

## NON-LINEAR EFFECTS MODELING FOR POLYPHONIC PIANO TRANSCRIPTION

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### ABSTRACT

Automatic identification of chords is being investigated and several methods has been proved. A method using spectral pattern recognition has been presented previously by the authors. In that method, the chord is detected iteratively, note by note, by means of a set of patterns generated by an acoustical model of the piano. In each iteration step, the spectral components of the detected note are eliminated from the signal spectrum using a mask related with the pattern of that note. When a "staccato" chord is played on a piano, the string is struck with a higher velocity and the excitation becomes more non-linear. As a result, intermodulation components appears in the spectrum. Taken into consideration the inharmonicity of the string vibration, the effect of those intermodulation products is a widening of each spectral component of the chord. This widening must be considered when the patterns and masks are applied during the identification process. We have found out that this widening varies with the partial and the note. It also depends on the octave (differences in hammer felt dimensions and stiffness) and on the force applied to the key ("piano", "mezzoforte" or "forte") A model for the calculation of the widening due to non-linearity is presented in this contribution. The results show that the application of this model improves the recognition process.

### 1.INTRODUCTION

In previous work [1], a method has been presented for identification of piano chords. The method recognizes the chord by iterative identification of the notes. Each time a note is detected, its spectrum is subtracted from the chord spectrum. The notes are identified evaluating the match between chord spectrum and a set of spectral patterns generated by a physical model of the piano, developed by the authors. The spectral subtraction is performed using spectral masks also calculated by the model. The model is trained with a few notes of the piano played. The results obtained have been reported in the referenced work and several improvements of the method, leading to better results, have

been included and presented in [2][3]. In this study we present a further improvement that solves the false identification obtained when the chord are played in staccato.

Staccato produce a short time excitation of the piano key with a higher initial velocity of the hammer. The hammer strikes the string with higher velocity and the hammer felt is more compressed due to its stiffness, so the excitation of the strings presents more non-linearity.

#### 1.1. Effects of Non-linearity

The effects of non-linearity are the intermodulation (IM) products, that are new spectral components that appears in the signal spectrum. Apparently, the spectral components are wider when the piano is played in staccato, but this is due to insufficient spectral resolution. Actually, several new components due to intermodulation appears close to the main components producing the apparent widening.

The spectral analysis that is performed is based on the calculation of the Hanning windowed FFT of the whole duration of the chord. As the sounds have been recorded specifically for this study using a Steinway grand piano, the chords are isolated and the FFT is calculated using 2 seconds of signal, from before the onset to the decay of the chord. The figure 1 shows the spectrum of chord CEG2 played legato and staccato. In this case, only widening can be seen. As will be explained below, the low value of inharmonicity coefficient  $B$  makes that every intermodulation component lies almost coincident with the main component. The figure 2 shows the same for octave 4 and the new components can be identified. Figure 3 shows the previous for octave 6 and, again, only widening is visible, but due to insufficient precision of the frequency scale. In the case of octave 6, the effect of intermodulation is lesser because only a few partials exists.

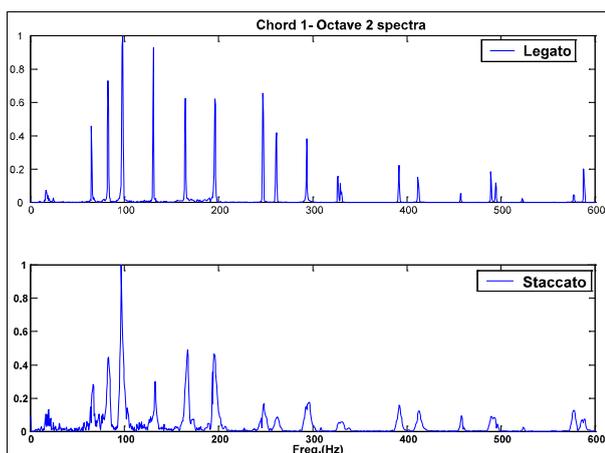


Figure 1. Octave 2 chord spectra.

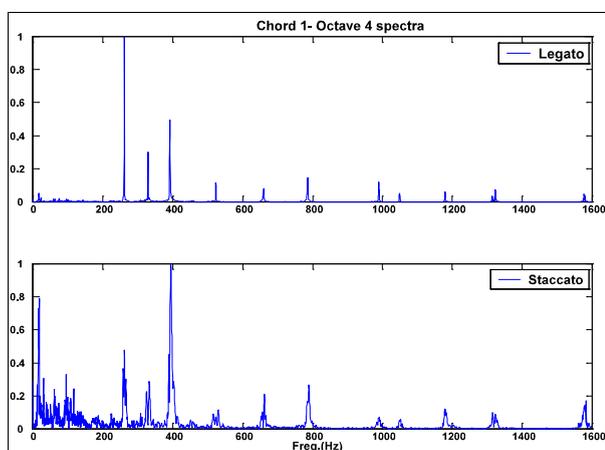


Figure 2. Octave 4 chord spectra.

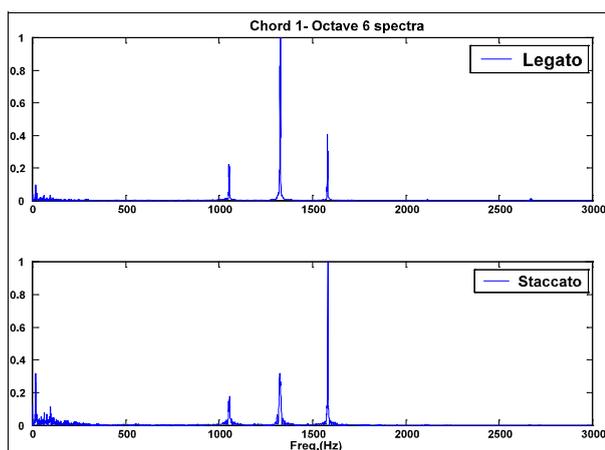


Figure 3. Octave 6 chord spectra.

As well as explaining the widening of the spectral components, the non-linear products also explains some of the under-fundamental components that appears in some chords. If the signal has a lot of partials, those IM components spreads very much in frequency, specially if the notes have larger values of inharmonicity.

### 1.2 Effect on Identification

If we do not take into consideration this widening, the spectral masks applied during spectral subtraction step of the identification algorithm, leave a lot of residual components that tend to confuse the next identification step.

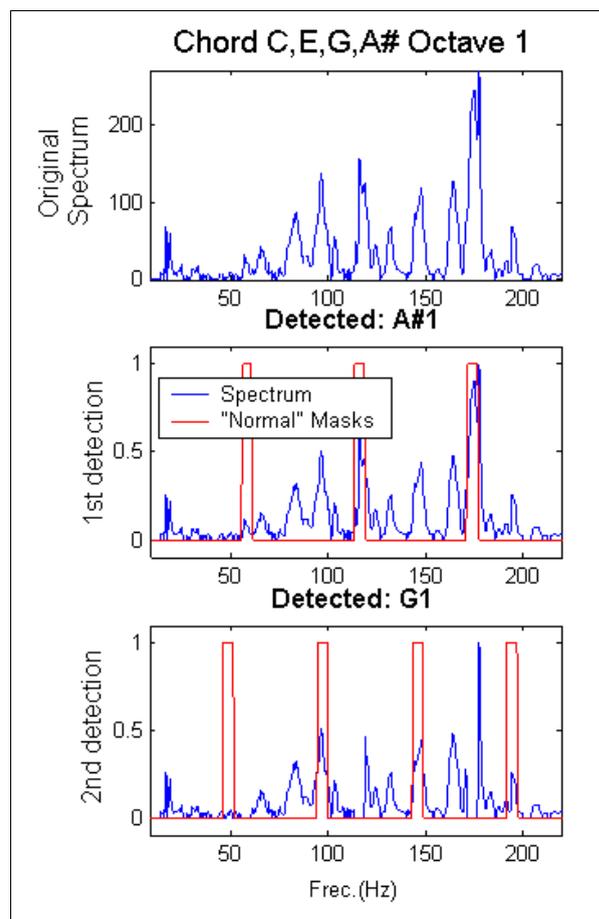


Figure 4. Two steps of the iterative identification algorithm. Can be seen that the mask of the detected note A#1 does not subtract correctly its spectrum.

## 2. MODELING NON-LINEARITY EFFECTS

Non-linearity of piano vibration have been studied widely and some references are [4][5][6]. The aim of this study is not to develop a complete non-linear model of the piano, but to obtain parameters to predict the widening of the spectral

components due to non-linearity, in order to modify the patterns and masks used in the recognition process.

The first step is to evaluate the frequency of the intermodulation products. The second is to verify that they appear in the staccato spectra. The third is to decide how many products are present and which is the order of the non-linear response. The fourth is to calculate the effect of the predicted non-linearity products as a widening factor to be applied to the generated pattern and masks pulses.

This modeling has been carried out for all the octaves of the piano. Almost every octave has differences in the hammer felt, so the degree of non-linearity changes between octaves. It has been developed for a “forte” staccato playing. The effect of different forces striking the key (i.e. “mezzoforte”, “forte”, “fortissimo”) is discussed at the end.

### 2.1. Predicted frequencies of Non-linearity products

From the non-linearity theory we know that for every two sinusoidal components with frequencies  $f_1$  and  $f_2$ , appears a set of intermodulation products with frequencies  $|\pm nf_1 \pm mf_2|$ , for every values of  $n$  and  $m$ . The value “ $n+m$ ” is named the order of the product. The higher the order, the lower the level of the product, which also depends on the levels of the intermodulated components. The highest order is the order of the non-linear polynomial that models the response. If  $m$  or  $n$  are equal to 0, then the equation gives the harmonics of  $f_1$  or  $f_2$ .

For real sounds, not only a couple of frequencies are present, but several components called partials. Every pair of partials produces a set of non-linear products that must be calculated

When  $f_1$  and  $f_2$  are harmonic, several products are coincident in frequency with  $f_1$  or  $f_2$ .

$$f_2 = kf_1 \Rightarrow |\pm nf_1 \pm mf_2| = |\pm nf_1 \pm mkf_1| = |\pm n \pm mk|f_1 \quad (1)$$

But piano strings produce inharmonic vibrations, so each partial is slightly above the harmonic. The equation of the partials frequency is:

$$f_p = pf_1 \frac{\sqrt{1+p^2B}}{\sqrt{1+B}} \quad (2)$$

where  $f_1$  is the fundamental frequency of the note,  $p$  is the partial order and  $B$  is the inharmonicity coefficient of the note.

The next table shows the equations of some non-linear products that lie close to the fundamental, when inharmonicity is present.

2nd Order	$f_2 - f_1 = f_1 \left[ \frac{2\sqrt{1+4B}}{\sqrt{1+B}} - 1 \right] > f_1 \quad (3)$
	$f_3 - f_2 = f_1 \frac{3\sqrt{1+9B} - 2\sqrt{1+4B}}{\sqrt{1+B}} > f_1 \quad (4)$
3rd Order	$f_3 - 2f_1 = f_1 \left[ \frac{3\sqrt{1+9B}}{\sqrt{1+B}} - 2 \right] \quad (5)$
	$2f_2 - f_3 = f_1 \frac{4\sqrt{1+4B} - 3\sqrt{1+9B}}{\sqrt{1+B}} < f_1 \quad (6)$

It can be seen that some of them are always below and others are always above  $f_1$ . This produces the widening of the spectral components. This must be taken into consideration for the design of the masks and patterns. The widening depends on the value of inharmonicity coefficient  $B$ . As the previously developed physical model approximates the coefficient  $B$  for every 88 notes, the widening for all the notes can also be evaluated.

Any pair of partials  $i, j$  with frequencies  $f_i, f_j$ , produce intermodulation products near other partial  $k$  with frequency  $f_k$ , if  $|\pm ni \pm mj| = k$ . We have developed an algorithm (“IM predictor”) to calculate all the IM products due to several partials, taking into account a maximum IM order.

The figure 4 shows the spectra of the chord CEG4 (zoomed on the fundamental of note C4) played in legato and staccato, and the spectrum of the C4 pattern with calculated non-linear products (the levels are not in scale). Each intermodulation (IM) component is displayed as an independent pulse and has been calculated considering only 3 partials of the pattern. It can be seen that the differences between legato and staccato correspond mainly to this IM products.

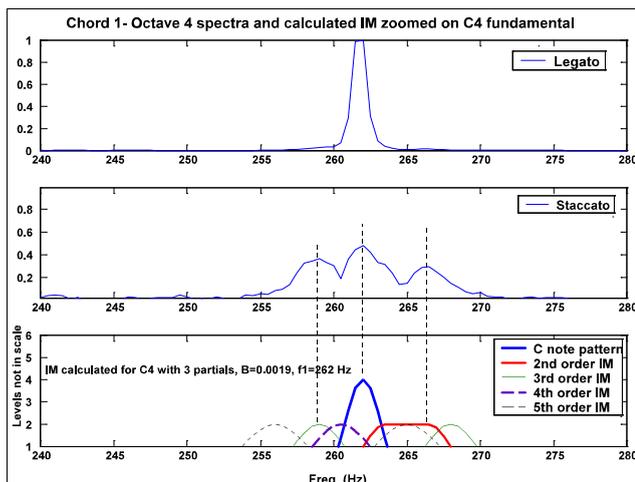


Figure 5. Octave 4 chord spectra and predicted IM products of several orders. Can be seen the coincidence of some of these IM with components of staccato spectrum, that neither exist in the legato spectrum nor in the original pattern.

### 2.2. Parameters and Equations for the Model

Using the recordings of one Steinway grand piano, the patterns of that piano and the “IM predictor” algorithm, we have tried to fit the “staccato” spectrum calculating the IM products of the patterns. Actually we have only fitted some partials, not the whole spectrum, and only a certain number of partials of the pattern have been used in the calculation. In the first step only the width of the partial has been fitted. The parameters related with this step are the following:

Octave	Non-linear order	Used Partial	Fitted Partial
1	Order 3	10	4
2	Order 3	6	5
3	Order 4	6	3
4	Order 5	4	3
5	Order 5	3	3
6	Order 3	3	2
7	Order 3	3	2

Using the previous parameters, in a second step, we have tried to fit not only the width but the shape of the spectrum of each partial, designing an approximated set of non-linear equations. This equations can be used further so that the widened patterns and masks can be calculated from the original ones.

### 3. RESULTS

The non-linearity equations obtained are:

Octave 1	$0.02 x^3 + x$
Octave 2	$0.01 x^3 + x$
Octave 3	$0.03 x^4 + 0.005 x^3 + 0.02 x^2 + x$
Octave 4	$0.0005 x^5 + 0.07 x^3 + 0.9 x^2 + x$
Octave 5	$0.001 x^5 + 0.01 x^4 + 0.04 x^3 + 0.05 x^2 + x$
Octave 6	$0.02 x^3 + 0.05 x^2 + x$
Octave 7	$0.02 x^3 + 0.05 x^2 + x$

The recognition of 4 piano chords played in staccato for every octaves (1 to 7) has been carried out with the following results, that are better than without non-linear effects modeling .

oct	Chord: C,E,G,A#				Chord:C,D#,F#,A			
1	A#1	G1	C1	<b>A0</b>	A1	F#1	D#1	C1
2	A#2	E2	C2	<b>C#1</b>	A2	D#2	<b>C1</b>	F#2
3	C3	A#3	E3	<b>D3</b>	C3	D#3	F#3	A3
4	A#4	C4	E4	<b>C3</b>	A4	D#4	C4	F#4
5	C5	G5	E5	A#5	A5	F#5	C5	D#5
6	E6	A#6	C6	G6	F#6	C6	A6	D#6
7	E7	A#7	C7	<b>E7</b>	D#7	F#7	C7	A7
Oct	Chord: C,D#,G,A#				Chord:C,E,G,B			
1	<b>D#2</b>	A#1	G1	C1	B1	C1	<b>A#0</b>	<b>A0</b>
2	<b>G1</b>	D#2	<b>C1</b>	A#2	C2	<b>E1</b>	<b>C#1</b>	<b>A0</b>
3	C3	D#3	G3	A#3	C3	G3	E3	B3
4	A#4	C4	D#4	<b>C3</b>	B4	C4	G4	E4
5	C5	D#5	G5	A#5	C5	E5	G5	B5
6	A#6	G6	C6	D#6	E6	B6	G6	C6
7	D#7	G7	A#7	C7	E7	G7	C7	<b>E7</b>

The mistakes appears in bold type. The notes of each chord are displayed in the same order they have been identified, so a mistake in 4<sup>th</sup> note is due to wrong masking of previous notes instead of wrong pattern detection. Mistakes in 1<sup>st</sup> and 2<sup>nd</sup> note only occurs in octaves 1 and 2 and are due to insufficient validation criteria of the apparently detected

note.

In order to compare, the following table shows the results obtained without non-linear modeling.

oct	Chord: C,E,G,A#	Chord:C,D#,F#,A
1	A#1 G1 E1 C1	F#1 A1 D#1 C1
2	A#2 E2 C2 C#1	D#2 D1 C1 B0
3	C3 A#3 E3 C3	C3 D#3 F#3 A3
4	A#4 C4 C3 E4	A4 D#4 C4 F#4
5	C5 G5 E5 A#5	A5 F#5 C5 D#5
6	E6 A#6 C6 E6	F#6 C6 A6 D#6
7	E7 A#7 C7 E7	D#7 F#7 C7 A7
Oct	Chord: C,D#,G,A#	Chord:C,E,G,B
1	A#1 G1 D#2 C1	B1 G1 C1 A0
2	D#2 A#1 G1 C1	E1 C2 C#1 A0
3	C3 G3 D#3 A#3	C3 G3 E3 B3
4	A#4 D#4 C4 C3	B4 C4 G4 E4
5	C5 D#5 G5 A#5	C5 E5 G5 B5
6	A#6 G6 C6 D#6	E6 B6 G6 C6
7	D#7 G7 A#7 C7	E7 G7 C7 E7

It can be seen that the improvements are only slight.

### 3.1. Discussion

Widening the masks using non linearity modeling, improve the recognition but not enough. The non-linearity modeling is a good approach to improve recognition, but needs to be improved taking into account some more parameters. The previous non linear equations have been derived using only one note (of every octave) played with only one force. The results seem to show that if the chord is played with lower or higher force, the modified mask may not fit.

Other important question is: Will different pianos have different non linearity equations?. Different pianos, from different manufacturers, must be analyzed to determine this issue. If true, the non linearity model will need to be trained.

### 3.2. Modeling for several forces and different pianos

Besides the Steinway piano, two Schimmel and one Kawai concert pianos has been recorded. We have recorded the note A of every octave using four different forces. The figure 5

shows the results for octave 4 that is very representative of what happens in the other octaves.

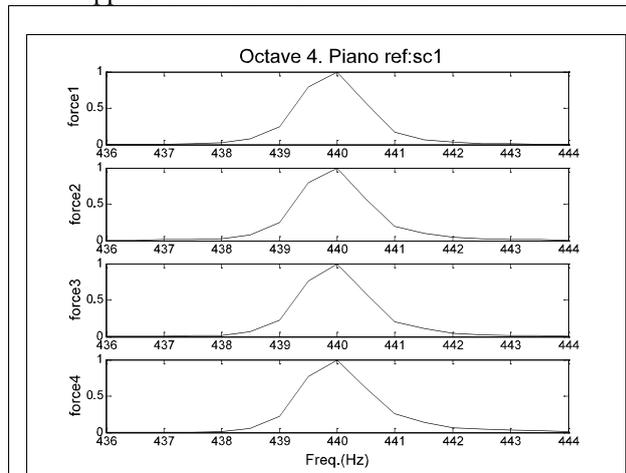


Figure 6. Fundamental of note A4. Force increases from force1 to force4. Piano Schimmel 256.

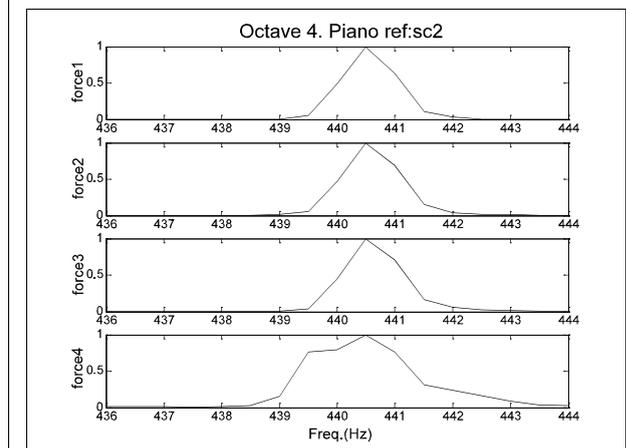


Figure 7. Fundamental of note A4. Piano Schimmel 116s.

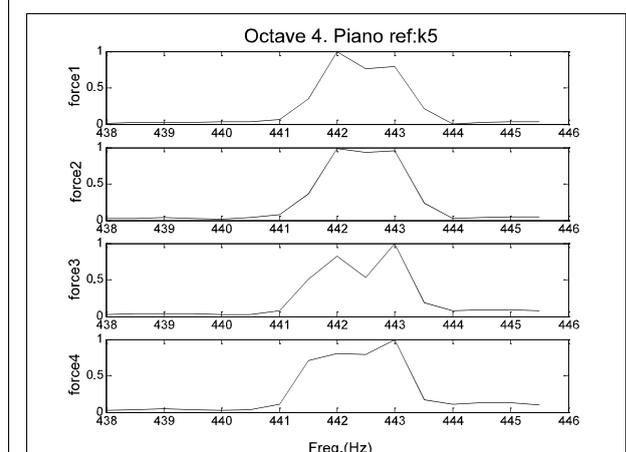


Figure 8. Piano Kawai RX2: 1.78m. Long

Each spectrum has been normalized to its maximum amplitude to show the relative importance of every part of it. Differences in tuning also can be seen, but these are irrelevant to this analysis.

It can be seen that the three pianos have different degree of effect due to non linearity. One of them (SC1: the Schimmel concert grand, 2.56 meters long) almost has no differences between different forces. Also can be seen that, for each piano, the effect is not only to make the spectral component wider but also to increase the lower part of it. As the force increases, the effect of higher order intermodulation products is more important, and it seems that are specially promoted the IM products below the partial frequency.

The pianos have been played by a pianist. The forces are not exactly the same for all the pianos (we do not use a mechanical exciter) but rather similar.

#### **4. CONCLUSIONS**

An improvement in staccato piano chord recognition is obtained using modeling of the effects of non-linear products, applied to the identification method previously developed by the authors. Although it is a slight improvement, it can be enhanced.

At this moment the model uses equations for one piano and one striking force. The effect of different striking forces is being included and we are developing a method for training the model playing one note of each octave using three forces. The piano model will calculate non-linearly distorted patterns and mask for several levels of force.

During recognition, it will be detected if the chord has been played in legato or staccato, in order to decide what set of patterns and masks are going to be used by the algorithm.

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