Decay Characteristics of Piano Tones

A study of piano decay time

Zhengshan Shi
N15500268
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Music Technology, New York University

***Abstract*—The Piano as a hammer struck, stringed instrument, is one of the most popular musical instruments in music world. Listeners have long been attracted by the piano's wonderful but complex sound. In addition to the complex frequency spectrum of each note, the piano has its own special envelope that contributes to its special timbre. Early on, Martin reported that a slope change existed in piano decay. This paper did experimentally based research into the piano's decay time for both the compound decay itself and the study of a piano synthesizer in order to provide a clear explanation of the piano's decay characteristics.**

***Keywords*— Piano decay, two stage decay, piano acoustics, physical-based modeling**

I. INTRODUCTION AND MOTIVATION

The piano is one of the most complicated musical instruments in terms of spectral evolution. The study of piano acoustics has been divided into various branches such as hammer-string action, soundboard vibration, timbre study, and mechanical comprehension. Among the existing body of research on piano acoustics, the frequency aspect has been studied thoroughly. Compared to this, the study of piano acoustics in the time domain is often neglected. The piano as a struck-string instrument has a more complicated envelope than other instruments, especially during the decay portion. The piano generates sound through string vibration by the action of hammer striking. Unlike other bowed instruments that can maintain energy through bowing, piano tones die away gradually with time from the moment the key is pressed. In addition to this, the decay time of piano is a non-linear and frequency-dependent movement. Different partials of tones have different decay times, which contribute to the complicated decay characteristics of piano tones.

From another aspect, in the area of piano synthesis, in order to obtain more realistic piano sounds, various techniques are developed to synthesize piano sound. In addition to the simulation of piano timbre itself, the time-domain parameters such as attack, decay, sustain and release are also taken into account. Due to the unstable factors of string vibration, piano decay is one of the toughest problems in terms of envelop shaping. The study of piano decay time helps in developing new techniques for piano synthesis. Physical-based modeling is one of the most advanced techniques that take piano decay characteristics into consideration.

This paper presents a review of the studies on piano decay times and focuses on grand piano decay times both from the acoustic theory and experimentation. The work aims to figure out how piano tones change through time and find out how the consideration of piano decay time contributes to the simulation of piano sounds in musical instrument synthesis.

II. LITERATURE RESEARCH AND CONTEXT

1. Physics of piano

The piano is a special string instrument: its sound comes from the collision of strings triggered by keys. Although the interface for users is the keyboard and the sound source comes from the strings; there is no direct contact between the two. Instead, it is the hammer connected to each key inside that activates the vibrating system. Figure 1 shows the internal mechanical structure connecting the key to the string.

When a key is pressed, it sets the corresponding hammer in motion: the end of the key kicks the hammer which strikes the strings and produces the sound. Meanwhile，the damper raises to allow string movements. When a key is released, the damper returns to the origin and inhibits the vibration. Hammers inside the piano fall back immediately after striking the string and leave a free string vibration [6]. The greater the velocity used on the key, the stronger the hammers hit the string and hence louder sounds are produced.

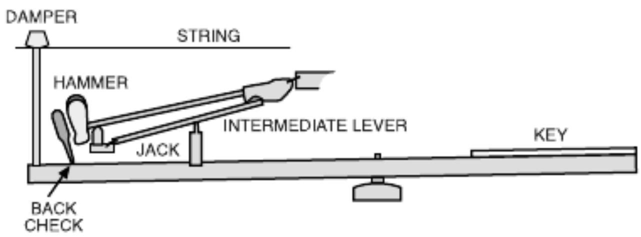

Figure 1: Mechanism for striking a piano string (from [9])

2. Piano decay phenomenon

Once a key is pressed on the piano, it will immediately produce a sharp attack of sound and then the sound diminishes gradually if the keys remains depressed. Piano tones decay through time because the vibration of a string will stop after a certain length of time. Therefore, how the string loses the energy directly affects the decay time. However, the decay rate of a piano tone is a complex process that is not linear in relation to the time. Research which has been conducted on piano decay indicates that piano decay times are a two-stage process and vary according to frequency.

According to former studies started by Martin in 1947, two stages of decay exist: the decay rate of a sustained piano tone decreases with time more rapidly at first, and following is a second stage where sound pressure level decreases more slowly. There is a switch from an original high-rate decay to a slow-rate decay between stages.

As stated previously, decay time is frequency-dependent. Different pitches have different decay and sustain times before the sound becomes inaudible. Since a piano tone has several overtones, even for a single note, the decay times of partials are different. The frequency-dependent character of piano decay affects the tone quality of the piano through time.

III. Measurement of Piano Decay

A. *Preparation and Predicted Data*

In order to observe the decay features of a piano, an experiment regarding the decay performance of the grand piano was implemented. Two comparisons are observed during the experiment. The first is to measure if the velocity of key affects the decay rate; the second is to identify how different pitch ranges exhibit varied decay characteristics.

Single notes in different frequency ranges were recorded throughout the experiments. The pianist was asked to play the note at a given velocity and keep pressing the key until the sound is inaudible in quiet studio conditions. Each note is recorded twice: once with a high velocity (fff as reference velocity) and second with a low velocity (fp as reference velocity).

During the experiment, two sets of data were expected to be collected:

(1) 8 octaves of Cs played in the velocity of “fff”; the keys were kept pressed until the sound was inaudible.
(2) 8 octaves of Cs played in the velocity of “fp”; the keys were kept pressed until the sound was inaudible.

B. *Procedure*

The sound level of eight C notes in different ranges (C1-C8) from a Yamaha grand piano were recorded in mono format utilizing in Neumann KM100 microphone through an Mbox2 interface in Studio A of New York University's Steinhardt Education Building. The studio has a reverberation time of approximately 0.6s. The pianist is a master's candidate majoring in piano performance in New York University's Music Department. The sustained pedal was not used in the experiment.

Data was analyzed through the software “Matlab”; plotting the decay of the envelope. Three factors are to be discussed:

(1) The general decay slope of piano notes.
(2) The relationship between decay time and velocity.
(3) The relationship between decay time and frequency.

According to the author's experience with piano sound, low tones are predicted to have much longer decay time than high pitch. In general, a tone dies away more rapidly during the first few seconds more than the remainder of the sound.

C. *Result*

(1) General decay slope

The experiment proves the existence of two-stages of decay in piano tones. Figure 2 is a typical piano decay. The figure shows a function of sound pressure level over time for four notes (C2, C3, C4, C5) with “fff” velocity. The note reaches the peak amplitude after a short time of attack, and then immediately drops by 10dB within two seconds. After that, the amplitude drops in a more gradual slope until it’s inaudible.

It is clear to see that the amplitude drops rapidly at an exponential rate from 0dB to -10dB during the first two seconds, and then it takes a longer period of time to decrease to an inaudible level. Although the slopes of four notes are different, they all share a common feature: There are apparently different slopes which exist during the decay process; the first down slope is sharper and the latter is flatter.

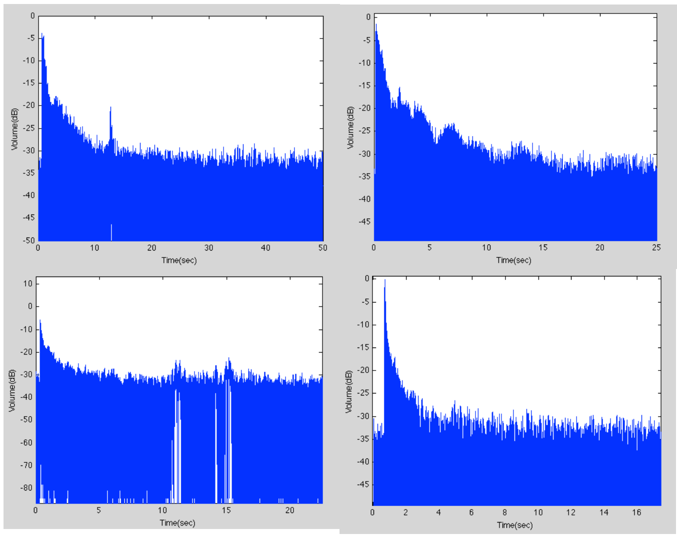

Figure 2: Yamaha Grand Piano Decay rate (C2 C3 C4 C5)

Figure 3 is a zoom-in of note C5, which shows in details how decay performs at the first four seconds of note.

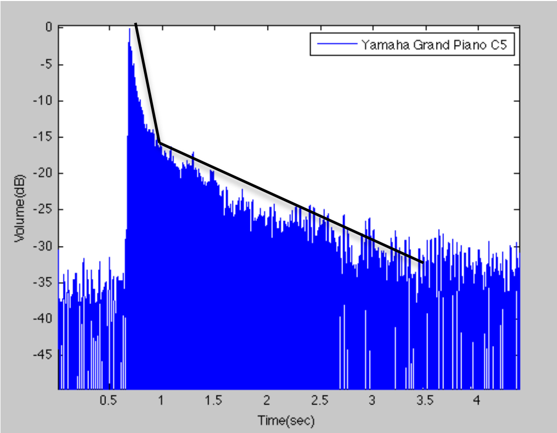

Figure 3: First 4 seconds of Yamaha Grand Piano C5

From the graph of overall sound pressure for the note C5, an apparently sharp slope appears in the first second of the note after reaching the peak velocity. Subsequently, the amplitude reduces slowly until the tone is inaudible. The decay rate of the first stage is approximately 30dB/s, and for the second stage decreases to about 7dB/s.

(2) Decay time and velocity

During the experiment, the same note with a different playing velocity is recorded and examined. Figure 4 is the "fp" velocity version of Yamaha Grand Piano note C5.

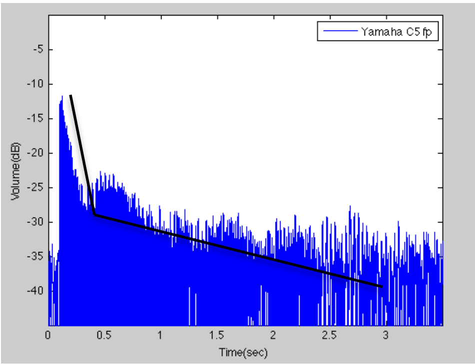

Figure 4: First 3 seconds of Yamaha Grand Piano C5 in "fp"

Although playing with different velocity, the boundaries of the two decay stages in the figure are still clearly visible. However, the slope of decay varies slightly. The result shows that the tone with a higher velocity is easier to lose its initial energy and will decay faster in the first stage. The decay rate is calculated in table 1.

Velocity	fff	fp
1st slope	30dB/s	26dB/s
2nd slope	7dB/s	6.5dB/s

Table 1: Comparison of decay slope of different velocity

(3) Decay time and Frequency

It is generally assumed by pianists and audiences that low pitches can sustain longer than higher pitches. In addition to this, according to the result of the experiment, low pitches have longer decay time in the first slope.

In order to observe the decay time differences for different pitches, the performance of C notes from different frequency ranges were analyzed. Due to the unstable harmonic partials for certain pitches, the lowest and the highest note (C1 and C8) were exempted from the analysis. Table 2 lists the double-decay time for all of the six C notes (from C2 to C7) with the decreasing rate of the overall sound pressure level in both of the stages.

Judging from table 2, it is observable that low pitch notes note only have a longer decay time both for the first stage and for the second stage. In addition, lower pitches have a slower decay rate in both stages compared to higher pitches. They can retain the energy better than the higher pitches.

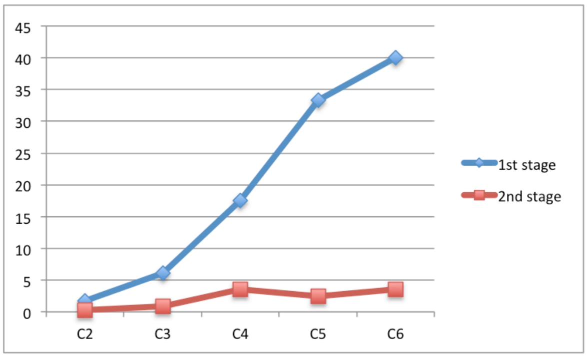

Chart 1: Decay rate comparison

Note		C2	C3	C4	C5	C6	C7
1st slope	Time	4.5s	1.3s	0.4s	0.3s	0.25s	0.1s
	dB decreasing	7.5dB	8dB	7dB	10dB	10dB	11dB
2nd slope	Time	18s	5.5s	1.4s	2s	1.4s	0.5s
	dB decreasing	5dB	5dB	5dB	5dB	5dB	15dB
Decay Rate	1st slope	1.67dB/s	6.15dB/s	17.5dB/s	33.33dB/s	40dB/s	110dB/s
	2nd slope	0.28dB/s	0.91dB/s	3.57dB/s	2.5dB/s	3.57dB/s	30dB/s

Table 2: two slopes decay rate for note C2 to C7

Chart 1 illustrates the decay rate difference. The difference is large in the 1st-stage decay among different frequency ranges. The X axis represents different tones from C2 to C6; the Y axis represents the sound pressure level decay rate (unit: dB/s). It is easy to see that higher pitches decrease their sound pressure level more rapidly than lower frequencies. The decay rate varies from 1.6dB/s to 40dB/s for the first stage, and from 0.28dB/s to 30dB/s for the second stage.

The reason for the longer decay time of lower pitches may be due in part to the air absorption. High frequencies are more easily absorbed by the air during the propagation. What is more important is that, piano tones are not just a single pure tone. They contain various harmonic partials. Thus, low pitches contain more partials at lower frequencies that decay more slowly than those of high pitches.

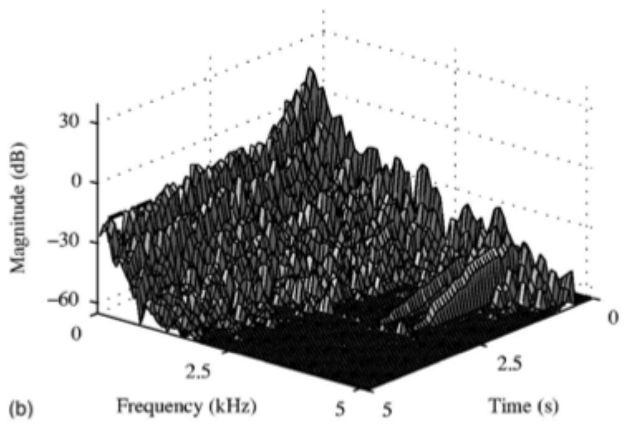

Figure 5: Time-Frequency plot of tone C4 (from [14])

Figure 5 is a three-dimensional plot of the tone C4 in both the time and frequency domains[14]. The figure displays that low frequencies have the ability to conserve energy better than high frequencies. This could explain the reason for the different decay times in various pitches.

D. Discussion

Piano decay characteristics were first studied by D. Martin in 1947. Generally the relationship between sound pressure level and decay times can be exponentially represented. However, the curve is not a simple function of time. According to Burred(1999) , the first phase of decay is known as immediate sound, and the second stage is known as the resonance[6]. This phenomenon is defined as "double decay" in piano acoustics. Both of the decay stages are of great importance in piano performance. The initial stage of decay has influenced decision making in the composition of piano works where most of the tones are not sustained longer than 5 seconds, as proved by Martin. However, according to Martin(1947), the second stage also affects sustained passages and the usage of the sustained pedal in piano composition.

The discovery of double decay phenomenon by Martin is an important feature of piano tones. The complicated mechanical reasons inside string vibration were then explained by other researchers. Due to the use of triple strings in piano, the movement of one string affects the others, which causes phase differences [6].

Another reason for the existence of the double-decay curve of piano tones could be attributed to the displacement of the soundboard in the piano. According to the research of Giordara (2010), the string vibrates differently as time passes when hit by a hammer. It initially vibrates the same way as the hammer's motion, which is perpendicular to the soundboard. However, after a short period of time, it vibrates horizontally due to the effect of the bridge on the soundboard. The perpendicular vibration dominates the first stage of decay and diminishes quickly when the vibration parallel to the soundboard happens, introducing a second type of decay. The shift from vertical vibration to horizontal vibration directly causes the two-stage decay.

The decay time also has some relationship with the change of velocity and frequency. According to the studies and experiments, trebles notes have a more rapid decay speed than bass notes. The reason for this could be that lower pitch notes have longer strings where the rate of energy transfer is small. Thus, bass strings lose energy at a slower rate than treble strings[7]. Martin(1947) listed the average decay time for grand piano for both stages (Figure 6). The upper line is for the second decay stage and the lower line is for the first decay stage. After a certain frequency range, these two stages merge. The threshold where the two decay stages is around the pitch of F5 [1].

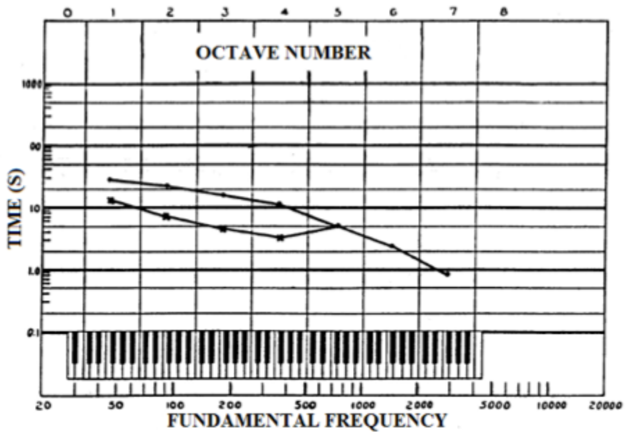

Figure 6: Aerage decay time for grand piano. (from [1])

IV. Extended: Decay time in Piano synthesis

Since its birth in the last century, the synthesizer has brought great impact on modern music production. Synthesizers are developed to produce various types of sounds by electrical means. They also overcome the space limitations and the storage problems sometimes caused by real instruments. Types of synthesis could be divided into: Additive/Subtractive synthesis, FM synthesis, Phase distortion synthesis, Granular synthesis, Sample-based synthesis, Physical modeling synthesis, etc. Three main methods are prevalent in piano synthesis: (1) Sample-based Piano Synthesis; (2) FM synthesized Piano (3) Physical Modeling. Despite the popularity of digital piano synthesis, the question of decay time is raised: how can the digital system accurately reproduces the two-stage compound decay characteristics of an acoustic piano? Decay times in electric synthesis methods were examined.

A. Sampling Piano

Sample-based synthesizers record notes with different velocity layers from a true instrument, and produce different tones using the samples. Excellent piano sampling synthesizers usually record a large length of the note assigning several velocity layers. The samples are so long that it covers the first stage decay and most of the second stage decay. After the sampling, a loop is made based on a portion with the note with a certain decay envelope. Since the main decay slopes were caught through the recording, there are no concerns of altering decay characteristics.

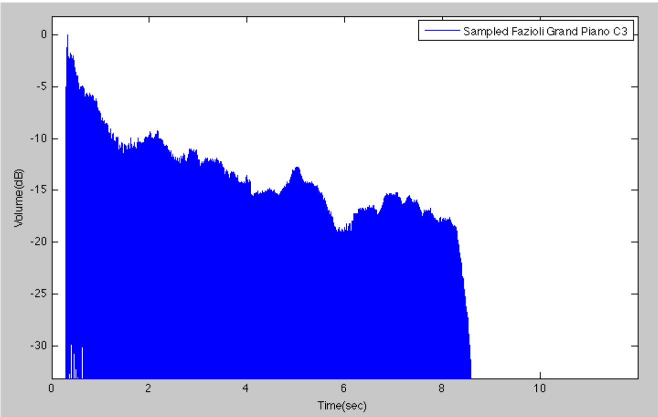

Figure 7: C3 from sampled grand piano “Fazioli”

Figure 7 is the time-domain plot of note C3 from the sampled piano bank “Fazioli Grand Piano”. Since the high quality sampled piano captures an extended sample, there are no deficiencies in the compound decay curve. The only difference is that the dropping rate for both of the stages happens more slowly than the Yamaha Grand Piano. This is due to the different manufacture and quality of the piano.

While sampling pianos such as “Ivory Grand Piano”, “Boesendorfer" provides the high quality a true piano sound, it requires a more robust storage system.

B. FM Synthesized Piano

Another way to synthesize piano tones involves Frequency-Modulation methods. Although it is convenient and efficient for systems with less capability, it’s difficult to reproduce the properties of a real piano. Part of the reason could attribute to the frequency modulation part itself. However, there’re also some problems from the time domain. The player might always feel that electric piano is not so vivid; part of the reason is from the decay time. Figure 8 is a plot of note Electric Piano timbre of the note C5 from Yamaha motif synthesizer.

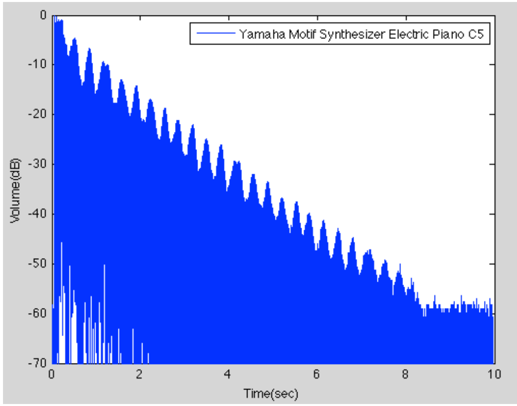

Figure 8: C5 from Yamaha Motif Synthesizer Electric Piano

Examining the time resolution plot, it is easily visible that the two-stage decay disappears in the electric timbre. A simple comb filter is applied with a delay line in order to represent the loss of energy. However, the lack of two-stage decay is less representative of a piano tone.

In other aspects, developers have considered simulating the acoustic piano utilizing analyses of the piano spectrum. However, the lack of consideration given to the time aspect will lead to un-nature results. Figure 9 plots a C4 note generated utilizing a commercial software package.

In figure 9, although there are two different decay slopes, the lack of consideration for the relationship between the decay time and frequency is apparent. High frequency notes tend to decay faster in the first stage. In addition, the decay curve is too smooth to present a true piano sound.

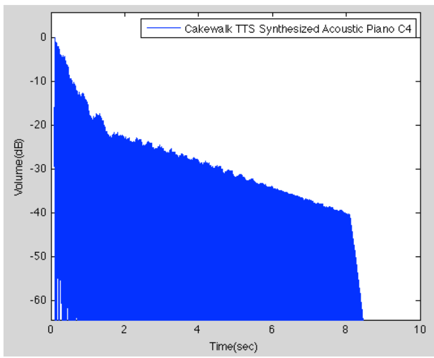

Figure 9: C4 of synthesized acoustic piano by Cakewalk TTS

C. *Physical modeling*

A new method based on physical representations of the instrument is physical-modeling sound synthesis, developed more recently than previously mentioned methods. Physical modeling utilized computer-based tools to model and simulate properties of real musical instruments[13]. While sample-based synthesizers have the limitation of representing a limited number of quantize dynamics, FM synthesis has deficiencies in time domain, the physical-based modeling technique resolves these problems incorporating acoustic properties of musical instruments. Research for physical models of piano are developed utilizing mathematic equations.

Digital waveguides are one of the popular techniques used in physical modeling especially for string instruments. During the research of physical modeling of the piano or other stringed instruments, the simulation of the physical losses of energy is an essential component. In order to obtain more realistic features, the loss and dispersion of energy in string vibration are taken into account. The research in piano decay time helps the development of physical modeling in the form of the loss filter.

In digital waveguide synthesis, losses are modeled with the feedback loop and the delay line set to match the true magnitude response of a piano according to the performance of different partials. Based on the special characteristics of piano decay times with frequency, a low pass FIR or IIR filter is usually used in the loss filter of digital waveguides. The most recent technique for loss filtering was developed by Rauhala et. al (2005). They designed incorporated a one-pole filter for the grand trend of decay rate, and used a comb filter to further tune the gain of partials. In addition, since different partials decay differently, an N-th order feed-forward comb filter is used for decay time variations according to different partials [11].

Figure 10 shows the magnitude response of the equalizer used in the loss filter designed by Rauhala et. al. The sub-filter considers the attenuation of certain partials in piano tones while other partials remain untouched. This accurately simulates how piano tones perform in the real world and thus makes the model more realistic.

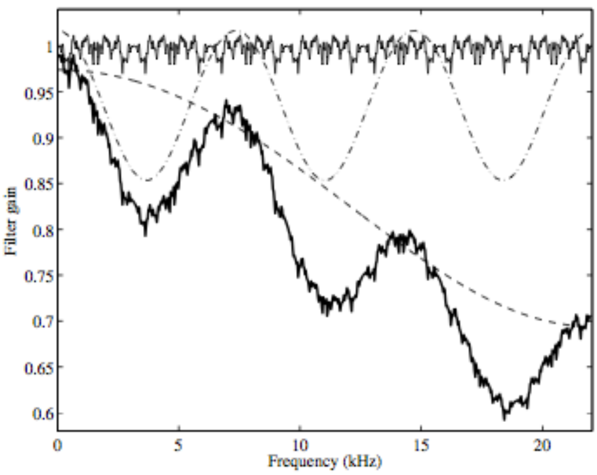

Figure 10: magnitude response of sub-filter (from [12])

V. CONCLUSION

Among the studies involving piano acoustics, emphasis have been placed on the touch and timbre of the piano. However, piano tones are also worth studying. The piano is a string instrument with a special envelope, especially during the decay portion. This paper has examined the decay aspects of piano tones and explained the double-decay character of piano tones based on current literature and through experimentation. Some conclusions from this study are:

(1) The initial slope of piano decay rate varies from 1.5dB/s to 100dB/s according to pitch.

(2) The second slope of piano decay rate varies from 0.3dB/s to 30dB/s according to pitch.

(3) Low tones have longer decay times than higher tones due to the acoustic principle of sound scattering and physical interaction of the string vibrations with the sound board.

(4) High velocity tones tend to lose initial energy faster than low velocity tones during the first stage.

Meanwhile, advanced techniques in piano synthesis are becoming more prevalent due to affordable computational power. This paper also provides an overview of the piano synthesis world. The sampling piano provides a high quality of acoustic piano tone but occupies a great deal of memory. When judging the FM synthesized electric piano, the lack of compound decay curve and consideration of its frequency-dependent characteristics lead to an un-nature result in piano sound reproduction. The most accurate representation is through the physical modeling of the piano: it accomplishes the simulation of piano decay time through the use of several sub-filters which treat decay partials differently. This paper presents a theoretical and practical way to learn piano acoustics in the time domain. The study of decay characteristics of the piano can aid the development of piano composition as well as the design of digital synthesis.

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