# PICKUP POSITION AND PLUCKING POINT ESTIMATION ON AN ELECTRIC GUITAR

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## ABSTRACT

This paper describes a technique to estimate the plucking point and magnetic pickup location along the strings of an electric guitar from a recording of an isolated guitar tone. The estimated values are calculated by minimising the difference between the magnitude spectrum of the recorded tone and that of an electric guitar model based on an ideal string. The recorded tones that are used for the experiment consist of a direct input electric guitar played on all six open strings and played moderately loud (*mezzo-forte*). The technique is able to estimate pickup locations with 7.75–9.44 mm average absolute error and plucking points with 10.45–10.97 mm average absolute error for single and mixed pickups.

***Index Terms***— electric guitar, pickup position estimation, plucking point estimation

## 1. INTRODUCTION

The electric guitar has been an influential instrument in Western popular music since its rise to popularity during the 1950s. It provides a vast amount of tonal diversity, allowing musicians to explore different choices of sound for their creative expression. One can alter the sound of the electric guitar by altering the pickup selection or adjusting its tone controls while guitar amplifiers and effects also make significant contributions to the tone. Case et al. [1] describe the electric guitar as a complex and nonlinear system, discussing a chain of contributions to the spectral content of the electric guitar tone, from the playing techniques of the musician to the microphone placement on the amplifier. Well-known musicians often have their own playing style and a particular combination of guitar, amplifier and effects that produce their characteristic sound. This is what makes some of them instantly recognisable and captures the attention of listeners, some of whom wanting to copy the sound of their own favourite artist go to the extent of purchasing the same set of guitar, amplifier and effects.

The transition of guitar technology to the digital domain now allows acoustic guitars, electric guitars, amplifiers and effects to be digitally emulated using signal processing techniques to achieve close resemblance in sonic quality to existing analogue products. Some academic research focuses on synthesising acoustic guitar [2, 3], electric guitar [4, 5, 6] and electric bass guitar [7, 8].

Hiller and Ruiz [9] were the first to apply the basic principles of string vibrations to digital synthesis by solving its wave equation. Fletcher [10] investigated the effects of the material of plucking device, the material of string and the playing style on the spectrum gaining closer correspondence to the behaviour of a real string. One of the effects that alters the timbre is the plucking position; harmonics that have a node at or near the plucking point are suppressed. This means that plucking near the bridge gives a brighter sound and plucking away from the bridge gives a warmer sound.

To replicate the sound of popular musicians digitally, we need to synthesise not only the playing style of the musician but also the sound produced by the equipment. Sullivan extended the Karplus-Strong model to achieve the resulting sound of an electric guitar by adding a model that simulates the effects of pickup positions [4]. The pickup position model can be approximated by a comb filter by analysing the standing waves on a string, whereby harmonics with nodes at the pickup position are suppressed [4, 5, 6].

Parameters for electric guitar synthesis need to be estimated in order to replicate the guitar tone of well-known musicians. One direct method of obtaining these parameters is to extract information from published recordings of these influential musicians. There are few papers that involve extracting information from electric guitar recordings, such as detecting the types of audio effects used in recordings [11] and predicting the decay time of electric guitar tones [12]. Research on extracting parameters of an electric guitar are somewhat lacking, however, there is related research that involves retrieving information from classical guitars and electric bass guitars. The extraction of plucking styles and dynamics of classical guitar [13] and electric bass guitar [14] tones has been studied. Moreover, there are papers that attempt to estimate the plucking point [15, 16, 17] of an acoustic guitar which is similar to our work, but here we estimate both the plucking point and pickup position of an electric guitar.

Physical models for electric guitar synthesis require that the location of the magnetic pickup along the string is specified. In order to successfully replicate the sound of electric guitars from audio recordings, this parameter needs to be estimated. In this paper, we propose a technique to estimate
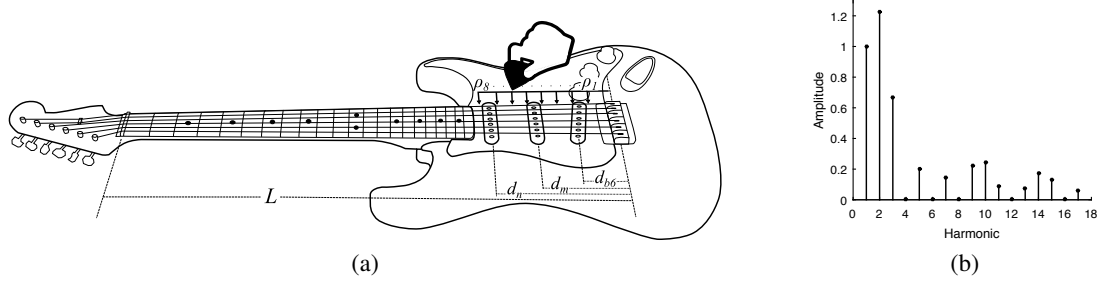
**Fig. 1**. (a) Distances of plucking points, $\rho_i$ ($i \in \{1, ..., 8\}$) and pickup locations, $d$ on the electric guitar measured from the bridge. The string, $j \in \{1, ..., 6\}$ of length $L_j$ is plucked at 8 positions. The subscript of $d$ denotes the pickup locations, where $n$ is neck pickup, $m$ is middle pickup and $b$ is bridge pickup. This figure only shows the distance of 6th string bridge pickup location, $d_{b6}$ from the bridge. Note that the bridge saddles are fixed for illustrative purposes. (b) The spectrum of electric guitar model plucked at one-fourth of the string and pickup location is at one-sixth of the string.

the plucking point and pickup position of electric guitar from an isolated guitar tone. Sec. 2 explains the datasets that are used in this paper. The derivations of the ideal string model that includes a pickup model are explained in Sec. 3 and we extend the existing models in Sec. 4. In Sec. 5, we introduce a method to find the plucking point and pickup position estimates given a direct input guitar track. We discuss the accuracy of the estimates when using either a single pickup or a mixed pickup in Sec. 6. Finally, the conclusions are presented in Sec. 7.

## 2. DATASET

The electric guitar that is used in this paper is a Squier Stratocaster [18]. We recorded a new dataset for the experiment which consists of individual guitar tones played moderately loud (*mezzo-forte*) at 8 different plucking points along the string for 5 different pickup configurations on each of the 6 open strings. Note that we only consider *mezzo-forte* tones to avoid dealing with pickup nonlinearity. The strings are plucked using a 0.88 mm plastic plectrum at 20 mm intervals between 30 mm and 170 mm from the bridge as drawn in Fig. 1(a). The 5 pickup selections comprise of neck pickup, middle pickup, bridge pickup, a mixture of neck and middle pickup and a mixture of middle and bridge pickup (with mixed pickups in phase with each other). The neck, middle and bridge pickups are situated at distances of 160 mm, 102 mm and 38.5-48 mm from the bridge respectively (the latter having a range because the bridge pickup is slanted on a Stratocaster). The length of the string is 652 mm. The signals from the three pickups were recorded with the sampling rate 44.1kHz.

The bridge saddles are adjustable, allowing each saddle to be adjusted towards or away from the nut, causing string lengths to differ slightly.

## 3. ELECTRIC GUITAR MODEL

In this section, we discuss the theoretical background of an electric guitar model based on the equation for an ideal plucked string.

An electric guitar typically produces sound using magnetic pickups to capture the vibration of its strings and convert it into electrical signals. Since the magnetic pickup senses the velocity of the string [19, 20], a time derivative of the ideal string model is needed to model the electric guitar string. The velocity $x(t)$ of an ideal string of length $L$ plucked with a vertical displacement $a$ at a distance $\rho$ from the bridge, sensed by a magnetic pickup modeled as a single point at distance $d$ from the bridge, is given by [12]:

$$x(t) = A_x \sum_{k=1}^{\infty} \frac{S_\rho S_d \sin(2\pi f_k t)}{k} \qquad (1)$$

where $A_x = \frac{-2ac}{\pi L R_\rho (1-R_\rho)}$, $c$ is the velocity of transverse waves, $k$ is the harmonic number, and the $k$th modal frequency $f_k = ck/2L$. $S_\rho$ and $S_d$ are sine terms where $S_\rho = \sin(k\pi R_\rho)$ and $S_d = \sin(k\pi R_d)$ with $R_\rho = \rho/L$, the ratio between string length and distance of plucking point from the bridge, and $R_d = d/L$, the ratio between the string length and the distance of pickup position from the bridge.

The effect of pickup placement on the timbre can be shown by considering its spectrum. The Fourier Series coefficients of the output of a magnetic pickup based on the ideal string equation, $\hat{X}_k$ can be expressed as:

$$\hat{X}_k = A_x \frac{S_\rho S_d}{k} \qquad (2)$$

Notice that for every $k = L/d$ harmonics are suppressed as shown in Fig. 1(b) where the electric guitar model is plucked at one quarter of the string length with a pickup placed at one sixth of the string length. This is the reason why a neck

pickup sounds warmer compared to bridge pickup, as less of its harmonics are sensed by the pickup.

## 4. EXTENDING THE EXISTING MODEL

In this section, we extend the ideal electric guitar string model to include the effects of pickup mixtures.

Electric guitars commonly have an option to mix the outputs of two pickups together. Tillman [21] and Paiva [6] studied the effect of mixed pickups and a model was introduced. The electric guitar model in Eq. 2 can be extended to include mixing two pickups of distance $d_1$ and $d_2$ along the string of length $L$, assuming that both pickups sense at a single point:

$$\hat{X}_k = A_x \frac{S_\rho (S_{d_1} + S_{d_2})}{k} \qquad (3)$$

Note that a mixed pickup boosts and attenuates certain harmonics depending on the placements of both pickups. The in-phase connection of the two pickups is more typical than out-of-phase (which can be modelled by subtraction in Eq. 3).

## 5. METHOD FOR ESTIMATING PLUCKING POINT AND PICKUP POSITION

This section explains our method to estimate the locations of the guitar pickup and plucking point. The method can be summarised as follows: 1) Extract the first period from the recorded tone; 2) compute its Fourier coefficients; 3) calculate errors between the Fourier coefficients and the electric guitar model for various plucking points and pickup locations using grid search and return the values that minimise the error.

### 5.1. Retrieving a period of the electric guitar tone

To analyse an electric guitar tone in the frequency domain using Fourier Series, a period of the tone needs to be extracted. Firstly, an onset detection algorithm is used to discard the beginning silent portion of the audio file. Spectral flux is used to estimate the onset time by measuring the spectral changes in the recorded guitar tone, summing positive changes in the magnitude in each frequency bin across all frequency bins for a frame [22]. Peaks in spectral flux indicate the times of possible onsets. A window size of length 11.6 ms and overlapping windows of 50% are used to calculate the spectral flux.

The onset detection method locates the onset time before the plucking noise which is not the start of the period. In order to locate the start of the period, a zero-crossing detection method is used. A frame of length 46 ms is analysed from the estimated onset location to find the first peak of the signal. Then, working backwards from the first peak of the signal toward the estimated onset location, a zero-crossing detection locates the starting point of the period.

The period $T$ of the recorded tone is measured using autocorrelation. The first peak of the autocorrelation function is detected excluding the point of zero lag, to determine the period of the tone.

### 5.2. Magnitude spectrum of the recorded tone

After extracting the period of the recorded tone, the Fourier series coefficients, $X_k$ are calculated. We assume that the range of plucking positions of an electric guitar is roughly around the magnetic pickup area as shown in Fig. 1(a). Hence, the closest pluck to the bridge could be at approximately one twenty-fifth of the string length. Thus, we set the total number of harmonics to 25 for analysis.

### 5.3. Minimising the error

We calculate the mean squared error between the magnitude spectrum of the observed data and electric guitar model for plucking points and pickup positions ranging from 27 mm to 180 mm with a spatial resolution of 1 mm. The minimum mean squared error corresponds to the estimated plucking point and pickup position. The model uses ratio values, so we convert the results to millimeters based on the known length of the string.

The range of ratios is from 0.03 to 0.3 with an interval of 0.0015 as a general set of grid search parameters for any given type of electric guitar. This will give grid search resolutions of 1 mm and 0.8 mm for the longest and shortest typical scale lengths respectively.

## 6. RESULTS

### 6.1. Estimate single pickup

This section shows the results for estimating the pickup and plucking position of the electric guitar from audio tracks recorded from each single pickup. We will provide a description of how well the system estimates parameters from an electric guitar with single coil pickups. We used the audio files that are described in Sec. 2, where we only take the electric guitar sound samples that are recorded from 3 single pickup configurations: bridge, middle and neck pickup. Each sample is played at one of 8 plucking points on each open string, thus a total of 144 (6 strings × 3 pickups × 8 plucking positions) audio samples are used for this experiment.

The predictions of the electric guitar model in Eq. 2 are compared with the observed data as discussed in Sec. 5. The method produces two sets of estimates where both sets have the same values but are mirrored. This is because Eq. 2 is symmetrical in $R_\rho$ and $R_d$, and will produce the same magnitude spectrum if the two parameters are interchanged. The method on its own cannot distinguish between estimates belonging to the plucking point and the pickup position. Therefore, further information is required by our method such as the expected pickup locations (i.e. the known physical positions of the pickups on the instrument under test). The estimated

| String | | Pickup position error (mm) | | | Plucking point error (mm) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| No. | Pitch | $\varepsilon_{d_b}$ | $\varepsilon_{d_m}$ | $\varepsilon_{d_n}$ | $\varepsilon_{\rho_1}$ | $\varepsilon_{\rho_2}$ | $\varepsilon_{\rho_3}$ | $\varepsilon_{\rho_4}$ | $\varepsilon_{\rho_5}$ | $\varepsilon_{\rho_6}$ | $\varepsilon_{\rho_7}$ | $\varepsilon_{\rho_8}$ |
| 1st | E4 | 20.63 | 4.00 | 4.63 | 67.83 | 13.50 | 10.17 | 4.17 | 16.17 | 1.83 | 2.50 | 7.50 |
| 2nd | B3 | 26.50 | 6.00 | 3.00 | 38.33 | 29.67 | 12.00 | 5.67 | 7.00 | 6.33 | 2.67 | 5.33 |
| 3rd | G3 | 15.30 | 4.13 | 1.63 | 28.33 | 27.67 | 11.33 | 3.67 | 6.67 | 3.33 | 3.33 | 3.67 |
| 4th | D3 | 14.25 | 3.25 | 2.00 | 27.67 | 25.33 | 7.33 | 3.33 | 5.33 | 2.67 | 3.33 | 3.33 |
| 5th | A2 | 9.63 | 2.50 | 2.38 | 44.00 | 7.67 | 8.67 | 4.00 | 2.67 | 2.67 | 4.00 | 1.00 |
| 6th | E2 | 15.13 | 3.00 | 1.63 | 20.33 | 7.00 | 10.33 | 3.67 | 5.33 | 2.33 | 3.00 | 2.67 |

**Table 1**. Average absolute error of pickup position and plucking point estimation for single pickups (mm), where $b$ is the bridge pickup, $m$ is middle pickup and $n$ is neck pickup. The means of pickup position errors are calculated over 8 different plucking points and the means of plucking point errors are calculated over 3 different pickup locations.

| | Plucking point error (mm) | Pickup position error (mm) | | |
|---|---|---|---|---|
| Config. | $\varepsilon_\rho$ | $\varepsilon_{d_b}$ | $\varepsilon_{d_m}$ | $\varepsilon_{d_n}$ |
| 1 | 14.27 | | 6.13 | 11.67 |
| 2 | 6.63 | 8.15 | 11.81 | |

**Table 2**. Average absolute errors of mixed pickup positions and plucking points, for two pickup configurations.

value that is closest to the expected pickup position is chosen as the estimated pickup position and the other value is the plucking point.

To validate the accuracy of the estimates we calculate the error distance between the estimated value and its ground truth $\varepsilon$ in millimeters. Table 1 shows the average absolute errors of the pickup position estimation $\varepsilon_d$ and the average absolute errors of the plucking point estimation $\varepsilon_\rho$.

Some estimates are highly accurate, e.g. the neck pickup estimates have $1 - 5$ mm average error, while others give larger errors, e.g. the bridge pickup estimates have $9 - 27$ mm error. The lowest error is 0 mm and largest error is 60.5 mm.

The plucking point estimates also show a similar trend with less accuracy when the guitar is plucked near the bridge. This is because the spectrum of the electric guitar model does not fit the observed data properly when the pickup position and plucking point are near the bridge. The ideal model produces a perfect comb filtering effect, whereas the observed data is flatter. Note that the estimation errors also increase as the plucking points approach the bridge in [16]. The estimates of plucking points at 150 mm from the bridge are the most accurate, yielding 3.14 mm error on average. The least accurate is the closest to the bridge which has an average of 37.75 mm error. The variations of the results in regards to the string might due to the nonlinear behaviour of the plucked string. Global average errors for pickup position and plucking point estimation are 7.75 mm and 10.97 mm respectively.

### 6.2. Estimate mixed pickup

We also tested two in-phase mixed pickup configurations: 1) a mix between neck pickup and middle pickup; and 2) a mix between middle pickup and bridge pickup. The method of estimating these values is described in Sec. 5. The electric guitar model in Eq. 3 is used for estimating plucking point and locations of two pickups from a mixed pickup signal.

For estimating mixed pickup signals, the system has a similar problem to estimating a single pickup position as described in Sec. 6.1 where two sets of estimates arise. This occurs because the two sets of parameters yield the same spectral shape. We can prove this by expanding Eq. 3 using trigonometric identities:

$$\hat{X}_k = 2A_x \frac{S_\rho \sin\left(k\pi\frac{R_{d_1}+R_{d_2}}{2}\right)\cos\left(k\pi\frac{R_{d_1}-R_{d_2}}{2}\right)}{k} \quad (4)$$

Here we can see that there are two sine functions (including $S_\rho$), similar to Eq. 2 except that the parameter for the second sine function uses the average of two pickup locations. The method cannot distinguish between estimates belonging to the plucking point and the average pickup location. Therefore, the estimated value that is closest to the expected average pickup location is chosen for the estimated pickup locations and the other value is the estimated plucking point.

Table 2 shows the errors of estimating plucking points and pickup positions for the two mixed pickup configurations. Overall, the system estimates the positions with less than 15 mm of error on average. The global average absolute error for pickup position and plucking point are 9.44 mm and 10.45 mm, respectively, which are not far from the results for single pickups.

### 7. CONCLUSIONS

We have described a technique to estimate the plucking point and pickup position used to produce a given electric guitar tone by finding the parameters of an ideal electric guitar model that fits the observed data. The accuracy of the approach is tested on recordings of single tones using a single or mixed pickup configuration. Our approach is able to estimate pickup locations with 7.75–9.44 mm average absolute error and plucking points with 10.45–10.97 mm average absolute error for single and mixed pickups. Further research could look into distinguishing between plucking point and pickup position, and could test the accuracy of the estimates while varying playing technique.

## 8. REFERENCES

[1] Alex Case, Agnieszka Roginska, Justin Matthew, and Jim Anderson, "Electric guitar – a blank canvas for timbre and tone," *The Journal of the Acoustical Society of America*, vol. 133, no. 5, pp. 3308, 2013.

[2] Matti Karjalainen, Vesa Välimäki, and Zoltán Jánosy, "Towards high-quality sound synthesis of the guitar and string instruments," in *Proceedings of the International Computer Music Conference*, 1993, pp. 56–63.

[3] Mikael Laurson, Cumhur Erkut, Vesa Välimäki, and Mika Kuuskankare, "Methods for modeling realistic playing in acoustic guitar synthesis," *Computer Music Journal*, vol. 25, no. 3, pp. 38–49, 2001.

[4] Charles R Sullivan, "Extending the Karplus-Strong algorithm to synthesize electric guitar timbres with distortion and feedback," *Computer Music Journal*, vol. 14, no. 3, pp. 26–37, 1990.

[5] Niklas Lindroos, Henri Penttinen, and Vesa Välimäki, "Parametric electric guitar synthesis," *Computer Music Journal*, vol. 35, no. 3, pp. 18–27, 2011.

[6] Rafael CD Paiva, Jyri Pakarinen, and Vesa Välimäki, "Acoustics and modeling of pickups," *Journal of the Audio Engineering Society*, vol. 60, no. 10, pp. 768–782, 2012.

[7] Erhard Rank and Gernot Kubin, "A waveguide model for slapbass synthesis," in *IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP)*, 1997, vol. 1, pp. 443–446.

[8] Patrick Kramer, Jakob Abeßer, Christian Dittmar, and Gerald Schuller, "A digital waveguide model of the electric bass guitar including different playing techniques," in *IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP)*, 2012, pp. 353–356.

[9] Lejaren Hiller and Pierre Ruiz, "Synthesizing musical sounds by solving the wave equation for vibrating objects: Part 1," *Journal of the Audio Engineering Society*, vol. 19, no. 6, pp. 462–470, 1971.

[10] Neville H Fletcher, "Plucked strings – a review," *Catgut Acoust. Soc. Newsletter*, vol. 26, pp. 13–17, 1976.

[11] Michael Stein, Jakob Abeßer, Christian Dittmar, and Gerald Schuller, "Automatic detection of audio effects in guitar and bass recordings," in *Audio Engineering Society Convention 128*. Audio Engineering Society, 2010.

[12] Arthur Paté, Jean-Loïc Le Carrou, and Benoît Fabre, "Predicting the decay time of solid body electric guitar tones," *The Journal of the Acoustical Society of America*, vol. 135, no. 5, pp. 3045–3055, 2014.

[13] Cumhur Erkut, Vesa Välimäki, Matti Karjalainen, and Mikael Laurson, "Extraction of physical and expressive parameters for model-based sound synthesis of the classical guitar," in *Audio Engineering Society Convention 108*. Audio Engineering Society, 2000.

[14] Jakob Abeßer, Hanna Lukashevich, and Gerald Schuller, "Feature-based extraction of plucking and expression styles of the electric bass guitar," in *IEEE International Conference on Acoustics Speech and Signal Processing (ICASSP)*, 2010, pp. 2290–2293.

[15] Caroline Traube and Julius O Smith, "Estimating the plucking point on a guitar string," in *Proceedings of the COST G-6 Conference on Digital Audio Effects*, Verona, Italy, 2000.

[16] Henri Penttinen and Vesa Välimäki, "A time-domain approach to estimating the plucking point of guitar tones obtained with an under-saddle pickup," *Applied Acoustics*, vol. 65, no. 12, pp. 1207–1220, 2004.

[17] Henri Penttinen, Jaakko Siiskonen, and Vesa Valimaki, "Acoustic guitar plucking point estimation in real time," in *IEEE International Conference on Acoustics, Speech, and Signal Processing (ICASSP)*. IEEE, 2005, vol. 3, pp. 209–212.

[18] Z. Mohamad, S. Dixon, and C. Harte, "Digitally moving an electric guitar pickup," in *Proc. of the Int. Conf. on Digital Audio Effects (DAFx-15)*, 2015, pp. 284–291.

[19] Nicholas G Horton and Thomas R Moore, "Modeling the magnetic pickup of an electric guitar," *American Journal of Physics*, vol. 77, no. 2, pp. 144–150, 2009.

[20] Thomas D Rossing and Graham Caldersmith, "Guitars and lutes," in *The Science of String Instruments*, Thomas D Rossing, Ed., pp. 19–45. Springer, 2010.

[21] J Donald Tillman, "Response effects of guitar pickup position and width," 2002, Available online at: http://www.till.com/articles/PickupMixing/index.html.

[22] Paul Masri, *Computer modelling of sound for transformation and synthesis of musical signals*, Ph.D. thesis, University of Bristol, 1996.