tracks the amplitude of each harmonic and the frequency deviations of the signal relative to integer multiples of the analysis frequency f_a provided by the user.

The analysis frequency f_a was selected initially to be 329.63 Hz for the note E_4, and 196 Hz for the note G_3, both corresponding to the nominal playing frequency of each note, according to the frequencies of an equally tempered scale. Once the analysis was done with this initial value of f_a, the mean frequency deviation relative to f_a of the fundamental (MFD_1) was calculated as follows:

$$MFD_1 = \left| \frac{\sum_{n=1}^{N} \Delta f_1(n \cdot dt)}{N} \right| \quad (1)$$

where Δf_1 is the frequency deviation of the fundamental relative to f_a, $dt = \frac{1}{2f_a}$ is the interval in seconds between each time frame and the next, N is the number of time frames taken in the analysis, and $N \cdot dt \approx$ 2s.
Whenever $|MFD_1| > 1$, a new f_a value was calculated by (algebraically) adding the MFD_1 to the original analysis frequency, so that:

$$f_{a_{new}} = f_a + MFD_1 \quad (2)$$

This is because the performance of the analysis done by SNDAN is best when f_a is set as close as possible to the frequency of the fundamental.

4 Calculations

Three physical and two psychoacoustical attributes of the sounds were calculated from the analysis files. The details of each calculation are described in the rest of this Section.

4.1 Physical attributes of the sounds

4.1.1 Average amplitude spectrum

The program SNDAN provides a snapshot of the spectrum of the signal at every time frame. The average over time of the amplitude of each harmonic was calculated as follows:

$$A_{k_{average}} = \frac{\sum_{n=1}^{N} A_k(n \cdot dt)}{N} \quad (3)$$

where A_k is the amplitude of the k^{th} harmonic. The resutling average amplitudes were then normalised with respect to the average amplitude of the first harmonic $A_{1_{average}}$.

4.1.2 Tristimulus diagram

The method described by Pollard and Jansson [8] was used to specify musical timbre. They generated the tristimulus diagram by calculating the loudness at different frequency bands. However, in this paper it was chosen to take the sum of the amplitude of the harmonics in each frequency band, instead of the loudness, to see how the spectrum itself evolves over time. Thus, it is in this case considered to be a physical attribute, rather than a psychoacoustical attribute.

The coordinates of the tristimulus diagram presented in this paper are: the amplitude of the fundamental, the amplitude of harmonics 2, 3 and 4, and the amplitude of harmonics 5 to K, where $K = \frac{f_s}{2f_a} - 1$ is the maximum number of harmonics that a signal with sampling frequency f_s can have. The coordinates x, y and z are calculated as follows:

$$A_{total}(t) = A_1(t) + A_2^4(t) + A_5^K(t) \quad (4)$$

$$x(t) = \frac{A_5^K(t)}{A_{total}(t)} \quad (5)$$

$$y(t) = \frac{A_2^4(t)}{A_{total}(t)} \quad (6)$$

$$z(t) = \frac{A_1(t)}{A_{total}(t)} \qquad (7)$$

where $A_{total}(t)$ is the total amplitude of the sound at time t. As $x + y + z = 1$ at any particular point in time, the tristimulus diagram plots $x(t)$ vs $y(t)$, as z can always be inferred from the other two.

4.1.3 RMS amplitude

The RMS amplitude was calculated from the resulting analysis using the following equation [1]:

$$RMS(t) = \sqrt{\sum_{k=1}^{K} A_k^2(t)} \qquad (8)$$

where $A_k(t)$ is the amplitude of the k^{th} harmonic at time t.

4.2 Psychoacoustical attributes of the sounds

4.2.1 Pitch

The pitch variation over time (in cents) is defined as the logarithm of the composite weighted-averaged frequency [1]:

$$\Delta P(t) = 1200 \cdot log_2 \left(\frac{f_a + \Delta f_c(t)}{f_a} \right) \qquad (9)$$

where

$$\Delta f_c(t) = \frac{\sum_{k=1}^{5} \frac{A_k(t) \cdot \Delta f_k(t)}{k}}{\sum_{k=1}^{5} A_k(t)} \qquad (10)$$

and $\frac{\Delta f_k(t)}{k}$ is the frequency deviation of the k^{th} harmonic relative to f_a.

4.2.2 Normalised spectral centroid

This measure is considered to be a psychoacoustical attribute, as it has been correlated to the perceived brightness of the sound (see for example [7]).

The normalised spectral centroid variation over time of a sound is defined as [1]:

$$NSC(t) = \frac{\sum_{k=1}^{n} k \cdot A_k(t)}{\sum_{k=1}^{n} A_k(t)} \qquad (11)$$

5 Results

The plots presented in this section corresponding to the RMS amplitude, average spectra and spectral centroid were generated by averaging the results across the 25 notes that were played. The error bars (vertical width of the lines) indicate the standard deviation of the mean. In the pitch and tristimulus diagram plots, all 25 results for each plectrum are plotted.

As the objective of this paper was to find out if the sound itself is altered by using different plectra, each plot shows the results from the three plectra simultaneously, for the purpose of comparison.

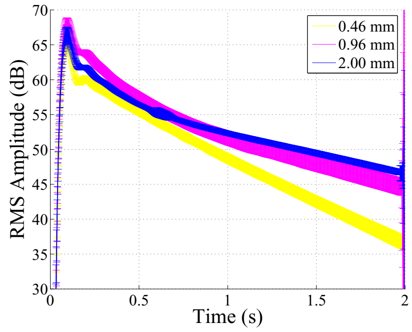

Figure 3: RMS variation over time of note E_4

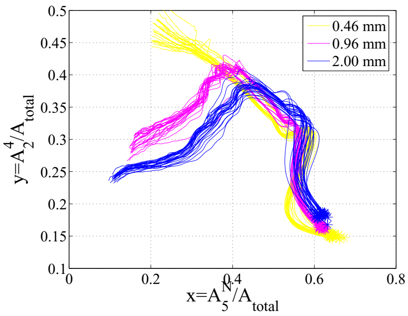

Figure 4: Tristimulus diagram of note E_4

5.1 Note E_4

5.1.1 Physical attributes

The first obvious difference between the sounds generated by different plectra, was the RMS amplitude, which is shown in Figure 3. Although the RMS amplitude at the beginning of the sound is about the same, two significant differences are noted:

- The sound corresponding to the thin plectrum has a faster decay than that of the other two plectra
- Therefore, after two seconds the RMS amplitude of the thin plectrum is approximately 8 dB smaller than that of the other two plectra

The tristimulus diagram is shown in Figure 4. It is a useful measure of how the spectra of the signals evolve over time. The star symbols (close to the bottom right corner of the plot) indicate the start of the sound. As each curve traces a different trajectory, it can be concluded that the spectra of the signals from the three different plectra evolve in different ways over time. For example, at the end of the sound, the thin plectrum will have most of its energy in harmonics 2, 3 and 4, whereas the thick one will tend to have more energy in the fundamental.

The average spectra are shown in Figure 2: a) shows the spectra from the signals from the microphone, and b) from the pick up. Figure 2 a) shows significant differences in amplitude of some of the harmonics, especially between harmonics 3 and 10, varying in the range from 5 to 10 dB. According to [3] (chapter 4), these differences should be enough for people to hear a difference in the sounds.

An interesting point can be seen in Figure 2 b): The amplitudes of harmonics 5, 10, 15 and 20 are significantly lower than their neighbours, for all three plectra. As these are spectra taken from the signals from the pick up, they show almost exclusively the string vibration, with little influence from the

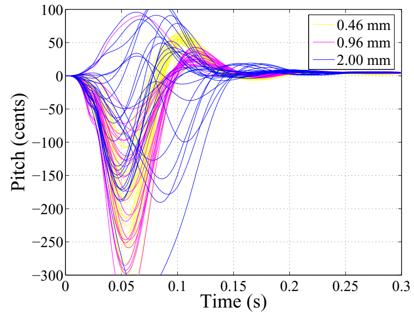

Figure 5: Pitch (relative to the nominal playing frequency of an equally tempered scale) of note E_4

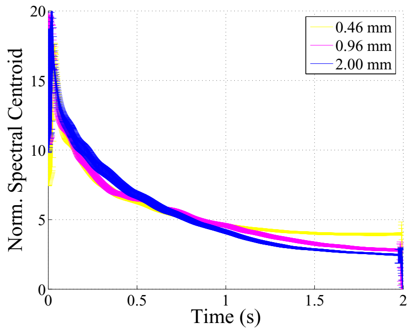

Figure 6: Spectral centroid of note E_4

body of the guitar. It can then be concluded (see for example [6] chapter 2) that the point where the string was plucked was approximately 1/5 of the total vibrating length of the string.

5.1.2 Psychoacoustical attributes

The pitch variaton over time is shown in Figure 5. All sounds were well in tune after approximately 200 ms. During the transient of the sound, there are significant pitch fluctuations. The pitch almost always goes down as much as 300 cents before stabilizing. It is unclear if the perceived pitch of each of the signals depends on the variations seen during the transient.

The spectral centroid variation over time is shown in Figure 6, which shows that after one second, the spectral centroid is different depending on which plectrum was used: A thick plectrum will generate a mellower sound, compared to a thin one. This agrees with the experience of one of the authors (MP, who is a professional guitarrist). He tends to use thicker plectra to avoid having a too bright and thin sound. The differences in spectral centroid seen are of up to 2 (adimensional) units, which according to [7], should be enough for people to perceive a difference.

5.2 Note G_3

5.2.1 Physical attributes

In the case of note G_3, there were also significant differences in the RMS amplitude of the sounds, which are shown in Figure 8. The amplitude of the thin plectrum is about 10 dB lower than the other two at the beginning of the sound, and about 5 dB at the end of the sound. The decaying rates seem to be approximately the same in all cases.

The tristimulus diagram, which is shown in Figure 9, shows that the signals corresponding to each plectrum follow different trajectories.

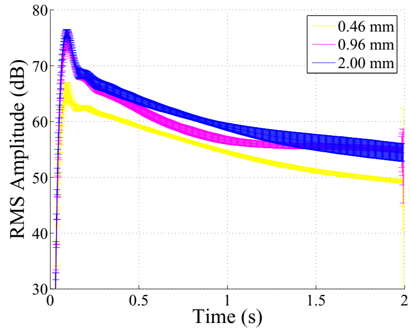

Figure 8: RMS variation over time of note G_3

The average spectra for note G3 are shown in Figure 7. The differences between harmonic amplitudes shown in Figure 7 a) are as big as 25 dB (in harmonic number 5) and 15 dB (in harmonic number 10). This suggests that the plucking point might have differed slightly, by placing the plectrum in a slightly different position on the machine itself. From Figure 7 b), it is concluded that, for the case of the two thinnest plectra, the plucking point was indeed close to 1/5 of the total vibrating length of the string, as the amplitudes of harmonic numbers 5, 10, 15 and 20 are, as in the case of note E_4, smaller than their immediate neighbours. In the case of the thick plectrum, the local minima are located in the harmonic numbers 4, 7, 10, 15 and 20, which suggest that the plucking point was between 1/4 and 1/5 of the total vibrating length of the string. This explains the big difference in amplitude between the thinnest and thickest plectra in harmonics number 5 and 10.

5.2.2 Psychoacoustical attributes

The pitch and spectral centroid corresponding to the note G_3 are shown in Figures 10 and 11 respectively. One interesting fact is that the pitch (see Figure 10) goes down up to 300 cents in the case of the thick and middle plectra, but only down to about 150 cents with the thin plectrum. Also, in the former case, the time when this minimum is reached, is 100 ms, while in the case of note E_4, was 50 ms for the three plectra. This suggests that both the thickness of the plectrum and the physical attributes of the string might define when and how low the pitch will fall.

In contrast with the note E_4, the spectral centroid (shown in Figure 11) does not show a significant difference between the three plectra: The curves corresponding to the thinnest and thickest plectra overlap most of the time, and while the difference of these two plectra with the middle one is of up to approximately 2 units, the time span where these differences occur seems to be too small to make any difference in the perceived sound.

6 Conclusions and future work

The aim of this study was to find out if the plectrum thickness influences the radiated sound of the guitar to the extent that the differences in the sound can be perceived. Two strings of a guitar (E_4 and G_3) were plucked with three plectra of different thicknesses.

Physical and psychoacoustical attributes of the sound were calculated. Both strings showed significant differences in

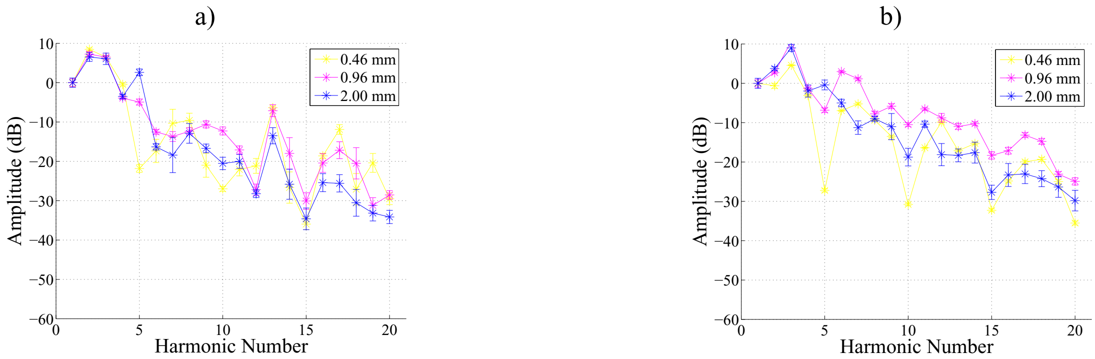

Figure 7: Normalised average spectra for note G_3 from a)microphone and b) pick up

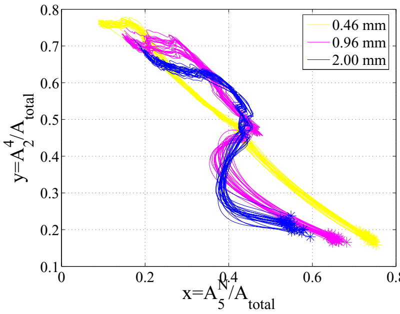

Figure 9: Tristimulus diagram of note G_3

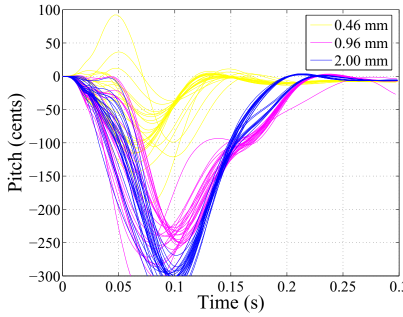

Figure 10: Pitch (relative to the nominal playing frequency of an equally tempered scale) of note G_3

RMS amplitude and the trajectory followed by the tristimulus diagram. The pitch fluctuated in the range of -300 to 100 cents during the attack of the note. However in the case of note G_3 the pitch fluctuations observed when it was plucked with the thin plectrum were consistently smaller than the other measurements: between -150 and 50 cents. In the case of note E_4, the differences in average spectra and spectral centroid were found to be big enough for people to perceive a difference. In the case of note G_3 these differences are thought to be insignificant. This leads us to conclude that the influence that the plectrum thickness has on the sound might also depend on the physical attributes of the string, as well as on whether it is wound or unwound.

Although we have found evidence that the plectrum thickness has a significant influence on the radiated sound of the guitar, at least in the case of note E_4, there are still many questions to be investigated:

- How does the physical attributes of the string affect the influence of the plectrum thickness?
- Why are the RMS amplitudes between thin and thick plectra consistently different, although the force applied to the string and the conditions of plucking were approximately the same, regardless of which plectrum was used?
- How does the amplitude of the sound influence its timbre? Are nonlinear effects involved?
- How does the choice of plectrum affect the playing technique?

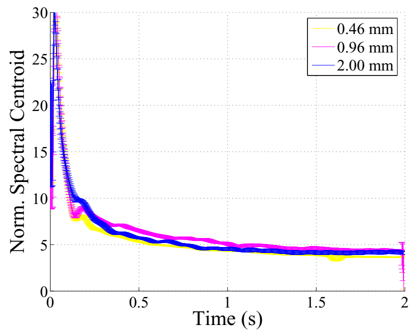

Figure 11: Spectral centroid of note G_3

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