Experimental Verification of Pickup Nonlinearity

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In this study the nonlinear mapping between the string displacement and a resulting magnetic pickup signal (magnetic flux) is studied experimentally. The presented experimental results are obtained by using a novel optical measuring technique based on the application of the line scan camera. The measurements of the string vibrations are carried out both for the vertical and horizontal planes relative to the pickup, and for different initial plucking conditions. This allows to reconstruct the vibrational motion of a single point of the string in a plane that is perpendicular to the direction of the string at rest. It is confirmed that the mapping between the string displacement and a pickup signal is nonlinear indeed, and it is responsible for enhancement of the high frequency harmonic content of the produced timbre. Also, the difference of the nonlinear mapping between the string position and a pickup signal for the vertical and horizontal string displacements is discussed.

1 Introduction

A pickup acts as a transducer that detects mechanical vibrations, usually from suitably equipped stringed instruments such as the electric guitar, electric bass guitar, Chapman Stick, or electric violin. The pickup converts the vibrational motion of the string to an electrical signal that is amplified, recorded, or broadcast. Most conventional types of pickups are magnetic, piezoelectric, and optical pickups. Different types of pickups rely on different physical laws and phenomena to convert the vibration motion of a string to an electrical signal. Among many types of pickups available, the magnetic pickup is the most common [1]. The magnetic pickup consists of a permanent magnet with a core made of material such as alnico or ceramic, and which is wrapped with a coil of several thousand turns of fine enamelled copper wire. Figure 1 shows typical construction of an electric pickup. The pickup is most often mounted on the body of the instrument, but can be attached to the bridge, neck or pickguard, as on many electro-acoustic archtop jazz guitars and string basses (cf. Fig. 2).

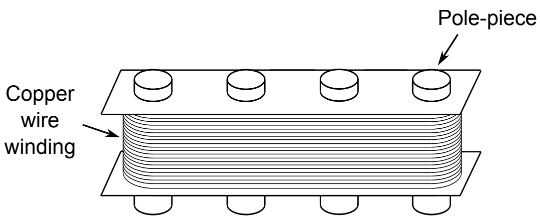

Figure 1: Magnetic pickup. The main components of the pickup are cylindrical permanent magnets called pole-pieces and the copper wire winding surrounding the magnets.

Working principle of the device is based on a straightforward application of the Faraday's law. An electrical signal or the current produced by the pickup is proportional to the rate of change of the magnetic flux through the pickup's coil(s) [2].

It is well known that the relationship between a string vibration signal and a corresponding pickup signal is a nonlinear function. Moreover, the nonlinear mapping between an obtained pickup signal and the corresponding string's transverse vibration is different for the string that vibrates in the vertical direction (*xz*-plane), compared to the string that vibrates in the horizontal direction (*xy*-plane) [2, 3].

The aim of this paper is to verify the nonlinearity of the bass guitar pickup by analysing the relationship between the string's waveform and a pickup signal. The analysis is carried out both for the string that vibrates in a vertical plane, which is perpendicular to the guitar body, and for a horizontal plane, which is parallel to it. The string displacement waveform is video recorded by a high-speed digital line scan camera (LSC), which is capable of ensuring a high-quality, high resolution vibration data.

2 Experimental set-up

In this section the measurement object, electric bass guitar Hohner model B500/MR shown in Fig. 2, the measurement set-up, the experimental apparatus, and the measurement methodology are introduced.

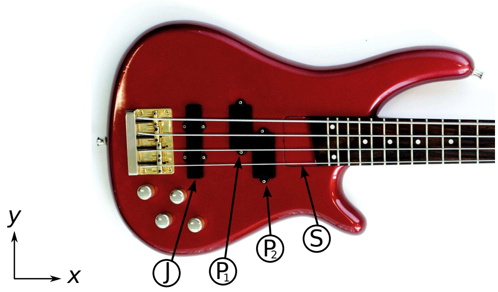

Figure 2: The Hohner bass guitar. Jazz bass style pickup is marked by J. Precision bass style pickups are marked by P_1 and P_2. Measured string is marked by S.

2.1 Bass guitar

Figure 2 shows the Hohner model B500/MR solid bodied electric bass guitar. The guitar has a P-J style pickup configuration. It is equipped with Ernie Ball Eb2836 Regular Slinky bass strings. All the measurements in this study are presented in connection to the string that corresponds to the note G_2 (fundamental frequency $f = 98.0$ Hz), which is shown by circled S in Fig. 2. The string of interest has a speaking length $L = 86.5$ cm and diameter $d = 1.651$ mm (gauge .065). The distance between the string and the pickup cover is 1.0 cm.

For the experimental measurements some slight modifications to the guitar are realized. In order to minimize the low-pass filtering effect of the inner tone/volume electric circuitry, the pickup P_2 is directly connected to the output jack [4]. Also the pickups J and P_1 are disconnected to minimize their electromagnetic distortion.

2.2 String displacement measurement

The string displacement is video recorded with high-speed LSC. We use a monochrome Teledyne Dalsa Piranha2 (1k 67 kHz) LSC. This digital camera has the capability to record up to 67 000 frames per second (fps). In this study we record the string displacement with 44 100 fps.

High resolution vibration data are extracted from the obtained video file by using appropriate video (image) analysis techniques. The detailed explanation of the working principle of the LSC and the data extraction technique, which are used here is presented in [5, 6].

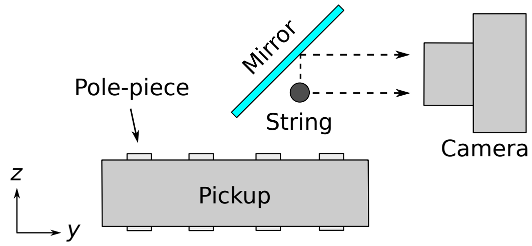

Figure 3: Optical string displacement measurement set-up that records the string vibration with respect to the vertical z-axis and horizontal y-axis simultaneously. A high speed line scan camera and a mirror that is placed under a 45° angle with respect to y-axis. Arrows with dashed lines indicate the direction of light propagation.

Figure 3 shows the string displacement measurement set-up. The guitar is placed horizontally on a rigid surface and securely fixed to it. The camera is placed to the side from the measuring string. It is carefully ensured that the LSC's direction of view (optical axis) is perpendicular to the xz-plane.

2.3 Pickup signal

An electrical signal from the guitar pickup is recorded by the Focusrite Saffire Firewire audio interface using the Audacity® recording and editing software. The pickup signal is recorded with a sampling rate of 44 100 Hz, and with a 32-bit sample depth.

As mentioned in Introduction, and according to the Faraday's law, a pickup signal is proportional to the string's velocity. For simplicity, henceforth we will refer to the time integral of the obtained pickup signal as to the pickup signal itself, and name it by u_ε.

2.4 String excitation

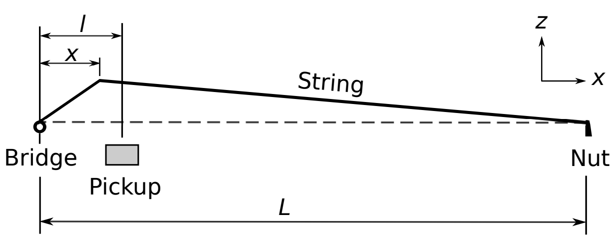

Figure 4: Triangular initial condition of the string, which is excited in the vertical direction. The string deflection maximum is located at x = 9.0 cm. String speaking length L = 86.5 cm. The location of the pickup is marked by l = 13.5 cm. Dashed line shows the form and the position of the string at rest.

The following method of controlled and repeatable string excitation is proposed and used. The main idea of the method is based on a fact that a thin cotton thread that is under a tension snaps quite rapidly if burned with a flame (cigarette lighter). The thread is looped around the string at a desired location, and the string is displaced to a suitable amplitude as well as in the desired direction (vertical or horizontal). This creates a triangular shaped initial displacement of the string that is shown in Fig. 4. It was estimated that the average duration of the snap resulting from the burning, for the used cotton thread and for the tension introduced in it, is approximately 1.0 ms.

2.5 Measurement procedure

A measurement for determining the nonlinear mapping between a pickup and an optical string displacement signals is carried out in the following order and manner. The LSC is prepared to record. The audio interface is connected to the guitar, and also set to record. The triangular initial string shape is induced by the cotton thread, and after the string stops to vibrate completely, the string is released (cut) by burning the thread. Resulting vibration is registered by the LSC and the pickup for a few seconds, which completes the measurement. Finally, the optical and a pickup signal are synchronised and analysed.

In the next section, we demonstrate the application of the method described in subsection 2.2, and present two typical examples of plucked bass guitar string vibration waveforms.

3 Plucked string vibration

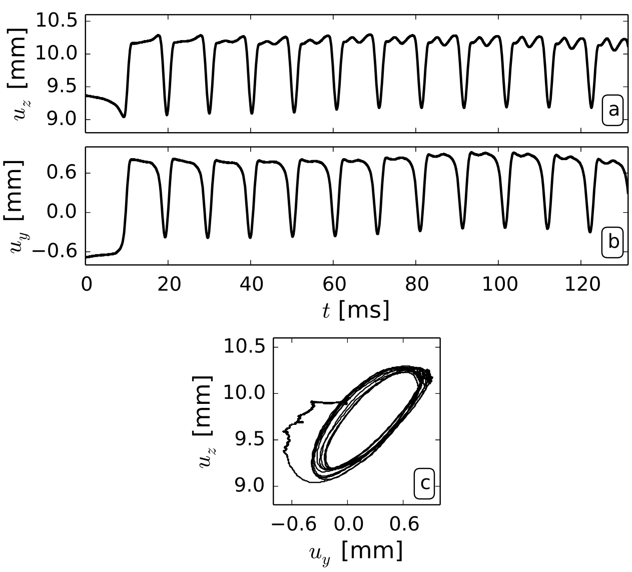

Figure 5: Vibration of the bass guitar string plucked with an index finger. a) String displacement in the vertical direction. b) String displacement in the horizontal direction. c) String motion with respect to yz-plane.

Figure 5 shows the vibration of the string, which is plucked with an index finger at point x = 9 cm, measuring from the bridge. The resulting displacement in the vertical direction u_z, and in the horizontal direction u_y measured at l = 13.5 cm are shown in Figs. 5 a and 5 b respectively. String's motion with respect to yz-plane is shown in Fig. 5 c, where one can see a typical elliptical trajectory of motion, which is similar to the one presented in [7].

Figure 6 shows a typical vibration of the bass guitar string, which is plucked with a plastic plectrum at the point

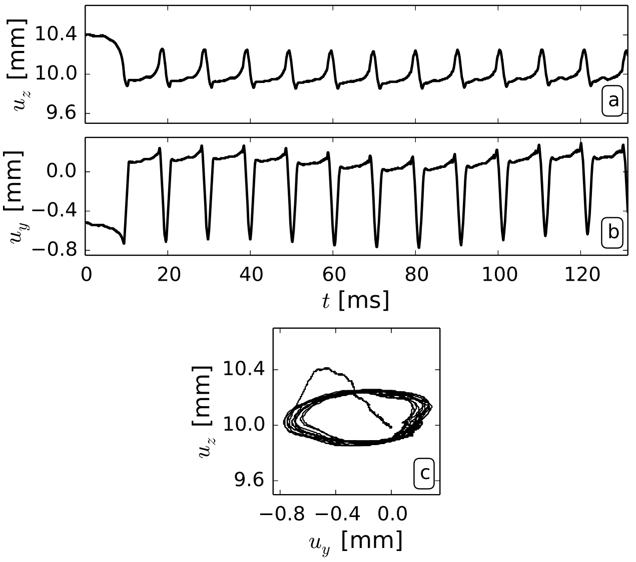

Figure 6: Vibration of the bass guitar string plucked with a plectrum. a) String displacement in the vertical direction. b) String displacement in the horizontal direction. c) String motion with respect to *yz*-plane.

$x = 9$ cm. In a similar manner, as shown in previous figure, the measured vibrations in the vertical direction u_z, and horizontal direction u_y are plotted in Figs. 6 a, and 6 b respectively. Figure 6 c shows the string motion with respect to *yz*-plane. In both cases the time series are assumed to start a few milliseconds before the finger, or the plectrum loses the contact with the string.

Comparison of both cases reveals that the string plucked with a finger has a much smoother waveform, and stronger dispersive behaviour both in the vertical and the horizontal vibration directions. Also, the elliptical trajectory of motion in *yz*-plane of the finger plucked string appears more oval compared to the motion of the string, which is plucked with a plectrum. Sharper waveform profiles in the case of the plectrum excitation are responsible for the increasing of the upper partial content of the string motion spectra. This in turn, is responsible for the guitar timbre that also has an enriched high-frequency partial content.

4 Pickup nonlinearity

4.1 Measurement results

Figure 7 shows the string vibration for the vertical and horizontal polarizations, as well as a corresponding pickup signal. The vibration is induced in the vertical direction (*z*-axis), using the method explained in the subsection 2.4.

Results for the string vibration that is excited mainly in the horizontal direction with a corresponding pickup signal are presented in Fig. 8.

The proposed method of the string excitation is capable of ensuring that the string vibrates mainly in one plane for approximately 15 periods. Figure 9 shows the evolution of the string vibration in *yz*-plane starting just after the excitation (Fig. 9 a) and approximately following the thirty-seventh period (Fig. 9 b). Data presented in Fig. 9 corresponds to the string vibration demonstrated in Figs. 8 a and 8 b. One can see that initially the string trajectory of

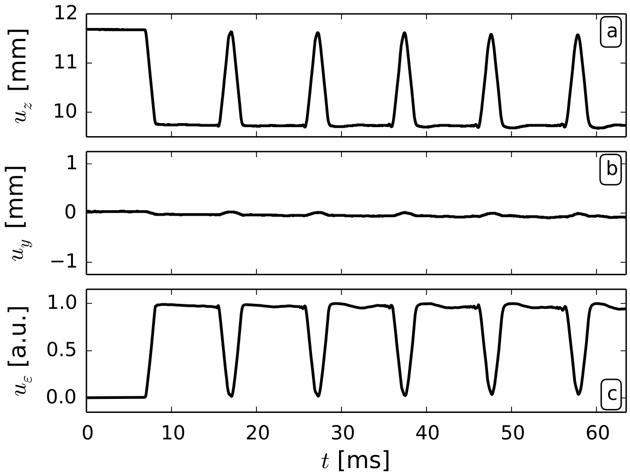

Figure 7: String vibration and a corresponding pickup signal. String is excited in the vertical direction. a) String displacement in the vertical direction. b) String displacement in the horizontal direction. c) A normalized pickup signal.

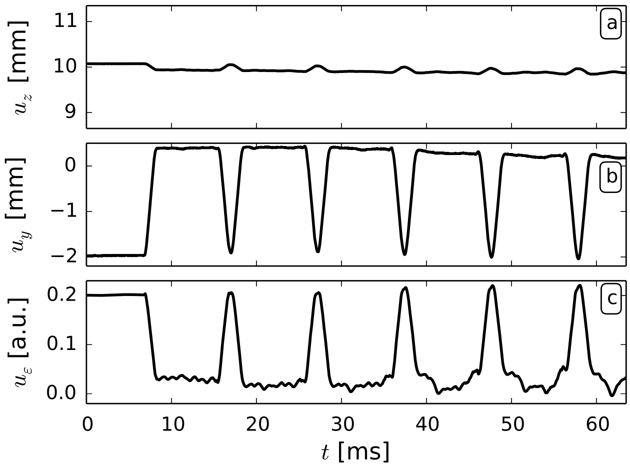

Figure 8: String vibration and a corresponding pickup signal. String is excited in the horizontal direction. a) String displacement in the vertical direction. b) String displacement in the horizontal direction. c) A normalized pickup signal.

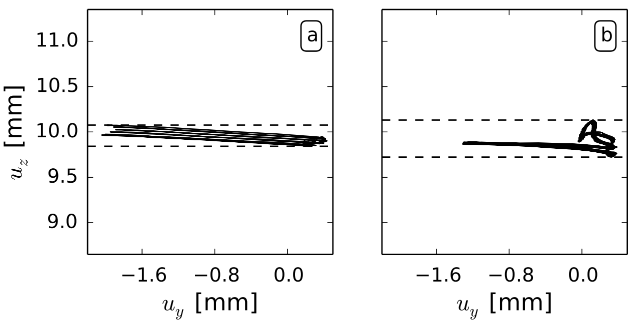

Figure 9: String vibration excited in the horizontal direction. a) The beginning of the vibration. b) Vibration 0.38 s later. Dashed lines indicate the amplitude extent in the vertical direction.

motion stays mainly in a horizontal plane, and 0.38 s later the motion trajectory changes and becomes more complicated.

In addition, the amplitude of the vibration with respect to the z-axis shown by dashed lines, becomes approximately two times larger. This phenomena indicates that the part of the transversal vibration energy distributed initially in a horizontal plane is transferred to a vertical plane. Most likely this is due to the different termination conditions for the vertical and horizontal string motion at the guitar bridge and the guitar nut.

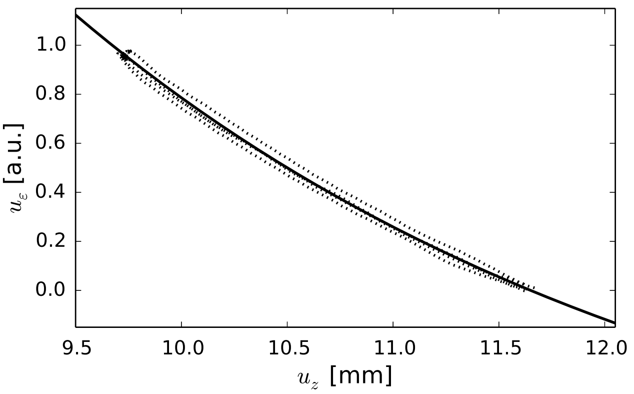

Figure 10: Mapping between the string's vertical displacements u_z and the corresponding pickup signal u_ε for the first three periods. The measured data are shown by dotted line. The fitted exponential function in the form $e^{-\alpha u_z}$ is shown by the solid line.

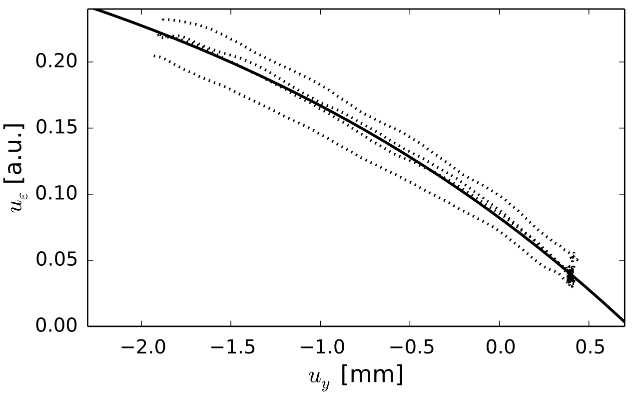

Figure 11: Mapping between the string's horizontal displacements u_y and the corresponding pickup signal u_ε for the first three periods. Measurement data is shown by dotted line. Fitted polynomial function is shown by solid line.

4.2 Measurement analysis

Figure 10 shows the mapping between the amplitude of the waveforms of the string vibrating mainly in a vertical plane and a corresponding pickup signal. The mapping shown in Fig. 10 corresponds to the first three periods of the measurement results shown in Fig. 7. As one can see, the relationship between the vertical string displacement and a pickup signal amplitude is nonlinear indeed, and can be described by the exponential function in the form $e^{-\alpha u_z}$. The averaged value of parameter α for the measured guitar and for the displacement range presented in Fig. 10 is 0.3.

The nonlinear mapping between the horizontal string position and the resulting pickup signal amplitude presented in Fig. 8 is shown in Fig. 11.

Figures 12 and 13 show the spectrograms of the measured vibration waveforms and corresponding pickup signals. All spectrograms are calculated using the Hanning window of the size 0.14 ms and the overlap value that is 40% of the window size.

The spectrograms for the vertical vibration polarization shown in Fig. 12 demonstrate that the pickup signal spectrum is significantly wider than the string vibration spectrum. This phenomena is most evident at the beginning of the vibration, and is directly caused by the pickup nonlinearity. The pickup modulates the string vibration signal by transferring the energy from the lower harmonics to the higher harmonics, thus widening the spectra and enriching the produced sound timbre.

The visual inspection of the spectrograms for the horizontal vibration polarization shown in Fig. 13 reveals that the pickup is less sensitive to the string's horizontal motion compared to the previous case [8].

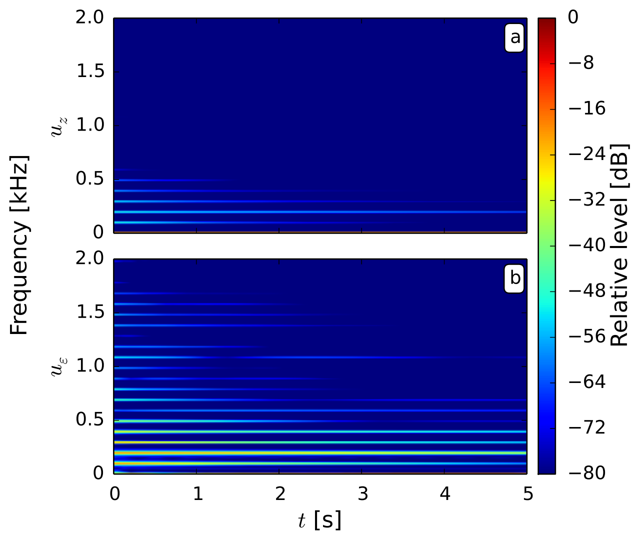

Figure 12: Spectrogram (a) of string vibration waveform that is excited in the vertical direction, and (b) of a corresponding pickup signal waveform.

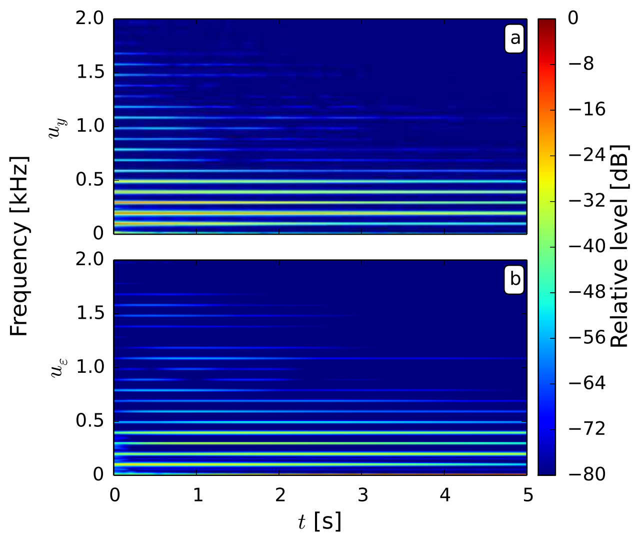

Figure 13: Spectrogram (a) of string vibration waveform that is excited in the horizontal direction, and (b) of a corresponding pickup signal waveform.

5 Discussion

In this study only one string of the guitar was measured, and therefore not presenting a complete overview of the pickup nonlinearity. It is well known that the electromagnetic field that surrounds the pickup is not homogeneous [2]. This means that the nonlinear mapping curves between the string vibration and pickup signals is strongly dependant on the string's horizontal position along the entire length of the pickup cover. Also, the ferromagnetic properties of the various guitar strings are different. The string with different ferromagnetic properties influences the current induced in the pickup coils. A more thorough experimental study of pickup nonlinearity that measures other strings on the bass guitar is planned in the future.

6 Conclusions

The bass guitar pickup nonlinearity was verified experimentally by analysing the relationship between the string waveform captured by a high-speed digital line scan camera and a pickup signal. The analysis was carried out both for the string that was vibrating mainly in a vertical plane and for the string that was vibrating mainly in a horizontal plane.

The method of controlled and repeatable string excitation was proposed. The main idea of the method is based on a fact that a thin cotton thread that is under a tension snaps quite rapidly by burned it with a flame. It was shown that this method can ensure the string vibration mainly in one vibration polarization plane for about 15 periods (for guitar used).

The mapping between the relative string position and the pickup signal was shown to be nonlinear indeed. The pickup distorts the vertical string vibration more significantly compared to the horizontal vibration by widening the spectra of the pickup signal.

In conclusion, the experimental work presented here confirmed that pickup is nonlinear indeed, and it is responsible for enhancement of the high frequency harmonic content of the bass guitar timbre.

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