ESTIMATING PICKUP AND PLUCKING POSITIONS OF GUITAR TONES AND CHORDS WITH AUDIO EFFECTS

Zulfadhli Mohamad , Simon Dixon,*

Centre for Digital Music,
Queen Mary University of London
London, United Kingdom
z.b.mohamad@qmul.ac.uk
s.e.dixon@qmul.ac.uk

Christopher Harte,

Melodient Limited
United Kingdom
chris@melodient.com

ABSTRACT

In this paper, we introduce an approach to estimate the pickup position and plucking point on an electric guitar for both single notes and chords recorded through an effects chain. We evaluate the accuracy of the method on direct input signals along with 7 different combinations of guitar amplifier, effects, loudspeaker cabinet and microphone. The autocorrelation of the spectral peaks of the electric guitar signal is calculated and the two minima that correspond to the locations of the pickup and plucking event are detected. In order to model the frequency response of the effects chain, we flatten the spectrum using polynomial regression. The errors decrease after applying the spectral flattening method. The median absolute error for each preset ranges from 2.10 mm to 7.26 mm for pickup position and 2.91 mm to 21.72 mm for plucking position estimates. For strummed chords, faster strums are more difficult to estimate but still yield accurate results, where the median absolute errors for pickup position estimates are less than 10 mm.

1. INTRODUCTION

The popularity of the electric guitar began to rise in the mid 1950s and it soon became, and has since remained, one of the most important instruments in Western popular music. Well known guitar players can often be recognised by the distinctive electric guitar tone they create. Along with the player's finger technique, the unique tone they achieve is produced by their choice of electric guitar model, guitar effects and amplifiers. Some popular musicians prefer using one or two choices of guitar models for recordings and live performances. Some guitar enthusiasts are keen to know how their favourite guitar players produce their unique tones. Indeed, some will go as far as to purchase the same electric guitar model, effects and amplifiers to replicate the sounds of their heroes.

The tones produced by popular electric guitar models such as Fender and Gibson are clearly distinguishable from each other, with different pickup location, width, and sensitivity, along with circuit response of the model leading to different timbres. The pickup location of an electric guitar contributes to the sound significantly, where it produces a comb-filtering effect on the spectrum. The tonal differences can be heard just by switching the pickup configuration of the guitar. Thus, if the type of electric guitar is known, the estimated pickup position can help distinguish which pickup configuration is selected. Equally, where the guitar model on a recording is not known, pickup position estimates could be useful in deducing which type of electric guitar could have produced a particular tone.

In 1990, research on synthesising electric guitar sound was proposed by Sullivan whereby the Karplus-Strong algorithm is extended to include a pickup model with distortion and feedback effects [1]. Commercial firms such as Roland and Line 6 produce guitar synthesisers that use hexaphonic pickups allowing them to process sound from each string separately to mimic the sound of many other popular guitars [2, 3]. They model the pickups of popular electric guitars including the effects of pickup position, height and magnetic apertures. Lindroos et al. [4] introduced a parametric electric guitar synthesis where conditions that affect the sound can be changed such as the force of the pluck, plucking point and pickup position. Further details of modelling the magnetic pickup are studied by Paiva et al. [5], which include the effect of pickup width, nonlinearity and circuit response.

Since electric guitar synthesis requires the pickup and plucking positions to be known, a method to estimate these parameters could be useful when trying to replicate the sound of popular guitarists from a recording. Several papers propose techniques to estimate the plucking point on an acoustic guitar, using either a frequency domain approach [6, 7] or a time domain approach [8]. A technique to estimate the plucking point and pickup position of an electric guitar is proposed by Mohamad et al. [9] where direct input electric guitar signals are used in the experiments.

Our previous work has dealt with recordings of isolated guitar tones. The first major contribution of the current paper is to extend the previous work to estimate the pickup and plucking locations of electric guitar signals that are processed through a combination of emulated electric guitar effect, amplifier, loudspeaker and microphone. This can bring us closer to estimating pickup and plucking locations of real-world electric guitar recordings. We also introduce a technique to flatten the spectrum before calculating the autocorrelation of the spectral peaks and finding the two minima of the autocorrelation. The second major contribution is to investigate the performance of our method on strummed chords and propose modifications to mitigate the effects of overlapping tones. We perform experiments with chords strummed at different speeds and with different bass notes to determine optimal parameters for our method.

In Sec. 2, we explain the comb-filtering effects produced in electric guitar tones. Sec. 3 describes the method for estimating the pickup and plucking position of an electric guitar. Sec. 4 explains the datasets that are used in this paper. There are two datasets where one is for testing the effects of different combinations of electric guitar effects, amplifier, loudspeaker and microphone and the other is for testing the effects of various chords. We evalu-

* Zulfadhli Mohamad is supported by the Malaysian government agency, Majlis Amanah Rakyat (MARA)

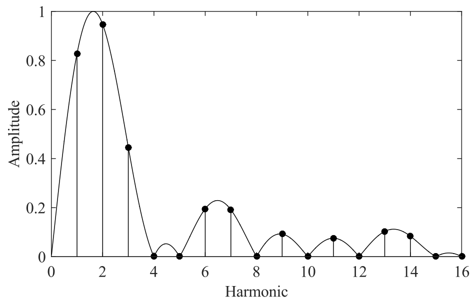

Figure 1: *The spectral envelope of the electric guitar model plucked at one quarter of the string length with pickup situated at one-fifth of the string length from the bridge.*

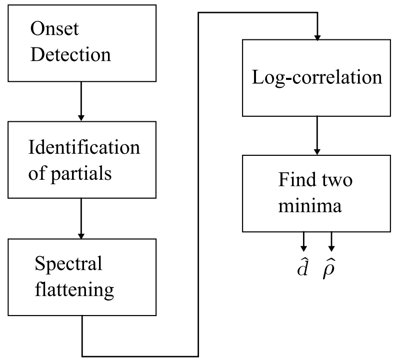

Figure 2: *Block diagram for estimating pickup position and plucking point of an electric guitar*

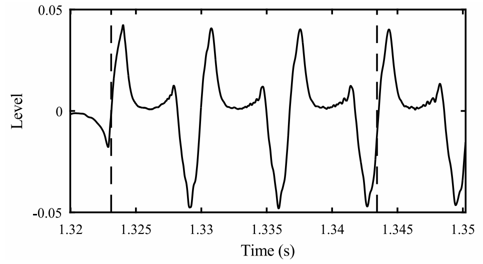

Figure 3: *An excerpt of an electric guitar tone where the string is plucked on the open 4th string at 110 mm from the bridge with a pickup located at 159 mm from the bridge. The dashed vertical lines mark the detected beginnings of the 1st and 4th periods.*

ate our method for various chains of effects in Sec. 5 and various chords in Sec. 6. The conclusion is presented in Sec. 7.

2. ELECTRIC GUITAR MODEL

When a string is plucked, two waves travel in opposite directions propagating away from the plucking point. The waves are then reflected back from the nut and bridge of the electric guitar producing a standing wave in the string. The vibrations of the strings are sensed by a pickup at a certain distance along the string thus certain harmonics (those with nodes at the pickup location) cannot be sensed. Similarly, harmonics with nodes at the plucking position are not excited. This means that depending on the locations of the pluck and pickup, certain harmonics are suppressed, resulting in two simultaneous comb-filtering effects. The spectral envelope of an electric guitar string model, $\hat{X}_k$ plucked at a point ρ, with a vertical displacement a, sensed at a point d is calculated as:

$$\hat{X}_k = A_x \frac{S_\rho S_d}{k} \tag{1}$$

where $A_x = \frac{-2ac}{\pi L R_\rho (1-R_\rho)}$, c is the velocity of transverse waves in the string, k is the harmonic number, $S_\rho = \sin(k\pi R_\rho)$, $S_d = \sin(k\pi R_d)$, R_d is the ratio between distance d and string length L and R_ρ is the ratio between distance ρ and string length L. Note that the comb filters have a -6 dB/octave slope.

An example using Eq. (1) is shown in Fig. 1 where the electric guitar is plucked at a quarter of the string length and is sensed by a pickup situated at one-fifth of the string length; every 4th and 5th harmonic is suppressed.

3. METHOD

The overview of the method for estimating the pickup and plucking positions of an electric guitar is shown in Fig. 2.

3.1. Onset and Pitch Detection

First, the spectral flux of the electric guitar signal is used to estimate the onset time [10]. The power spectrum for a frame is compared against the previous frame, where positive changes in the magnitude in each frequency bin are summed. Peaks in the spectral flux suggest possible onset times. We set the window size to be 40 ms with 10 ms overlapping windows to find the onset times.

Due to the window overlap, the initial estimated onset time typically comes before the plucking noise, thus it is necessary to refine the estimate to be closer to the plucking event. Starting from the initial onset time estimate, the peaks of the signal are detected and peaks less than 30% of the maximum peak are discarded to avoid unwanted small peaks at the beginning due to plucking noise. Starting from the first peak and working backwards, the first zero-crossing is taken to be the start time of the tone. Fig. 3 shows an excerpt of an electric guitar tone plucked on the open 4th (D) string at 110 mm from the bridge with a pickup located at 159 mm from the bridge, which starts from the initial onset time (around 1.32 s) and the first vertical dashed line represents the estimated start time of the tone.

After estimating the onset time, the fundamental frequency f_0 is estimated using YIN [11], where we set the window size to be 46 ms.

3.2. Identification of Partials

From the onset time of the tone, the STFT of the signal is performed using a hamming window and zero padding factor of 4 to analyse the first few periods of the waveform. In this example, the first 3 periods are taken for STFT analysis as shown in Fig. 3. The advantage of taking such a small window is that time modulation effects such as reverb and delay will not be prevalent during the first few periods of the signal.

Each spectral peak is found in windows of $\pm$ 30 cents around estimated partial frequencies calculated based on typical inhar-

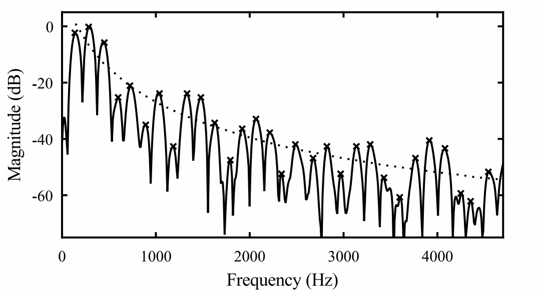

Figure 4: *Spectrum of the electric guitar tone in Fig. 3 with the detected spectral peaks (crosses) and slope of the spectrum (dotted line).*

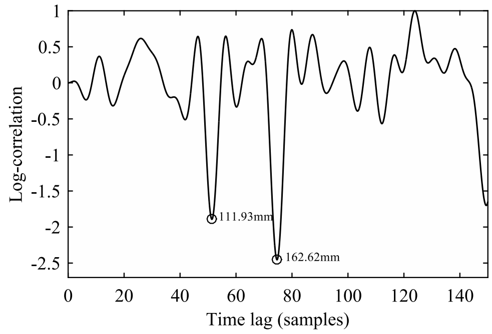

Figure 5: *The log-correlation of an electric guitar plucked on the open 4th string at 100 mm from the bridge with a pickup located at 159 mm from the bridge.*

monicity coefficients for each string [12]. Quadratic interpolation is used to refine the magnitudes and frequencies of the spectral peaks [13]. From each pair of estimated partial frequencies, the inharmonicity B can be determined. The median of all B values is taken as our estimated inharmonicity coefficient $\hat{B}$.

Some spectral peaks may be falsely detected, for instance, some estimated partial frequencies may be located on top of or close to each other. This is mainly because the initial inharmonicity coefficient that we set might be more or less than the actual inharmonicity coefficient of the string. Therefore, we need to set a threshold to identify any falsely estimated partial frequencies. We calculate the target frequencies using the inharmonicity coefficient $\hat{B}$ estimated earlier:

$$f_k = k f_0 \sqrt{1 + \hat{B} k^2} \tag{2}$$

Then, any estimated partial frequencies deviating by more than $\pm$ 30 cents from their target frequencies are identified as false. The corrected spectral peak is found in the revised window, and refined using quadratic interpolation. If no peak is found in the window, the corrected partial frequency is set equal to its target frequency.

Fig. 4 shows the spectrum of the electric guitar signal in Fig. 3 with the detected spectral peaks.

3.3. Spectral flattening

In this paper, we introduce an approach to flatten the spectrum of the observed data X_k. We do this because the ideal model of Sec. 2

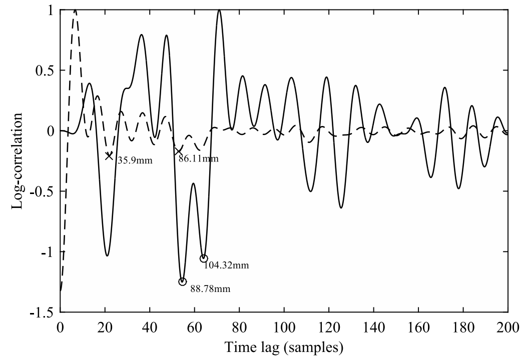

Figure 6: *The log-correlation of an electric guitar tone with spectral flattening (solid line) and without spectral flattening (dashed line). The electric guitar is plucked on the open 5th string at 90 mm from the bridge with a pickup located at 102 mm from the bridge.*

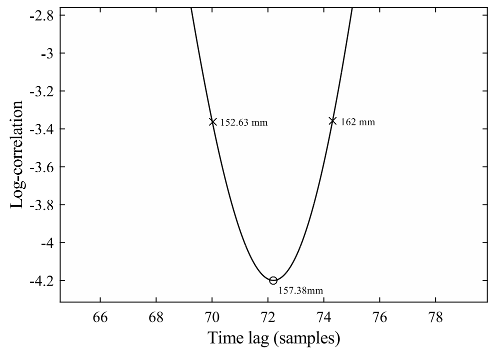

Figure 7: *The log-correlation of an electric guitar tone where the string is plucked on the open 4th string at 150 mm from the bridge with a pickup located at 159 mm from the bridge, resulting in the two troughs merging into a single trough.*

ignores the low-pass filtering effect of the finite widths of the plectrum and pickup. Flattening the spectrum reverses this effect by increasing the level of higher harmonics.

The best fitting curve for the log magnitude X_k in the log-frequency domain is calculated using polynomial regression. We compare linear and third-order polynomial regression to approximate the frequency response produced by the guitar signal chain. Matlab's `polyfit` function is used to retrieve the coefficients of the polynomial $p(x)$. The polynomial regression curve for the spectrum in Fig. 4 is shown as a dotted line.

Then, the spectrum X_k can be flattened as follows:

$$\bar{X}_k = \frac{X_k}{e^{p(\log(k))}} \tag{3}$$

where $\bar{X}_k$ is the flattened spectrum of the observed data X_k.

3.4. Log-correlation

Since the plucking point ρ, and pickup position d, produce two comb-filtering effects as shown in Eq. (1), the delay of the comb filters can be estimated using the autocorrelation of the log magnitude of the spectral peaks. The log-correlation as described by

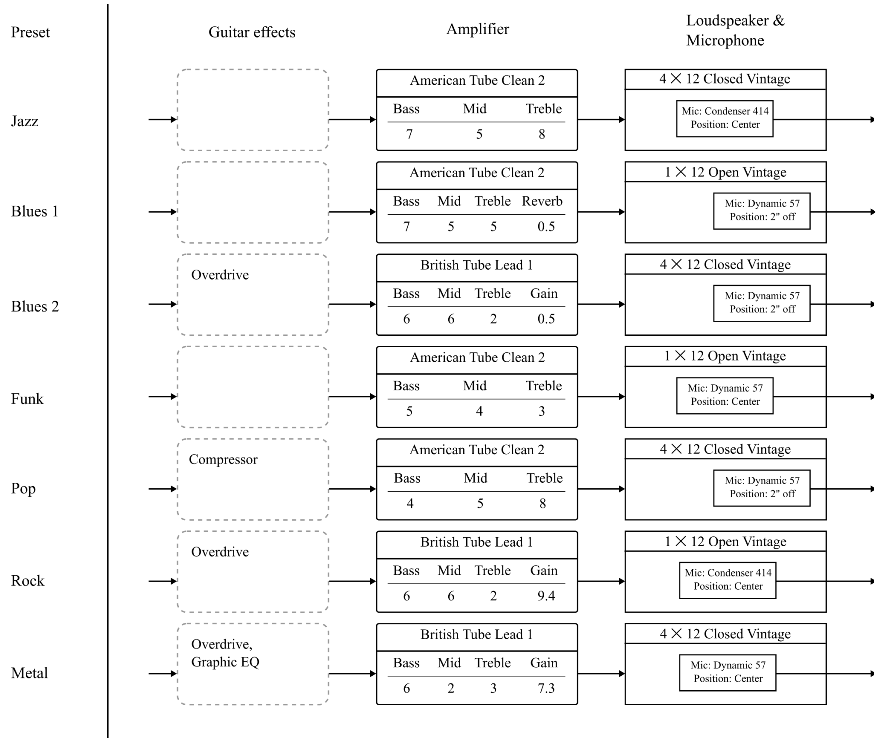

Figure 8: *Seven combinations of emulated electric guitar effects, amplifier, loudspeaker and microphone.*

Traube and Depalle [7] is calculated as:

$$\Gamma(\tau) = \sum_{k=1}^{K} \log(\bar{X}_k^2) \cos(\tfrac{2\pi k \tau}{T}) \tag{4}$$

where T is the period of the signal. For an electric guitar, it is expected that we would see two minima in the log-correlation where the time lag of one trough τ_d indicates the position of the pickup and the time lag of the other τ_ρ indicates the position of the plucking event. Therefore, the estimated pickup position, $\hat{d}$ and plucking point $\hat{\rho}$ can be calculated by finding the time lags, $\hat{\tau}_d$ and $\hat{\tau}_\rho$ in the log-correlation using trough detection, where $\hat{d} = \frac{\hat{\tau}_d L}{T}$ and $\hat{\rho} = \frac{\hat{\tau}_\rho L}{T}$.

3.5. Find two minima of the log-correlation

The method for finding the two minima of the log-correlation can be described by an example where the electric guitar tone in Fig. 3 is taken for analysis. The log-correlation is calculated until T samples ($f_0 = 147.59$ Hz) where the time lag resolution is 0.01 samples. The log-correlation of the electric guitar tone is shown in Fig. 5, where the lowest two troughs that correspond to the pickup and plucking locations are visible where one time lag is 74.66 samples (or 162.62 mm) and the other is 51.38 samples (or 111.93 mm).We are only interested in the lowest two troughs located in the first half of the log-correlation but it is not possible to determine which represents the pickup and which is the pluck point from this information alone. Instead, given that we already know what model guitar was used to produce the sounds, we take the trough that is closest to a known pickup location as our estimated pickup position and the other as the estimated plucking point.In this example, the absolute errors for the pickup position and plucking point estimates are 3.62 mm and 1.93 mm respectively.

Without flattening the spectrum, the troughs are not as apparent and it could be difficult to detect the two minima. An example is given in Fig. 6, where the electric guitar is played on the open 5th string, plucked 90 mm from the bridge with the pickup situated at 102 mm from the bridge. It shows two log-correlations of the spectral peaks where one is with spectral flattening (solid line) and the other is without spectral flattening (dashed line). We can see that the troughs corresponding to the pickup and plucking positions are emphasised if the spectrum has been flattened. The plucking point estimate is also closer to the known plucking point.

There are cases where the plucking point is at or near the pickup position, causing the two troughs to merge together. We need to set a threshold to define whether that is the case. If the second lowest trough detected is above 40% of the lowest trough, then only the lowest trough is selected. By taking an example of an electric guitar plucked at 150 mm from the bridge with the pickup located at 159 mm from the bridge, Fig. 7 shows the only trough detected where the time lag is 72.2 samples (or 157.38 mm). Since the two troughs are merged together, it will be less accurate if we assume that the plucking point is at the pickup location. Thus, we take the time lags where both are at 80% of the minimum value. This also applies to plucks that are at the pickup position, where the width of the trough is thinner. Fig. 7 shows the estimated pickup position and plucking point which are 162 mm and 152.63 mm respectively.

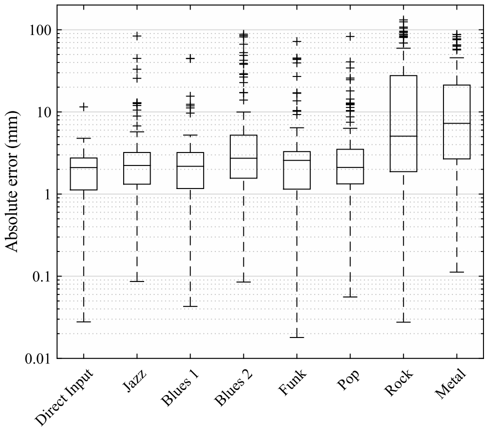

Figure 9: *Box plot of absolute error in pickup position estimates for each preset. Note that the y-axis is in log scale.*

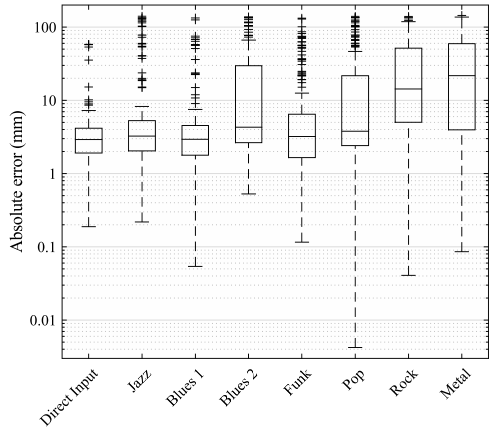

Figure 10: *Box plot of absolute error in plucking point estimates for each preset. Note that the y-axis is in log scale.*

Table 1: *Median absolute error for pickup position and plucking point estimates for each preset, comparing between no spectral flattening (NSF), linear regression spectral flattening (LRSF) and polynomial regression spectral flattening (PRSF).*

Preset	Median absolute error (mm)					
	Pickup position			Plucking point		
	NSF	LRSF	PRSF	NSF	LRSF	PRSF
Direct Input	2.56	2.03	2.10	4.14	2.87	2.91
Jazz	2.44	2.17	2.23	3.61	3.42	3.25
Blues 1	2.32	2.28	2.18	4.25	3.04	2.94
Blues 2	3.22	3.62	2.73	4.52	6.90	4.30
Funk	2.55	2.03	2.57	4.61	3.06	3.21
Pop	2.34	2.25	2.11	4.05	3.90	3.79
Rock	5.58	4.17	5.07	17.01	14.75	14.29
Metal	9.54	8.84	7.26	34.60	31.08	21.72
Average	3.82	3.42	3.28	9.60	8.63	7.05

4. AUDIO SAMPLES

In this paper, we use 144 direct input electric guitar signals recorded by Mohamad et al. [9] with sampling rate, f_s 44.1 kHz. The signals are recorded from a Squier Stratocaster and consist of moderately loud (*mezzo-forte*) plucks on 6 open strings at 8 plucking positions using 3 single pickup configurations. The strings are plucked at 30 mm to 170 mm from the bridge at 20 mm intervals. The pickup configurations consist of neck, middle and bridge pickup where their distances are measured around 160 mm, 100 mm and 38 – 48 mm (slanted pickup) from the bridge respectively. The length of the strings is around 650 mm. Note that the offsets of the measurements due to different adjustments of each saddle bridge are taken into account.

All the signals are processed through 7 combinations of digitally emulated electric guitar effects, amplifier, loudspeaker cabinet and microphone in Reaper [14], resulting in 1152 audio samples in total (8 $\times$ 144 samples, where direct input signals are also included). We select 7 presets that are freely available in Amplitube Custom Shop by IK Multimedia, where each of them produces a tone for a certain style [15]. Common styles are selected which are Jazz, Blues, Funk, Pop, Rock and Metal. As shown in Fig. 8, there are 3 emulated guitar effects, 2 emulated amplifiers, 2 emulated loudspeaker cabinets and 2 emulated microphones. Note that each preset has different equipment settings and microphone placement.

Additionally, a second dataset is used to test the accuracy of the estimation on various downstroke chords. We recorded 81 direct input electric guitar signals which consist of 3 chords (E major, A major and G major) strummed at 3 positions (on top of each pickup) with 3 different speeds and 3 pickup configurations (neck, middle and bridge pickup). The same electric guitar was used for this dataset and these signals are also processed through the 7 combinations of effects discussed earlier.

5. RESULTS: ELECTRIC GUITAR EFFECTS, AMPLIFIER, LOUDSPEAKER AND MICROPHONE

In this section, we examine the effects of different combinations of emulated electric guitar effects, amplifier, loudspeaker and microphone on the estimates. We test on the 8 combinations mentioned in Sec. 4, where the emulated equipment used is shown in Fig. 8. The method described in Sec. 3 is used to find the estimates, where the spectrum is flattened using polynomial regression. The first 10 cycles of the tones are taken for the STFT analysis for all presets. For clean tones i.e. Direct Input, Jazz, Blues 1, Funk and Pop presets, the total number of harmonics K is set to 40. For overdriven and distorted tones i.e. Blues 2, Rock and Metal presets, the total number of harmonics K is set to 30.

Fig. 9 and 10 show the absolute errors for pickup position and plucking point estimates respectively. The line inside each box is the median and the outliers are represented by cross symbols (+). Overall, the median absolute errors for pickup position estimates are less than 8 mm ranging from 2.10 mm – 7.26 mm. The median absolute errors for plucking point estimates are less than 30 mm ranging from 2.91 mm – 21.72 mm.

In Fig. 9, the third quartiles for most presets are less than 10 mm which suggests that the pickup position estimates are robust to most presets. The errors for pickup position estimates increase as the signal gets heavily distorted. The errors for plucking point estimates also show a similar trend as shown in Fig. 10, where errors increase as the electric guitar signal is more distorted.

Finally, we compare the two spectral flattening methods described previously which are linear regression spectral flattening (LRSF) and polynomial regression spectral flattening (PRSF). Ta-

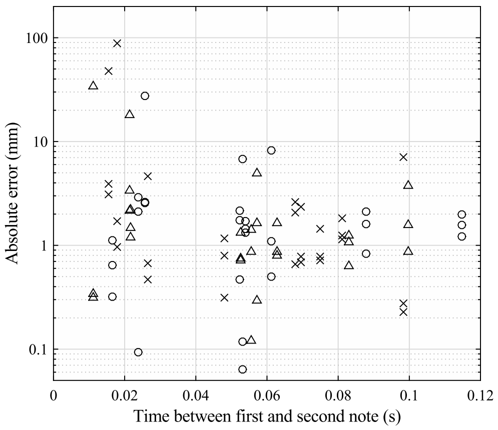

Figure 11: *Absolute errors for pickup position estimates of chords. The crosses represent E major chords, circles represent A major chords and triangles represent G major chords. Note that the y-axis is in log scale.*

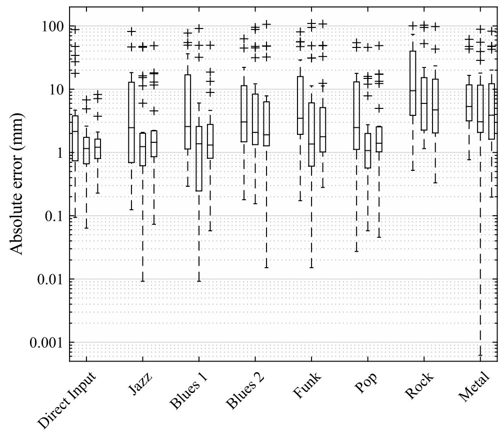

Figure 13: *Box plot of absolute error in pickup position estimates for chords for each preset. Each preset has three box plots, where the boxes (from left to right) are for fast, slow and very slow strums respectively. Note that the y-axis is in log scale.*

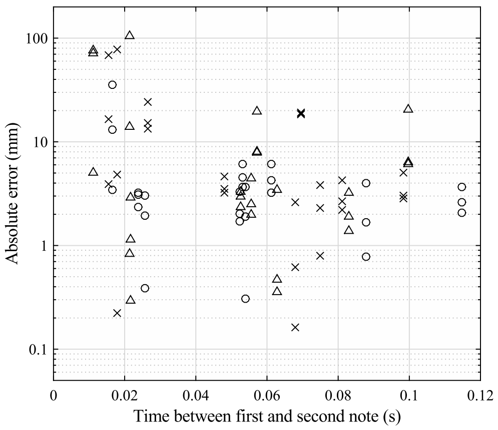

Figure 12: *Absolute errors for plucking point estimates of chords. The crosses represent E major chords, circles represent A major chords and triangles represent G major chords. Note that the y-axis is in log scale.*

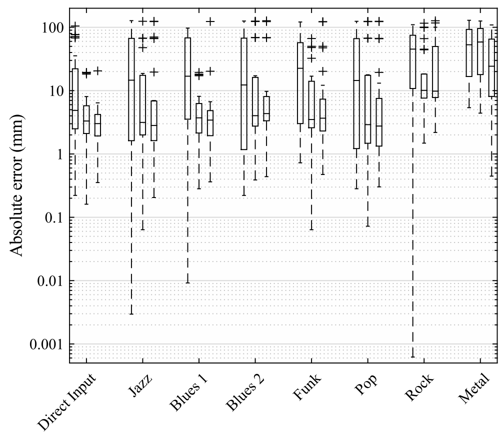

Figure 14: *Box plot of absolute error in plucking point estimates for chords for each preset. Each preset has three box plots, where the boxes (from left to right) are for fast, slow and very slow strums respectively. Note that the y-axis is in log scale.*

ble 1 shows the median absolute errors for pickup and plucking position estimates. The average median absolute error across all presets for pickup and plucking position estimates decrease by 0.14 mm and 1.58 mm respectively using PRSF compared to LRSF. Overall, the median absolute errors decrease when the spectral flattening methods are applied. This suggests that we improved the method by introducing a technique to flatten the spectrum.

6. RESULTS: CHORDS

In this section, we test the accuracy of our method on strummed chords. The chords played are E major, A major and G major, where the first string to be struck is the 6th string for all chords (downstrokes). Each chord is strummed at 3 different speeds and 3 positions. Since the pickup and pluck positions are unlikely to change during the strum, and our method only requires the first few pitch periods of the electric guitar tone, it should be possible to estimate the pickup and plucking positions where the second note is plucked after a few cycles of the first note. Furthermore, we manually measure the time between the first and second note, t_c. For our method to be unaffected by the strum, the shortest time allowed between the first and second note would be 36.4ms (3 cycles of note 82.41 Hz) for the worst case scenario of the first pitch being E2, the lowest pitch on the guitar. However, natural strumming of a guitar leads to values of t_c of 80ms for slow strums and 20ms for fast strums.

The method described in Sec. 3 is used to estimate the pickup and plucking positions of each chord, where the spectrum is flattened using PRSF. The fundamental frequencies of the first note struck on each chord are known in advance, which are 82.41 Hz (E major and A major) and 98.00 Hz (G major). To present the worst case scenario, the A major chord is played in second inversion (i.e. with a low E in bass). Multiple pitch estimation could be used to estimate the fundamental frequency of the first note [16]. The total number of harmonics K is set to 40 for Direct Input, Jazz, Blues 1, Funk and Pop presets and 30 for Blues 2, Rock and Metal presets. The first 2 cycles are taken for the STFT analysis when t_c is shorter than 40ms and the first 3 cycles are taken when t_c is longer than 40ms. A shorter window is needed for faster strums so that less of the second note is included in the STFT analysis.

Fig. 11 and 12 show the absolute errors for pickup and plucking position estimates respectively for direct input signals. The absolute errors increase for faster strums, nevertheless, most of the errors are less than 20 mm for both pickup and plucking position estimates even though the second note starts to bleed into the window. In Fig. 11 and 12, the shortest t_c for E major, G major and A major chords are 15ms, 11ms and 17ms respectively. This means that the second note for each chord overlaps 38%, 45% and 10% of the analysed window respectively. Chords with later second notes (i.e. a smaller overlap) yield more accurate results, for example, in Fig. 11 shows that the pickup estimates are all less than 2 mm error for A major chord at $t_c = 17$ms. Furthermore, the accuracy of the pickup and plucking position estimates increases when t_c is more than 20ms.

Fig. 13 and 14 show the box plots of absolute errors in pickup and plucking position estimates respectively for each preset. Similar to single note guitar tones, the errors increase as the signal gets more harmonically distorted. Errors also increase for fast strums. Nevertheless, the median absolute errors for pickup position estimates are less than 10 mm.

7. CONCLUSIONS

We have presented a technique to estimate the pickup position and plucking point on an electric guitar recorded through a typical signal processing chain i.e. electric guitar effects, amplifier, loudspeaker and microphone with different settings for each equipment. For each preset, the median absolute errors for pickup position and plucking point estimates are 2.10 mm – 7.26 mm and 2.91 mm – 21.72 mm, where errors increase when signals are more distorted. The other aspects of the signal chain appear to have little effect on our results. Pickup position estimates can be used to distinguish which pickup is selected for a known electric guitar. For an unknown electric guitar, the estimates can be used to distinguish between typical electric guitar models.

The method can reliably estimate the pickup position of most clean, compressed and slightly overdriven tones i.e. with the Jazz, Blues 1, Blues 2, Pop and Funk presets, where 89% – 99% of the errors are less than 10 mm. For Rock and Metal presets, 57% and 63% of the errors are less than 10 mm respectively. Nevertheless, the median absolute errors for both presets are less than 8 mm. We also introduced a flattening method using linear and polynomial regression, where the errors decrease after applying the spectral flattening method. The median absolute errors for pickup and plucking position estimates decrease by 0.14 mm and 1.58 mm respectively across all presets compared to linear regression flattening method.

Furthermore, we evaluate our method for various downstroke chords. Pickup and pluck positions for most chords are detected correctly, with errors similar to those observed for single notes. A small number of outliers are observed which are mostly caused by overlapping tones disturbing our analysis method. The pickup position estimates are quite robust to downstroke chords where the median absolute errors for each preset are less than 10 mm. The errors increase for faster strums (t_c less than 30ms). This may suggest that upstroke chords would pose less of a problem, where the first string struck has a higher pitch (or shorter period).

Further investigation could look into distinguishing between pickup position and plucking point estimates. Plucking positions vary constantly while the pickup position almost always remains fixed in one place; distinguishing the estimates from each other might therefore be achieved by determining which estimates deviate more frequently over a sequence of notes. An electric guitar commonly has an option to mix two pickups together, so in our further work, we are looking into estimating the pickup positions and plucking point of a mixed pickup signal.

8. REFERENCES

[1] C. 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.

[2] A. Hoshiai, "Musical tone signal forming device for a stringed musical instrument," 22 November 1994, US Patent 5,367,120.

[3] P. J. Celi, M. A. Doidic, D. W. Fruehling, and M. Ryle, "Stringed instrument with embedded dsp modeling," 7 September 2004, US Patent 6,787,690.

[4] N. Lindroos, H. Penttinen, and V. Välimäki, "Parametric electric guitar synthesis," *Computer Music Journal*, vol. 35, no. 3, pp. 18–27, 2011.

[5] R. C. D. Paiva, J. Pakarinen, and V. Välimäki, "Acoustics and modeling of pickups," *Journal of the Audio Engineering Society*, vol. 60, no. 10, pp. 768–782, 2012.

[6] C. Traube and J. O. Smith, "Estimating the plucking point on a guitar string," in *Proceedings of the Conference on Digital Audio Effects (DAFx)*, 2000, pp. 153–158.

[7] C. Traube and P. Depalle, "Extraction of the excitation point location on a string using weighted least-square estimation of a comb filter delay," in *Proceedings of the Conference on Digital Audio Effects (DAFx)*, 2003.

[8] H. Penttinen and V. 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.

[9] Z. Mohamad, S. Dixon, and C. Harte, "Pickup position and plucking point estimation on an electric guitar," in *IEEE International Conference on Acoustics, Speech, and Signal Processing, 2017 (ICASSP)*, 2017, pp. 651–655.

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

[11] A. De Cheveigné and H. Kawahara, "YIN, a fundamental frequency estimator for speech and music," *The Journal of the Acoustical Society of America*, vol. 111, no. 4, pp. 1917–1930, 2002.

[12] S. Dixon, M. Mauch, and D. Tidhar, "Estimation of harpsichord inharmonicity and temperament from musical recordings," *The Journal of the Acoustical Society of America*, vol. 131, no. 1, pp. 878–887, 2012.

[13] J. O. Smith, "Spectral audio signal processing," Available at: https://ccrma.stanford.edu/ jos/sasp/, accessed April 8, 2017.

[14] Cockos, Inc., "Reaper: Digital audio workstation," Available at http://www.reaper.fm/, accessed April 8, 2017.

[15] IK Multimedia, "Amplitube custom shop," Available at https://www.ikmultimedia.com/products/amplitubecs/, accessed April 8, 2017.

[16] A. P. Klapuri, "Multiple fundamental frequency estimation based on harmonicity and spectral smoothness," *IEEE Transactions on Speech and Audio Processing*, vol. 11, no. 6, pp. 804–816, 2003.