SPECTRAL ENVELOPE MICROVARIATIONS AND ITS EFFECT ON INSTRUMENTAL TIMBRE

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ABSTRACT

The analysis of the spectrum of a single violin tone, to better understand how the various partial components contribute to the sound produced, is undertaken. The analysis involves determining which partials are present and how these partials evolve with respect to time. The short-time Fourier transform is used to implement a solution for the time varying spectra by slicing the sound into short segments called windows and analysing each segment sequentially. Results indicate that spectrum changes over time contribute significantly to the timbre of the violin tone. A slight shifting of the fundamental frequency was also observed in the sound spectrum of all the sub-sections of the waveform, although this shifting was most marked in the attack and release portions of the ADSR envelope. The results also showed that the intensity of the fundamental harmonic was weaker in the initial attack stage, only dominating when the timbre of the tone stabilised. Within the release portion, inharmonic overtones were shown to occur in the upper partials of the sound spectrum.

1.0 INTRODUCTION

A complete mathematical model of a musical tone consists of periodic and non-periodic functions. Periodic functions are generally modelled as summations of simple sinusoids, according to Fourier's theorem. Non-periodic functions, such as the amplitude envelope, transient sounds and residual noise, contribute towards the realism of the tone.

The periodic function is contributed by the addition of the partials that occur in the sound waveform. This can be shown through the analysis of the sound waveform using spectrum analysis to identify the partials that occur. The sound waveform can be defined as in the Equation 1 below:

$$y = a_1\sin(2\pi f_1 t_1) + a_2\sin(2\pi f_2 t_1) + a_3\sin(2\pi f_3 t_1) + \ldots + a_n\sin(2\pi f_n t_1)$$

(Equation 1)

where,
y = the waveform of the sound signal
a = the harmonics amplitude relative for the sound
f = frequency of the harmonics that occurs in the sound signal
t = the time at which the waveform is captured

This equation usually assumes that the waveform does not change over time. However, according to the formula above, the waveform does change with time. Therefore, the exact contribution of each of these modes is time varying with respect to the overall sound. This exact contribution needs to be determined through research.

The objective of the study is to analyse the spectrum of a single violin tone, to better understand how the various harmonic or partial components contribute to the sound produced. The analysis involves determining which partials are present and how these partials evolve with respect to time. The parameters obtained in this way may then be used for resynthesising the violin tone. The purpose of this resynthesis is to obtain savings in data bandwidth – in other words, to create the same sound [or as close to the original sound as possible], using minimal memory requirements.

2.0 LITERATURE REVIEW

Spectral modelling synthesis was developed by Xavier Serra and Julius Smith, in 1990 (Vaggione, 1996). The spectral modelling synthesis technique is a set of techniques and software implementations for the analysis, transformation and synthesis of musical sounds. Spectral modelling synthesis technique is developed through Fourier analysis, which considers a pitched sound to be made up of various sinusoidal components, where the frequencies of the higher components are integral multiples of the frequency of the lowest component (Miranda, 1998). Acoustic characteristics which correspond with physical and behavioural properties of sound sources [such as spectral centroid and inharmonicity] are most important for discrimination of different sounds (Martin, 1998). Conclusions drawn from McAdam *et al* (1999) indicate that spectral-envelope shape [jaggedness and irregularity in the shape of the spectrum] and spectral flux [change in the shape of the spectral envelope over time] are the most important physical parameters in timbre discrimination. Literature on musical instrument sounds has suggested that there are many other acoustic features that are also useful for instrument identification such as inharmonicity (Benade, 1990), spectral centroid (Handel, 1995), and intensity (Beauchamp, 1982). Most spectral modelling techniques work in two stages: analysis and resynthesis (Miranda, 1998). Analysis is a process of digitising sound from a natural musical instrument first and then analysing it to determine the content of partial frequencies and the associated amplitude and frequency envelopes, while resynthesis is the process of synthesising sound on the basis of information derived from the analysis of another sound (Dodge and Jerse, 1997).

3.0 METHODOLOGY

3.1 Recording the Violin Tone to be used in the Analysis

The violin used in recording the musical instrument tone for this research was a *Charles Buthod* handmade French violin. The violin strings used were *Thomastik "Dominant"* violin strings, and the bow was a *Mirecort* bow. The recording of the violin sound was conducted in a quiet and acoustically dry [non-reverberant] room, with the aim of minimising reverberation and background sounds [which generate energy affecting the recorded spectrum partials]. With a sampling rate of 44100 Hz and a resolution of 16 bits, a compact disc quality violin sound was recorded. During the recording, only the monophonic [single melodic line] violin sound was recorded. This was to ensure that successful analysis could be done. The analysis of the polyphonic sound may also be carried out, but the analysis result is not so useful as data to be transformed in the synthesis process, as the combination of the sound from the two channels may cause interference effects due to phase differences between the two channels, unnecessarily adding complexity to the analysis process.

3.2 The Analysis Methodology

Spectrum analysis is important for spectral modelling, as samples alone do not inform the spectral constituents of a sampled sound. There are two categories of spectrum analysis, which have been created to analyse the spectrum of the sounds. They are harmonic analysis and formant analysis. Harmonic analysis focuses on the identification of the frequencies and amplitudes of the spectrum components, while formant analysis uses the estimation of the overall shape of the spectrum's amplitude envelope.

The Fourier transform decomposes or separates a waveform or function into sinusoids of different frequency, which sum to the original waveform (Hoffman, 1998). It identifies or distinguishes the different frequency sinusoids and their respective amplitudes (Brigham, 1998). The Fast Fourier Transform (FFT) is a Discrete Fourier Transform (DFT) algorithm developed by Tukey and Cooley that reduces the number of computations from the order of N_0^2 to $N_0 \log N_0$. (Hoffman, 1999). The short-time Fourier transform (STFT) implements a solution for time varying spectra by chopping the sound into short segments called windows and analysing each segment sequentially. It uses FFT to analyse these windows, and plots the analysis of the individual windows in sequence in order to trace the time evolution of the sound. The result of each window analysis is called an FFT frame. Each FFT frame contains two types of information. One is a magnitude spectrum which depitching the amplitudes of every analysed component, and the other one is the phase spectrum that shows the initial phase for every frequency component (Miranda, 1998). In this research, the phases that occur in the sound spectrum are not considered. This is due to the fact that in determining the timbre or sound quality of the wave the spectral component amplitudes are far more important than their phases (Berg and Stork, 1995).

The sample waveform of the recorded violin note is recalled and divided into four main portions, according to the attack-decay-sustain-release (ADSR) envelope consisting of the attack portion, decay portion, sustain portion, and release portion. Each portion is further subdivided into even smaller sections. The minimum duration time of each section was set at 0.1 seconds. [Portions with duration times of less than 0.1 seconds produce significant fluctuation of results when the FFT function is applied]. The sections for data analysis are also overlapped. Overlapping is one of the methods used to improve the periodogram estimation of the results.

3.3 The Resynthesis Process

In order to resynthesise the original sound, the results obtained from the analysis are inserted back into the Equation 1 according to their time-varying components. All the contributing equations are concatenated, which means that all the waveforms created through the equations are appended one after another according to their time-varying intervals. Through this method, the waveform produced consists of a sound spectrum that changes over time. A comparison between the synthesised sound and the original sound is then carried out. The purpose of resynthesising the sound is to find out how authentically the equation manages to generate the sound compared with the original sound. It also helps in discovering other factors needed to improve the quality of the sound produced.

4.0 RESULTS

The recorded violin tone is an A4 violin tone recorded on stereo channels using a sampling rate of 44.1 kHz with a resolution of 16-bits. The complete duration of this tone is 2.575 seconds, and is stored in the `.wav` file format using 221 KB of hard disk space. This A4 violin tone, as explained previously, is divided into four portions according to ADSR parameters. These four portions are the attack, decay, sustain and release portions (Figure 1). The attack portion occurs between time T0 and T1, the decay portion between T1 and T2, the sustain portion between time T2 and T3, and the release portion between T3 and T4.

The Attack Portion

The sound spectrum of all the four sections within the attack portion consists only of harmonic overtones [which are integer multiples of the fundamental harmonic, f]. Within the attack portion, there is an occurrence of a weaker intensity on the fundamental harmonic. In the first two sections [which are section A1 and A2], the fundamental frequency does not contain the highest power spectrum density compared with other partials in the sound spectrum. In fact, the highest power spectrum density focuses on the fifth harmonic, 5f. It is then followed by the second harmonic and then only the fundamental harmonic. The relative amplitudes of the fundamental harmonic within section A1 and A2 are only 0.7498 and 0.9469, while the second harmonic records values of 0.9710 and 0.98. The highest power spectrum density in section A1 is –82.23164 decibels which is about 2.501147 decibels louder than the fundamental harmonic, while in section A2 the highest power spectrum density is –80.958757 decibels, which is about 0.473661 decibel louder than the fundamental harmonic. Thus, one can see that the difference between the fundamental harmonic and the second harmonic in these two sections becomes smaller.

Table 2 shows the changes, with respect to time, in the relative amplitudes of the sound spectrum within the attack portion. In section A1, the relative amplitude of the fundamental frequency is only 0.7498. In section A2, the relative amplitude of the fundamental frequency starts to increase and from section A3 onwards the fundamental frequency contains the highest relative amplitude within the sound spectrum. This result indicates that the initial attack portion does not start with a strong fundamental harmonic, but is developed over time. From section A1 to A4, the relative amplitude of the fundamental frequency starts to strengthen, while the amplitude of the fifth partial starts to weaken. The sixth harmonic and the eighth harmonic are very consistent throughout. Throughout the entire attack portion, there are no changes in the relative amplitudes of the sixth and eighth harmonics.

Table 2. Changes in the Relative Amplitudes of the Sound Spectrum over Time within the Attack Portion.

Harmonics, f	A1	A1+A2	A1+A2+A3	A1+A2+A3+A4	A2+A3+A4	A3+A4	A4
1.0	0.7	0.8	0.9	1.0	1.0	1.0	1.0
2.0	1.0	1.0	1.0	0.9	0.8	0.7	0.6
3.0	0.4	0.4	0.4	0.4	0.4	0.3	0.3
4.0	0.2	0.2	0.2	0.2	0.2	0.1	0.1
5.0	1.0	1.0	1.0	0.9	0.9	0.8	0.8
6.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1
7.0	0.2	0.2	0.3	0.3	0.3	0.3	0.3
8.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1
9.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10.0	0.2	0.2	0.2	0.2	0.2	0.2	0.2
11.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
12.0	0.0	0.1	0.1	0.1	0.1	0.1	0.1
13.0	0.1	0.1	0.1	0.1	0.0	0.0	0.0
14.0	0.0	0.1	0.1	0.1	0.1	0.0	0.0
15.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
16.0	0.0	0.1	0.1	0.1	0.1	0.0	0.0

The results also record the occurrence of a shift in frequency. In the first two sections the fundamental frequency is 442.77649 Hz, while sections A3 and A4 have a slightly different fundamental frequency. For example, fundamental frequency of A3 is 442.10358 Hz and the fundamental frequency of A4 is 441.43066. Table 4 shows the difference in the fundamental frequency of all sections within the attack portion.

Table 3. Difference in the Fundamental Frequency of the Sections within the Attack Portion.

Fundamental Frequency (Hz)	Section
442.7764	A1
	A2
442.10358	A3
441.43066	A4

The Decay Portion

Within the decay portion, the sound spectrum of all the sections consists only of harmonic partials. There are no occurrences of inharmonic partials. The sections in this portion have some differences when compared with the sections in the attack portion. In this portion, each occurrence of the fundamental harmonic always has the highest intensity [also called the power spectrum density or perceived loudness] level compared with other partials, which also occur in the sound spectrum. This is unlike the attack portion, in which there are some occurrences of the fundamental harmonic with an intensity level lower than other harmonic partial values, even though the perceived tone is still the A4 note. In the decay portion, all the peak relative amplitude values focus on the fundamental harmonic only.

A shift in the frequency is also found to occur within this portion. Table 5 displays the shift frequency of each section within the decay portion. In this portion, although there is a shift in frequency, most of the fundamental frequency focuses on 441.43066 Hz. There is only one fundamental frequency that focuses on another frequency [442.10358 Hz]. This occurs in the first section within the decay portion [also called D1].

Table 4. Difference in the Fundamental Frequency of all Sections within the Decay Portion.

Fundamental Frequency (Hz)	Section
442.10358	D1
441.43066	D2
	D3
	D4
	D5
	D6
	D7
	D8

Table 5 displays the changes over time in the relative amplitudes of the sound spectrum within the decay portion. This table clearly displays the consistency of the relative amplitudes of the eighth, tenth, twelfth and fourteenth harmonics. Throughout the decay portion, there is no change in their relative amplitudes, which remain at 0.1.

Table 5. Changes in the Relative Amplitudes of the Sound Spectrum over time within the Decay Portion.

n f	D1	D1+D2	D1 +D2 +D3	D1+D2 +D3 +D4	D1+D2 +D3+D4 +D5	D2+D3 +D4+D5 +D6	D3+D4 +D5+D6 +D7	D4+D5 +D6+D7 +D8	D5+D6 +D7+D8	D6+D7 +D8	D7 +D8	D8
1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
2.0	0.5	0.5	0.5	0.5	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
3.0	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
4.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2
5.0	0.7	0.7	0.7	0.7	0.7	0.7	0.8	0.8	0.8	0.8	0.8	0.8
6.0	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
7.0	0.2	0.2	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
8.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
9.0	-	-	-	-	-	-	-	-	-	-	-	-
10.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
11.0	-	-	-	-	-	0.1	-	-	-	-	-	-
12.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
13.0	-	-	0.1	-	-	-	-	-	-	-	-	-
14.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
15.0	-	-	-	-	-	-	-	0.1	0.1	0.1	0.1	0.1
16.0	0.1	0.1	0.1	0.1	0.1	0.1	-	-	-	-	-	0.1
17.0	-	-	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1

The Sustain Portion

As in the previous two portions, all the sections in the sustain portion consist of only harmonic partials. In this portion, every section records each occurrence of the fundamental frequency at the highest intensity compared with other partials. This is very similar to the decay portion. Table 6 shows the shift in frequency which occurs in each section within the sustain portion. These results indicate that most sections within the sustain portion focus on the frequency of 441.43066 Hz. There are only two sections with a fundamental frequency that focuses on another frequency: section S4 and S13. In these two sections, the fundamental frequency focuses on 442.10358 Hz.

Table 6. Difference in the Fundamental Frequency of each Section in the Sustain Portion.

Fundamental Frequency (Hz)	Section
441.43066	S1
	S2
	S3
442.10358	S4
441.43066	S5
	S6
	S7
	S8
	S9
	S10
	S11
	S12
442.10358	S13

The results within the sustain portion show that most partials begin to evolve throughout this portion. This is especially marked at section S13 where only the first nine partials occur. Table 8, which shows changes in the relative amplitude of the sound spectrum over time, clearly show the intensity of high frequencies [beginning at the seventeenth harmonic] becoming so low that their relative amplitudes become insignificant. In this portion, as all partials in the sound spectrum start to evolve, there are no partials with consistent relative amplitudes other than the high frequencies [beginning at the seventeenth harmonic] whose relative amplitudes need no longer remain under consideration.

Table 7. Changes in the Relative Amplitudes of the Sound Spectrum over time within the Sustain Portion.

nf	S1	S1 +S2	S2 +S3	S3 +S4	S4 +S5	S5	S6	S7	S8	S9	S10	S10+ S11	S10 +S1 1+S 12	S11+ S12	S11+ S12+ S13	S12+ S13	S13
1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
2.0	0.6	0.6	0.6	0.6	0.6	0.6	0.5	0.5	0.5	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
3.0	0.2	0.2	0.2	0.2	0.3	0.3	0.2	0.2	0.2	0.3	0.2	0.2	0.2	0.2	0.2	0.3	0.3
4.0	0.2	0.1	0.1	0.1	0.1	0.1	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1		
5.0	0.9	0.8	0.8	0.7	0.7	0.7	0.8	0.7	0.6	0.5	0.5	0.5	0.5	0.5	0.4	0.4	0.3
6.0	0.1	0.1	0.2	0.3	0.3	0.3	0.2	0.2	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.4
7.0	0.3	0.3	0.3	0.2	0.2	0.2	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.1	0.1
8.0	0.1	0.1	0.1	0.1	0.1	0.1	-	-	-	-	-	-	-	-	-	-	-
9.0	-	-	-	-	0.1	0.1	-	-	-	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
10.0	0.2	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	-
11.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	-
12.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	-
13.0	-	-	-	-	-	-	-	-	-	-	0.1	0.1	0.1	0.1	0.1	0.1	-
14.0	0.1	0.1	0.1	0.1	-	-	0.1	-	0.1	-	0.1	0.1	0.1	0.1	-	-	-
15.0	0.1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
16.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	-	-	0.1	0.1	-	-	-	-	-
17.0	-	-	-	-	0.1	-	-	-	-	-	-	-	-	-	-	-	-

The Release Portion

In this portion, the partials that appear in the spectrum consist of both harmonic and inharmonic partials. Most of the inharmonic partials occur after the fourth harmonic. Table 8 shows the changes in the relative amplitude of the sound spectrum over time within the release portion. After the first section, the peak amplitude displaces to the second harmonic. In the release portion, all the partials are evolving, and in the final two sections [R7 and R8], there are only three partials remaining. Table 9 shows the shift in frequency that occurs within the release portion. These results indicate that all sections within the release portion do not focus on a specific frequency. The fundamental frequencies shift very frequently among the frequencies 442.10358 Hz, 441.43066 Hz, 440.75775 Hz, 438.0661 Hz, 437.39319 Hz and 435.37445 Hz.

Table 8. Changes in the Relative Amplitudes of the Sound Spectrum over time within the Release Portion.

nf	R1	R1+R2	R2	R2+R3	R3	R3+R4	R4	R4+R5	R5	R5+R6	R6	R7	R7+R8	R8
1.0	1.0	1.0	0.8	0.8	0.9	0.6	0.4	0.3	0.2	0.3	0.3	0.3	0.4	0.4
2.0	0.4	0.7	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
3.0	0.2	0.4	0.4	0.5	0.6	0.6	0.6	0.5	0.5	0.5	0.5	0.5	0.4	0.3
4.0	0.1	0.1	-	0.2	0.2	0.1	0.1	0.1	-	-	-	-	-	-
4.1	-	0.2	0.2	0.2	-	-	-	-	-	-	-	-	-	-
5.0	0.1	0.1	-	0.1	0.1	0.1	-	-	-	0.1	0.1	-	-	-
5.1	-	0.3	0.3	0.3	-	-	-	0.1	0.1	0.1	-	-	-	-
6.0	0.3	0.3	-	-	-	-	-	-	-	-	-	-	-	-
6.1	-	0.5	0.5	0.4	0.4	0.2	0.1	0.1	0.1	0.1	-	-	-	-
7.0	0.1	0.1	-	-	-	-	-	-	-	-	-	-	-	-
7.1	-	0.1	0.1	0.1	0.1	0.1	-	-	-	-	-	-	-	-

Table 9. Difference in the Fundamental Frequency of each Section within the Release Portion.

Fundamental Frequency (Hz)	Section
440.75775	R1
435.37445	R2
438.0661	R3
	R4
437.39319	R5
441.43066	R6
442.10358	R7
441.43066	R8

5.0 DISCUSSION

The results show that the power spectrum of each of the partials varies with respect to time. These changes in the loudness of each partial over time contribute to the timbre of the violin tone. The shifting fundamental frequency that occurred in the sound spectrum of the recorded violin signal occurs in the sound spectrum of all the sections of the waveform (Table 10).

Table 10. The Shifting Fundamental Frequency that Occurs In All Sections

Fundamental Frequency (Hz)	Window [which contains this fundamental frequency]
442.7764	Attack portion – A1, A2
442.10358	Attack portion – A3 Decay portion – D1 Sustain portion – S4, S13 Release portion – R7
441.43066	Attack portion – A4 Decay portion – D2, D3, D4, D5, D6, D7, D8 Sustain portion – S1, S2, S3, S5, S6, S7, S8, S9, S10, S11, S12 Release portion – R6, R8
440.75775	Release portion – R1
438.0661	Release portion – R3, R4
437.39319	Release portion – R5
435.37445	Release portion – R2

These results indicate that the most frequent fundamental frequency is 441.43066 Hz, which is the focus point of most of the sections in the decay and sustain portions. Fundamental frequencies such as 440.75775 Hz, 438.0661 Hz, 437.39319 Hz, and 435.37445 Hz are only held by sections within the release portion.

A weaker strength or intensity of the fundamental harmonic, especially within the initial attack portion, was discovered. Table 2 indicates that within the first three windows, which occur from the starting point [0.00 seconds] to 0.06 seconds, the highest spectrum energy does not focus on the fundamental frequency, but instead focuses on the second harmonic. These results indicate that the intensities of the fundamental harmonic only dominate when the timbre of the tone becomes much stronger and more stable.

Within the release portion, several inharmonic overtones are found to occur. The inharmonic overtones only occur in the upper partials of the sound spectrum.

6.0 CONCLUSION AND SUGGESTIONS FOR FURTHER STUDY

It has been shown that for the single violin tone, the microvariations in the sound spectrum contribute significantly towards the timbre of the tone. When these parameters are used for resynthesis purposes, a significant file size saving is obtained, with minimal concessions to the sound quality. Further study needs to be done to complete the model for the violin for all notes within its range and for all techniques of performance. Further to this, detailed study needs to be done on further data simplification that may be undertaken without sacrificing the sound quality.

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