A PICKUP MODEL FOR THE CLAVINET

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ABSTRACT

In this paper recent findings on magnetic transducers are applied to the analysis and modeling of Clavinet pickups. The Clavinet is a stringed instrument having similarities to the electric guitar, it has magnetic single coil pickups used to transduce the string vibration to an electrical quantity. Data gathered during physical inspection and electrical measurements are used to build a complete model which accounts for nonlinearities in the magnetic flux. The model is inserted in a Digital Waveguide (DWG) model for the Clavinet string for its evaluation.

1. INTRODUCTION

Among other fields, computational acoustics has recently led to very accurate analysis and modeling of stringed instruments. Thorough analysis and advanced computational models are now available in literature for classical music stringed instruments, such as the piano [1, 2, 3, 4] and the clavichord [5, 6] or modern instruments such as the electric guitar [7, 8] or the Clavinet [9, 10, 11].

Modern stringed instruments, however, often rely on electronic devices for transduction, amplification and processing. Research in this field, usually referred to as *virtual analog* is still ongoing [12]. While several works have brought to a better understanding and emulation of vacuum-tube amplifiers [13, 14], distortion circuitry [15, 16] and analog transformers [17], magnetic transducer such as the guitar pickups have been rarely addressed, although they are used in many instruments including electric bass and guitar, the Clavinet and electric pianos. Introductory works on this topic are fairly recent [18, 19], and a complete discussion on the guitar pickups, reported in [20], has only recently been published. These works enable a generic model of magnetic pickups to be built, which is not limited to guitar pickups.

The aim of this study is to improve the sound quality produced by the DWG model of that instrument described in [10] that does not consider the nonlinearities introduced by pickups.

In this paper, an overview of the Clavinet pickups is provided in Section 2. A complete model accounting for its linear and nonlinear behavior is then discussed in Section 3. Simulations from measured data are provided and Clavinet tones from the DWG (Digital Waveguide) model in [10] are compared to those filtered with the discussed pickup model in Section 4. Finally Section 5 concludes the paper.

2. ANALYSIS OF THE CLAVINET PICKUP

An overview of the Clavinet components is shown in Figure 1. The Clavinet has two pickups placed close to the far end of the string. These are magnetic single coil pickups, coated in epoxy and similar to electric guitar pickups, although instead of having one coil per string, there are six metal bar coils intended to transduce ten strings each. Each metal bar is 0.5 cm wide and approximately 3.7 cm long for the center pickup and 3.3 cm long for the bridge pickup. The thickness of the magnets as well as the number of windings cannot be measured as they are coated in epoxy.

The two pickups are electrically identical but they have different shapes and positions. The center pickup lies above the strings at a distance from the string termination that varies between 18.5 cm for the lowest string and 6.5 cm for the highest string, while the bridge pickup lies below the strings, at a constant distance of 4 cm from the string termination, and is tilted at approximately 30° with respect to the center pickup.

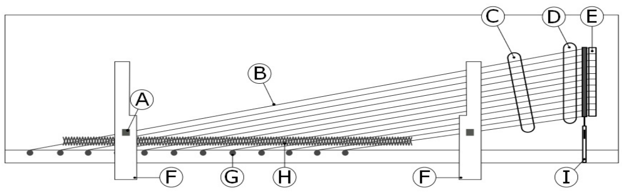

Figure 1: *Top view of the Clavinet. Parts: A) tangent, B) string, C) center pickup, D) bridge pickup, E) tailpiece, F) key, G) tuning pin, H) yarn winding, I) mute bar slider and mechanism.*

The Clavinet also includes an amplifier stage, with tone control and pickup switches. The tone control switches act as simple equalization filters. The pickup switches allow the independent selection of pickups or sums of pickup signals in phase or in antiphase. The pickup selector switches are two, featuring ’A’ and ’B’ or ’C’ and ’D’, as illustrated in Table 1.

The tonal quality of the pickups is very different: the bridge pickup, has a bright sound, while the center pickup has a warmer sound. This is due to the different distance from the string termination, which determines the position of the notches of the resulting comb filtering effect [21]. When the pickups signal is summed in phase the obtained timbre is *full* and deep, while when it is summed in anti-phase the fundamental is damped and the resulting timbre is *thin*.

Table 1: A listing of possible pickup combinations.

Switch 1	Switch 2	Configuration name
A	C	center pickup only
B	C	bridge pickup only
A	D	sum of both signals, anti-phase
B	D	sum of both signals, in phase

Finally, the combination of the unshielded single coil pickups and the transistor amplifier produces a fair amount of noise, also depending on electromagnetic interferences in the surrounding environment. For this reason humbucking replacement pickups are available that show a lower vulnerability to electromagnetic coupling. In this work only original Clavinet pickups have been considered.

3. MODELING OF THE CLAVINET PICKUP

The pickups have an important role in characterizing the distinctive Clavinet timbre. Their effects can be studied observing each one separately. The main features of the pickup are the distance from the string termination, the nonlinearity given by the relation between string movement and magnetic flux generated. These are summarized in Figure 2.

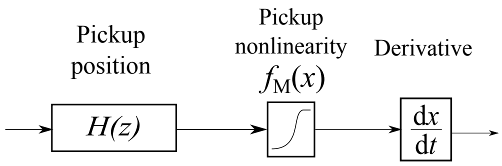

Figure 2: Signal flow chart of the Clavinet pickup model. (Adapted from [20])

Compared to the electric guitar pickup model described in [20] some features have not been modeled either because they do not apply to the Clavinet pickup model or because they can be considered negligible. For instance, the horizontal displacement nonlinearity given by the magnetic flux variation in the horizontal axis is not modeled, because the horizontal dimension of a Clavinet pickup coil is much greater than the maximum horizontal string displacement, thus the horizontal magnetic flux variation is negligible with respect to the one generated by the vertical string displacement as later explained in 3.2. Furthermore, with the Clavinet model in use the derivative need not be applied as the input variable from the model is a velocity variable.

3.1. Position

As discussed above, the position of the pickup affects its timbre. Both progressive and regressive waves traveling along the string are captured by the pickup. As the string termination reflects (and ideally inverts) an incoming progressive wave, the pickup signal can be seen, at any time, as the sum of the progressive wave and a delayed and inverted copy, with the delay being equal to twice the time for the wave to travel from the pickup position to the string termination [20]. This can be emulated with a feedforward comb filter with a negative gain, i.e.

$$H(z) = 1 - \beta z^{-2N} \tag{1}$$

where N is the time the wave takes from the bridge to the pickup in samples and beta is the reflection coefficient. The frequency response of the $H(z)$ for the two pickups is shown in Figure 3. For a string of 67.8 cm and fundamental frequency of 161 Hz the estimated N is 200 for the center pickup (equivalent to 4.2 ms), and 84 for the bridge pickup (equivalent to 1.8 ms). For the sake of presentation in Figure 3 the reflection coefficient β is set to 1 because the loss has been considered nonexistent at the termination of the string.

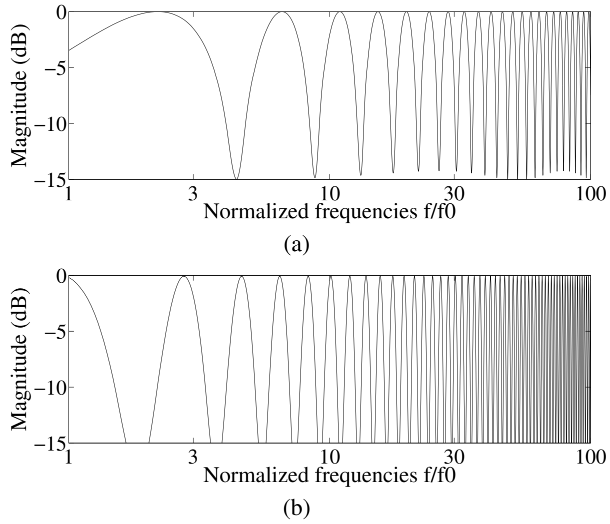

Figure 3: Plot of (a) the bridge pickup $H(z)$, (b) the center pickup $H(z)$.

3.2. Nonlinearity

The nonlinearity is given by the magnetic flux variation with respect to string displacement. Computer aided simulations were performed with the commercial software *Vizimag*, in order to evaluate the nonlinear relation between the string displacement and the magnetic flux. The pickup magnet was represented as a magnetic rectangle with proper dimensions and the string is represented as a circle of different diameter for different string gauge as shown in Figure 4. Various simulations have been carried out with different distance between the string and the magnet (from 0 mm to 20 mm) in 21 steps.

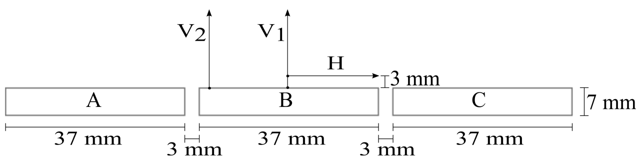

Figure 4: Overview of the geometry used in Vizimag for the simulations. A, B and C represent three contiguous magnets, V_1 and V_2 represent the displacement sweep used to measure the vertical variation of magnetic flux, both at the center of the pickup and next to the edge of the pickup; H represents the displacement sweep used to measure the horizontal variation of magnetic flux along half of the magnet (considered symmetrical in the horizontal axis).

Figure 4 shows the geometry used in the simulation. V_1 and V_2 represent the displacement sweep used to measure the vertical variation of magnetic flux, both at the center of the pickup and next to the edge of the pickup, whereas H represents the displacement sweep used to measure the horizontal variation of magnetic flux along half of the magnet (considered symmetrical in the horizontal axis). Figure 5(a) represents the measure of the magnetic flux variation with respect to the horizontal displacement H, with the black dots representing the position of the strings, while Figure 5(b) compares the variation of magnetic flux for position of the string varying from 0 to 2 cm from the pickup for the two horizontal positions V_1 and V_2.

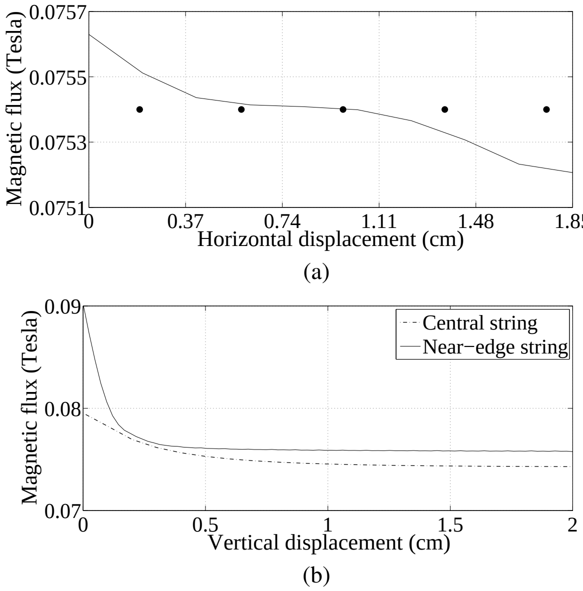

Figure 5: Simulation of the magnetic flux against horizontal and vertical displacements: (a) magnetic flux variation against the horizontal displacement of all the strings on the right of the center of the pickup that are represented as dots; (b) magnetic flux variation against vertical central string displacement (dashed line) and vertical displacement of the string near the edge of the pickup (solid line).

Simulations show that the curve of the magnetic flux for the horizontal displacement of the string has the maximum value at the center of the magnet and the minimum value at the edge of the magnet (Figure 5(a)), and for the vertical displacement of the string the magnetic flux varies as a negative exponential (Figure 5(b)), in accord to previous works [18, 19, 20]. It is also possible to note in Figure 5 (a) that for the string placed near the edge of the pickup the horizontal displacement produces an increase of the magnetic flux if the string goes closer to the center of the pickup and a decrease of the flux if it moves in the opposite direction.

The energy corresponding to the vertical displacement E_{V} can be compared to that corresponding to the horizontal displacement E_{H}. The energy is obtained as:

$$E = \sum_i (y_i - \langle y \rangle)^2 \tag{2}$$

where y_i are the samples of a sinusoidal signal of oscillation 1 mm peak-to-peak inputed to the nonlinearity at the string position and $\langle y \rangle$ is the mean of the samples y_i. Results show that with a maximum peak-to-peak oscillation of 1mm in both the vertical and horizontal axes, E_{V} is much greater than E_{H} and the ratio $E_{\mathrm{V}}/E_{\mathrm{H}}$ is about 25 dB for a string placed at the center of the pickup, or even more (30 dB) for a string placed near the end of the pickup. For this reason, the horizontal displacement can be considered negligible and it is not emulated.

The pickup nonlinearity can thus be implemented as an exponential, or a N-th order polynomial. The former can have a low precision on embedded processors and DSPs (it is usually performed by table lookups or approximation methods). The latter has a lower computational cost and it can be computed on modern DSP architectures with N-1 consecutive MACs (Multiply-Accumulate) and N multiplications. If x_i is the i-th sample, the polynomial

$$y_i = p_N x_i^N + p_{N-1} x_i^{N-1} + ... + p_1 x_i + p_0 \tag{3}$$

can be computed by the Horner scheme, an algorithm to evaluate polynomials at a certain input value x_i. The iterative procedure consists in the following steps:

$$\begin{aligned} b_N &= p_N; \\ b_{N-1} &= p_{N-1} + b_N \cdot x_i; \\ &... \\ b_0 &= p_0 + b_1 \cdot x_i. \end{aligned} \tag{4}$$

The computational cost of this algorithm is N-1 products and N-1 sums. The polynomial coefficents used are reported in Table 2.

Figure 6 compares the exponential fit to the simulated data and the polynomial fit both performed using the *Curve Fitting Tool* a tool included in the commercial software *Matlab*. The exponential fit has a slightly lower RMSE index (Root Mean Square Error), proving a better approximation to the pickup nonlinearity. The polynomial fit, however, scales better to embedded devices for its lower computational cost and higher precision.

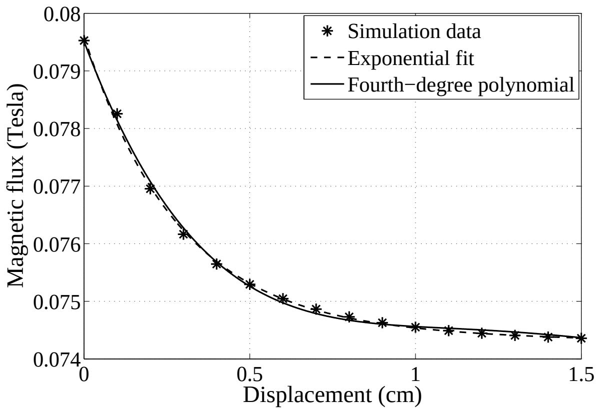

Figure 6: Magnetic flux variation against vertical string displacement (marker), an exponential fit (dashed line) and a fourth-degree polynomial approximation (solid line).

Table 2: The polynomial coefficents used to implement Eq. 3.

p_0	0.7951
p_1	-1.544
p_2	$1.818 \cdot 10^2$
p_3	$-9.508 \cdot 10^3$
p_4	$1.817 \cdot 10^5$

4. SIMULATIONS

To evaluate the timbre quality of a Clavinet tone a DWG model first proposed in [10] and shown in Figure 7 is connected with the pickup model discussed in Section 3.

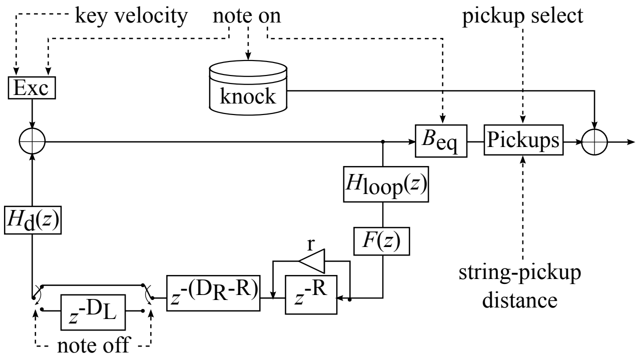

Figure 7: Overview of the DWG Clavinet connected with the new pickup block. (Adapted from [10])

The string model is composed by several parts: a first-order allpass fractional delay filter $F(z)$ [22], a one-pole filter $H_{\mathrm{loop}}(z)$ [23] and an allpass dispersion filter $H_{\mathrm{d}}(z)$ [24]. The delay line is divided into two parts $z^{\mathrm{D_R}-\mathrm{R}}$ and $z^{-\mathrm{R}}$ to include a ripple filter [25]. There is also a beating equalizer block B_{eq} [26] cascaded with the delay loop and a pickup module. The first pickup model implemented in [10], only considered the effect given by the pickup position, by means of comb filtering.

In the Matlab model the string-pickup distance can be changed in order to increase or decrease the effect of the nonlinearity. This is done by shifting the polynomial curve.

Informal listening tests have been performed by listening to Matlab generated tones. Those tests have shown significant differences for different string-magnet distances and *forte* excitations. Audio examples can be found at:
http://www.acoustics.hut.fi/publications/papers/dafx12-pickup/.

The computational cost of the entire pickup block is low compared to the string model. The comb filters (one for each pickup) only require one sum and one multiplication each.

5. CONCLUSION

This paper deals with the analysis and modeling of Clavinet pickups including nonlinear aspects related to the magnetic flux variation with respect to string position. Other physical aspects have been taken into account including their position, size and properties of their magnets and the mixing of the output signal. Particularly, in opposition to single-coil guitar pickups, where each string has a dedicated magnet, ten Clavinet strings are transduced by one magnet, and analysis shows that nonlinearities in the magnetic flux affect each string differently depending on its position with respect to the magnet.

The emulation of these transducing devices do not require a high increase in the computational cost, while introducing a remarkable change in the overall sound and more variability in timbre from string to string. A strategy for implementing the nonlinear characteristic is reported. Listening tests need to be addressed in the future to assess the importance of the pickup emulation.

6. REFERENCES

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