Experimental Study of a Guitar Pickup

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This work deals with experimental study of the string-pickup coupling in an electric guitar. The effect of the string movement on the pickup output signal is studied by mean of an experimental bench which provides a purely sinusoidal string movement along only one direction. It appears out that the pickup has a weakly non-linear behaviour and is primarily sensitive to one of the two polarizations of the string. The effect of the pickup on the string is examined in a second step. A lab guitar prototype is developed which allows to study this coupling in a real gaming situation. The results show that the pickup has an impact on the energy exchange between the two polarizations and reveals that the presence of pickup decreases the guitar sustain if it is set too close to the string.

1 Introduction

Compared to its acoustic cousin, the electric guitar is a modern instrument. It was born in the twentieth century, the need to develop electrified instruments being then the difficulty of certain instruments to be heard in large ensembles. The first electric guitars were developed in the late 1920s. They first looked like acoustic guitars equipped with transducers. But, in the early 1940s, the electric guitar took a design very similar to those in use today, that is a solid-body guitar equipped with compact magnetic pickups[1].

The literature on the acoustic guitar is fairly abundant, (see for example [2, 3, 4]). The admittance or the point mobility at the bridge seems to be a key point to model an acoustic guitar [5, 6]. This does not seem to be the case for an electric guitar. Indeed, the body of an electric guitar consists of a wooden board (solid-body) and the exchange energy from the string to the body is not essential. This is the pickup which senses the vibration of the string and translate it into an electric signal. There are different types of pickups: piezoelectric, optic or magnetic. The magnetic pickups are the most popular. They are comprised of permanent magnets surrounded by a coil of wire with typically several thousand turns. The guitar strings consist of wires made of a ferromagnetic material and are parallel to the face of the magnets. The magnetic field resulting from the interaction between the pickup and the strings, and thus the magnetic flux through the coil, depends critically on the position of the strings. Therefore, moving a string changes the magnetic flux through the coil. According to Faraday's law the current induced inside the coil is proportional to the time rate of change of the magnetic flux through the coil. As the string moves through the magnetic field, a time-varying current is then produced in the coil. This current is used to produce a potential drop across a resistor, which is then amplified and sent to a speaker.

Although the electric guitar is a very popular instrument, the scientific literature about it is surprisingly quite poor. One can cite [1] for an overview, [7, 8, 9, 10] who studied the the coupling between the string vibrations and those of the body, [11, 12] who tried to propose a model of the guitar pickup and [13, 14] for sound synthesis. The aim of this article is to study the string-pickup coupling in an experimental way.

The pickup is driven by the motion of the strings. This motion is nonplanar and may be seen as the composition of two movements in perpendicular planes. A string vibrates in two polarisations[15, 16], one parallel to the pickup (called y-polarization in the following) and the other perpendicular to the pickup (called z-polarization)(Fig. 1). Thus, when considering a single string, the pickup can be seen as a system with two inputs and one output. In addition, the vibration of a plucked string can be seen as a sum of decreasing harmonic components: the pickup is thus driven by a complex signal[15, 18].

In a first part, the effect of the string motion on the pickup output is studied. For this purpose, an experimental set-up has been developed in order to drive the pickup with a lonely polarisation of the string. The effect of each polarisation on the pickup output can then be studied. In a second part, the effect of the pickup on the string vibration is studied. A prototype of a lab electric guitar has been designed. It allows to study the decrease of a plucked response as a function of to the position of the pickup.

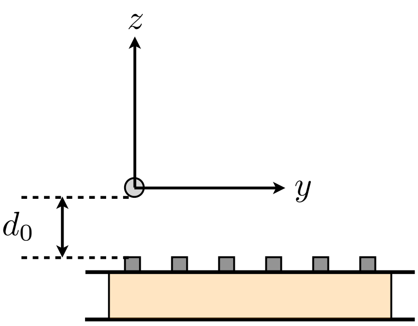

Figure 1: Definition of the axis.

2 Effects of the string on the pickup signal

2.1 Experimental set-up

To study the effect of each polarisation of the string movement on the pickup signal, we used the system shown in Fig. 2. A portion of steel string (diameter 1.42 mm) is fixed on a non-magnetic support, itself fixed to a shaker. The driven frequency F_0 and the amplitude of the displacement d_{max} of the shaker can be tuned by the operator. In the following, the frequency is chosen to be $F_0 = 85$ Hz, which approximatively corresponds to the fundamental frequency of the open low E string. The pickup under test (here a single coil Seymour Duncan SSL-1) is set on a precision movement device which allows to adjust the distance at rest d_0 between the string and the magnet. Two test configurations are considered, corresponding to each polarization of the string. The motion of the string is measured by an accelerometer fixed on the string support. Since the shaker can exhibit a non linear behaviour, additional content is added at the harmonics of the excitation frequency, causing a harmonic distortion of the displacement. To ensure a purely harmonic motion of the string, an active harmonic control technique is used [17]. This technique adds higher harmonics to the excitation voltage $u(t)$ provided to the shaker, so that $u(t) = U_1 sin(\omega_0 t) + \Sigma_{k=2}^{N} U_k sin(k\omega_0 t + \phi_k)$, N being the number of harmonics added to the input voltage. The goal of the active harmonic control is to eliminate the higher harmonics contained in the displacement signal so that only the fundamental response remains. It searches for the best combination of amplitudes U_k and phases ϕ_k, that relate to linearizing the displacement signal $d(t)$.

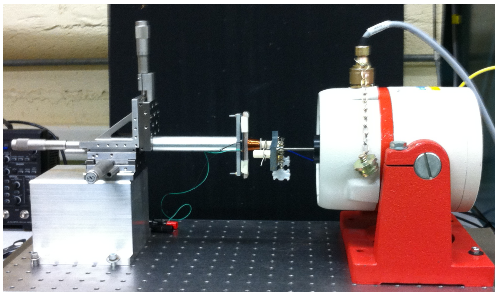

Figure 2: Experimental set-up to study the influence of each string polarisation on the pickup output. On the photography, the pickup is set to measure z-polarisation.

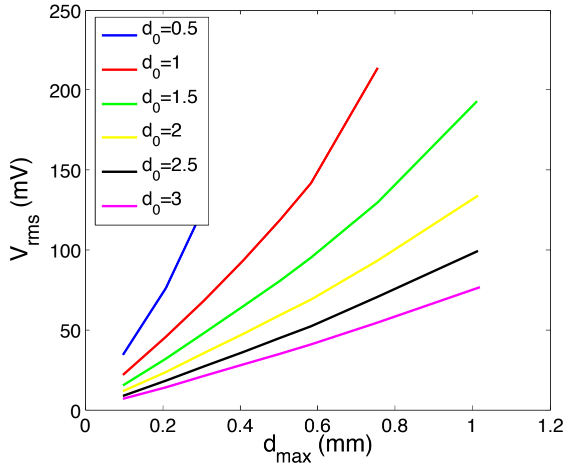

Figure 3: Pickup output signal (RMS) produced by a string motion along z-axis according to the amplitude of the string displacement for several d_0.

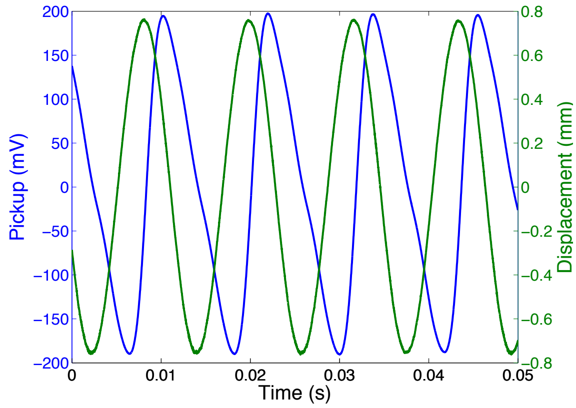

Figure 4: Temporal evolutions of the string displacement along z-axis (blue line) and the pickup signal (green line) for d_0 = 1.5 mm and d_{max} = 0.78 mm.

2.2 Results

2.2.1 Displacement along z-axis

The effect of a displacement of the string along z-axis is first studied. The output RMS voltage of the pickup is plotted as a function of the amplitude of the string displacement for several initial positions d_0 in Fig.3. One can see expected results: the pickup signal RMS amplitude increases with the amplitude of displacement $d(t)$. Moreover, for a fixed amplitude of displacement, the output signal RMS amplitude decreases when the position at rest d_0 increases. In addition, the input/output characteristic of the sensor seems to be non-linear when the pickup is close to the string (weak d_0). When d_0 increases, the input/output characteristic of the pickup seems to be linear. Figure 4 represents the temporal evolutions of the accelerometer signal (blue line) and the pickup signal (green line) for d_0=1.5 mm and for a displacement of d_{max} = 0.78 mm. The pickup signal seems to be weakly distorted. This last result can be appreciated quantitatively on Fig.5, which represents the relative amplitude of the first three harmonics of the pickup signal for different displacement amplitudes and for d_0 = 0.5 mm (top figure) and d = 2 mm (bottom figure). Non-linearities remains weak even for large displacements. In any case, $\frac{H2}{H1} < -10$ dB and $\frac{H3}{H1} < -20$ dB. At last, one can notice that the pickup signal and the accelerometer signal are $\pi/2$ out of phase : the pickup is a velocity sensor.

2.2.2 Displacement along y-axis

In this section, the same measurements as in the previous section are performed but the displacement is now along the y-axis. Figure 6 represents the pickup output RMS level according to the amplitude of displacement for different initial positions d_0. As expected, the pickup output RMS voltage increases with the amplitude of displacement.

Figure 7 represents the temporal evolutions of the accelerometer signal (blue line) and the pickup signal (green line) for a rest position d_0=1.5 mm and for a displacement amplitude of d_{max} = 0.8 mm: the pickup signal is clearly distorted. The non-linear behaviour of the pickup can be seen more quantitatively on Fig.8 which represents the relative amplitude of the first three harmonics of the pickup output signal for several displacement amplitudes d_{max} and for two rest positions d_0= 0.5 mm (top figure) and d_0 = 2 mm (bottom figure). The response of the pickup according y-polarization is more distorted than the one according z-polarization. This is especially the case for d_0 = 0.5 mm and for strong excitations. Under these conditions, the amplitude of the second harmonic is higher than the fundamental one. This is an expected result: According to the symmetry of the problem, excitation in the y-axis at F_0 results in a pickup response at $2F_0$. Nevertheless, given the symmetry of the problem, this behaviour should be observed whatever d_0 and d_{max}. It is not the case. This can be explained by the fact that the string may not be perfectly positioned at the center of the magnet top face.

2.2.3 Comparison between both polarisation

Comparing results presented on Figs. 3 and 6, we can see that the pickup is much more influenced by the motion along z-polarisation: the motion along y-polarisation is negligible. This result confirms results obtained by other means in a previous study [10].

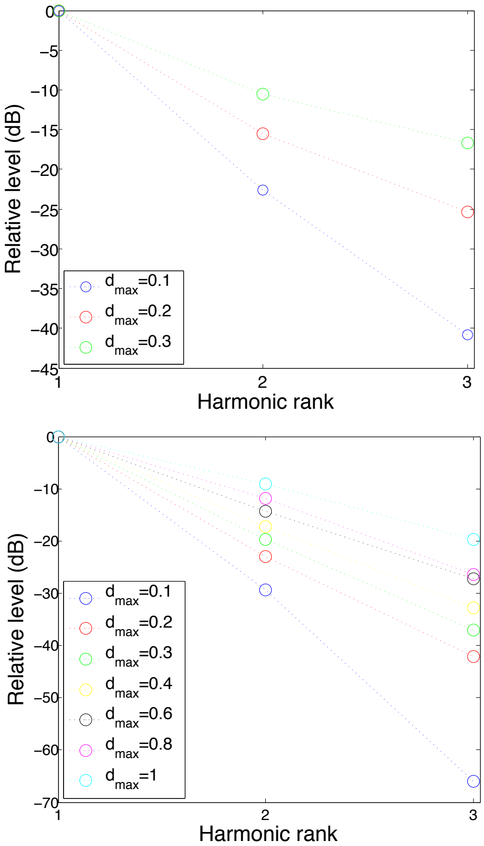

Figure 5: Harmonics amplitude for several amplitudes of string displacement along z-axis for $d_0 = 0.5$ mm (top) and $d_0 = 2$ mm (bottom). The reference level is the amplitude of the fondamental H1. Dotted lines are represented for eyes guiding.

3 Effects of the pickup on the string motion

The previous part of the work allows to study the behaviour of the pickup for a sinusoidal excitation by decoupling the two polarisations. In this section, we study the coupling between the string and the pickup in real gaming situation. For that purpose, we have designed a lab guitar prototype which allows to precisely adjust the position of the pickup and provides repeatable pluck responses.

3.1 Experimental set-up

The experimental setup is shown in Fig. 9

A guitar string is fixed on an exotical wooden beam (sapele) having the following dimensions : 910mm x 140 mm x 140mm. The string has a diameter of 1,42 mm and is tuned as open low E (f_0 = 82 Hz). The string is fixed by some mechanical accessories whose references are ”TonePros LPCM02 C” for bridge/tailpiece set, ”Graph Tech PQ 6060 00” for the slotted nut and ”Gibson PMMH-015” for grover tuners. The pickup is set on a mechanical arm on which some precision movement pieces are fixed. Thanks to this system, the pickup position can be adjusted along the 3 axes. The string is excited by a plectrum attached to a moving system (ZABER T-LMS025B) controlled by computer via a serial RS232. It allows a good repeatability (see following section). To visualize the motion of the

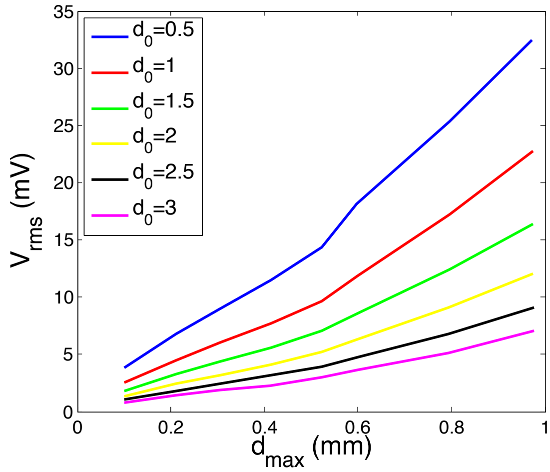

Figure 6: Output signal produced by a string motion along y-axis according to the amplitude of the string displacement for several d_0.

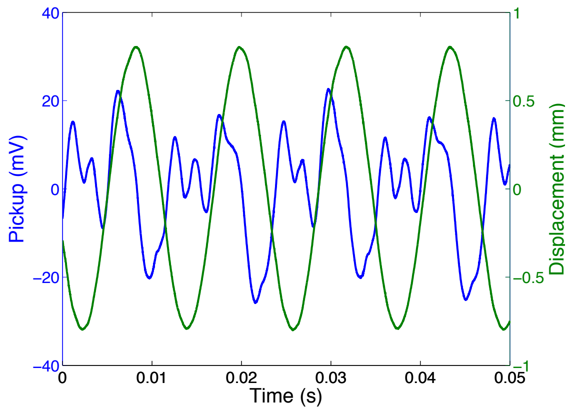

Figure 7: Temporal evolutions of the string displacement along y-axis (blue line) and the pickup signal (green line) for $d_0 = 1.5$ mm and $d_{max} = 0.8$ mm.

string in both polarisations, two Polytec laser vibrometers (OFV 3000 and OFV 3001) and controllers (OFV302 and OFV303) are used.

The pickup signal and the vibrometers signals are recorded with a data acquisition card connected to a computer. The sampling frequency is 10 kHz and the acquisition time is 30 s.

3.2 Definition of the sustain

The vibration of a plucked string can be seen as the superposition of several harmonics, each of them having their own decay rate. So a sustain can be defined harmonic by harmonic. In this work, the sustain is defined for the entire signal. Thus, the definition of the sustain is similar to that used in room acoustics to estimate the reverberation time [19]. The main idea is to calculate the remaining energy in the plucked response as :

$$E_r(t) = \int_t^{\infty} s(t')^2 dt', \qquad (1)$$

where $s(t)$ represents the pickup signal or the vibrometers signals. It is more convenient to express the energy decay in decibel with the total energy of the signal as reference :

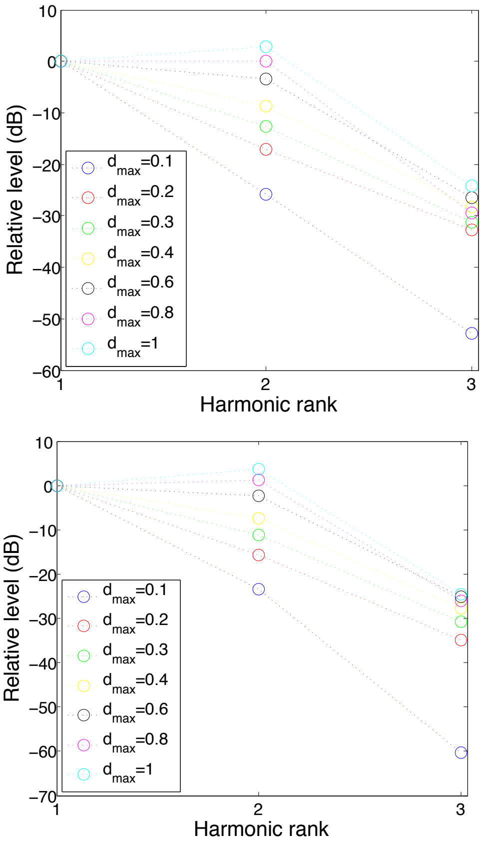

Figure 8: Harmonics amplitude for several amplitudes of string displacement along y-axis for d_0 = 0.5 mm (top) and d_0 = 2 mm (bottom). The reference level is the amplitude of the fondamental H1. Dotted lines are represented for eyes guiding.

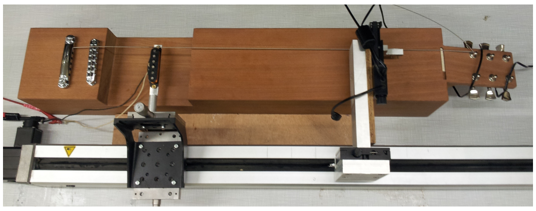

Figure 9: Lab guitar prototype

$$dec(t) = 10 \log \left(\frac{E_r(t)}{E_r(0)} \right). \tag{2}$$

In the following, we define the sustain as the time required for a decrease of 20 dB.

3.3 Results

Fig. 10 represents the sustains of the pickup signal and vibrometers signals in both polarisations according to the distance d_0 between the string and the pole piece. The pickup is a Seymour Duncan SSL1 positioned at 41.5 mm from the bridge. For each distance d_0, 10 measurements are performed. The curves represents the average. Errobars are also given and allow to ensure that the set-up provides a sufficient repeatability.

Fig. 10 shows that the sustain of z-polarisation is a function globally growing up to $d_0 \approx 3$ mm. Beyond this distance, the sustain no further change. The pickup has therefore an influence on the z-polarisation : when the pickup is close to the string, he tends to reduce the sustain. Beyond $d_0 \approx 3$ mm, the sustain no further change : the pickup has no influence on the string.

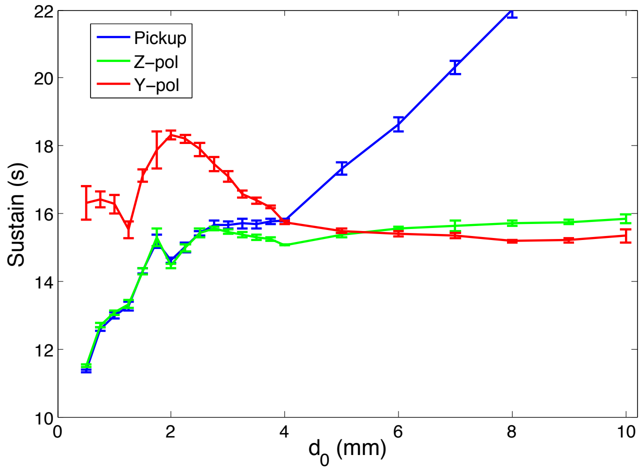

Figure 10: Sustain according to d_0.

In addition, Fig. 10 shows that the sustains of z-polarisation and pickup signal are almost identical up to a distance $d_0 \approx 4$ mm. This is a confirmation of the previous section : the pickup mainly senses the z-polarisation. Beyond this distance, the pickup sustain diverges: the coupling with the string is too weak and the pickup signal is too noisy to estimate a 20 dB decay.

Regarding the sustain of the y-polarisation, there is an unexpected behaviour: the sustain is greater when the pickup is close to the string. The pickup acts as a vibration sustainer. This is particularly the case for d_0 = 2 mm where the sustain of the y-polarisation goes through a maximum.

These results are confirmed by the analysis of figure 11 which represents the energy decrease as calculated with eq. 2 as a function of time and for different initial distance d_0. The first observation is that the pickup and z-polarisation decreases are mingled. This is a conclusion of the previous section: the pickup mainly senses the string vibration of the z-polarisation. The divergence between theses two decreases for d_0 = 5 mm is visible. Moreover, when the pickup is close to the string, the energy decrease of y-polarisation is slower than the two others. At last, one can see an interesting phenomenon when focussing on the decrease of both polarisations. For d_0 = 3 and 5 mm, curves intertwine. Everything happens as if there was an energy exchange between both polarisations. The decrease is locally accelerated or slowed down depending on the direction of the exchange. Again, one can see the action of the pickup as these interlacings depend on the position of the pickup. When the pickup is very close to the string, there is no interlacing. As the y-polarization decrease is slower, it is conceivable that the pickup promotes energy transfer from z- to y-polarisation.

4 Conclusions

In this paper, we experimentally study the coupling between the pickup and the string in an electric guitar. In the first part, an experimental system is designed in order to provide a purely sinusoidal string movement along only one polarization. Results show that the pickup is only sensitive

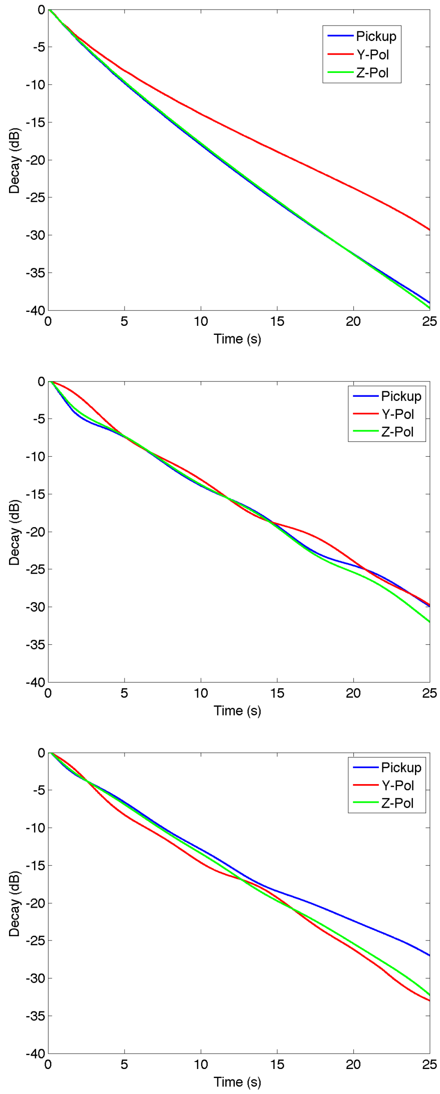

Figure 11: Energy Decrease for several d_0. a. d_0=0.5, 3 and 5 mm

to one of the two polarizations. In addition, the pickup output signal appears to be fairly linear except when the excitation is very strong and/or when d_0 is very low.

The effect of the pickup on the string is examined in a second step. An lab guitar prototype is developed which allows to study this coupling in a real gaming situation. Results show that the pickup has an effect on the string motion. This effect is investigated through the energy decay of the pickup output and the energy decay of the vibrometers signals in both polarisations. The pickup has an effect on the energy exchanges between both polarisations depending on the distance d_0 between the string and the pickup. At last, it is shown that the pickup has an impact on the sustain: when d_0 is weak, the pickup slow down the z-polarisation and the sustain diminishes.

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