

ISTANBUL TECHNICAL UNIVERSITY★GRADUATE SCHOOL

**SENSORY DISSONANCE CURVES WITH ADSR ENVELOPE & PARTIAL
TYPE ANALYSIS AS AN ADDITIVE SYNTHESIS STRATEGY**



M.A. THESIS

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Department of Music

Music Programme

Thesis Advisor: Assoc.Prof. Manolis EKMEKTSOGLU

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İSTANBUL TEKNİK ÜNİVERSİTESİ★ LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ

**BİR EKLEMELİ SENTEZLEME STRATEJİSİ OLARAK ADSR ZARFI VE
DOĞUŞKAN TİPİ ANALİZİ İLE GENİŞLETİLMİŞ DUYUMSAL
UYUMSUZLUK EĞRİLERİ**

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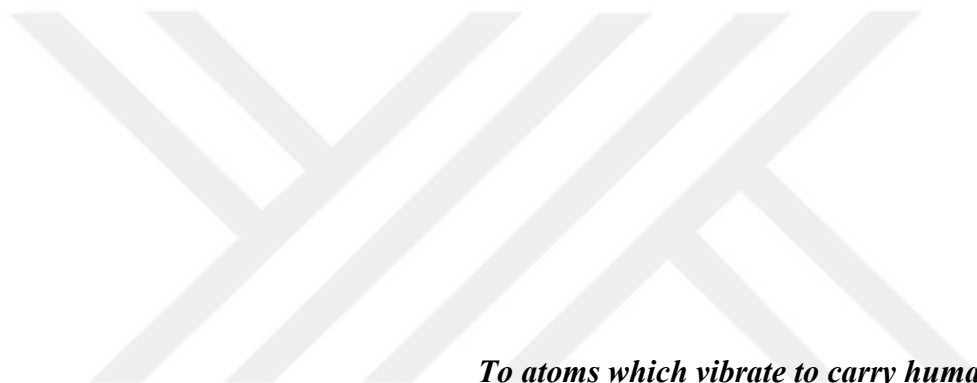
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To atoms which vibrate to carry human messages,



FOREWORD

Since the day I started to use computers for musical purposes, I have always been eager to learn how a practical tool works and which mechanisms are structured to achieve the output of this tool. This eagerness increased exponentially in the years and transformed into an academic appearance. Understanding a musical system under the computational scope with an infrastructural level of inspection became a primary motivation and curiosity for me so that it pushed me to go further to the lowest levels of musical computation, such as Fourier transform for wavelet transformations, low-level music information retrieval concepts and many more to investigate the capacities of the digital tools as well as designing such systems besides my artist appearance. In addition to this theoretical pursuit of knowledge, the relationship between the creator and a musical interface took my attention, regardless of the type, such as an instrument, an empty score sheet, a circuit, or a computer program. Since I can be considered a purist disciple of creativity, I always thought that a creator should be authentically connected with his/her/they creation and should create the environment and reality around the creation. In this sense, I have always admired not only the people who create but also the people who create the ways, techniques, methods, philosophies, and tools of creation and who have control over the interface which is used for creation. My passion for computational ways of creation coincides with such an academic and artistic approach. So briefly, the first years of my involvement with computational creativity were learning to use the tools, then, in time, the complexity of the tools increased. I started using graphical user interfaces rather than pre-determined tools and consequently coded and designed my programs and systems for musical purposes. Consequently, I wanted to cover a similar concept academically, which investigates a specific property of musical systems in relation to the digital possibilities.

The specification of this thesis emerged from another interest and curiosity of mine within the context of music and sound. The latter is a priori phenomenon to the former, so this specification concerns the relationship between music and sound. Details of this concentration are investigated and explained as a research discourse throughout the paper; hence I want to express my interest and focus more informally here in the foreword section. Since my introduction to the electronic and digital ways of creating sound, I am always fascinated with the realm of vibrations and their relationship with frequency, sound, music, communication, and in a broader sense with reality. Investigating the sound and music in the context of vibration established a broader discourse of music for me which has a quantitative appearance at first look, but I came up with the thought that the more my understanding becomes quantitative and systematic by learning mathematical concepts, the more it becomes intellectual and spiritual for me. In this sense, I can say that what I want to study and to be a disciple of in my career should be established on top of concepts that can be proven by quantitative experimentation, but it should have an authentic reflection on my mind. Consequently, when I started to conduct my research, I also tried to find a way to represent this understanding of mine.

Kerem Eren Altaylar





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ABBREVIATIONS

sr	: Sample Rate
ms	: Millisecond
μs	: Microsecond
Hz	: Hertz
libfmp	: Fundamental Music Processing Library
DFT	: Discrete Fourier Transform
STFT	: Short Time Fourier Transform
FFT	: Fast Fourier Transform
SPL	: Sound Pressure Level
db	: Decibel
VSC	: Visual Studio Code



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SENSORY DISSONANCE CURVES WITH ADSR ENVELOPE & PARTIAL TYPE ANALYSIS AS AN ADDITIVE SYNTHESIS STRATEGY

SUMMARY

This research focuses on the concept of sensory dissonance and its relation to the complex nature of tone and timbre systems. It can be described as the amount of harmonic beating occurring between two tones which correspond to the fluctuation in the perception of their amplitude. Two research questions are set to investigate this concept. The first one is whether the envelope components of a partial, which are also known as ADSR parameters, affect the sensory dissonance calculation of that timbre which consists of the sine wave partials or not. Previous studies are using pure amplitude values of partials for calculation and focused on theoretical aspects of sensory dissonance. The aim of adding envelope information and testing it is an attempt to extend the concept of sensory dissonance to more practical usage. The second question is, does the type of a harmonic partial effect the total sensory dissonance. In this research, there are virtual tests which were held to find possible answers to these questions.

In the introduction section, the scope of computational analysis of sound and music is investigated through its components and methods. In addition to that, the concept of sensory dissonance is described with its mechanisms and is contextually connected to the research questions in terms of structure. The second section shows the test designs regarding the concepts in the introduction section. The first test includes timbre data generation consisting of sine waves, calculation of the weight for those timbres, and their effects on the amplitude weights of the partials. Second test includes the different types of harmonic partials and their effects on the sensory dissonance curves as well as the attempts of replacing the integer frequency ratios of harmonic partials with inharmonic partial ratios consisting of different tone systems. Section 3 is containing the results of two tests and Section 4 have the remarks on the tests.

KEYWORDS: Sensory Dissonance, CDC-5, Amplitude Envelope, Harmonic Partial, Sine Wave, Computational Musicology



BİR EKLEMELİ SENTEZLEME STRATEJİSİ OLARAK ADSR ZARFI VE DOĞUŞKAN TİPİ ANALİZİ İLE GENİŞLETİLMİŞ DUYUMSAL UYUMSUZLUK EĞRİLERİ

ÖZET

Bu araştırmanın odak noktası, duyuşsal uyumsuzluk kavramı ve bunun ton ve tını sistemlerinin karmaşık doğasıyla ilişkisidir. Bu kavram genliklerinin algılanmasındaki dalgalanmaya karşılık gelir ve iki ton arasında oluşan harmonik ritim miktarı olarak tanımlanabilir. Bu kavramı incelemek için iki araştırma sorusu oluşturulmuştur. Birincisi, ADSR parametreleri olarak da bilinen doğuşkan zarf bileşenlerinin, sinüs dalgası parçalarından oluşan bir tının duyuşsal uyumsuzluk hesabını etkileyip etkilemediğidir. Önceki çalışmalar, hesaplama için doğuşkan genlik değerlerini kullanıyor ve duyuşsal uyumsuzluğun teorik yönlerine odaklanıyor. Zarf bilgisi eklemenin ve bunu test etmenin amacı, duyuşsal uyumsuzluk kavramını daha pratik bir kullanıma taşıma olarak belirtilebilir. İkinci soru, harmonik doğuşkan tipinin toplam duyuşsal uyumsuzluğu etkileyip etkilemediğidir. Bu çalışmada, yukardaki soruların olası cevaplarını bulmak için sanal deneyler yapılmıştır.

Giriş bölümünde, ses ve müziğin bilgisayar vasıtasıyla analizinin kapsamı, bileşenleri ve yöntemleri incelenmektedir. Bu bağlamda ilk olarak ses ve müziğin arasındaki ilişki dijital izleme yöntemleri üzerinden incelenmiştir. Ses doğası gereği iki ayrı kategoride algılanabilir ve incelenebilir. Fiziksel ve algısal olarak ayrılan bu özellikler araştırmanın içinde yer alan kavramlar ve hesaplamalar için bir temel teşkil etmektedir. Frekans-nota perdesi ve genlik-algılanan ses yüksekliği arasındaki ilişkilerin kendi aralarında tanımlanmasının ardından bunların araştırma kapsamında ne öneme sahip oldukları hem insan merkezli algısal bir bakış açısından hem de algıdan bağımsız bir biçimde inceleme ve hesaplama için nicel bir bakış açısından açıklanmıştır. Ses ve müzik araştırmalarının geçmişten günümüze getirdiği bilgi ve deneyimler çerçevesinde derlenen bu bilgiler bu alanların içinde yapılabilecek test ve deneyler için bir prosedür olarak düzenlenmiş ve tekrar edilebilirlik açısından önemli bir konumda değerlendirilmiştir. Ses ve müziğin, kayıt teknolojileri vasıtasıyla mümkün olan dijital yollarla kaydedilip, dönüştürölüp, saklanıp, işlenmesi vasıtasıyla bir incelemeye tabi tutulması, bu dijital yolların bahsedilen ses özelliklerini nasıl temsil ettiği sorusuyla bir sonraki odak noktası olmuştur. Bu konu dijital ses örnekleri için niceleme ve Fourier dönüşümlerinin üzerinden takip edilmiştir. Bu yapı üzerinden araştırmanın takip ettiği asıl konu olan duyuşsal uyumsuzluk için ölçülebilir parametrelerin nasıl elde edildiği ve temsil edildiği incelenmiştir. Bu noktada, duyuşsal uyumsuzluk kavramı,

içerdiği mekanizmalar ile açıklanmış ve yapısı itibariyle araştırma sorularıyla bağlamsal olarak ilişkilendirilmiştir. İki sinüs dalgasının birleşmesiyle oluşan sonuç dalgasının algılanmasında, bu iki dalganın frekans ve genlik bilgileri ile ilişkili bir biçimde bir bozukluk olarak tanımlanabilecek olan duyusal uyumsuzluğun son çalışmalar ışığında matematiksel olarak nasıl tanımlandığı, programlama yöntemleri sayesinde nasıl izlendiği ve bu parametrenin nasıl grafik bilgisine dönüştüğü incelenmiştir. Buna ek olarak da daha önceki çalışmalarda yer alan 2'den fazla sinüs dalgasından oluşan kompleks dalgaların davranışının üzerinden de aynı bakış açısıyla geçilmiştir. Bu noktaya kadarki kümülatif bilgi Hermann von Helmholtz'un başlattığı R. Plomp, W.J.M Levelt, William Sethares and Jan Haluska gibi araştırmacı akademisyenlerin yarattığı sistematik düşünce üzerinden oluşturuldu. Bu araştırma için belirlenen test konusu da aynı şekilde bu alanın üzerinde tasarlandı. Yukarıda belirtilen araştırmacıların çalışmalarında duyusal uyumsuzluğun hem matematiksel olarak hesaplanması hem de bu hesaplamaları yapan bir algoritma programlanması için her bir sinüs dalgasının frekans ve genlik değerleri kullanılmıştır. Bu bağlamda bu araştırmanın ilk merkezi frekans ve genlik bilgilerinin yanına genliğin zaman içindeki değişimi olarak tanımlanabilecek zarf bilgisinin eklenmesi ve de bunun sonuçları olarak belirlenmiştir. İkinci konsantrasyon alanı farklı sayıda ve de farklı frekanslara sahip sinüs dalgası kombinasyonlarının incelenmesi ve de iki frekansın arasındaki oranın müzikal olarak nasıl sonuçlar yarattığı olarak tanımlanmıştır. Bu iki araştırma konusu, programlama ve de müzikal bilgi çıkarım alanlarının sağladığı olanaklar ile birer teste çevrilmiştir.

İkinci bölümde giriş bölümünde yer alan kavramlara yönelik deney tasarımları gösterilmektedir. İlk deney, sinüs dalgalarından oluşan tını verilerinin oluşturulmasını, bu tınların denklemsel etkilerinin hesaplanmasını ve doğuşkanların zarf bilgisinin genlik ağırlıklarına etkilerini içermektedir. İkinci deney, farklı türdeki harmonik doğuşkanları, bunların duyusal uyumsuzluk eğrileri üzerindeki etkilerini ve harmonik doğuşkanların tamsayı frekans oranlarını farklı ton sistemlerinden oluşan inharmonik doğuşkan oranlarıyla değiştirme girişimlerini içerir. Bu testlerin bileşenlerinin ve de sonuçlarının verimli bir şekilde incelenebilmesi için sonuç rapor tasarımları hem testlerin kontrol parametrelerinin hem de sonuç grafiklerinin beraber incelenebilmesine olanak sağlayacak şekilde tasarlanmıştır.

3. bölüm deneylerin sonuçlarını ve 4. bölüm deneylerin sonuçları üzerine açıklamaları içerir. Birinci testin sonucunda sinüs dalgalarının genlik bilgisinin zarf bilgisiyle genişletilmesinin, eğrilerin temsil ettiği toplam duyusal uyumsuzluğu azalttığı ama bu azalmanın enerji kaybı olarak da tanımlanabileceği; buna ek olarak zarf bilgisi içindeki maksimum genlik noktalarının farklı frekans bilgisine sahip sinüs dalgaları üzerindeki dağılımının duyusal uyumsuzluk grafiğinin davranışı üzerinde bir etkiye sahip olduğu gözlemlenmiştir. İkinci deneyin sonucu ise 4'lü, 5'li ve 6'lı harmonik doğuşkan kombinasyonlarının duyusal uyumsuzluklarının müzikal notalar ile olan ilişkisinin bir kataloğa çevrilmesidir. Bu sonuçların üzerine duyusal uyumsuzluk parametresinin, eklemeli ses sentezlemesi metotları ile paralel kullanımı için stratejiler oluşturulmuştur. Bu araştırma bu stratejiler ve de testler göz önüne alındığında duyusal uyumsuzluk kavramının müzikal kullanımı ve de müzik analizi için bir bileşen olması yolunda başlangıç seviyesinde verimli bulunmuştur. Gelecek araştırmalar ve testler için de bir şablon tasarımı olarak değerlendirilmesi mümkündür. Sadece teknik ve teorik açıdan kavramın ele alınması durumunu değiştiren bir bakış açısıyla, eklemeli sentezleme metotlarının oluşturulması ve de genişletilmesi için duyusal uyumsuzluğun

bir parametre olarak tını tasarımında kullanılabilmesi ise sonuçlar ışığında bir motivasyon ve potansiyel yaratmıştır.

ANAHTAR KELİMELER: Duyusal Uyumsuzluk, CDC-5, Genlik Zarfı, Harmonik Doğuşkan, Sinüs Dalgası, Bilgisayarlı Müzikoloji





1. INTRODUCTION

Since this research is conducted on the scope of computational musicology, in the upcoming chapters, many visual representations of sound are generated in the programming environment. The capacity of such a medium provides many new opportunities for music analysis. Especially if the scope of analysis can be narrowed down to microseconds and samples, there is a realm of many features that can be extracted by digital signal processing methods. Current machine learning and deep learning systems within the context of music are performing their tasks based on the data and structure of these features. This field of research is called music information retrieval. Timbre analysis and synthesis are also a subset of this area. In order to work with mass sound data and deep learning applications, there is a need of designing attributes and features to be used and calculated from the digital sound data. Sensory dissonance is one of these attributes and used for various purposes. The aim of this research is extending the usage of sensory dissonance to be a factor in additive synthesis methods and to be a control mechanism for timbre design in accordance with a tone system consisting of individual intervals. But in order to investigate such concept, the starting point for inspection is the basic properties of sound.

1.1 Sound Properties

Sound as a physical and perceptual phenomenon can be considered a priori to the concept of music which is considered to be a form of art and phonetic communication or the collection of sounds that are temporally organized by a person for the purpose of enriching or intensifying an experience of emotion (Levinson, 2011). This statement is questioned and evaluated by many philosophers and musicologists in terms of its comprehensiveness of it. The reason for such interrogation is the cases in which there is no sound but music. A musical score or a midi note file can be examples of a situation where the form of music can be seen and evaluated. But there are no vibrating atoms carrying the mechanical wave information; in other words, there is no physical existence of the sound (Tyndall, 1897). Another description with two distinct

understandings of sound is that it is the disturbance in a specific medium and the auditory sensation which is caused by it (Rossing, 2014). According to this description, sound has epistemological and ontological duality. In this sense, sound requires two realms of inspection, and there are properties of sound that coincide with the phenomenon which are used to describe the sound. These properties can be divided into two categories that can be traced to former explanations of the sound. Firstly, there are physical attributes of sound. They are frequency, amplitude, waveform, and duration. The standard and protocol to label these as physical is that they can be measured by quantitative methods. On the other hand, there are perceptual attributes that can be accessed by only hearing. They are pitch, loudness, timbre, and psychological time. In this sense, if the physical sound is modeled, Fourier series or wavelets can be used to represent it, but if the perceptual objects are desired to be modeled, a set of numbers or qualities are used to represent it (Haluska, 2003). These two categories are significant to investigate since they are used to describe and analyze musical tone systems.

1.2 Computational Musicology and Music Analysis

A computational approach to physical properties and the whole concept of musical tones is also very crucial. Because the resolution of the measurement of the physical properties has been developing in accordance with the advancements in computational technology. The thought systems of music and the technological improvements, which are cumulatively everchanging, intersect within the discipline of computational musicology, which can be described as the interdisciplinary research area that uses both theoretical knowledge and information systems of musicology and computer science (Volk & Wiering & Kranenburg, 2011). The method of analysis in this field can be described as the working of a computer program. The music or a subset of musical data is given as input to a program while it is labeled, divided, and transformed in accordance with the type of analysis, then the program gives the desired information as output (Meredith, 2016). In this sense, for the analysis and visualization of musical data, Python programming environment, the Librosa Music Information Retrieval Library, and Fundamentals of Music Processing Library (libfmp) are used in this research.

1.2.1 Waveform and time domain

Sound can have many forms of data which can be used for measuring various musical properties as the object of the analysis. In order to investigate the bridge between a sinusoid as the smallest unit of digital sound and a musical tone system as a complex system of information, let's go over the waveforms and Fourier transform, which are the basic building blocks of current digital sound technology. A waveform representing sound magnitude changes in time digitally stores the information that a sound wave mechanically carries through a point or an area filled with a physical medium. This representation and data are used as the source of decomposition in which the signal is evaluated through periodicities in order to provide frequency information and spectrum (Brixen, 2020). In figure 1.1, this representation can be seen.

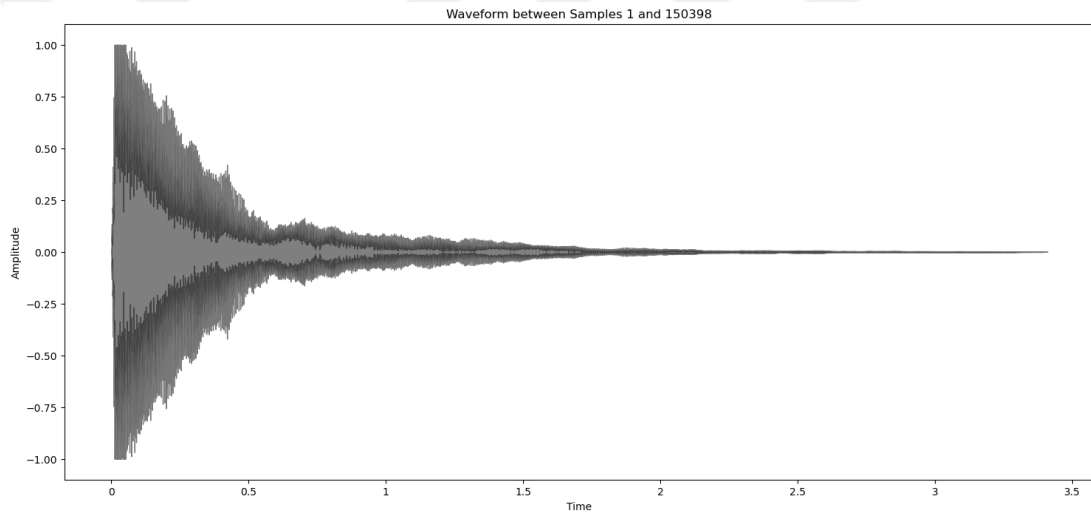


Figure 1.1: Waveform of a harpsichord recording consisting of 150398 samples with 44100-hertz sampling rate (librosa)

Since this form carries the time domain information, the duration of the recording can be calculated precisely with the knowledge of the sample rate and the number of samples in the recording. The sampling rate is the number which corresponds to the number of samples into which 1 second of sound can be divided (Rumsey, 2021). Librosa library provides a function to extract the number of samples that recording have. This number is multiplied with the sample size which is $1/\text{sr}$. This gives the exact duration of the recording to us. The recording in Figure-1-1 is 3.41038548752834458355209790170192718505859375 seconds. This number is the result of the multiplication of 150398 samples and the sample duration which is 0.0000226757369614512476298836401999992062883393373340368270874023437 seconds. This is the duration of one sample derived from the $1/\text{sr}$ formula with 44100-

hertz sampling rate. The number 44100 carries the frequency resolution information as well that the half of the sampling rate is the number of the highest frequency that can be stored due to the result of the Fourier transform.

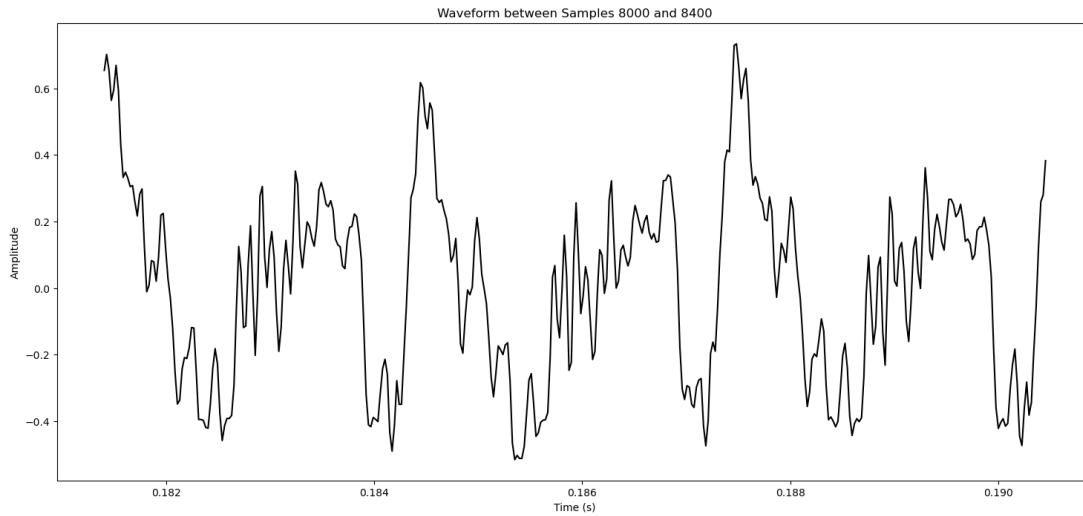


Figure 1.2: Waveform of the same harpsichord recording consist of 400 samples with 44100 hertz sampling rate (librosa)

In Figure 1.2, the graph represents 400 samples rather than 150398 samples which is the whole recording. The length of this scope as a window gives the duration of it, 0.00907029478458049910616356470427490421570837497711181640625 seconds.

In this representation, details of the waveform and the changes in the amplitude have a higher resolution because the former graph and this graph have the same width, but the duration which the width represents is very small in the latter compared to the former.

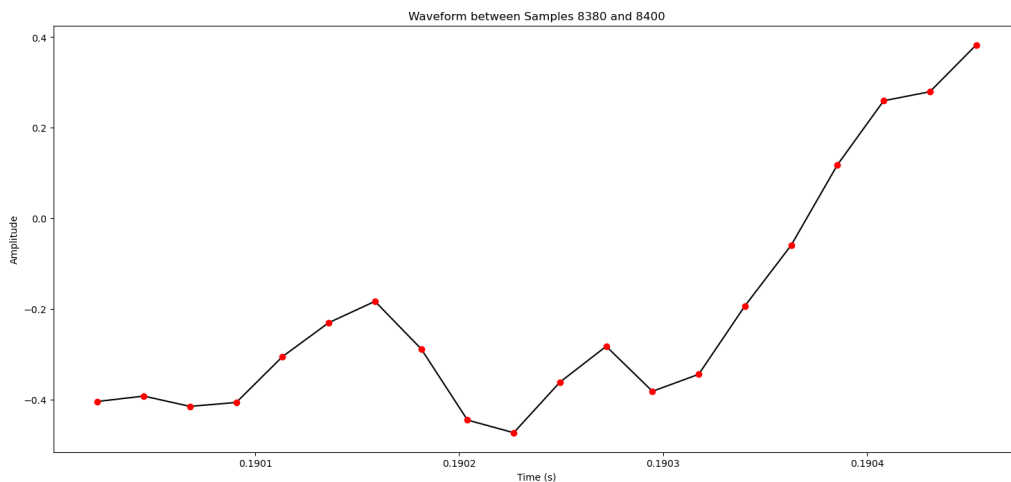


Figure 1.3: Waveform of harpsichord recording consist of 20 samples and visualization of data points which are the results of quantization (librosa)

Figure 1.3 represents only 20 samples, so it can be considered as the highest resolution compared to Figure 1-1 & 1-2. Red dots are the sequential data array that is constructed after the sample quantization. Quantization is the process of transforming the continuous range of amplitude values to the discrete range of values (REF). This process can be measured by the bit depth of the audio digital conversion. As it can be observed from the recent figures, the amplitude axis has a minimum and maximum values such as -1 and 1. How many steps this range is sliced to represent the desired outcome is the value for which the bit depth stands for. An 8-bit depth, for instance, is equal to 256 amplitude steps, while 16-bit is 65.526 and 24-bit is 16.68 million steps (Müller, 2015).

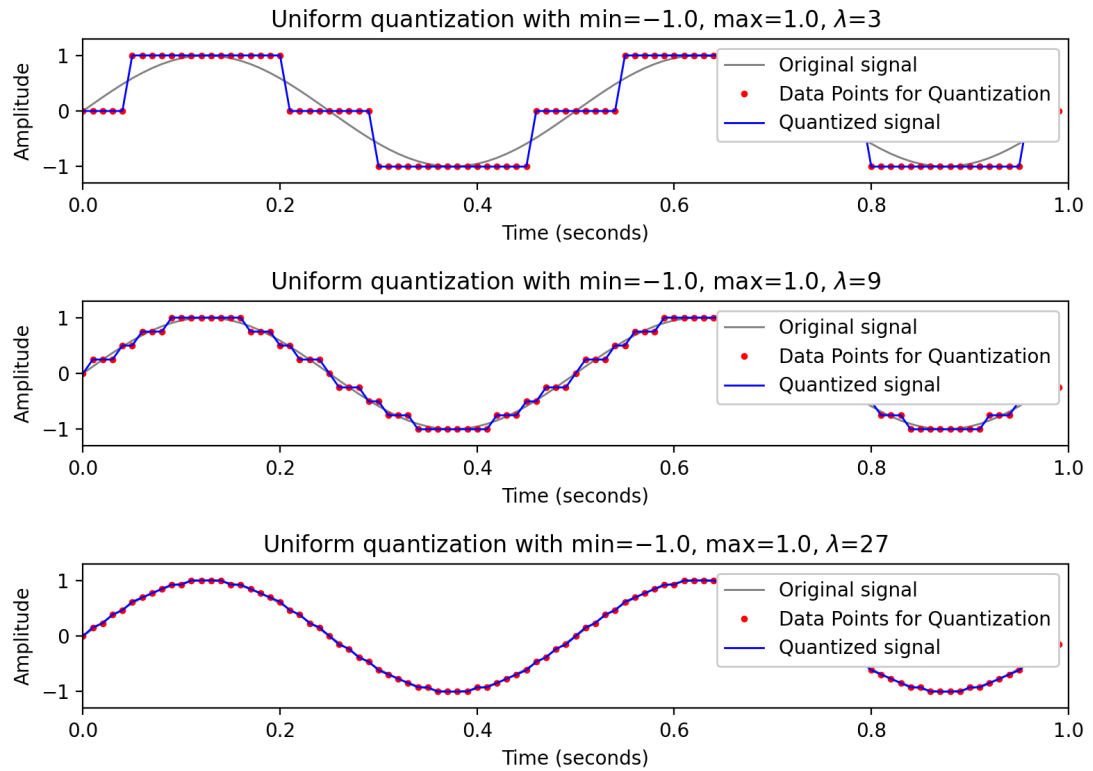


Figure 1.4: Quantization structure for different quantization levels (libfmp)

Considering 1-bit depth can store two steps of amplitude, the total steps of a system can be described as the 2 to the power of the bit depth. In Figure 1.4, there are 3-step, 9-step, and 27-step quantization of a two Hz sinusoid. It can be claimed that these three values are in the range of 1 & 5 bit depth. In this sense, bit depth correlates with the amplitude resolution and is a significant determinant of the process in which the reconstruction of a sound occurs. The sample rate is also a determinant of the same process but in a different way. As mentioned in the previous paragraphs, the sample rate determines the frequency range capacity of the reconstruction or the

deconstruction of a sound. Fourier transform of the wavelet information is responsible for that range. Since the sound is stored as piece by piece or sample by sample, rather than applying continuous Fourier transform, discrete Fourier transform is the choice of function. It is described as the decomposition of time-amplitude information of the sound signal into the frequencies with the help of complex number calculations and monitoring this decomposition for a range of frequencies that is half the sampling rate. (Amiot, 2016).

1.2.2 Discrete Fourier transform and frequency domain

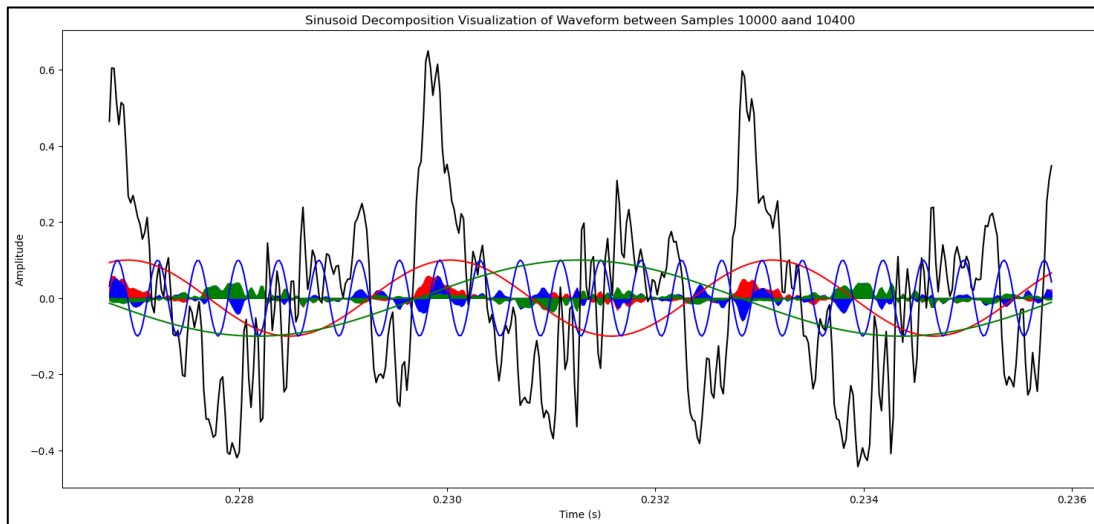


Figure 1.5: Waveform of same harpsichord recording consists of 400 samples and visualization of sinusoidal decomposition of the waveform for the fourier transform with 161.5, 323 & 2684 hertz periods (librosa)

In a very simplified perspective, DFT and IDFT are the transformation mechanisms between the time-amplitude information of a sound and time-frequency-amplitude information of the same sound. The transformation method calculates the maximum similarity between the waveform and a sinusoid wave with frequency, magnitude, and phase information. For example, frequency range of sampling rate 256 is 128. This means that highest possible frequency information can be stored is 128 hertz which represents a sinusoid wave oscillating 128 times in a second. With the sampling rate 256, one second can be divided into 256 parts and stored as 256 values. DFT divides one 256-part data into two 128-part data which consist of magnitude (128) and phase (128) information for each index that represent the frequency. This information is used to decompose or reconstruct the sound (Smith, 1999). As shown in Figure 1.5, for a given number of samples, the maximum similarity in the phase and magnitude information between the waveform of the original sound and three specific frequencies

in the frequency range of the sampling are intended. Extracting this information for each frequency in the range for a given number of samples establishes the fundamental mechanism of the DFT.

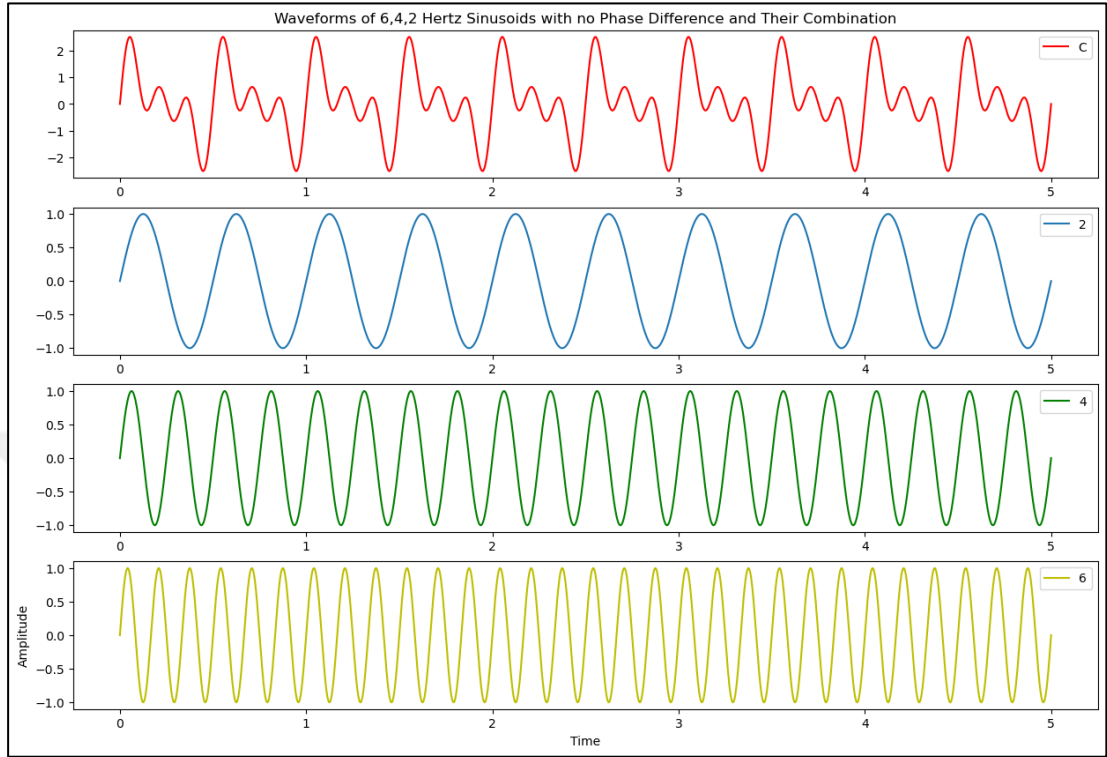


Figure 1.6: Waveforms of 6,4,2 hertz sinusoids with no phase difference and their combination (librosa)

The decomposition and construction of complex tones are exemplified in Figure 1.6. Three pure sine tones with no phase difference combined together, and a complex tone are established. Actually, this is an example of a very simple IDFT in that 3-dimensional phase-frequency-amplitude information over time is transformed into 1-time-amplitude information. A sinusoidal wave can be represented with the mathematical definition in which phase, angle, and magnitude reside, and complex waves can be fractalized into isolated sinusoid waves (Tohyama, 2018).

Consequently, this is the mechanism in which the computational analysis of music is held. For each aspect of the analysis, there are many components that can be transformed into each other such as the time domain attributes and frequency domain attributes. In this sense, the resolution of measuring these attributes from the physical properties of the sound is a significant factor for the essence of the analysis.

1.3 Musical Tones

The concept of a musical tone can refer to a wide range of sounds. But it can be simplified as a sound that creates a distinct pitch sensation. These tones can be either pure or complex. Complex tones have both harmonic and inharmonic structures within themselves. The harmonic complex tones are periodic and have a fundamental frequency. They are composed of sinusoids that have frequencies that are all whole number multiples of the fundamental frequency. In contrast, inharmonic complex tones have sinusoids that are not whole number multiples of any common fundamental frequency (Deutsch & Oxenham, 2013). This collection of sinusoids establishes the structure, which can be regarded as the spectrum of a sound from a physical point of view. The frequency of a tone can be described as the number of times per second the carrier vibrates and can be measured with Hertz (Jedrzejewski, 2006). In this sense, basic information to open a discourse about musical tones is first, a sound that has a harmonic character with a fundamental frequency. To advance on this concept, let's investigate spectrogram graphs that provide the necessary visualization.

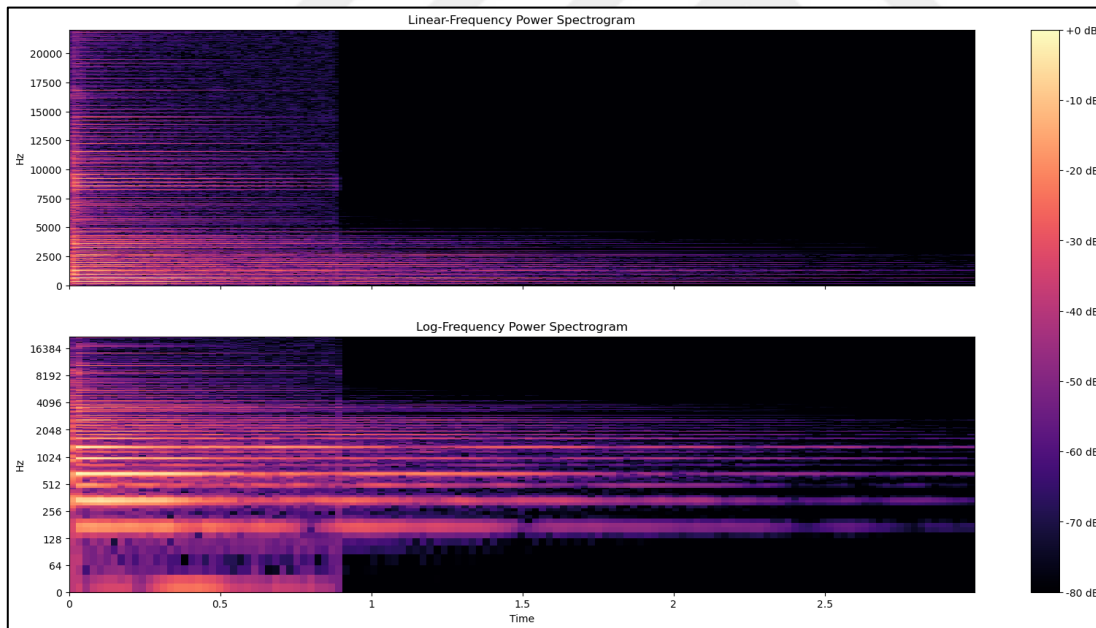


Figure 1.7: Linear and Logarithmic Frequency Spectrogram of a Harpsichord Note (librosa)

As shown in Figure 1.7, A single note of any instrument or sound source can be divided into a collection of sinusoids. These two frequency representations are derived from the recorded audio waveform by relevant Fourier transform of it. What Fourier transform does is to decompose the information recorded on the plain of a time-amplitude coordinate system into a frequency-amplitude plain. If the time axis is added

to the system in this sense, this frequency-amplitude representation becomes a spectrogram as a 3-dimensional data storage in which the amplitude is represented with a color bar, time is represented on x-axis and frequency is represented on y-axis (Müller, 2015). Figure 1-7 shows horizontal continuums on specific frequencies with higher amplitudes. Those represent the harmonic partials of a musical tone. For further analysis of tones and tone systems, let's visualize the concept of fundamental frequency and analyze it on the spectrogram.

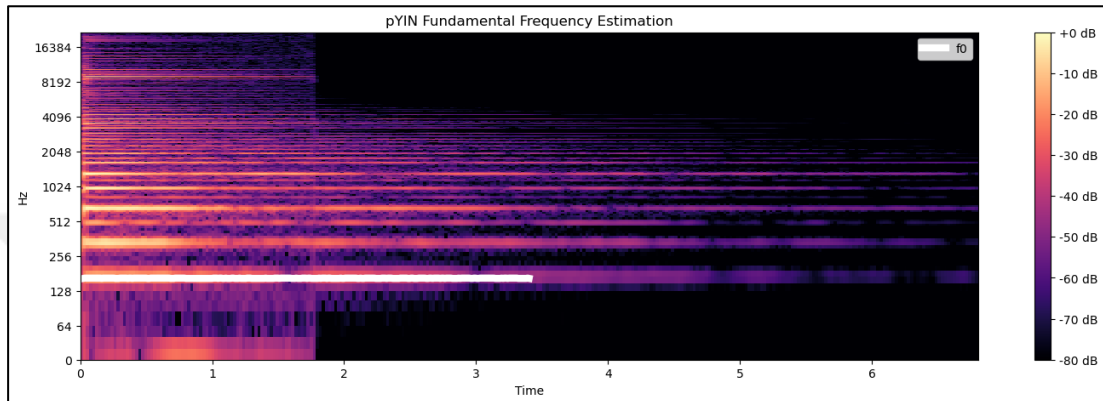
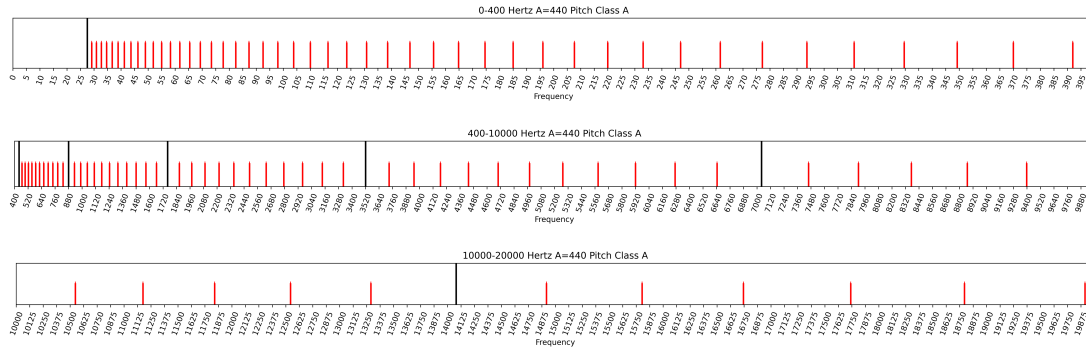


Figure 1.8: pYIN FFE function showing the fundamental frequency (f_0) of the harpsichord note with white line (librosa)

In Figure 1.8, the white line represents the fundamental frequency of the tone, which can be described as the first partial with the lowest frequency in terms of periodicity or the bottom edge of the superposition of the sinusoids (Benwards & Saker, 2004). The information that fundamental carries have a musical function in that it gives a location and an identity to a musical tone in a tone system. A tone system is a collection of individual tones which can be described as sounds with harmonic partial information. In this sense, the quality which is determined by this location and identity is a perceptual attribute of sound called pitch, and it is in relation to frequency information which is a physical attribute of sound. The fundamental frequencies of the tones in a tone system have distances between themselves in frequencies. These distances are called intervals, and they also carry pitch distances (Klapuri & Davy, 2006). In other words, intervals carry frequency ratio information which have a pitch information equivalent. On the other hand, pitch and frequency have a fundamental difference in growth besides their correlation. The distance and difference between two tones have a linear function and growth in pitch but a logarithmic function and growth in frequency (Doering, 2018). Furthermore, there is a kind of relationship between tone pairs whose corresponding fundamental frequencies are in the ratio of

powers of two. Human perception processes these tone pairs as in the same pitch class. In other words, they are different pitches, but the role and identity of the tone are the same in the system. This phenomenon is called “Octave Equivalence” (Randel, 2003).



In this sense, in Figure 1-9, the formula is used as $n = 12$, but there are other systems in which n is 5, 7, 10, 22, 31, 46, 53, and many more. But although all of the frequency ratios in the tone system are generated from the formula, there is a need to pinpoint where the first tone is located. In other words, the dual existence of sound attributes requires a passing point to transcend to each other. In order to connect the perceptual pitch attributes to physical frequency attributes, determining the reference frequency for the tone system is necessary. For the euro-genetic 12-tone systems, it is commonly used after the International Conference in 1939 that 440 Hertz at 20°C corresponds to the A4, but frequencies like 422.5, 423.3, 428, 435.4, 456.1 and many more had been used throughout the history of musical tone systems (Haluska, 2003).

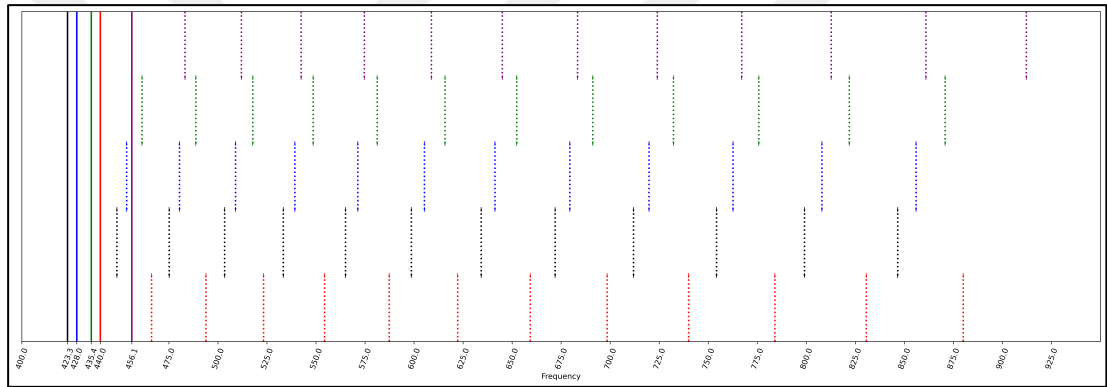


Figure 1.10: Reference frequencies 422.5(black), 428(blue), 435.4(green), 440(red), 456.1(purple) and their relative 12 Tone Equally Tempered Tone Systems

In Figure 1.10, the results of change in the reference frequency represented for the octave range starting with A4 to A5. This visualization shows that while having the same pitch information, the frequency information can vary according to the reference frequency.

1.4 Musical Timbres

Another perceptual attribute of the sound besides the pitch and loudness is timbre. One of the descriptions of the timbre is: “That attribute of auditory sensation which enables a listener to judge that two nonidentical sounds, similarly presented and having the same loudness and pitch, are dissimilar” (ANSI, 1994). Also, there are two aspects of the timbre that can be considered more complex information than pitch and loudness. Firstly, the structure of the information is multi-dimensional and consists of different

elements, so that it requires to be called with discrete categorizations with qualitative approaches such as bright, nasal, rich, and many more. Secondly, timbre is an element that is mostly used in sound recognition, identification as well as tracking of the changes in sound over time (Deauchs & McAdams, 2004). In this sense, the identity of the sound resides mostly within the timbre. But it is proper to remind that the identity of the fundamental frequency within the tone system is a different phenomenon that should not be confused with the timbre as the identity of the sound. Recent studies and the computational approaches try to compensate the discrete descriptions and categorizations of the timbre by transforming the discourse from a qualitative perspective to a more quantitative method. Rather than defining a complex sound with adjectives only, investigating the attributes of those adjectives corresponding to the spectrum and waveform of the recorded or synthesized sound became a focus. This approach has been developing rapidly with the computational aid to monitoring sound as well as the early forms of action is held theoretically or within the medium of analog recording and analysis techniques. The main methodology behind the effort again is trying to transcend the physical attributes of the sound to perceptual attributes of the sound or vice versa. In section 1.2, the concentration of such transcendence was the musical tones and the tone systems. Fundamental frequency was the main component of the inspection. But for the timbre analysis, the fundamental frequency is only a component of the subset containing harmonic partial information and equilibrium. For the timbre, there are inharmonic partials which can be considered as the rest of the frequency information except the harmonic partials. In order to demonstrate a such concept, two additional phenomena are necessary. The first one is the human hearing range since the object of analysis is the relation between the physical and perceptual attributes of the sound. This is bounded to human perception since the waveform is the continuum of the change in the amplitude with a micro time scale, it is decomposed to the frequencies, and the human hearing system cannot perceive all the frequency information in the physical reality.

The human hearing range is approximately between 20 hertz and 20000 hertz. But this range is not uniformly perceived in terms of loudness. Loudness is also a perceptual attribute of the sound, which is again confronted by its physical equivalent amplitude and power. The main difference between the two is very similar to frequency and pitch in that loudness is perceived with a function whose growth is logarithmic, compared

to the measurement of the power, which is linear (Brixen, 2020). This can be seen in figure 1.11.

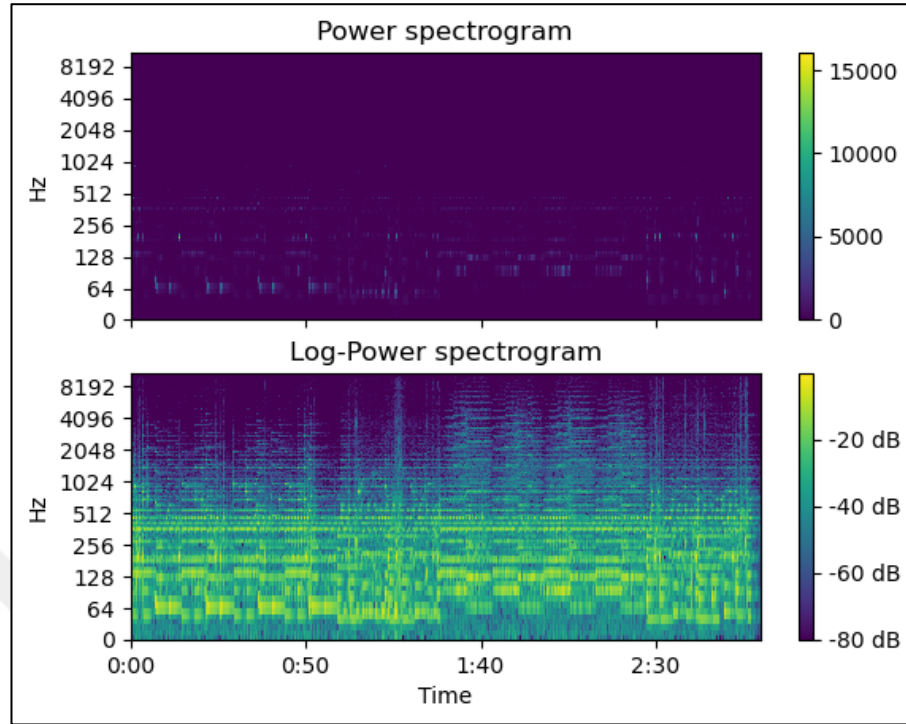


Figure 1.11: Power and Logarithmic Power(db) measurements for spectrogram analysis of piano (librosa)

To represent the logarithmic growth, Brixen (2020) uses the formula of the conversion between watts to decibels:

$$10 \cdot \log_{10} \frac{P_1}{P_2} \quad 1-3$$

This formula can be used to measure the difference in two values for sound power in watt and give the db equivalent. For example, the difference between the values $P_1 = 300$ and $P_2 = 150$ is 3db. But for the values $P_1 = 15.000$ and $P_2 = 30.000$, the result is the same, which is 3 db. This is an example of logarithmic growth.

Also, some of the frequency ranges are becoming audible at different SPL levels. This means that our ear is sensitive to some of the frequencies while others need to be louder to be perceived as the favored frequencies (Heffner & Heffner).

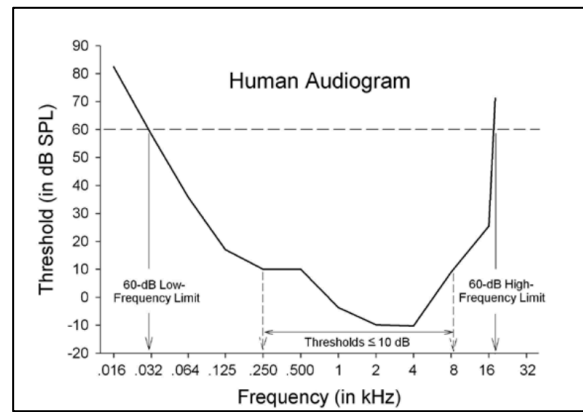


Figure 1.12: Adapted from Heffner, H. E., & Heffner, R. S. (n.d.). Hearing Ranges of Laboratory Animals. *Journal of the American Association for Laboratory Animal Science*.

In this sense, humans have a capacity for the sensation of sound. Also, some of the frequencies within the range of this capacity need to be louder to be sensed and figure 1.12 shows different frequency bands for such capacity. Perceiving the sound starts after the sensation; hence this was the first concept to progress on the timbre.

The second concept is, with the awareness of the human range, the components of the timbre. Since the frequency information between 20-20,000 hertz contributes to the waveform of the sound, all the energy and envelope within every single frequency affect the timbre. Some of them have more effect on the general perception of the timbre or, in other words, more weight to affect the outcome. But these are not only complexities of timbre because these individual frequencies also affect each other. This increases the number of dimensions of the complexity. But before investigating the structure of such complexity, let's analyze the terminal points of the timbre. If all the frequencies within the human hearing range (they have not to be in the range actually, due to the fact that all the information above or below the range would not be sensed by humans but would be physically present.) are produced with the same loudness, this can be considered as zero information and the maximum capacity of the timbre. Actually, this phenomenon is a kind of noise called white noise and represented in figure 1.13.

White noise is noise in which the frequency and power spectrum are constant and independent of frequency. The signal power for a constant bandwidth (centered at frequency f_0), does not change if f_0 is varied. Its name comes from a similarity to white light, which has equal quantities of all colors. (Mancini, 2003)

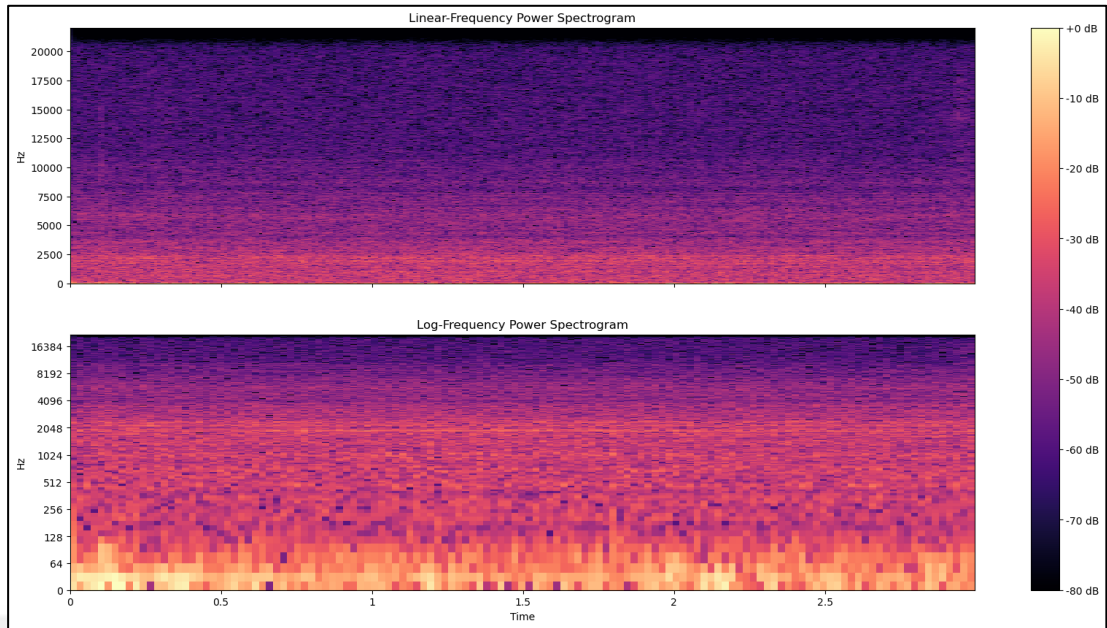


Figure 1.13:White Noise on logarithmic and linear spectrogram (librosa)

On the other edge of the limits in which, a timbre can consist of one frequency minimum. This phenomenon is a sinusoid wave that corresponds such a description. Sinusoid waves are significant components of this research as well as the whole computational musicology field because of the fact that digital signal processing and storage decomposes the information in an amplitude-time continuum to a variable number of frequencies which depends on the sample rate as well as on a concept called window size of the discrete Fourier transform. In this sense, sinusoid waves can be considered as building blocks of digital sound processing and figure 1.14 shows one.

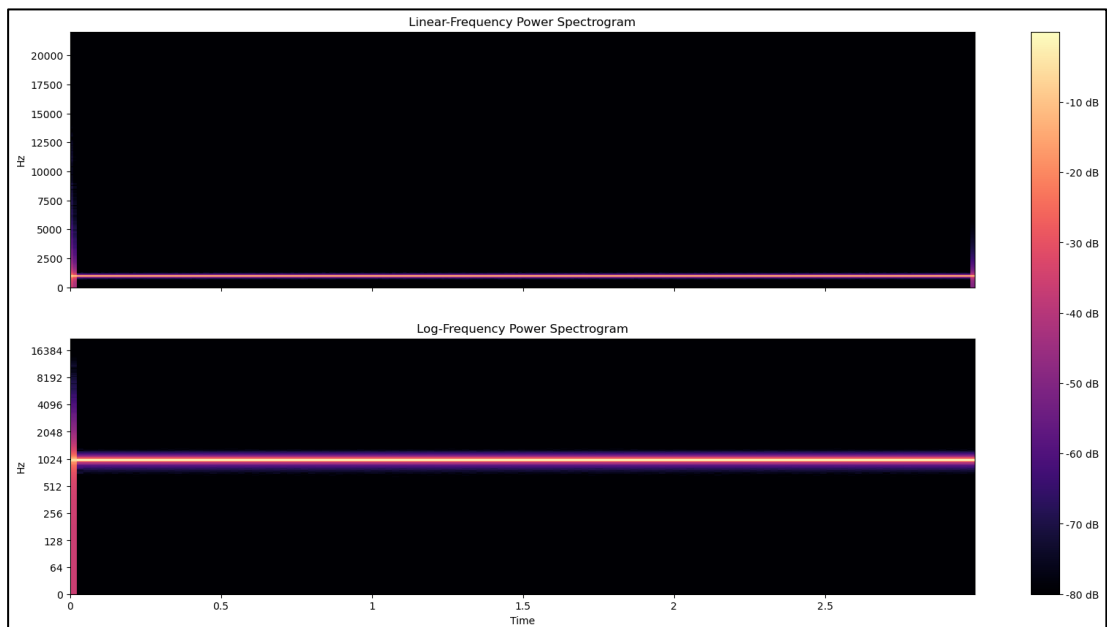


Figure 1.14: 1000 Hz sinusoid wave on both linear and logarithmic spectrogram

The range of information that can be sensed by the human hearing system is between the white noise and a single sinusoid wave in terms of structure and approximately 20-20000 hertz in terms of the frequency range.

Furthermore, there is another term called partial for sinusoid waves as the building blocks of sound or vibrations. If a sound consists of one partial, it is a simple tone or basically a sine wave. If it has more than one partial, it is a compound or complex tone (Helmholtz, 1889). The fundamental frequency is the main partial of a sound, while other partials are called harmonic and inharmonic partials of the sound. Harmonic partials are the integer or whole number multiples of the fundamental frequency as represented with marks in the figure 1.15, while inharmonic partials are a fractional numbers or float multiples of the fundamental frequencies. These are the first layer of a partial tree. Harmonic partials are divided into two categories: even harmonic partials and odd harmonic partials. Even harmonic partials are the even number multiples of the fundamental frequency, while odd harmonic partials are the odd multiples of the fundamental frequency.

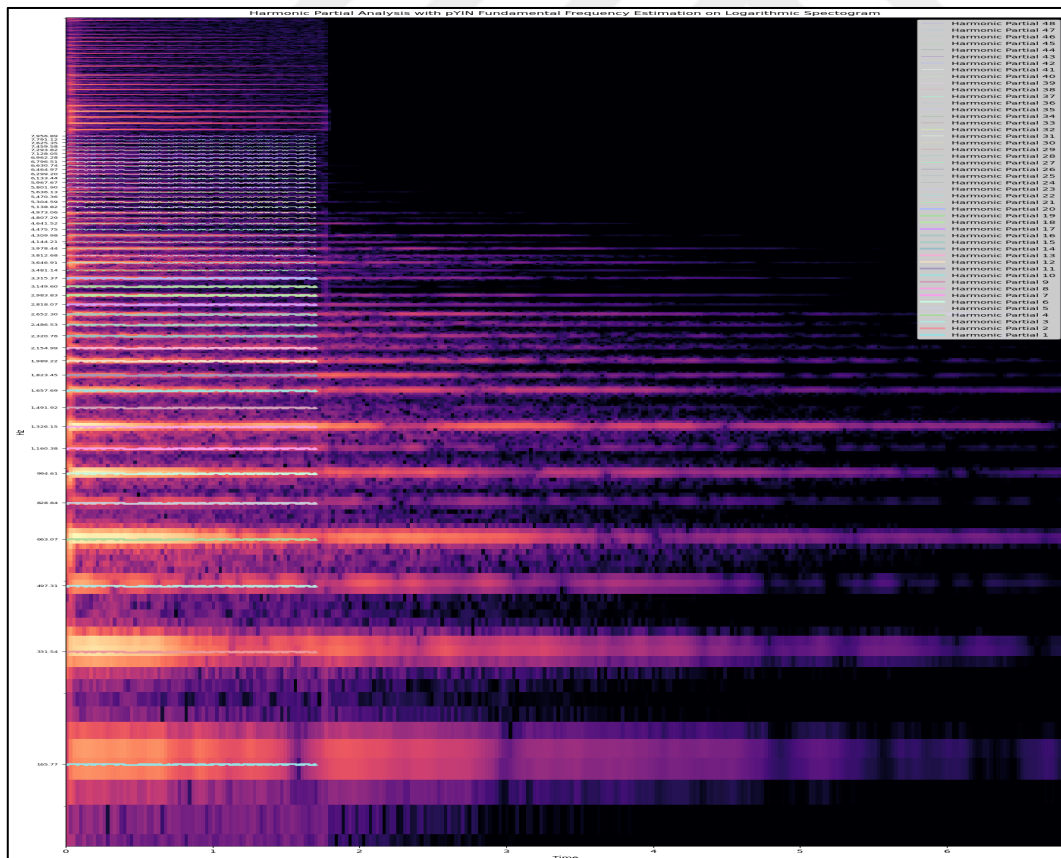


Figure 1.15: Harmonic partials of the harpsichord note on top of the pYIN fundamental frequency detection algorithm

In this research, further categorization of partials is investigated and used. This attempt aims to define the characteristics and effects of these further four partial types to the timbre of the sound on Helmholtz's definition. The components in this additional layer of categorization are used in the digital experimentation section of this research to gather more information about the nature of these partials in terms of similarities and, more significantly, in terms of differences. These are significant categorizations for the scope of this research.

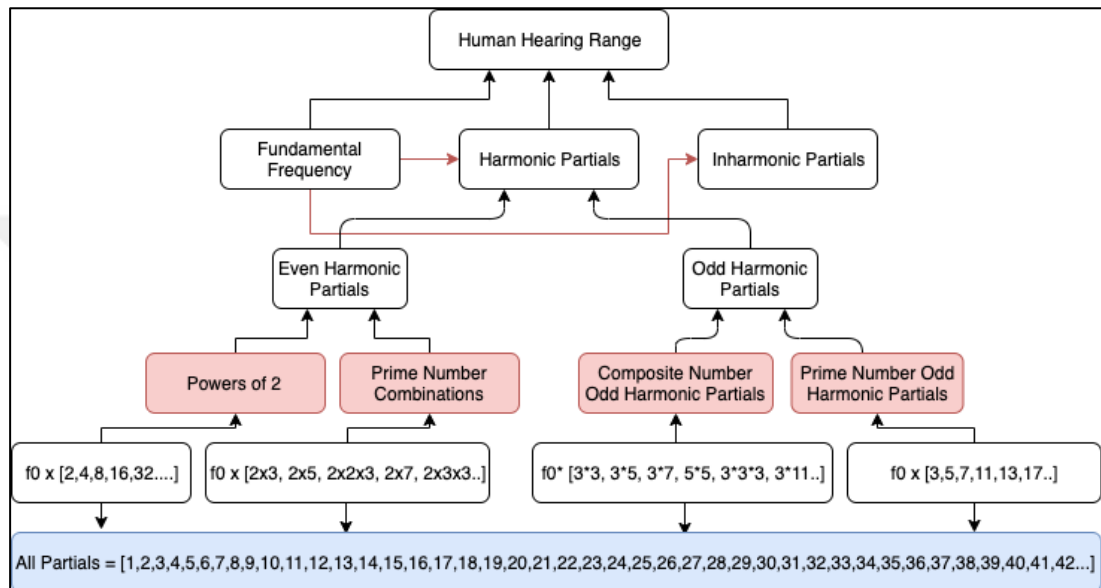


Figure 1.16: Further Partial Categorization on Helmholtz's Description

In Figure 1.16, red boxes represent this additional layer of categorization for the partial analysis. The information in these groupings can be considered as having musical contexts besides mathematical definitions. For example, partials, the powers of two, are the octaves of the fundamental frequency. Even prime number combinations include all n-limit just-intonation intervals, while odd harmonic partials do not carry any octave information within themselves. In this sense, since harmonic partials carry such musical information, they can be used for timbre analysis with a scope for the relation between physical and perceptual attributes of sound, furthermore, they can be used for the investigation of the relationship between pitch and timbre.

1.5 Concepts of Consonance and Dissonance: Sensory Dissonance

Previous chapters in the introduction were representing the parameters and concepts which are the subjects of the analysis for this research. In this section, concepts of consonance and dissonance are the focus which represents what these subjects, such as partials, intervals, and tone systems, are tested for. In this sense, consonance is a phenomenon that is searched in the relation between two sounds that can be either two individual partials or, in a more macro perspective, two chords in a chord progression in euro-genetic tradition. William Sethares (2004) investigates this concept on top of cumulative knowledge of previous studies in his work “*Tuning, Timbre, Spectrum and Scale*,” which also establishes the basis and fundamentals of the experimentation in this research. He investigates consonance by dividing it into categories in accordance with and on top of the cumulative research, which is expressed in the literature review section of this paper, held in the past. The first category is melodic consonance, measured for successive tones, while polyphonic consonance is for simultaneous tones. His third category is contrapuntal consonance which corresponds to the rules of counterpoint and voice leading techniques. On the other hand, functional consonance is measured for a single tone relation to the first tone of a tone system which can be considered as the root of the tone system. The final and most significant category for this research is psychoacoustic consonance or sensory dissonance, which traces the concept of harmonic beating, which is a measurable phenomenon occurring between two tones. Furthermore, he introduces three implications for this type of consonance. This phenomenon can occur between two separate sounds, it can be intrinsically existing within a single sound, and it is a continuum rather than an absolute property. The last implication is that it can measure how much consonant or dissonant a single sound or more rather than just labeling them consonant or dissonant as a binary decision.

1.5.1 Harmonic beating

The concept of harmonic beats can be traced to Hermann Helmholtz’s (1862) work “*On the Sensation of Tone*”. According to his approach, the interference of two tones on a medium creates a sensory effect which is called harmonic beating. After this work, many scholars have worked on this subject and extended it up to the computational approach. It can be described as a fluctuation of a tone with an envelope of a sinus wave whose frequency is the difference between the fundamentals of two separate

tones. This phenomenon results in a sensory effect which he claims that this is the beats occurring between two tones. The frequency difference is the determinant of this beating, like a carrier frequency.

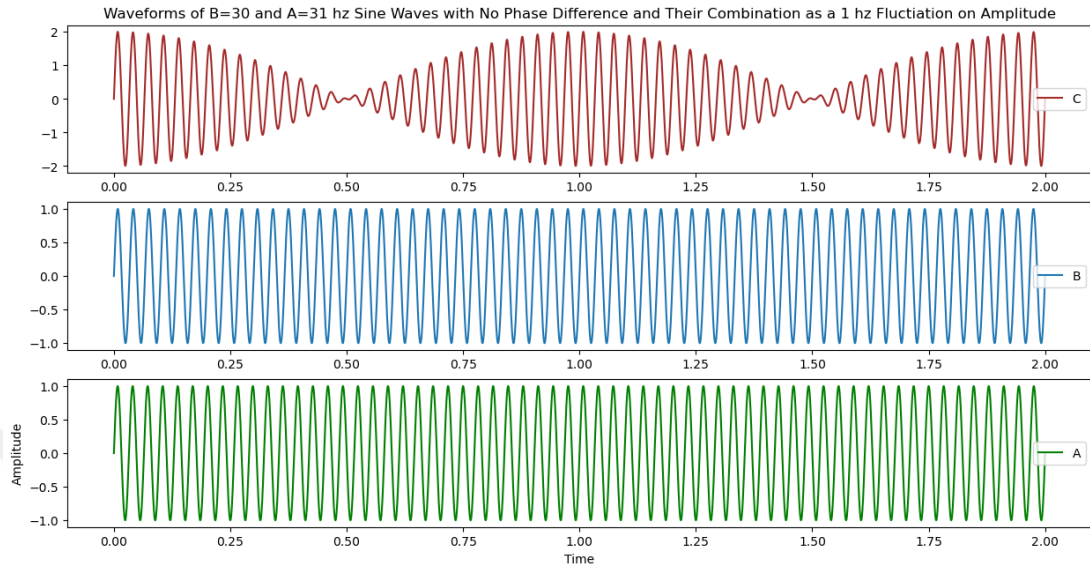


Figure 1.17: Harmonic beating visualization of two sine waves at the frequencies 30 and 31

In Figure 1.17, the frequency of the sine wave A is 31 Hz and B is 30 Hz. Their difference is one Hz which is the frequency of the beating. The reason for such an occurrence is that the phase cancellation of two waves. It can be visualized in Figure 1.18.

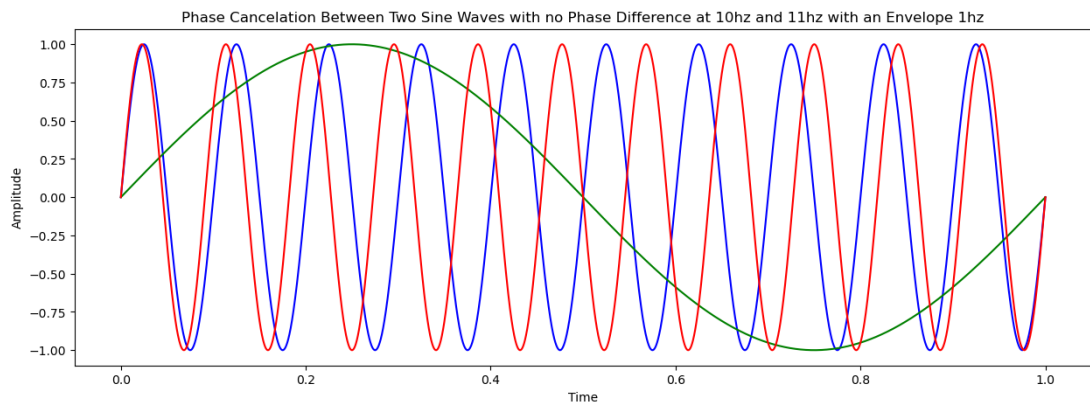


Figure 1.18: Phase cancellation envelope represented with green line as a 1 Hz sine wave which is the difference of 11 Hz and 10 Hz sine waves that are represented with blue and red lines

Actually, what is shown as the green line in the Figure 1.18 is the amplitude envelope of the combined signal. The slope of the green line shows us the increase and the decrease in the difference between the locations of two sine waves. It can be seen that red and blue curves are nearly aligned in the time 0, they slowly fall apart from each other until the time 0.5 and then they gradually come closer until the time 1.

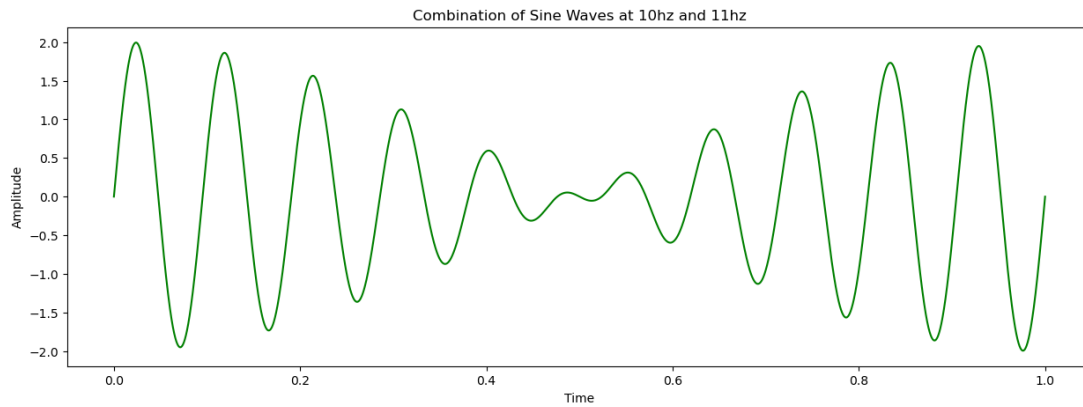


Figure 1.19: Combination of the two sine waves at 10hz and 11hz in Figure 1-18

The amplitude envelopes of the combined signal can be seen in Figure 1.19 that the phase cancellation starts gradually until the time equals to 0.5, reaches its maximum, and decreases until the time equals to 1.

1.5.2 Combination tones

Helmholtz (1867) argues that if the phenomenon of beating occurs for a bigger interval than the human hearing range, this combination tone can be heard. These combination tones are not occurring in every situation, but they should be in accordance with the other information of tones, such as amplitude and phase. Furthermore, if the combination tone has the frequency of the difference between two sine waves, he calls it a difference tone. He also introduces another type of combination tone in which the difference in frequency of two waves is not but the sum of them. He calls them summation tones. He claims that the difference tones are stronger than the summation tones and adds that only the tones with the highest amplitude in the equilibrium can produce these tones. Also, there is the discourse of partials in that chapter that every partial in a tone has some kind of relationship with each other in terms of beating and combinations of tones. Before explaining this relation, another example of harmonic beating can be considered. Let's assume three sine waves are played simultaneously.

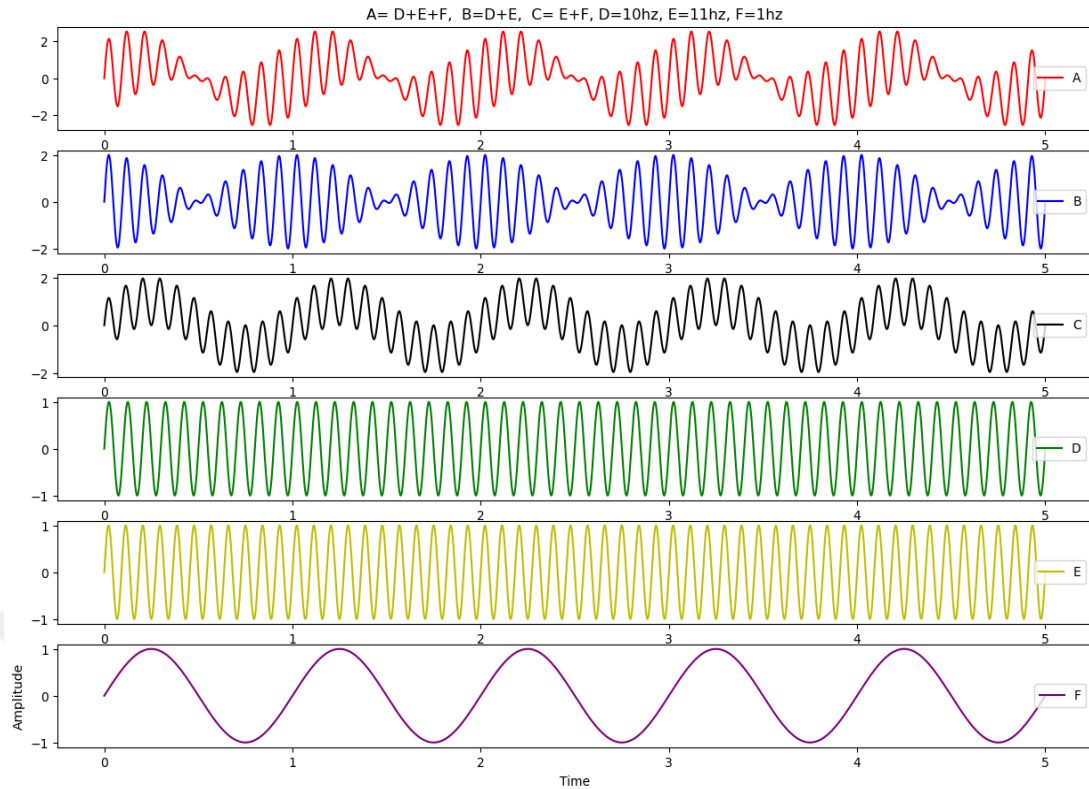


Figure 1.20: 10 Hz(D), 11 Hz(E) and 1 Hz(F) and their combinations as $A = D+E+F$, $B = D+E$, $C = E+F$

The combination in figure 1.20 is made in the python code which combines 10 Hz, 11 Hz and 1 Hz this time. Red wave (A) in the figure 1-20 is combination of 10, 11 and 1 Hz; Blue wave is of 10 and 11 Hz while black (C) is combination of 11 and 1 Hz. The reason for showing this visualization is that the situation in which there are more than two sine waves. In those configurations, combinations of three sine waves are affecting the general waveform.

1.5.3 Sensory dissonance

Sethares (2004) has formulized the equation which accepts the frequency ratios and amplitudes of 2 sine waves and outputs the amount of beating or in other words sensory dissonance. He uses the formulation and the data from the Plompt and Levelt's (1969) work. Previous chapter shows us the concept of beating but all the sine waves which are visualized in that chapter are with the amplitude one and largest difference tone was 10 Hz. Sethares's formula enables us to calculate every frequency within the resolution of the formula in an octave range and visualize this dataset with a graph called the sensory dissonance curve. Haluska (2003) also tries to establish

mathematical theorems over this phenomenon that defines this situation from a purely mathematical perspective.

1.5.4 Dissonance curve of two sine waves

A sensory dissonance curve is a graph visualization showing the amount of harmonic beating between two tones. The term sensory roughness is also used as an alternative to beating. Sethares (2004) and Haluska (2003) are using the equation of Plomt and Levelt (1967) and extended it for further investigation:

$$d(x) = e^{-b_1x} - e^{-b_2x} \quad 1-4$$

In this equation, x is the frequency difference between tones, while b_1 and b_2 represent the rise and fall of the function. They used this formula and gradient minimization of squared error between the averaged data and function $d(x)$; this gives the values $b_1=3.5$ and $b_2=5.75$. From this function, further formulation for two sine waves with different amplitudes goes like this:

$$d(f_1, f_2, a_1, a_2) = \min(a_1, a_2) \left[e^{-\frac{0.8(f_2-f_1)}{0.021f_2+19}} - e^{-\frac{1.38(f_2-f_1)}{0.021f_2+19}} \right] \quad 1-5$$

This formula gives the sensory difference amount of two sine tones. If this formula is used for frequencies in an octave by fixing one sine wave still and moving the other one up until the octave, it results in a data set of values. This dataset can be represented with a graph. In this paper, the sensory dissonance curves are generated with the python code, which is taken from Sethares's website directly or generated with the modifications made by the author of this paper by changing the code of the formulation or using it for new cumulative representations. It is a good example of the advantages of computational systems in musical analysis and the study of music theory. There are many nested or iterative structures on top of these formulas in the upcoming chapters. In this sense, computation provides the necessary precision for complexity. For example, the next chapter investigates the sensory dissonance curves of a timbre with n number of partials. This requires a calculation for each partial as well as the storage of this multi-dimensional data. But before increasing the complexity of the calculation, let's investigate a simple dissonance curve.

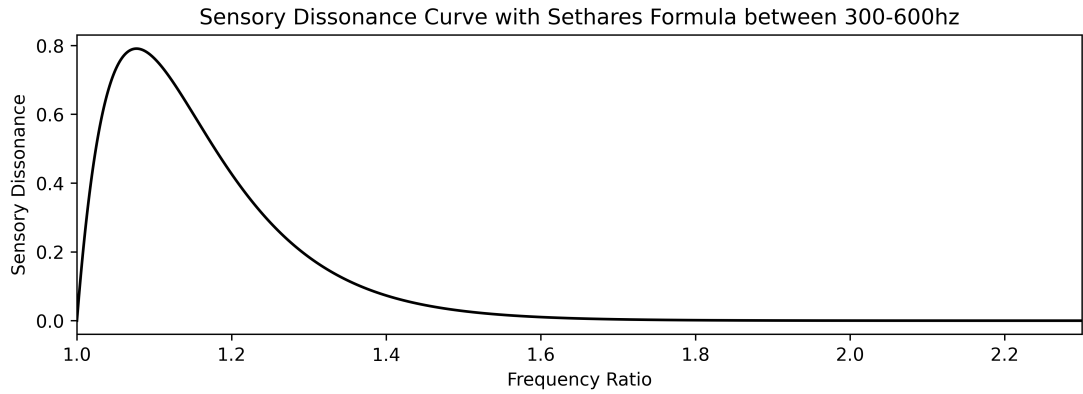


Figure 1.21: Sensory dissonance curve of 300-600 Hz frequency range for two sine waves

This graph is called a sensory dissonance curve. This curve can be considered as a representation of the harmonic beating amount in an octave range. It is significant to remind that this graph and data set change in accordance with the root and octave frequency due to the logarithmic nature of pitch perception. As can be seen in the Figure 1.21, the octave range in the example is 300 Hz. In this sense, if the root is moved to 20 Hz, the octave becomes 40 Hz, and the range is 20 Hz now. The nature of harmonic beating relies on the frequency information, not the pitch information. Hence the difference in the range, changes the graph and the data set.

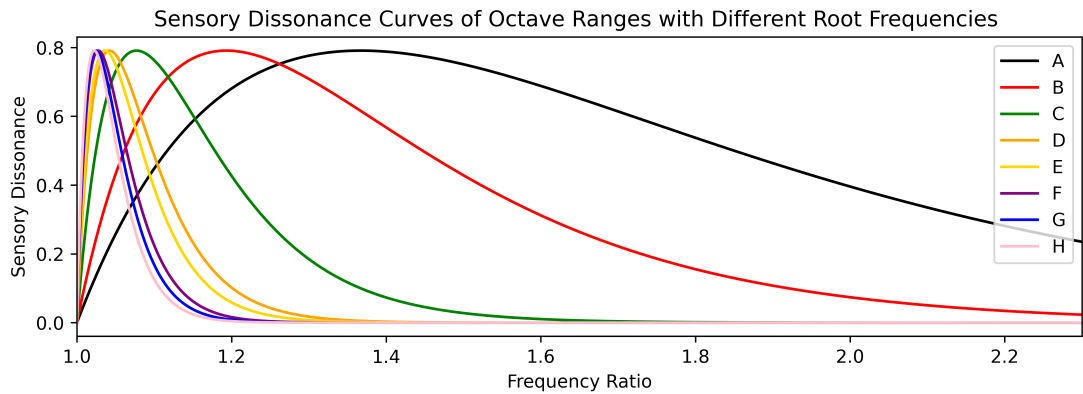


Figure 1.22: Sensory dissonance curves for A=50, B=100, C=300, D=750, E=1000, F=2000, G=3000, H= 5000 Hz

Figure 1.22 shows the difference between the sensory dissonance curves with different root frequencies and ranges. This information is significant for further investigation because the partials of a timbre have a broad range of octaves.

1.5.5 Dissonance curve of two complex tones with n-partial timbres

Given the information about the partials in the previous chapter, a complex tone is a set of partials that are in accordance with the fundamental frequency. Let's consider an artificial timbre with five partials. First partial is creating a harmonic beating with

2,3,4, and 5. Partial. If all combinations of the five partials are calculated and summed, this gives the sensory dissonance of a timbre just within itself while playing a note. Sethares (2004) and formulates this function as:

$$D_T = \frac{1}{2} \sum_{i=1}^n \sum_{j=1}^n d(f_i, f_j, a_i, a_j,) \quad 1-6$$

This equation contains all of the partial combinations, and sums their relative sensory dissonance values. If this function is applied to the frequencies in an octave range, the result is a data set like a single sine wave version. This data can be visualized again, and the results are n-Partial Timbre Sensory Dissonance Curves.

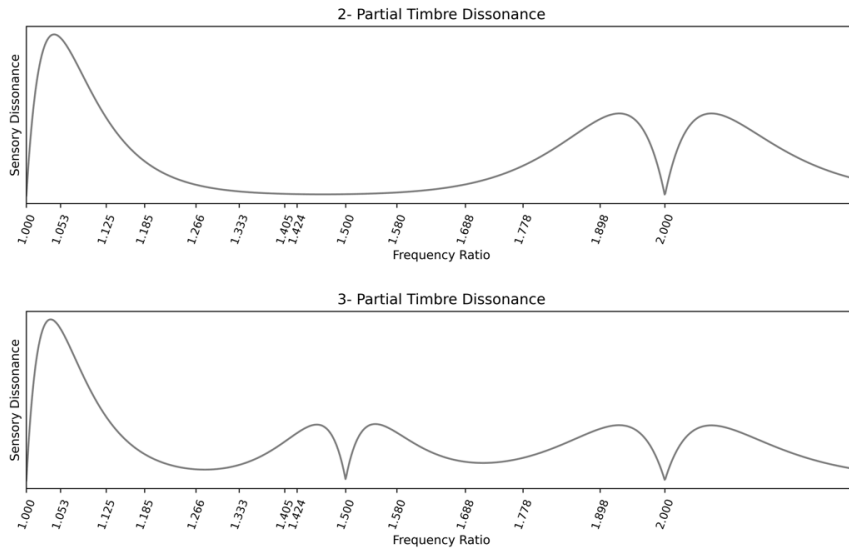


Figure 1.23: Two & Three Partial Timbre Dissonance Curves with all partial amplitudes set to 1
 Figures 1.23 and 1.24 show that when a partial is added to the artificial timbre with an amplitude value 1, there is a decrease in the beating on the frequency ratio, which is the equivalence of the partial's frequency ratio in the same octave. If the number of partials increases with amplitude 1, there are many new local minima points for the

curve.

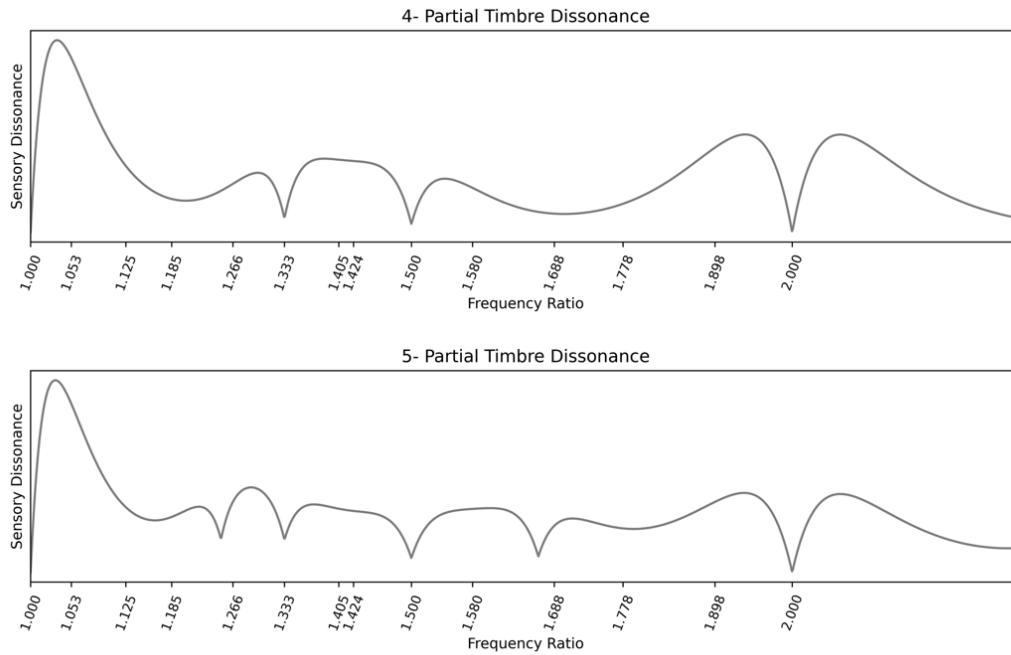


Figure 1.24: Four & Five Partial Timbre Dissonance Curves with all partial amplitudes set to 1

1.6 Extending the Amplitude Weight of Each Partial with the Envelope Weight

The formula for a tone's total sensory dissonance includes each tone's amplitude information. This indicates that each partial combination has a specific weight in accordance with the amplitude values, which determine how much does the combination effect the total dissonance. The amplitude values are between 1 and 0. Lower partials starting with the fundamental, have higher amplitude values than the higher ones. The code Sethares provided on his website has two methods to calculate this weight. One is called “*min*” which means the minimum of the two amplitude values, and the second one is “*product*” which means the combination of two values. These two methods are efficient in investigating the theoretical aspects of sensory dissonance since they represent the true superposition of the sine waves. This provides a stable environment to measure and monitor the behavior of each partial. This indicates and accepts that each partial has the same lifetime. This means that the time in which each partial has energy or amplitude is above 0. But to extend the concept of sensory dissonance to sound synthesis, amplitude values should change in time, they should increase or decrease gradually. Secondly, each partial does not have the same lifetime, higher partials tend to exist shorter than the lower ones. Actually, this does

not stand for every sound source since the nature of different sound sources can result in various partial envelopes and lifetimes. One of the determinants of the timbre belongs to a tonal instrument. In this sense, one of determinants of the timbre can be considered as not only this superposition of partials but also the multi-dimensional nature of this superposition. The model to store this envelope and lifetime information is presented in the second chapter of this paper, as well as the experimentation with different partial distributions and their resulting sensory dissonance curves.

1.7 Sub-categories of Harmonic Partials & their Effect on Sensory Dissonance

Each harmonic partial is an integer multiple of the fundamental frequency, but as it is discussed in the previous sections the nature of partials differs with the quality of the multiplier number. Since there are four different sub-categories of harmonic partials, one of the categories can have a distinctive potential effect on the total sensory dissonance as well as their distribution on different octave ranges. They represent different qualities of the pitch for human perception since the various alterations a temperament of euro-genetic music tradition had been using this partial information to micro-tune the intervals of a scale. In a brief explanation, there is a model in the second chapter which includes different timbres consisting of sine wave partials that belong to these four different sub-categories of harmonic partials. The experimentation over these timbres is represented on the sensory dissonance curves, and they can potentially reflect additive synthesis methods since the experimentation of these different timbres can give different results on sensory dissonance curves.

1.8 Methodology

For the extension in the formalization of the sensory dissonance curves with the addition of envelope information and for the investigating the differences between different sub-sets of partial types in sensory dissonance curves, virtual tests were held in the Python programming environment which is established on the Visual Studio Code Interface. For particular tasks many extension libraries are used for Python in the environment. The list of used libraries is given in the table 1.1:

Name of the Library	Attributes
numpy	<i>Mathematical Functions</i>
scipy	<i>Optimization</i>
random	<i>Randomness Attributes</i>
turtle	<i>Coloring</i>
Matplotlib.pyplot	<i>Visualization</i>
librosa	<i>Music Information Retrieval</i>
libfmp	<i>Music Information Retrieval</i>

Table 1.1: Libraries used in this research for Python on Visual Studio Code

Also, there are some extensions which are used to extend the capabilities of the Visual Studio Code Interface for specific usages. Table 1.2 shows the extensions used for the VSC:

Name of the Extension	Attributes
Jupyter	<i>Live Coding and Cell Execution</i>
Path Auto Complete	<i>Document Path Extractor</i>
Prettier	<i>Code Formatter</i>

Table 1.2: Extensions used in this research for Visual Studio Code

All the data and further results are represented in the results chapter of this paper. The main flow and structure of the system are designed as virtual experimentation in a virtual environment. In this sense, the data which is tested; the system which determines what is tested, how it is tested and why it is tested; and the results which represent the system's outcome are explained in detail below. It is significant to remind that the reproducibility of the input/system/output structure is ensured. Accordingly, this test aims to be considered as a deterministic virtual experimentation. Another aspect of the experimentation is the focus and method of the research. As mentioned and explained in the first section of this research, quantifiable properties of sound are measurable and deterministic, but the perceptual ones cannot be explained with pure mathematical information. They require to be perceived by a human or preferably a

test group. Then, the statistical methods are used to measure the object of experimentation according to the number of perceivers. As a pure concept, sensory dissonance requires testing both physical and perceptual information. But the formulation of the sensory dissonance in which the affection amount of the ratio of two sound sources, whether it is a single sinusoid or a complex tone, is a quantified source of knowledge. Furthermore, the system can be traced to the decomposition of the tone into sinusoids, and the effect of the two sinusoids on the combination of them can be monitored on the waveform, which is a physical attribute of the sound. In this sense, this concept is tested with no sonification and pure quantity in this research.

The code is taken from William Sethares's website to calculate the sensory dissonance data and the visualization. Sethares mentions the GitHub user with the username "endolith" for the python translation of the code. Then, additions and modifications are made with modular design within the code for experimentation by the author of this paper. Although there are two virtual test designs, the testing structure remains the same for each test. The first one investigates the effects of the partial envelope information on sensory dissonance, while the second experimentation aims to find the effects of partial distribution, which is in accordance with the mathematical nature of the partials. The structure of them is established on a basis. There is input information which is explained in detail in the next chapter, this information is tested with the system, which is established mostly on Sethares's methodology but with modifications, and the results are stored as data and visualized.

1.9 Literature Review

The cumulative research and studies for the relationship between sound, music, and mathematical perspective go back to ancient scholars such as Pythagoras with *Musica Universalis*, Aristoxenus, with *Elementa Harmonica*, Ptolemy with *Harmonikon*, Gaudentius with *Introduction Harmonique*, Cleonides with *Harmonic Introduction* and many more. They established the foundation of the discourse and investigated concepts such as harmony, consonance, dissonance, concord, discord, symphony, intervals, and many more. This period is labeled as the pre-polyphonic era (Tenney, 1988). His work *A History of Consonance and Dissonance* enlightens the history of the discipline. Following the periodization of music's history, Tenney categorizes Consonance and Dissonance in a systematic way. As an abbreviation for

Consonance-Dissonance Concept, CDC is used in his work. CDC-1 stands for melodic consonance and the above-mentioned period, CDC-2 for the polyphonic era and mostly the medieval period with figures such as Hucbald with *Treatise de Harmonica* (10th century), Guido d'Arezzo with *Micrologus* and anonymous *Musica enchiriadis* (10th century). It is significant to mention that these works are mostly including the information of their precessors and progress cumulatively. CDC-3 is for counterpoint, and roughly renaissance period, there are works of Johannes de Garlandia with *De Mensurabili Musica* (1240) and may more music theorists such as Pietro Aaron, Zarlino, Jerome Cardan. CDC-4 was used to add functional harmony and was mostly named by the music theorist Jean-Philippe Ramau. His works concerned with such topic are *Treatise on Harmony Reduced to Its Natural Principles* (1722), *New theoretical music system* (1726), *Generation Harmonic, or Treatise on Theoretical and Practical Music* (1737) and *Demonstration of the Principle of Harmony* (1750). Last one is CDC-5 and it is mostly associated with the psychoacoustical elements of music and music theorist Hermann von Helmholtz and his work *On the Sensations of Tone* (1863). This is the work that introduced the concepts of beatings and changed the scope of the music theory with regard of sensory dissonance.

In the 20th century, the fundamental pillar which carried the discourse of sensory dissonance was the article by Plomp and Levelt (1965) named *Tonal Consonance and Critical Bandwidth*. This article and the proceedings connect the discourse of Helmholtz to the current research areas. It has significance for the field of sensory music theory because it developed the formula for calculating the beating as a function which can be visualized with the graphical representation. Furthermore, it emphasizes the relation of critical bandwidth in which the sensed tone resides with the sensory dissonance. Akio Kameoka and Mamoru Kuriyagawa (1969) wrote *Consonant Theory Part I: Consonance of Dyads* and *Consonance Theory Part II: Consonance of Complex Tones and Its Calculation Method* in nearly the same period. These demonstrate the distribution of the dissonance weights on the partials, which belong to a complex tone. Norman Cazden has two articles which were also written in the second half of the 20th century, they are *Sensory Theories of Musical Consonance* (1962) and *The Definition of Consonance and Dissonance* (1980). These are investigating the principles that establish consonance and dissonance from a more anthological perspective.

In the 21st century, William Sethares and his work *Tuning, Timbre, Spectrum and Scale* (2004) can be considered as a continuation of the previous works of sensory dissonance and creates an environment that is necessary for a discipline to function. He connects the tuning of a sound, source, timbre of a sound source, and the scale which is played with that sound source in a systematic way that results in a broad field of research for a new generation of music scholars, especially with the opportunities of digital analysis and generation methods. Jan Haluska is another contributor to the field whose work *The Mathematical Theory of Tone Systems* (2003) investigates tone systems across the world and analyzes them. He transforms this information into mathematical theorems and fuses them with past studies. This paper uses the formulation and system of these two works for sensory dissonance calculation and tone system calculation.

Current projects and research are using Sensory Dissonance as a practical tool for music and computational methods. *An Interactive Tool for Synthesis of Consonant Timbres based on Dissonance Models* (Silve & Faria & Bayeh, 2017) can be an example for such topic. *Dyad's Consonance and Dissonance: Combining the Compactness and Roughness Approaches* (Masina & Presti & Stanzial, 2022) is a current research that experiments over the optimization of the sensory dissonance curves in accordance with the compactness information of the sound with the roughness information of the sound. *Register Impacts Perceptual Consonance through Roughness and Sharpness* (Eerola & Lahdelma, 2021), is another work in which the Sensory Dissonance is investigated with computational tools. Keith Mashinter (2006) have also tested other models for the sensory dissonance curves in *Calculating Sensory Dissonance: Some Discrepancies Arising from the Models of Kameoka & Kuriyagawwa, and Hutchinson & Knopoff*. Computational Approaches have had a significant place in the last 20 years. They provided tools for complex analysis of sound, requiring multi-dimensional scaling and calculating complex tones and sound recordings consisting of samples. In this sense Lluís Trullà & Nicola Di Stefano and Alessandro Giuliani extend the discourse of computational approaches for musicological analysis in their work *Computational Approach to Musical Consonance and Dissonance* (2018). There is a subsection of Computational Musicology in which the audio descriptors are used as the training data for machine learning and deep learning applications for musical purposes. Timbre synthesis with such a system is

especially a popular research topic in which the complex analysis of sound is required. *A Comparison for of Deep Learning Methods for Timbre Analysis in Polyphonic Automatic Music Transcription* (2021) by Carlos Hernandez Olivan, Ignacio Zay Pinilla, Carlos Hernandez-Lopez, Jose R. Beltran and *Latent Timbre Synthesis* (2021) by Kıvanç Tatar & Daniel Bisig and Philippe Pasquier are examples of such systems and research.

1.10 Hypothesis

The concentration of this thesis is the effects of the harmonic partial information on the sensory dissonance of a sound source. Two main research questions are:

- 1) Does envelope information of the partials in a complex tone established from sine waves affect the total sensory dissonance of that sound?
- 2) Does the type of harmonic partial information affect the sensory dissonance of the sound?

Experiments were carried out so that possible responses to these questions could be found, as well as to establish and provide data for experiments that will take place in the future. The type of experiments can be considered as virtual data tests in which a particular data set is taken into a computer program and the program gives the intended measurement.

2. SENSORY DISSONANCE CURVES WITH ADSR ENVELOPE INFORMATION AND PARTIAL TYPE

2.1 Design of Test 1

2.1.1 Amplitude envelope weight information design

The model is designed to generate timbres consisting of sine waves for the experimentation of envelope addition. Sethares's model and the formula accept the amplitude value of each partial as the weight of the sine wave combination.

$$D_T = \frac{1}{2} \sum_{i=1}^n \sum_{j=1}^n d(f_i, f_j, a_i, a_j) \quad 2-1$$

And

$$d(f_1, f_2, a_1, a_2) = \min(a_1, a_2) \left[e^{-\frac{0.8(f_2-f_1)}{0.021f_2+19}} - e^{-\frac{1.38(f_2-f_1)}{0.021f_2+19}} \right] \quad 2-2$$

The variables a_1 , and a_2 represent the amplitude of each partial, and the model is designed to accept the minimum of the to as the weight. Sethares also included an alternative by Davide Verotta for weighting as the product of two rather than accepting minimum value, but it is irrelevant for this research since the aim is not to change the weighting type but the weighting variables. The offered formulation adds the envelope information to the amplitude information for partial weights for the total equation. In this sense, the formula is modified, and the result is:

$$\begin{aligned} d(f_1, f_2, \varepsilon_1, \varepsilon_2, a_1, a_2) \\ = \min(a_1, a_2) \varepsilon_{\min(a_1, a_2)} \left[e^{-\frac{0.8(f_2-f_1)}{0.021f_2+19}} - e^{-\frac{1.38(f_2-f_1)}{0.021f_2+19}} \right] \end{aligned} \quad 2-3$$

And

$$D_T = \frac{1}{2} \sum_{i=1}^n \sum_{j=1}^n d(f_i, f_j, \varepsilon_i, \varepsilon_j, a_i, a_j)$$

The model for ε is based on an ADSR envelope which is specified for further additive synthesis methods and applications. This information consists of an attack value, attack peak value, decay value, sustain level value, sustain value, and release value. These values establish the general envelope of a sound as well as the lifetime of a sound. Table 2.1 shows the details of these parameters.

Variable	Description	Minimum Value	Maximum Value
<i>Attack</i>	<i>The time from 0 amplitude to attack peak</i>	0.01	1
<i>Attack Peak</i>	<i>The peak difference over sustain level</i>	minApeak	0.2
<i>Decay</i>	<i>The time from attack peak to sustain level</i>	0.01	1
<i>Sustain Level</i>	<i>The amplitude point of sustain phase</i>	minSlev	0.8
<i>Sustain</i>	<i>The time from start of sustain to start of release</i>	0.01	1
<i>Release</i>	<i>The time from start of the release to 0 amplitude</i>	0.01	1

Table 2.1: Envelop variables and their minimum/maximum values

The numbers for maximum and minimum values are prepared for this research. *minApeak* and *minSlev* values are left as variables to be tested for different numbers. These values establish the envelope of a sound. If an envelope graph is visualized for a sound, these values determine the lifetime of a sound as well as the shape of the amplitude of the sound in time with changes. An example of envelope values is shown in table 2.2.

Attack	Attack Peak	Decay	Sustain Level	Sustain	Release
0.47	0.05	0.76	0.38	0.36	0.919

Table 2.2: An example set of ADSR parameters

With these numbers lifetime of the partial is the sum of attack, decay, sustain and release. 2.509 seconds is the total lifetime of this sound. But the amplitude over this time is not uniform since these values represent the changes in the amplitude over time. In order to visualize these values, the envelope graph of this sound can be considered as a way of representation. The amplitude of the sound changes over time, and as a result of this, there is the envelope of the sound.

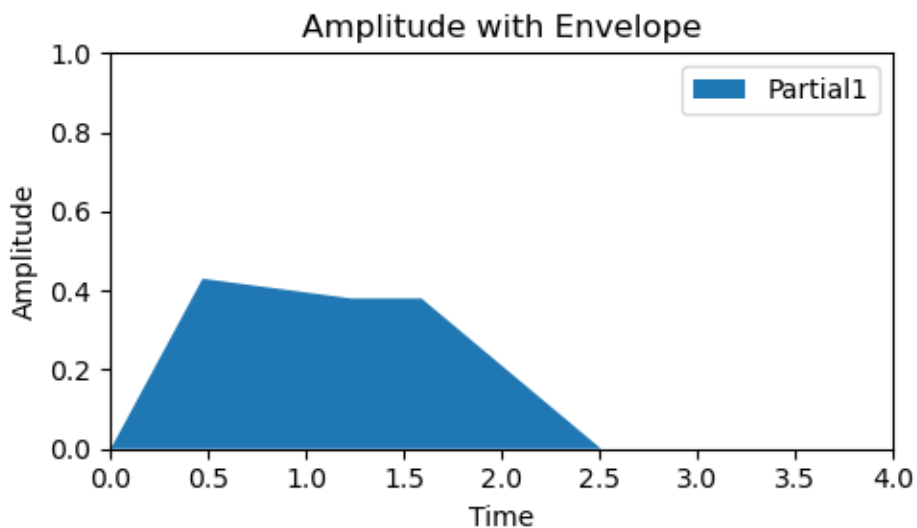


Figure 2.1: ADSR graph for the values in table 2.1.2

Figure 2.1 shows the envelope graph of the values in table 2.1. In order to visualize the usage of envelope information rather than a single amplitude value, let's visualize the same sound with the same lifetime but no change in amplitude which is set to 0.43, the sum of the attack peak value and the sustain level value.

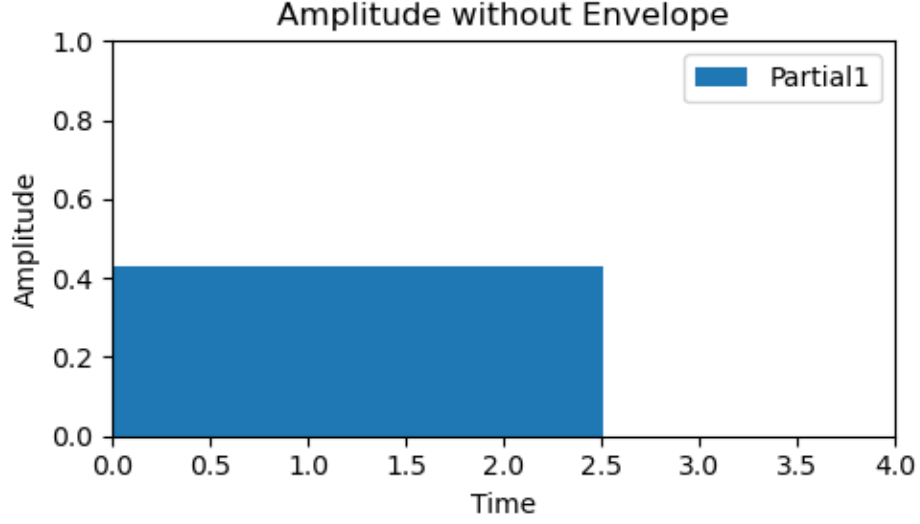


Figure 2.2: ADSR graph of the same sound in Figure 2-1 without envelope information

This difference has two possible explanations. Firstly, the area of the ADSR graph without the envelope information can return a weight value for the formula of sensory dissonance between sine waves. It is a multiplication of the lifetime of the partial, and the amplitude value gives the weight. In this sense, since there is no lifetime information in the original formula, it can be assumed that every partial has same lifetime, and it does not cause a difference between partials. Secondly, if the lifetime was one second in Figure 2.2, the area of the ADSR would be the amplitude value directly, the same as the weight itself. From this point of view, in order to calculate the weight of a partial envelope, the equation can be formed as:

$$\text{Envelope Weight} = \frac{\text{Area of ADSR Function with Envelope}}{\text{Area of ADSR Function without Envelope}} \quad 2-5$$

And

$$\varepsilon_{\omega} = \frac{\Delta \mathcal{E}}{\Delta A} \quad 2-6$$

This calculation gives the ratio of the enveloped amplitude to the amplitude without the envelope. If this ratio is multiplied by the amplitude value or alternatively the sum of the attack peak and sustain level values, it can be considered as a new weight in which the envelope information is represented. This can be seen as:

$$\varpi = \min(a_1, a_2) \varepsilon_{\min(a_1, a_2)}$$

2-7

Since the method for weight selection is a minimum of two for the partial combinations, the envelope which belongs to the minimum amplitude is also selected. This can be considered as an additional information to the amplitude weight, which can be useful for future additive synthesis methods since the musical designs include the envelope information of the partials, whether it is just a sine wave or a complex tone. This addition provides an efficient application of sensory dissonance monitoring to the additive synthesis techniques while keeping the superposition of partial amplitudes.

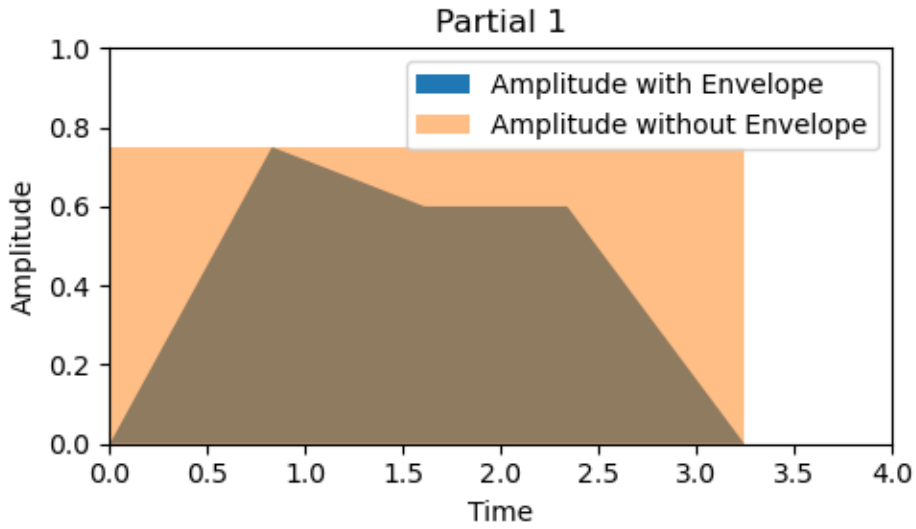


Figure 2.3: Amplitude envelope visualization of Partial 1

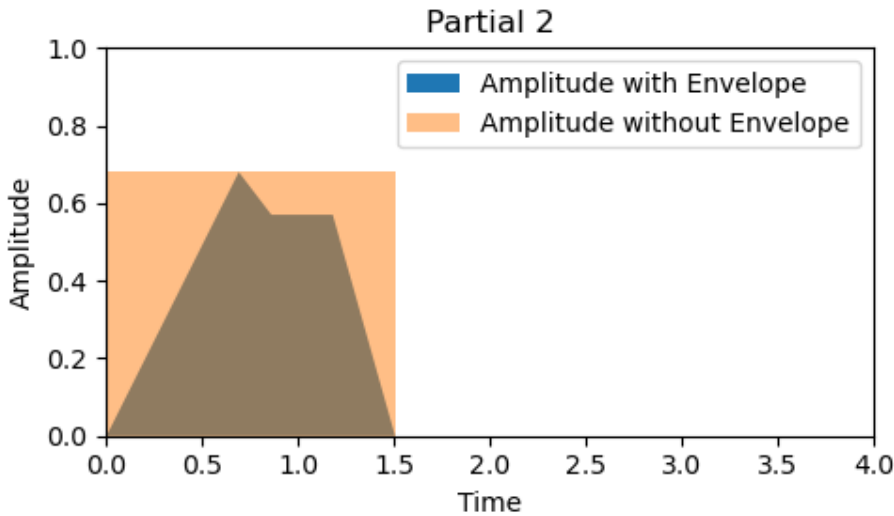


Figure 2.4: Amplitude visualization of Partial 2

The ratio which is added to the calculation of the partial combination weight can be seen in figures 2.3 and 2.4. The area of the enveloped amplitude is necessary to calculate the ratio between the enveloped and unenveloped amplitudes. This can be achieved with the envelope components that the time periods attack, decay, sustain and release can be calculated separately, and then they can be represented as one area value by summing them up. Upon this calculation, when this area value is divided by the area of the unenveloped amplitude area, the total equation can return the envelope weight. Consequently, if this envelope weight is multiplied by the unenveloped amplitude's constant amplitude value, this can return the total weight of the intended partial combination. The formulation for this concept is:

$$\varepsilon_{\omega} = \frac{\Delta \mathcal{E}}{\Delta A} ; A_{\omega} = \text{sustain level} + \text{attack peak} \quad 2-8$$

And

$$\varpi = \varepsilon_{\omega} * A_{\omega} \quad 2-9$$

Last components of the equation:

$$\Delta \mathcal{E} = \text{Attack Period} + \text{Decay Period} + \text{Sustain Period} + \text{Release Period}$$

$$\text{Attack Period} = (\text{Attack Peak} + \text{Sustain Level}) \times \left(\frac{\text{Attack}}{2} \right)$$

$$\text{Decay Period} = (\text{Decay} \times \text{Sustain Level}) + \left(\frac{\text{Decay} \times \text{Attack Peak}}{2} \right) \quad 2-10$$

$$\text{Sustain Period} = (\text{Sustain Level}) \times (\text{Sustain})$$

$$\text{Release Period} = \frac{\text{Release} \times \text{Sustain Level}}{2}$$

And

$$\Delta A = (\text{Sustain Level} + \text{Attack Peak}) \times \text{Lifetime of Partial} \quad 2-11$$

$$\text{Lifetime of Partial} = \text{Attack} + \text{Decay} + \text{Sustain} + \text{Release}$$

This modification is used to compare the sensory dissonance curves of an n-partial complex tone, one of which includes envelope information and the other has not.

2.1.2 Timbre data generation and storage

In order to test the amplitude envelope weight addition to the sensory dissonance calculation and make this investigation meaningful to the additive synthesis techniques, a well-organized data structure is necessary. First, for calculating various combinations of parameters for the envelope information, the generator should be iterative, and the generation output should be storable with proper dimensionality. In this sense, the system should be able to generate six values with minimum and maximum limitations. Then these six values should be stored as a partial data within the timbres data.

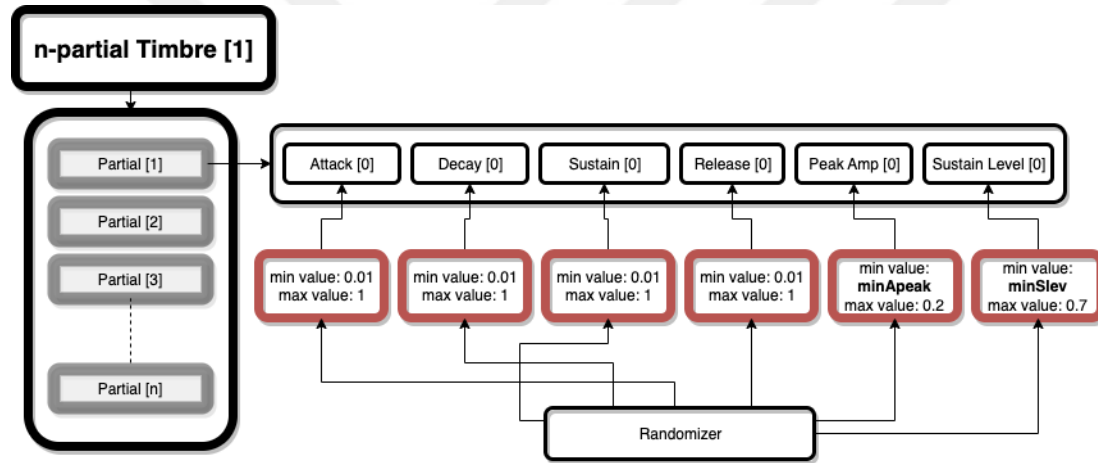


Figure 2.5: n-partial timbre generator and the data storage diagram

Figure 2.5 represents the generation and the storage of a timbre with n partials. As a function, this generation mechanism accepts three variables to be set. The first one is the number of partials, the second is the minimum value for the Amplitude Peak, whose abbreviation is *minApeak* in the figure and the last one is the sustain level which is represented as *minSlev*. This mechanism generates six values in accordance with partial number, minimum attack peak value, and minimum sustain level value. Then stores this as a partial and generates the next one until the last partial is generated and stored. The most significant value is the minimum sustain level because it is the control parameter for the test, and the expected change determinant for the dissonance curve calculation with the envelope information is this parameter.

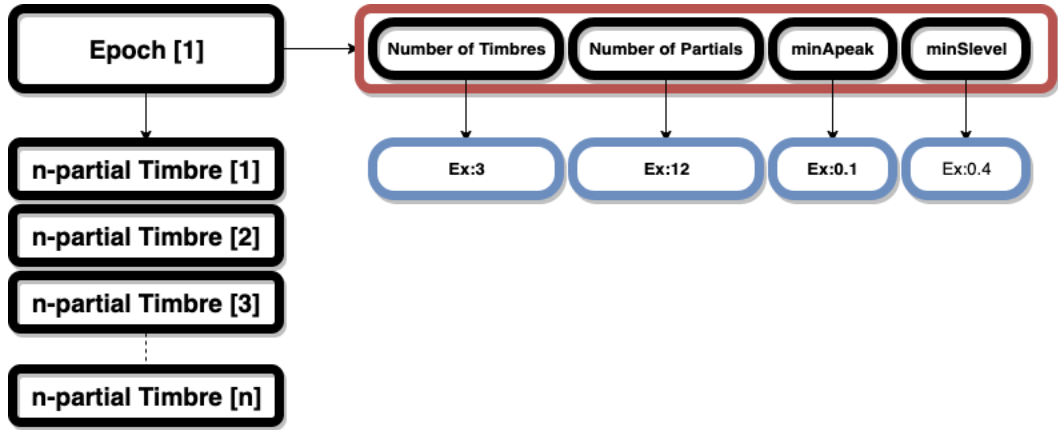


Figure 2.6: Timbre data set generator controlling the timbre generator

Figure 2.6 contains the structure of the epoch generator. One epoch has timbres as much as the indented parameter *Number of Timbres*. If that value is set 3, system generates three distinct timbres, which consist of the individual partials with the quantity of parameter *Number of Partials*. *MinApeak* and *MinSlev* determine the bottom limit for the attack peak and sustain level generations.

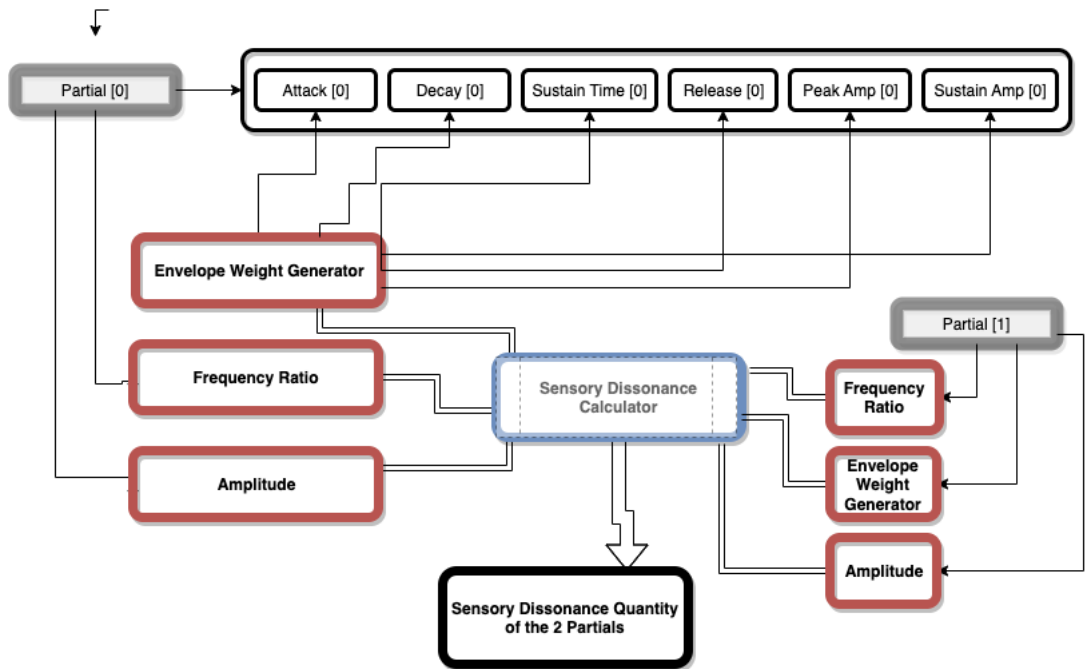


Figure 2.7: The calculation of the sensory dissonance of two partials whose data is taken from the epoch generation

Figure 2.7 shows that the function which calculates the sensory dissonance calls the necessary parameters of two partials, calculates envelope weight, combines it with amplitude values and frequency ratios values, and outputs the sensory dissonance amount of two partials.

```

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```

Figure 2.8: Data structure for generation Epoch (3 timbres, 12 partials, 0.2 Attack Peak, 0.7 Sustain Level)

The storage of that is shown in Figure 2.8. One Epoch has three timbres which contain six parameters for twelve partials. This structure provides the capability of recalling partial information or timbre information. Hence the calculator function calls the data from this structure and calculates the sensory dissonance. The data can be accessed with a high level of accessibility that the attack value of the first partial in the timbre belonging to the first epoch can be called easily. This is an efficient capability to use the data after the analysis.

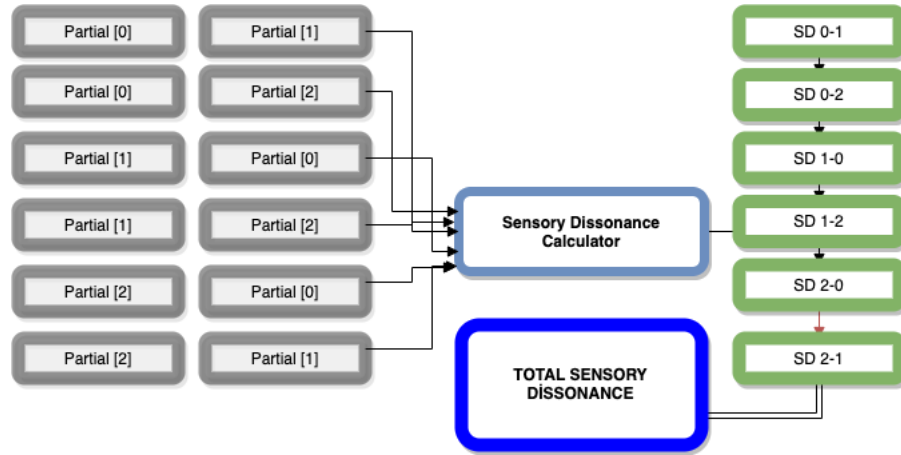


Figure 2.9: Calculation of total Sensory Dissonance for a Timbre

In the final phase of the system as shown in the figure 2.9, the total sensory dissonance value for the given timbre is calculated by the sum of each partial combination value divided by two. After this phase, data is ready to be visualized.

2.1.3 Data visualization and analysis

In order to test and control the effect of amplitude envelope on the sensory dissonance, firstly, there is a need to keep the original sensory dissonance curve and data. This curve should be the control data derived from the same number of partials, frequency ratios, and amplitudes as the test data as shown in figure 2.10. Test data is the sensory dissonance curves with the amplitude envelope weights. Comparing these in a single graph can be considered as a way of analysis.

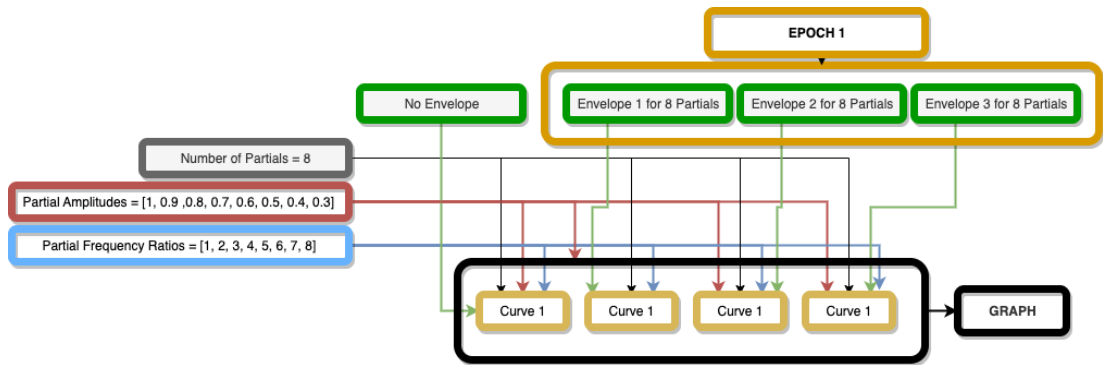


Figure 2.10: The structure of the test 1

2.2 Design of Test 2

2.2.1 Frequency ratio designs

Previous investigation and modification were focused on the amplitude plane of the sensory dissonance calculation with regard to each partial's envelope and amplitude information. The second design focuses on the frequency plane for experimentation. The normal distribution of the partials for the timbre analysis and sensory dissonance calculation is an n -partial ratio set:

$$n - \text{partial set} = [1, 2, 3, \dots, n]$$

This set contains all of the harmonic partials. But since the aim of this research is to investigate sensory dissonance for additive synthesis techniques, the distribution of the set can be divided in regard to the harmonic partial types. As mentioned in the first chapter of this paper, there are subsets of harmonic partials whose description prioritizes the numeric nature of the ratio.

Type	Description	Set
Even Harmonic Partial	Powers of 2	2, 4, 8, 16...
Even Harmonic Partial	Prime Number Combinations	6, 10, 12, 14...
Odd Harmonic Partial	Pure Prime Number Partial	3, 5, 7, 11...
Odd Harmonic Partial	Prime Number Combinations except 2	9, 15, 21, 25...

Table 2.3: Subsets of Harmonic Partial

In this sense, the model for comparison between these subsets for the sensory dissonance is including five-partial combinations in which the fundamental and four upper partials are represented as shown in the table 2.3. The rationale behind the test's design is to investigate a possible property that belongs to one of these subsets and can be used for further sound synthesis techniques. For the experimentation, amplitude of five partials set constant values for these four categories in order to focus on the nature of these subsets. Previous amplitude envelope modification to the experiment is also excluded from this test, since its concentration point was different from this investigation. Accordingly, the partial ratios are also set constant to five values for each category and these four groups of five-partial sets are tested for the sensory dissonance calculation and visualized with sensory dissonance curves.

2.2.1.1 First group

Test Group	Subset of Ratios
A	[1,2,4,8,16]
B	[1,6,10,12,14]
C	[1,3,5,7,11]
D	[1,9,15,21,25]

Table 2.4: Test layout for the partial ratio subsets

Figure 2.4 shows the layout of the partials is the main set of tested parameters. Since the objective of Test 2 is to find characteristics of different partials, the groups can be considered as both test and control data themselves. For further investigation of the concept, a second phase of the test is designed with regard of partial combinations. They are not the main focus of the experimentation, but they can be useful for further investigation of the relation between the interval ratios and partial numbers. These sets are shown in table 2.5.

2.2.1.2 Second group

Test Group	Subset of Ratios
4 Partial	[1,2,3,4],[1,2,4,5],[1,3,5,6],[1,5,6,7],[1,3,4,5],[1,2,5,6],[1,3,5,7],[1,2,4,6]
5 Partial	(1, 2, 3, 4, 5), (1, 2, 3, 4, 6), (1, 2, 3, 4, 7), (1, 2, 3, 5, 6), (1, 2, 3, 5, 7), (1, 2, 3, 6, 7), (1, 2, 4, 5, 6), (1, 2, 4, 5, 7), (1, 2, 4, 6, 7), (1, 2, 5, 6, 7), (1, 3, 4, 5, 6), (1, 3, 4, 5, 7), (1, 3, 4, 6, 7), (1, 3, 5, 6, 7), (1, 4, 5, 6, 7)
6 Partial	(1,2, 3, 4, 5, 6), (1,2, 3, 4, 5, 7), (1,2, 3, 4, 6,7), (1,2, 3, 5, 6, 7), (1,2, 4, 5, 6, 7), (1,3, 4, 5, 6, 7)

Table 2.5: Harmonic Partial Combinations for Test 3

Second group includes the frequency ratios which are the 4,5 and 6 partial subsets of the partial combinations. This selection of this group aims to find correlations between specific partials and accordingly use the findings for additive synthesis.

The purpose of this is experimentation and creating useful data for further analysis, hence the results can be unusual compared to the previous attempts of changing the partial distribution. Figure 2.11 shows the layout of the test 2.

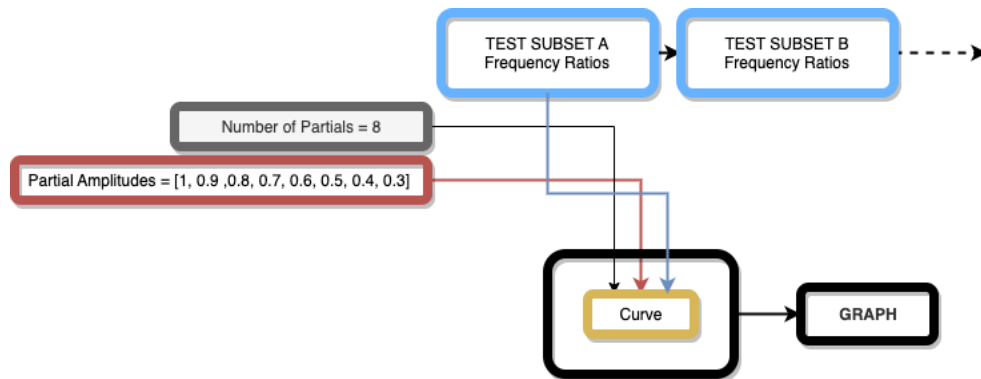


Figure 2.11: Layout of Test 2

3. TESTS AND RESULTS

3.1 Test 1

Test 1 has epochs that describes the tries in the tests, containing information for three different timbres generations. The data and graph below show the epochs and relevant information. Figures 3.1, 3.2, 3.3, 3.4, 3.5, 3.6 and 3.7 are the reports of each epoch.

3.1.1 Epoch1 report

```
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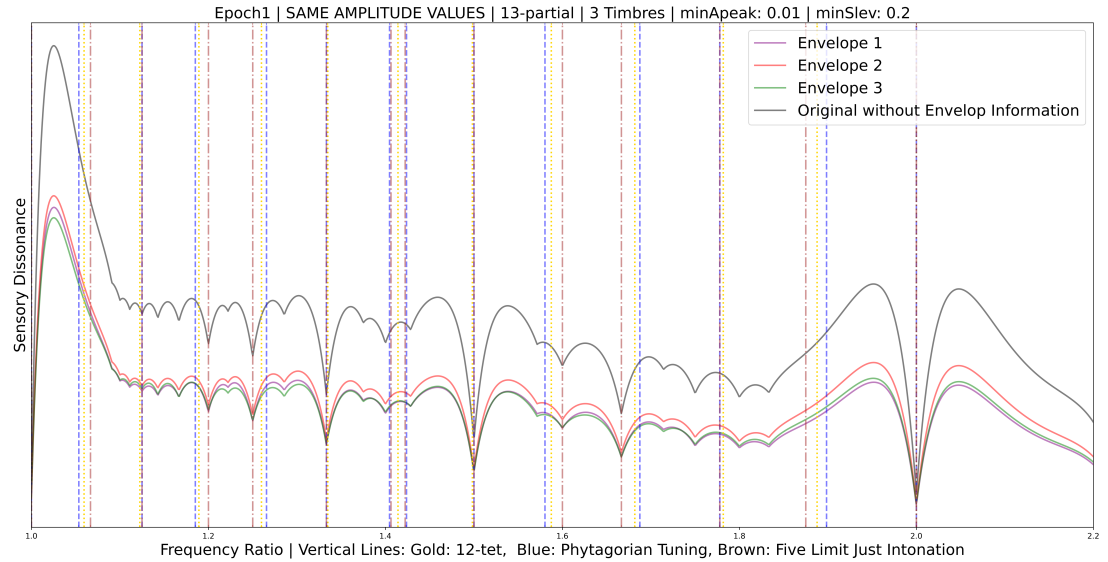


Figure 3.1: Epoch 1 Output Graph

3.1.2 Epoch2 report

```
[{'partial': 'partialNumber 1', 'Attack': 0.57, 'Decay': 0.54, 'Sustime': 0.47, 'Release': 0.17, 'Peak': 0.15, 'Sustain': 0.08, 'Ratio': 1}, {'partial': 'partialNumber 2', 'Attack': 0.88, 'Decay': 0.04, 'Sustime': 0.21, 'Release': 0.79, 'Peak': 0.16, 'Sustain': 0.46, 'Ratio': 2}, {'partial': 'partialNumber 3', 'Attack': 0.94, 'Decay': 0.45, 'Sustime': 0.14, 'Release': 0.38, 'Peak': 0.18, 'Sustain': 0.66, 'Ratio': 3}, {'partial': 'partialNumber 4', 'Attack': 0.97, 'Decay': 0.31, 'Sustime': 0.25, 'Release': 0.6, 'Peak': 0.14, 'Sustain': 0.4, 'Ratio': 4}, {'partial': 'partialNumber 5', 'Attack': 0.03, 'Decay': 0.95, 'Sustime': 0.76, 'Release': 0.24, 'Peak': 0.16, 'Sustain': 0.58, 'Ratio': 5}, {'partial': 'partialNumber 6', 'Attack': 0.81, 'Decay': 0.27, 'Sustime': 0.88, 'Release': 0.52, 'Peak': 0.16, 'Sustain': 0.63, 'Ratio': 6}, {'partial': 'partialNumber 7', 'Attack': 0.11, 'Decay': 0.76, 'Sustime': 0.5, 'Release': 0.05, 'Peak': 0.17, 'Sustain': 0.65, 'Ratio': 7}, {'partial': 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'Decay': 0.99, 'Sustime': 0.55, 'Release': 0.58, 'Peak': 0.19, 'Sustain': 0.33, 'Ratio': 9}, {'partial': 'partialNumber 10', 'Attack': 0.8, 'Decay': 0.9, 'Sustime': 0.01, 'Release': 0.69, 'Peak': 0.16, 'Sustain': 0.35, 'Ratio': 10}, {'partial': 'partialNumber 11', 'Attack': 0.3, 'Decay': 0.13, 'Sustime': 0.73, 'Release': 0.56, 'Peak': 0.17, 'Sustain': 0.69, 'Ratio': 11}, {'partial': 'partialNumber 12', 'Attack': 0.16, 'Decay': 0.45, 'Sustime': 0.03, 'Release': 0.35, 'Peak': 0.15, 'Sustain': 0.6, 'Ratio': 12}, {'partial': 'partialNumber 13', 'Attack': 0.2, 'Decay': 0.28, 'Sustime': 0.36, 'Release': 0.75, 'Peak': 0.18, 'Sustain': 0.15, 'Ratio': 13}], [{'partial': 'partialNumber 1', 'Attack': 0.33, 'Decay': 0.14, 'Sustime': 0.1, 'Release': 0.17, 'Peak': 0.18, 'Sustain': 0.57, 'Ratio': 1}, {'partial': 'partialNumber 2', 'Attack': 0.03, 'Decay': 0.02, 'Sustime': 0.37, 'Release': 0.92, 'Peak': 0.19, 'Sustain': 0.41, 'Ratio': 2}, {'partial': 'partialNumber 3', 'Attack': 0.02, 'Decay': 0.77, 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'Release': 0.51, 'Peak': 0.19, 'Sustain': 0.1, 'Ratio': 10}, {'partial': 'partialNumber 11', 'Attack': 0.27, 'Decay': 0.13, 'Sustime': 0.34, 'Release': 0.9, 'Peak': 0.13, 'Sustain': 0.05, 'Ratio': 11}, {'partial': 'partialNumber 12', 'Attack': 0.35, 'Decay': 0.56, 'Sustime': 0.75, 'Release': 0.58, 'Peak': 0.15, 'Sustain': 0.23, 'Ratio': 12}, {'partial': 'partialNumber 13', 'Attack': 0.93, 'Decay': 0.52, 'Sustime': 0.77, 'Release': 0.31, 'Peak': 0.17, 'Sustain': 0.35, 'Ratio': 13}]] [array([[0. , 0.57, 1.11, 1.58, 1.75]
```

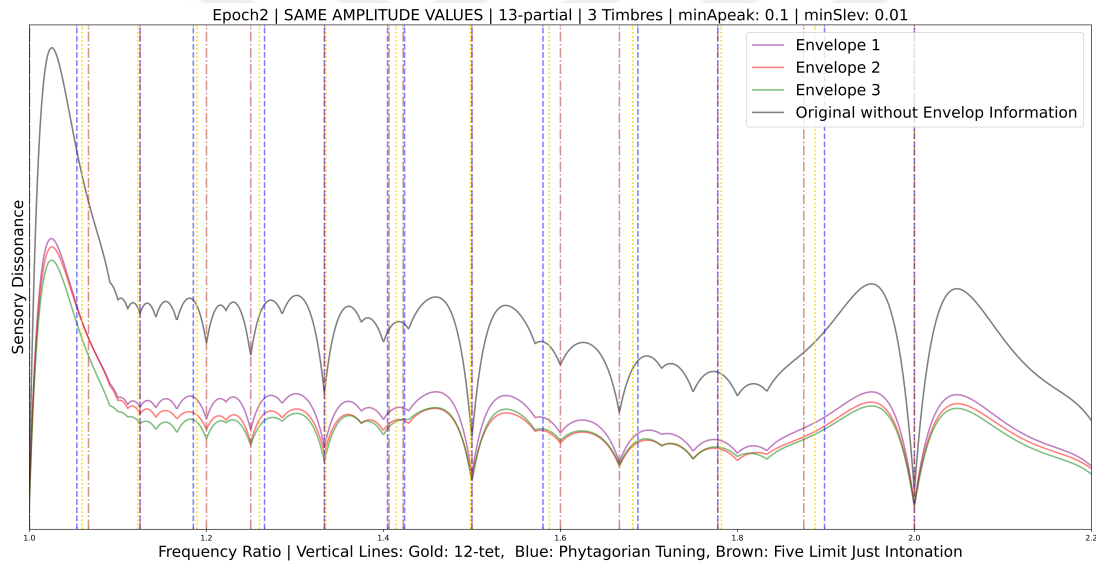


Figure 3.2: Epoch 2 Output Graph

3.1.3 Epoch3 report

```
[[{'partial': 'partialNumber 1', 'Attack': 0.62, 'Decay': 0.55, 'Sustime': 0.62, 'Release': 0.07, 'Peak': 0.2, 'Sustain': 0.66, 'Ratio': 1}, {'partial': 'partialNumber 2', 'Attack': 0.07, 'Decay': 0.15, 'Sustime': 0.96, 'Release': 0.11, 'Peak': 0.14, 'Sustain': 0.65, 'Ratio': 2}, {'partial': 'partialNumber 3', 'Attack': 0.21, 'Decay': 0.14, 'Sustime': 0.65, 'Release': 0.98, 'Peak': 0.12, 'Sustain': 0.61, 'Ratio': 3}, {'partial': 'partialNumber 4', 'Attack': 0.34, 'Decay': 0.88, 'Sustime': 0.69, 'Release': 0.35, 'Peak': 0.13, 'Sustain': 0.52, 'Ratio': 4}, {'partial': 'partialNumber 5', 'Attack': 0.14, 'Decay': 0.03, 'Sustime': 0.8, 'Release': 0.37, 'Peak': 0.19, 'Sustain': 0.5, 'Ratio': 5}, {'partial': 'partialNumber 6', 'Attack': 0.79, 'Decay': 0.08, 'Sustime': 0.02, 'Release': 0.5, 'Peak': 0.13, 'Sustain': 0.56, 'Ratio': 6}], [{'partial': 'partialNumber 1', 'Attack': 0.95, 'Decay': 0.12, 'Sustime': 0.36, 'Release': 0.68, 'Peak': 0.15, 'Sustain': 0.55, 'Ratio': 1}, {'partial': 'partialNumber 2', 'Attack': 0.05, 'Decay': 0.36, 'Sustime': 0.64, 'Release': 0.87, 'Peak': 0.13, 'Sustain': 0.62, 'Ratio': 2}, {'partial': 'partialNumber 3', 'Attack': 0.37, 'Decay': 0.96, 'Sustime': 0.62, 'Release': 0.89, 'Peak': 0.15, 'Sustain': 0.58, 'Ratio': 3}, {'partial': 'partialNumber 4', 'Attack': 0.84, 'Decay': 0.75, 'Sustime': 0.92, 'Release': 0.26, 'Peak': 0.18, 'Sustain': 0.62, 'Ratio': 4}, {'partial': 'partialNumber 5', 'Attack': 0.83, 'Decay': 0.35, 'Sustime': 0.85, 'Release': 0.99, 'Peak': 0.12, 'Sustain': 0.52, 'Ratio': 5}, {'partial': 'partialNumber 6', 'Attack': 0.7, 'Decay': 0.92, 'Sustime': 0.95, 'Release': 0.95, 'Peak': 0.13, 'Sustain': 0.57, 'Ratio': 6}], [{'partial': 'partialNumber 1', 'Attack': 0.83, 'Decay': 0.14, 'Sustime': 0.17, 'Release': 0.82, 'Peak': 0.12, 'Sustain': 0.63, 'Ratio': 1}, {'partial': 'partialNumber 2', 'Attack': 0.76, 'Decay': 0.85, 'Sustime': 0.48, 'Release': 0.73, 'Peak': 0.17, 'Sustain': 0.61, 'Ratio': 2}, {'partial': 'partialNumber 3', 'Attack': 0.54, 'Decay': 1.0, 'Sustime': 0.37, 'Release': 0.73, 'Peak': 0.12, 'Sustain': 0.61, 'Ratio': 3}, {'partial': 'partialNumber 4', 'Attack': 0.59, 'Decay': 0.07, 'Sustime': 0.06, 'Release': 0.32, 'Peak': 0.16, 'Sustain': 0.61, 'Ratio': 4}, {'partial': 'partialNumber 5', 'Attack': 0.02, 'Decay': 0.35, 'Sustime': 0.9, 'Release': 0.82, 'Peak': 0.18, 'Sustain': 0.63, 'Ratio': 5}, {'partial': 'partialNumber 6', 'Attack': 0.73, 'Decay': 0.48, 'Sustime': 0.33, 'Release': 0.33, 'Peak': 0.16, 'Sustain': 0.54, 'Ratio': 6}]]
```

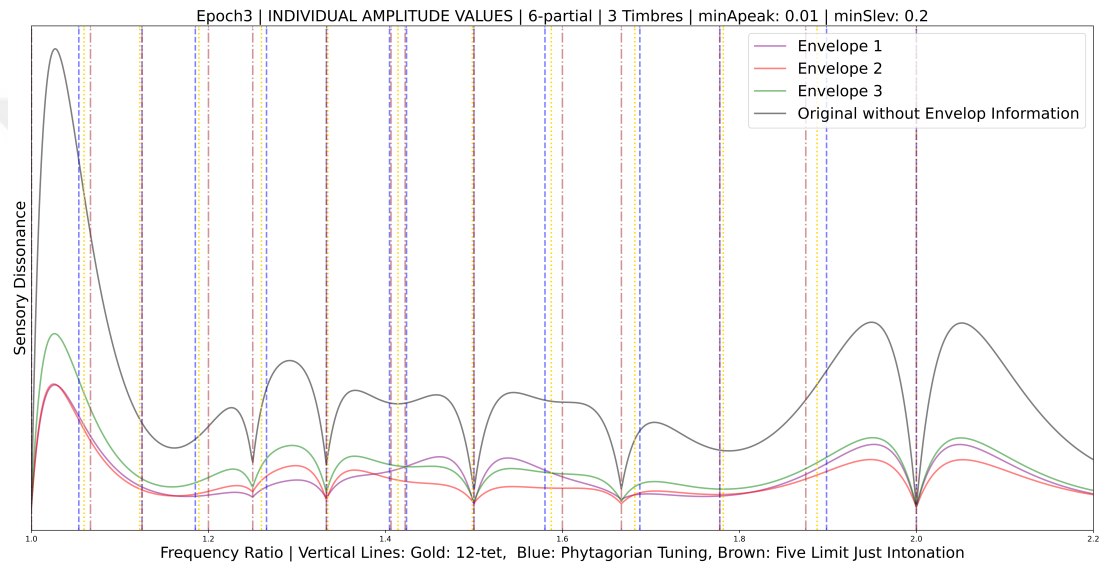


Figure 3.3: Epoch 3 Output Graph

3.1.4 Epoch4 report

```
[[{'partial': 'partialNumber 1', 'Attack': 0.56, 'Decay': 0.53, 'Sustime': 0.16, 'Release': 0.62, 'Peak': 0.14, 'Sustain': 0.55, 'Ratio': 1}, {'partial': 'partialNumber 2', 'Attack': 0.75, 'Decay': 0.56, 'Sustime': 0.36, 'Release': 0.24, 'Peak': 0.17, 'Sustain': 0.63, 'Ratio': 2}, {'partial': 'partialNumber 3', 'Attack': 0.76, 'Decay': 0.33, 'Sustime': 0.67, 'Release': 0.55, 'Peak': 0.19, 'Sustain': 0.49, 'Ratio': 3}, {'partial': 'partialNumber 4', 'Attack': 0.79, 'Decay': 0.64, 'Sustime': 0.88, 'Release': 0.95, 'Peak': 0.14, 'Sustain': 0.64, 'Ratio': 4}, {'partial': 'partialNumber 5', 'Attack': 0.97, 'Decay': 0.01, 'Sustime': 0.96, 'Release': 0.37, 'Peak': 0.16, 'Sustain': 0.51, 'Ratio': 5}, {'partial': 'partialNumber 6', 'Attack': 0.47, 'Decay': 0.1, 'Sustime': 0.83, 'Release': 0.55, 'Peak': 0.14, 'Sustain': 0.39, 'Ratio': 6}, {'partial': 'partialNumber 7', 'Attack': 0.38, 'Decay': 0.59, 'Sustime': 0.43, 'Release': 0.73, 'Peak': 0.15, 'Sustain': 0.66, 'Ratio': 7}, {'partial': 'partialNumber 8', 'Attack': 0.6, 'Decay': 0.03, 'Sustime': 0.45, 'Release': 0.23, 'Peak': 0.12, 'Sustain': 0.59, 'Ratio': 8}, {'partial': 'partialNumber 9', 'Attack': 0.22, 'Decay': 0.31, 'Sustime': 0.51, 'Release': 0.07, 'Peak': 0.18, 'Sustain': 0.62, 'Ratio': 9}, {'partial': 'partialNumber 10', 'Attack': 0.67, 'Decay': 0.49, 'Sustime': 0.02, 'Release': 0.2, 'Peak': 0.12, 'Sustain': 0.48, 'Ratio': 10}, {'partial': 'partialNumber 11', 'Attack': 0.02, 'Decay': 0.11, 'Sustime': 0.15, 'Release': 0.41, 'Peak': 0.15, 'Sustain': 0.66, 'Ratio': 11}], [{"partial": 'partialNumber 1', 'Attack': 0.1, 'Decay': 0.91, 'Sustime': 0.45, 'Release': 0.59, 'Peak': 0.15, 'Sustain': 0.64, 'Ratio': 1}, {'partial': 'partialNumber 2', 'Attack': 0.83, 'Decay': 0.76, 'Sustime': 0.08, 'Release': 0.16, 'Peak': 0.12, 'Sustain': 0.55, 'Ratio': 2}, {'partial': 'partialNumber 3', 'Attack': 0.27, 'Decay': 0.87, 'Sustime': 0.58, 'Release': 0.75, 'Peak': 0.12, 'Sustain': 0.63, 'Ratio': 3}, {'partial': 'partialNumber 4', 'Attack': 0.91, 'Decay': 0.94, 'Sustime': 0.95, 'Release': 0.44, 'Peak': 0.14, 'Sustain': 0.34, 'Ratio': 4}, {'partial': 'partialNumber 5', 'Attack': 0.1, 'Decay': 0.4, 'Sustime': 0.76, 'Release': 0.89, 'Peak': 0.16, 'Sustain': 0.61, 'Ratio': 5}, {'partial': 'partialNumber 6', 'Attack': 0.4, 'Decay': 0.17, 'Sustime': 0.9, 'Release': 0.43, 'Peak': 0.17, 'Sustain': 0.3, 'Ratio': 6}, {'partial': 'partialNumber 7', 'Attack': 0.65, 'Decay': 0.46, 'Sustime': 0.43, 'Release': 0.67, 'Peak': 0.18, 'Sustain': 0.44, 'Ratio': 7}, {'partial': 'partialNumber 8', 'Attack': 0.8, 'Decay': 0.3, 'Sustime': 0.35, 'Release': 0.44, 'Peak': 0.16, 'Sustain': 0.61, 'Ratio': 8}, {'partial': 'partialNumber 9', 'Attack': 0.44, 'Decay': 0.75, 'Sustime': 0.69, 'Release': 0.33, 'Peak': 0.17, 'Sustain': 0.65, 'Ratio': 9}, {'partial': 'partialNumber 10', 'Attack': 0.31, 'Decay': 0.93, 'Sustime': 0.44, 'Release': 0.73, 'Peak': 0.11, 'Sustain': 0.49, 'Ratio': 10}, {'partial': 'partialNumber 11', 'Attack': 0.71, 'Decay': 0.87, 'Sustime': 0.11, 'Release': 0.64, 'Peak': 0.12, 'Sustain': 0.32, 'Ratio': 11}], [{"partial": 'partialNumber 1', 'Attack': 0.89, 'Decay': 0.02, 'Sustime': 0.3, 'Release': 0.1, 'Peak': 0.14, 'Sustain': 0.52, 'Ratio': 1}, {'partial': 'partialNumber 2', 'Attack': 0.6, 'Decay': 0.17, 'Sustime': 0.31, 'Release': 0.14, 'Peak': 0.16, 'Sustain': 0.33, 'Ratio': 2}, {'partial': 'partialNumber 3', 'Attack': 0.22, 'Decay': 0.41, 'Sustime': 0.4, 'Release': 0.1, 'Peak': 0.1, 'Sustain': 0.55, 'Ratio': 3}, {'partial': 'partialNumber 4', 'Attack': 0.34, 'Decay': 0.27, 'Sustime': 0.79, 'Release': 0.4, 'Peak': 0.13, 'Sustain': 0.46, 'Ratio': 5}, {'partial': 'partialNumber 6', 'Attack': 0.28, 'Decay': 0.28, 'Sustime': 0.14, 'Release': 0.94, 'Peak': 0.17, 'Sustain': 0.55, 'Ratio': 6}, {'partial': 'partialNumber 7', 'Attack': 0.05, 'Decay': 0.02, 'Sustime': 0.73, 'Release': 0.41, 'Peak': 0.14, 'Sustain': 0.64, 'Ratio': 7}, {'partial': 'partialNumber 8', 'Attack': 0.33, 'Decay': 0.92, 'Sustime': 0.1, 'Release': 0.65, 'Peak': 0.19, 'Sustain': 0.31, 'Ratio': 8}, {'partial': 'partialNumber 9', 'Attack': 0.14, 'Decay': 0.17, 'Sustime': 0.02, 'Release': 0.66, 'Peak': 0.15, 'Sustain': 0.58, 'Ratio': 9}, {'partial': 'partialNumber 10', 'Attack': 0.68, 'Decay': 0.79, 'Sustime': 0.54, 'Release': 0.77, 'Peak': 0.16, 'Sustain': 0.64, 'Ratio': 10}, {'partial': 'partialNumber 11', 'Attack': 0.7, 'Decay': 0.16, 'Sustime': 0.77, 'Release': 0.82, 'Peak': 0.18, 'Sustain': 0.46, 'Ratio': 11}]]
```

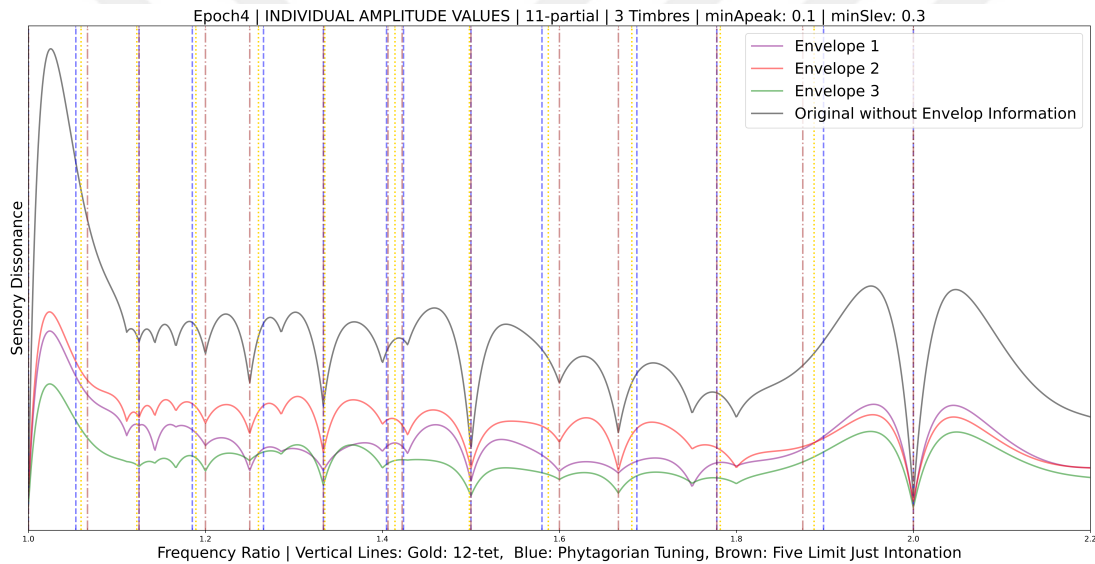


Figure 3.4: Epoch 4 Output Graph

3.1.5 Epoch5 report

```
[[{'partial': 'partialNumber 1', 'Attack': 0.63, 'Decay': 0.59, 'Sustain': 0.04, 'Release': 0.52, 'Peak': 0.1, 'Sustain': 0.42, 'Ratio': 1}, {'partial': 'partialNumber 2', 'Attack': 0.19, 'Decay': 0.13, 'Sustain': 0.79, 'Release': 0.45, 'Peak': 0.13, 'Sustain': 0.38, 'Ratio': 2}, {'partial': 'partialNumber 3', 'Attack': 0.21, 'Decay': 0.34, 'Sustain': 0.94, 'Release': 0.92, 'Peak': 0.2, 'Sustain': 0.49, 'Ratio': 3}, {'partial': 'partialNumber 4', 'Attack': 0.89, 'Decay': 0.12, 'Sustain': 0.42, 'Release': 0.71, 'Peak': 0.12, 'Sustain': 0.7, 'Ratio': 4}, {'partial': 'partialNumber 5', 'Attack': 0.29, 'Decay': 0.18, 'Sustain': 0.21, 'Release': 0.68, 'Peak': 0.16, 'Sustain': 0.32, 'Ratio': 5}, {'partial': 'partialNumber 6', 'Attack': 0.64, 'Decay': 0.64, 'Sustain': 0.96, 'Release': 0.59, 'Peak': 0.16, 'Sustain': 0.59, 'Ratio': 6}, {'partial': 'partialNumber 7', 'Attack': 0.99, 'Decay': 1.0, 'Sustain': 0.78, 'Release': 0.19, 'Peak': 0.07, 'Sustain': 0.5, 'Ratio': 7}, {'partial': 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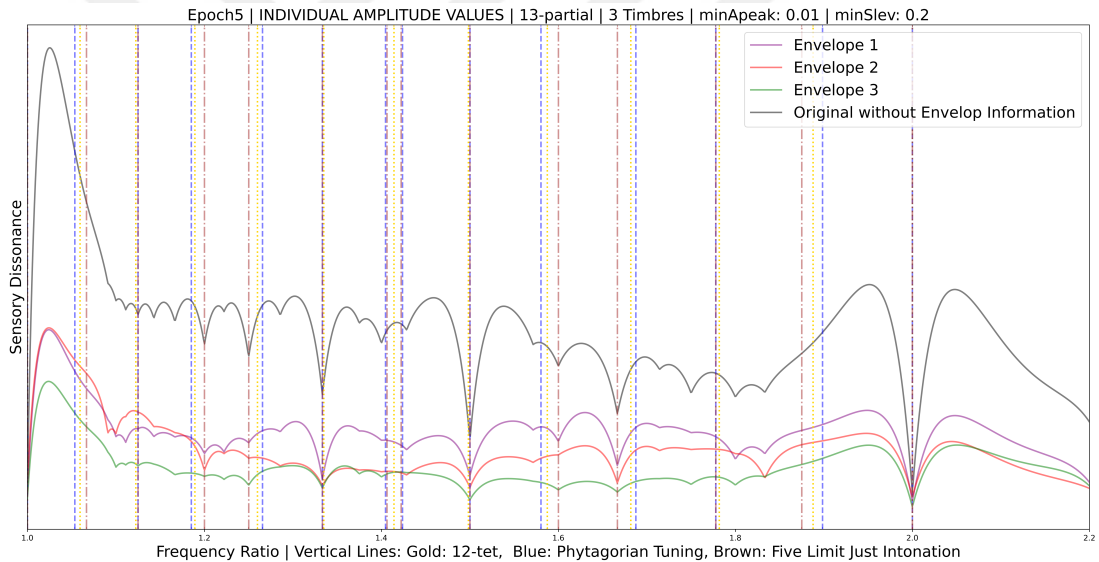


Figure 3.5: Epoch 5 Output Graph

3.1.6 Epoch6 report

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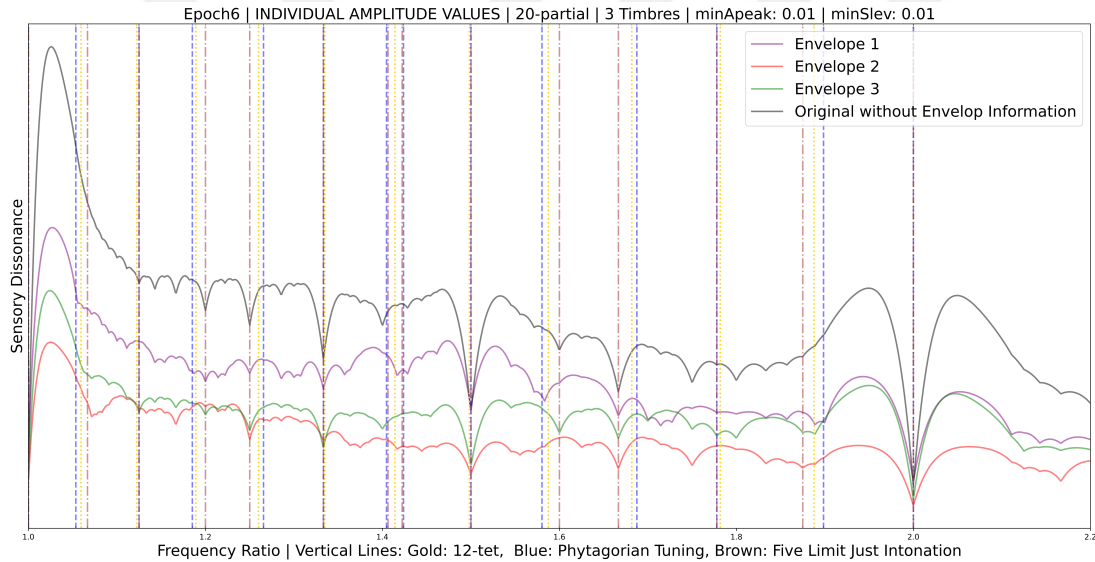


Figure 3.6: Epoch 6 Output Graph

3.1.7 Epoch7 report

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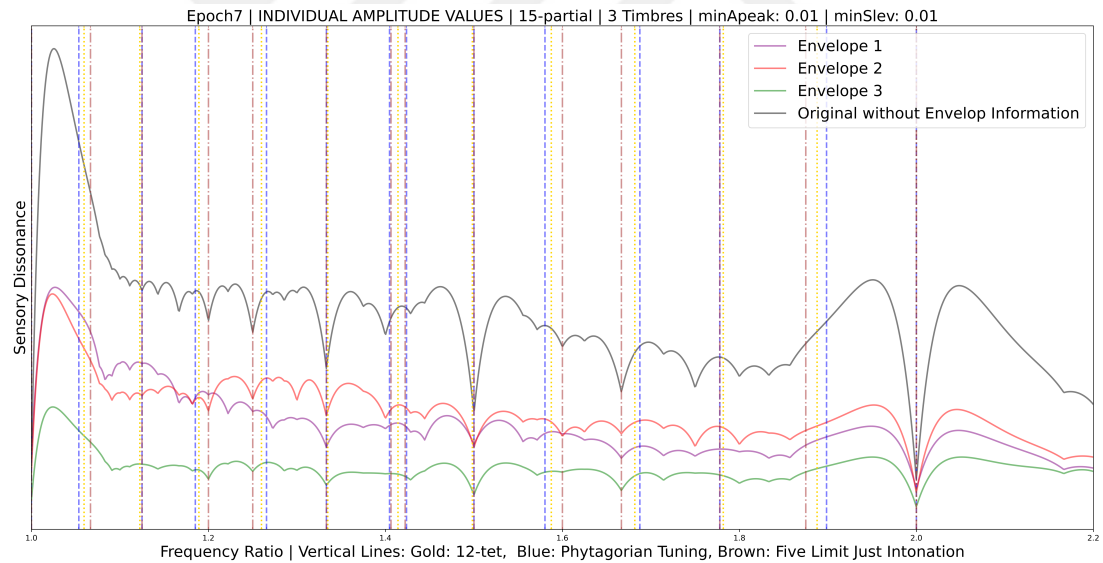


Figure 3.7: Epoch 7 Output Graph

3.2 Test 2

3.2.1 First group

The first group of results belong to the harmonic partial subsets. The ratios are represented on the titles of the sensory dissonance curves. The vertical lines are placed to visualize the tone systems and their relative intervals. Figures 3.8, 3.9, 3.10 and 3.11 are the results.

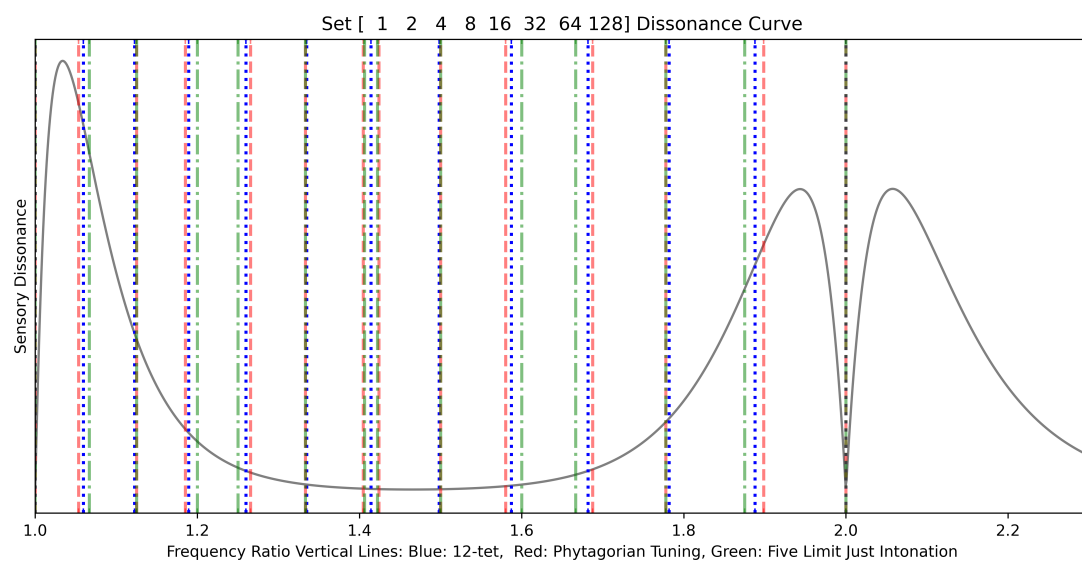


Figure 3.8: Even Harmonic Partial: Powers of Two

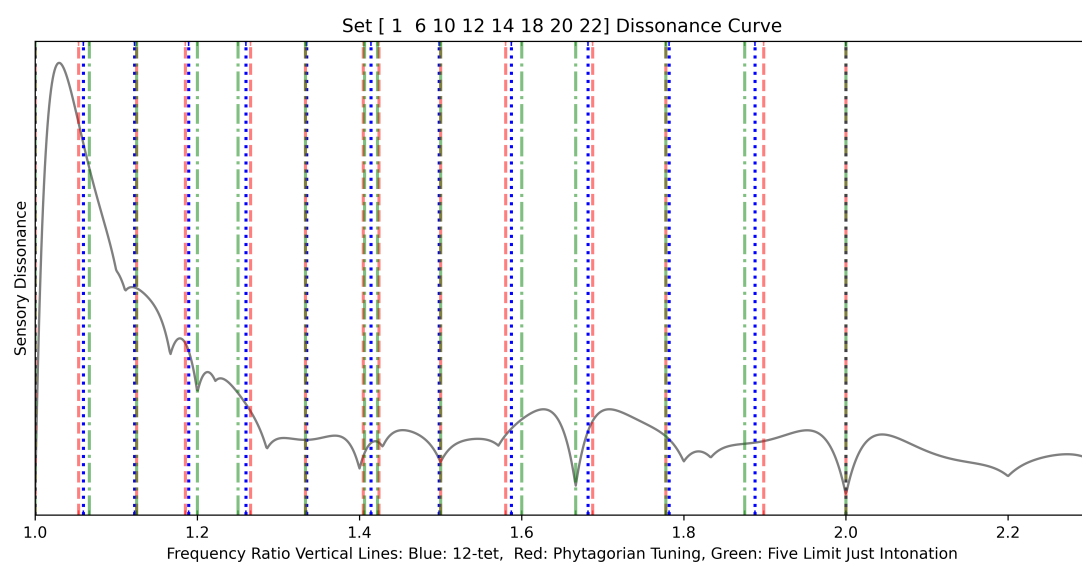


Figure 3.9: Even Harmonic Partial: Prime Number Combinations

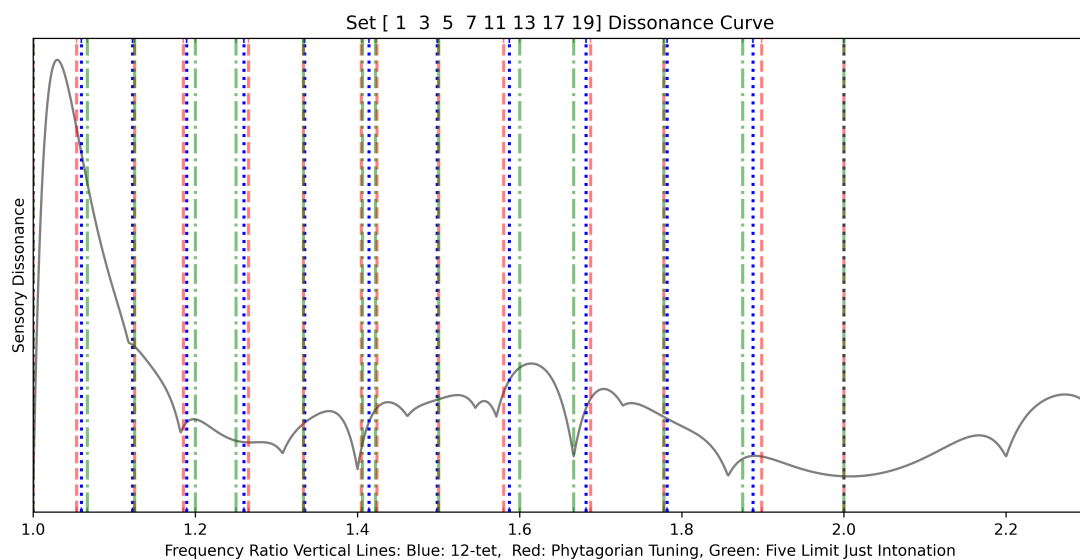


Figure 3.10: Odd Harmonic Partial: Prime Numbers

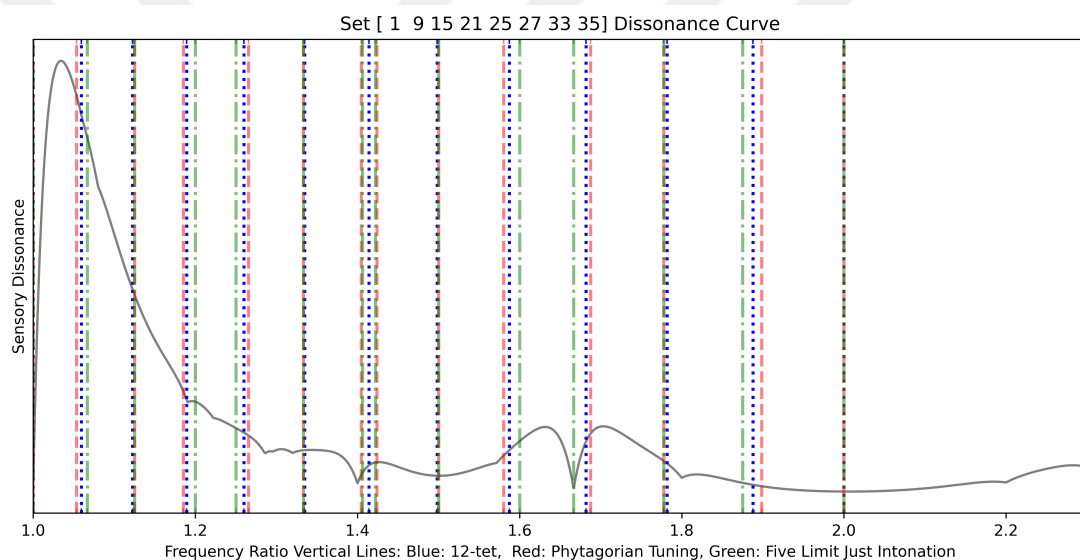


Figure 3.11: Odd Harmonic Partial: Composite Numbers

3.2.2 Second group

The second group uses 4, 5 and 6 partial subsets of all combinations until 8th partial as the frequency ratios. This means that there are absences of some partials in some of the dissonance curves. Figures 3.12, 3.13, 3.14, 3.15, 3.16, 3.17, 3.18, 3.19, 3.20, 3.21, 3.22, 3.23, 3.24, 3.25, 3.26, 3.27, 3.28, 3.29, 3.30, 3.31, 3.32, 3.33, 3.34, 3.35, 3.36, 3.37, 3.38, 3.39, 3.40 are the results of different partial combinations.

3.2.2.1 4-Partial subsets

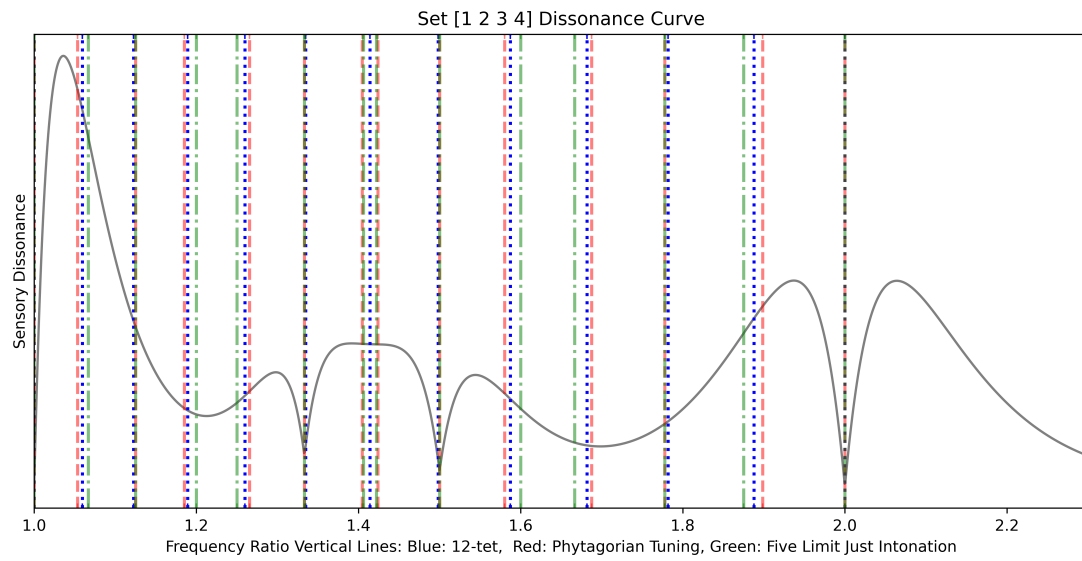


Figure 3.12: Dissonance Curve of Partial 1,2,3,4

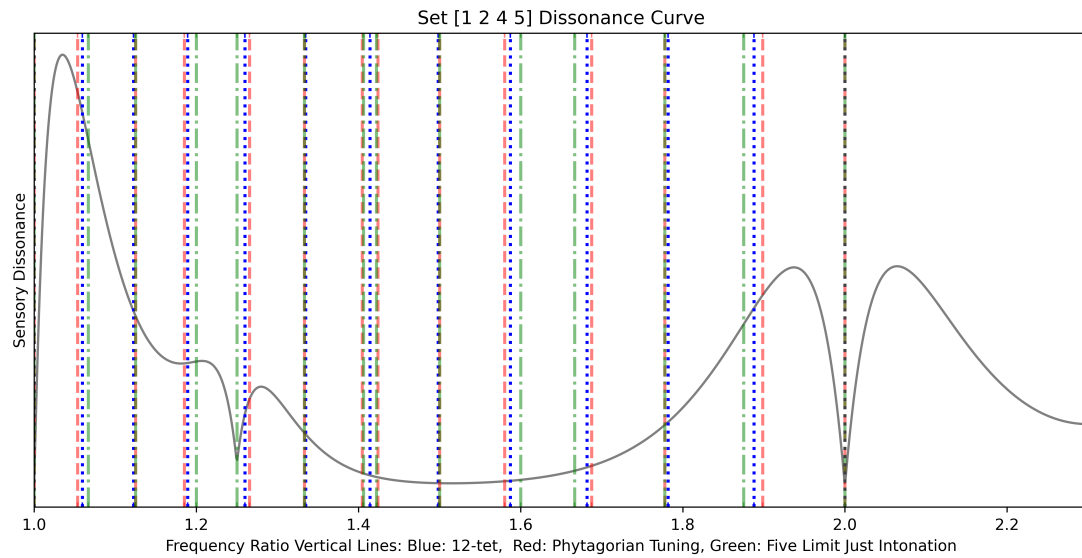


Figure 3.13: Dissonance Curve of Partial 1,2,4,5

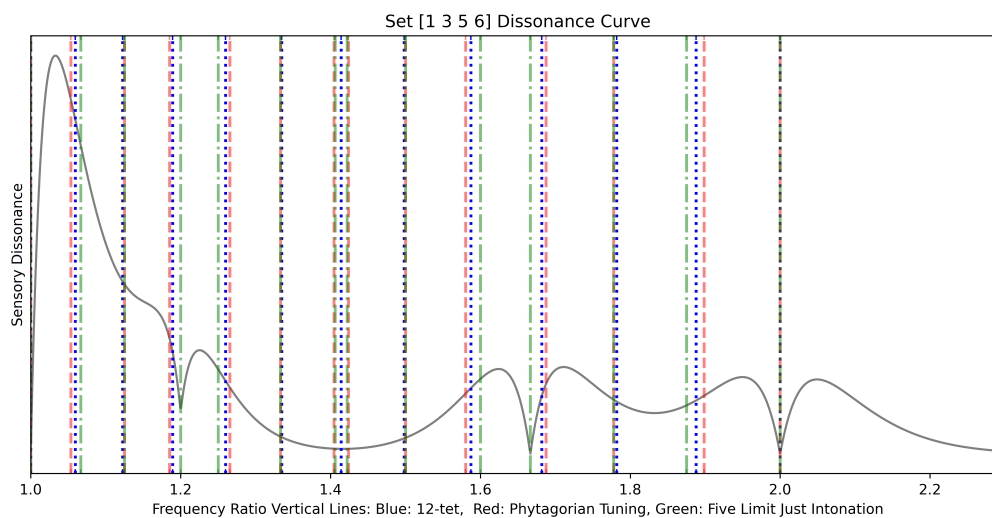


Figure 3.14: Dissonance Curve of Partial 1,3,5,6

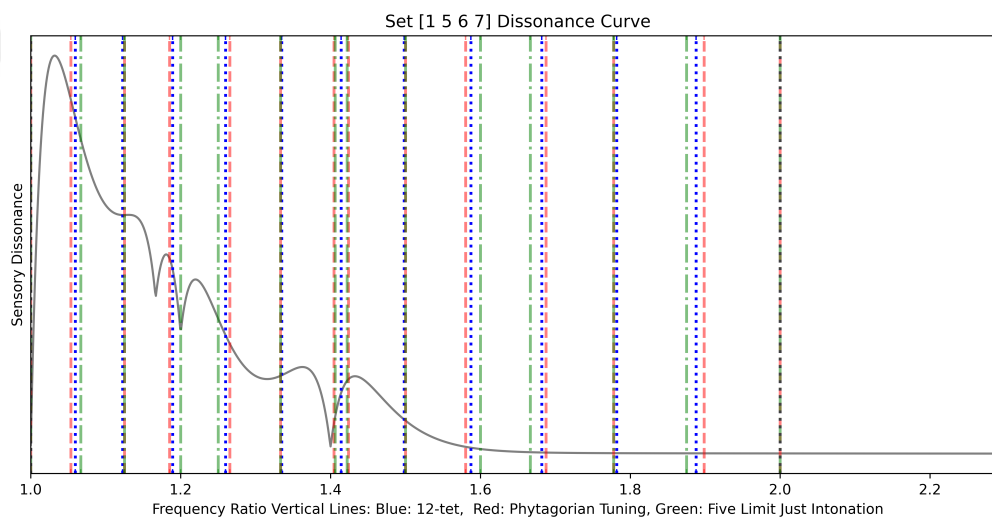


Figure 3.15: Dissonance Curve of Partial 1,5,6,7

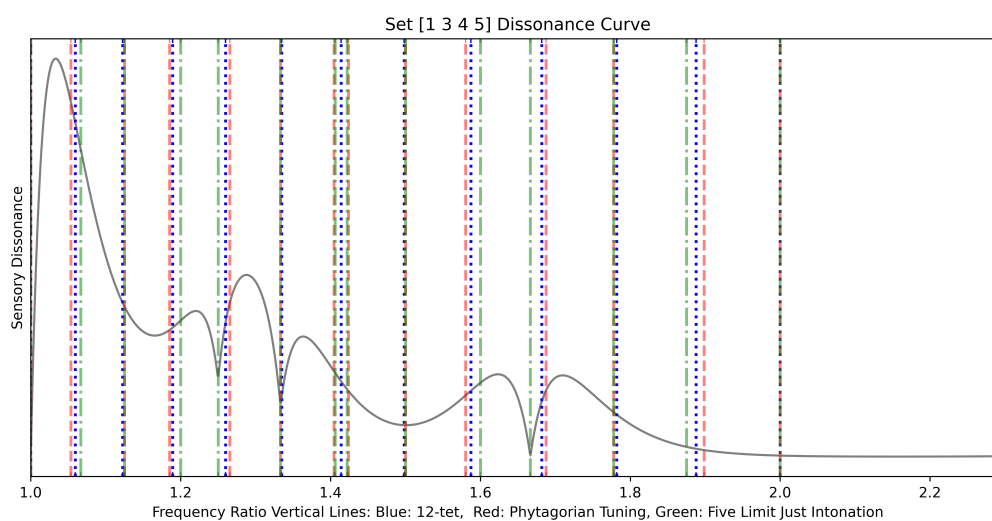


Figure 3.16: Dissonance Curve of Partial 1,3,4,5

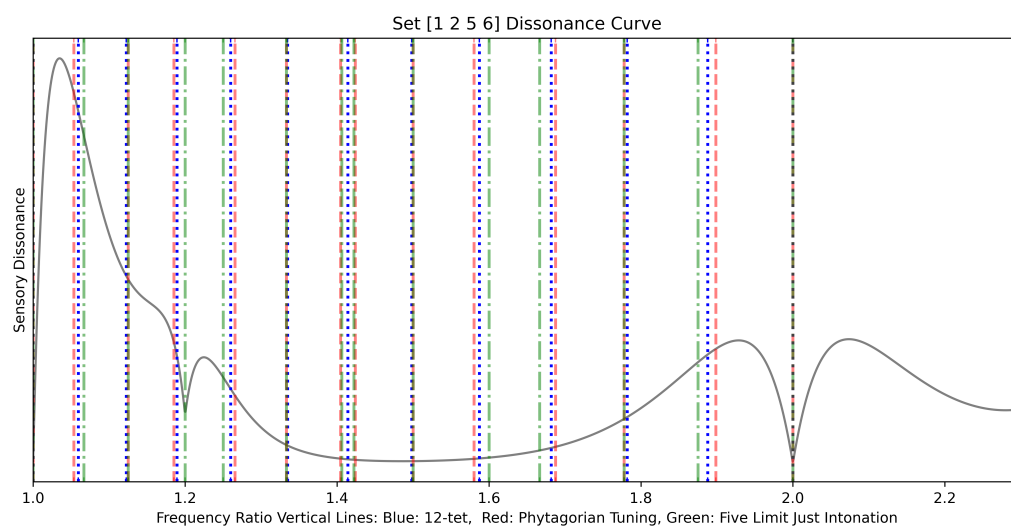


Figure 3.17: Dissonance Curve of Partial 1,2,5,6

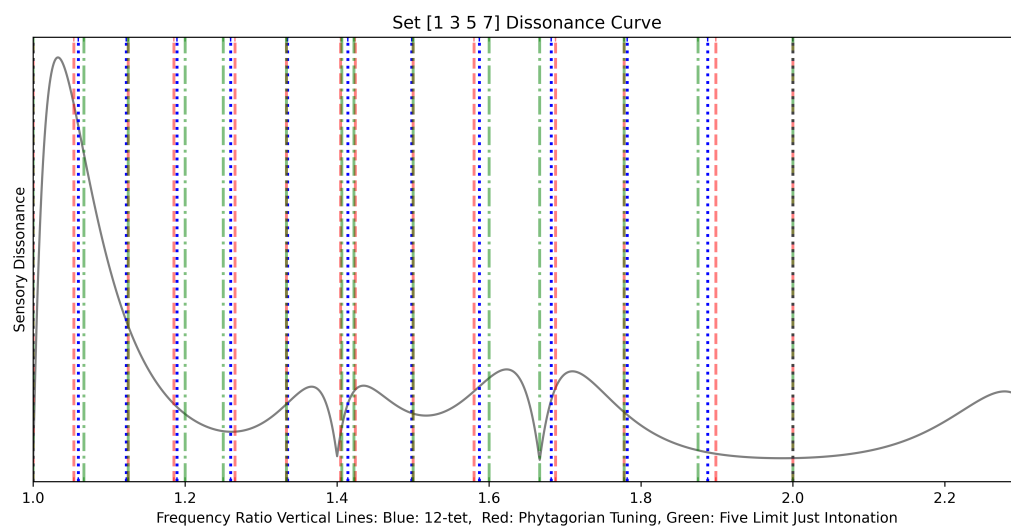


Figure 3.18: Dissonance Curve of Partial 1,3,5,7

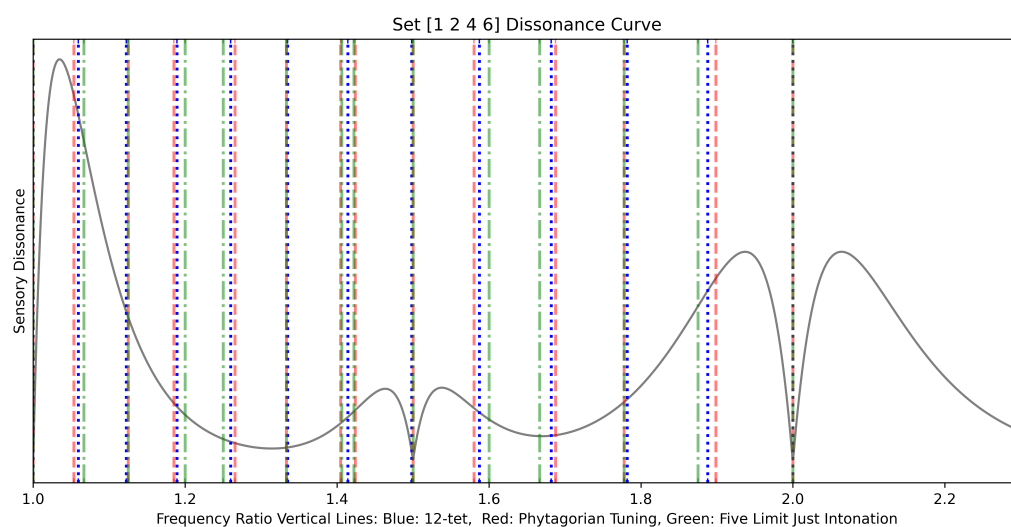


Figure 3.19: Dissonance Curve of Partial 1,2,4,6

3.2.2.2 5-Partial subsets

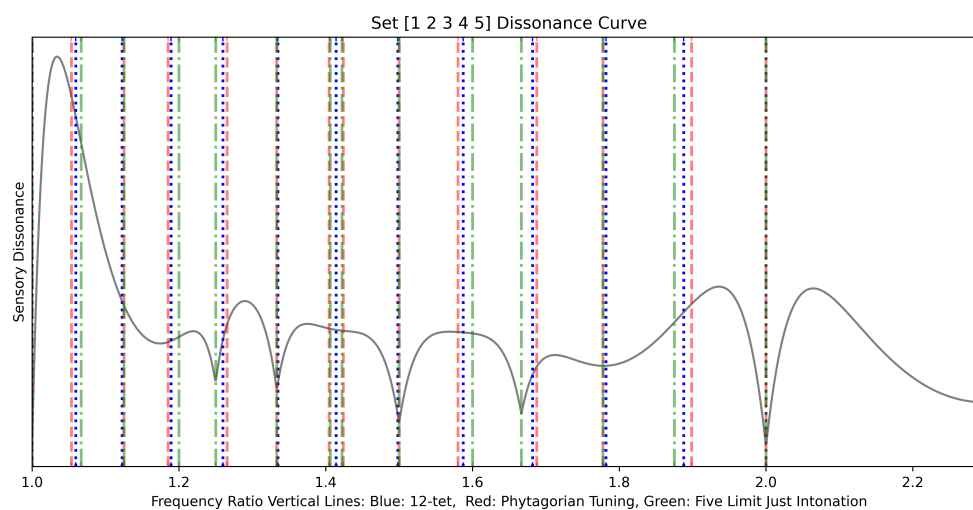


Figure 3.20: Dissonance Curve of Partial 1,2,3,4,5

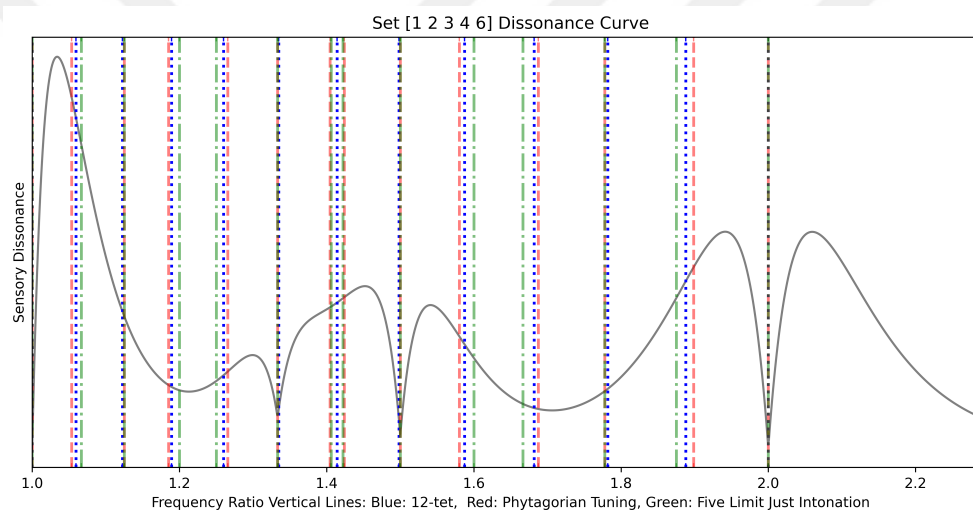


Figure 3.21: Dissonance Curve of Partial 1,2,3,4,6

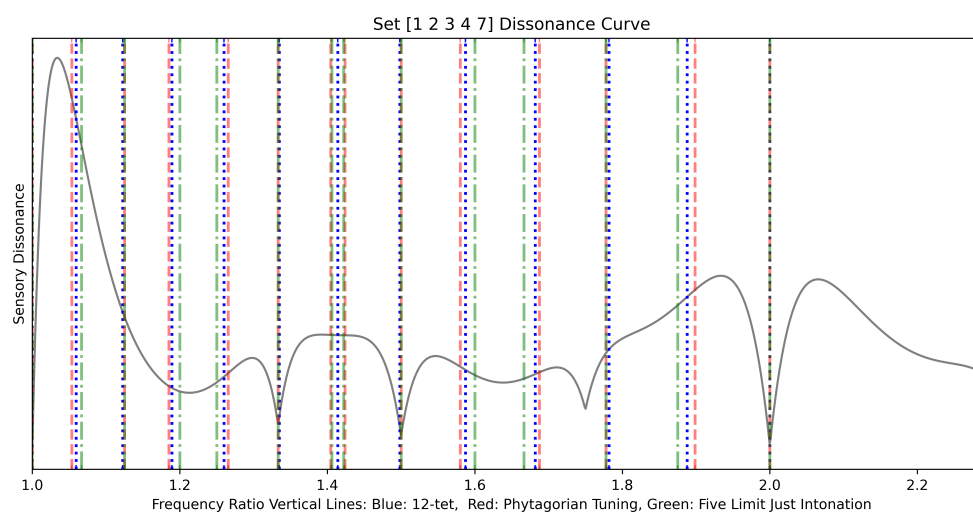


Figure 3.22: Dissonance Curve of Partial 1,2,3,4,7

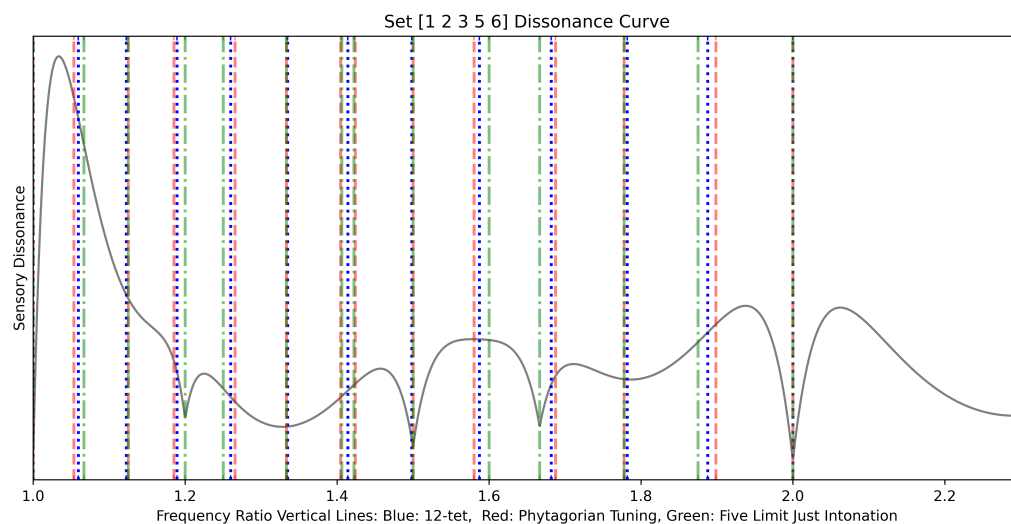


Figure 3.23: Dissonance Curve of Partial 1,2,3,5,6

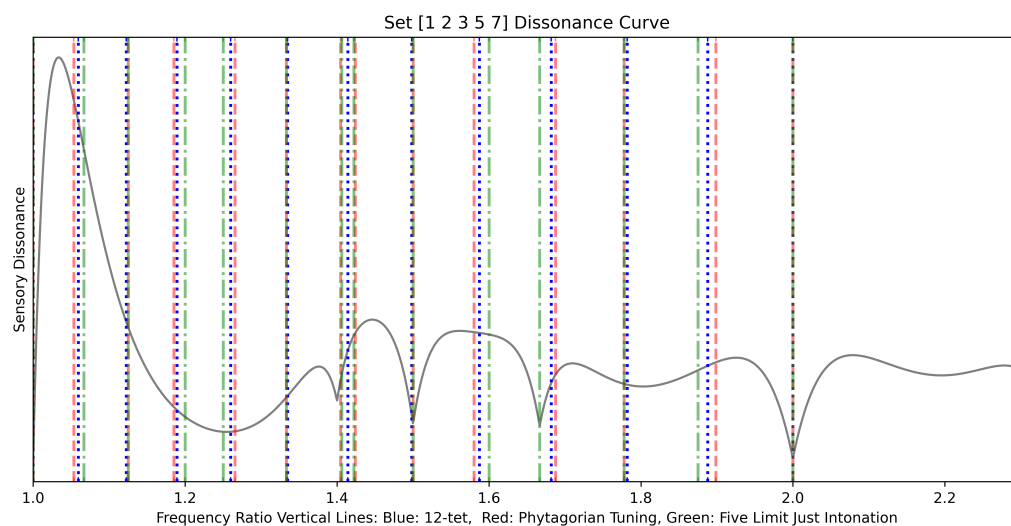


Figure 3.24: Dissonance Curve of Partial 1,2,3,5,7

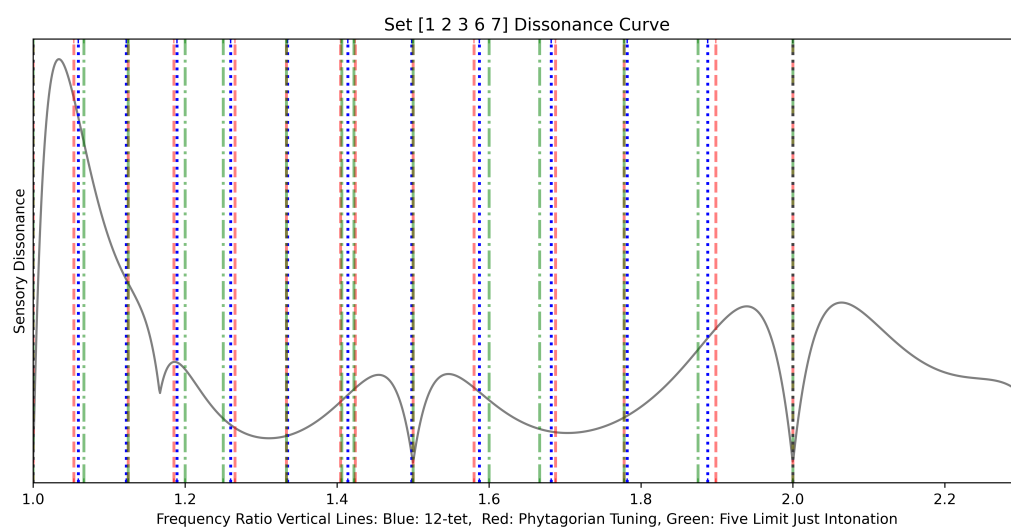


Figure 3.25: Dissonance Curve of Partial 1,2,3,6,7

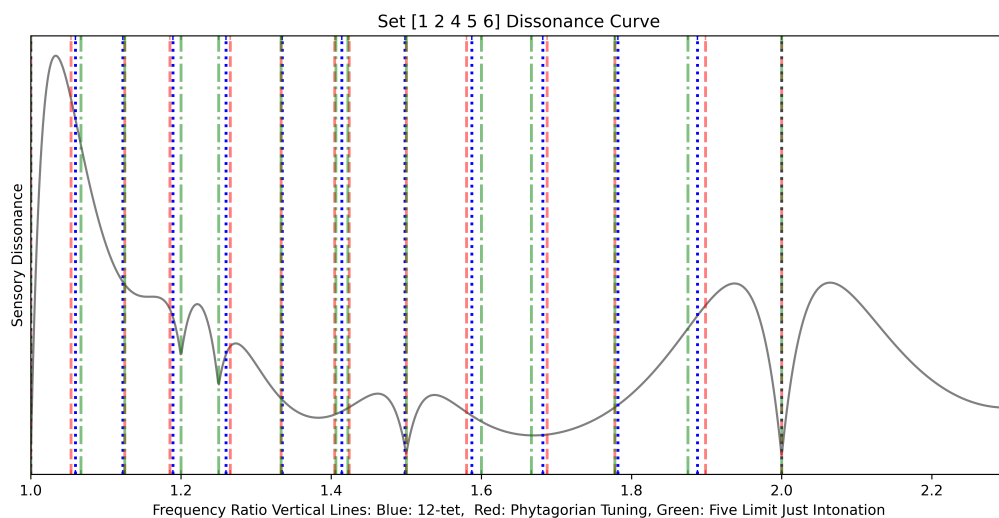


Figure 3.26: Dissonance Curve of Partial 1,2,4,5,6

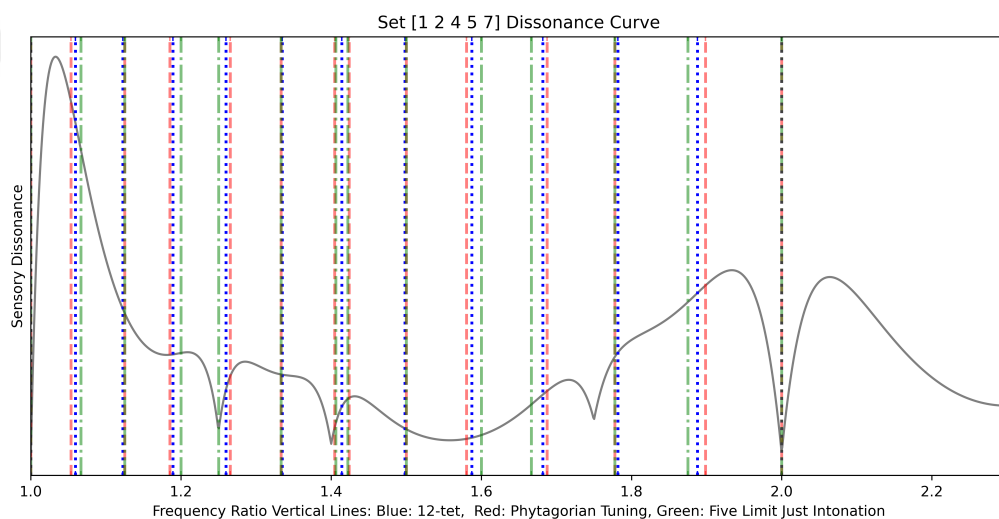


Figure 3.27: Dissonance Curve of Partial 1,2,4,5,7

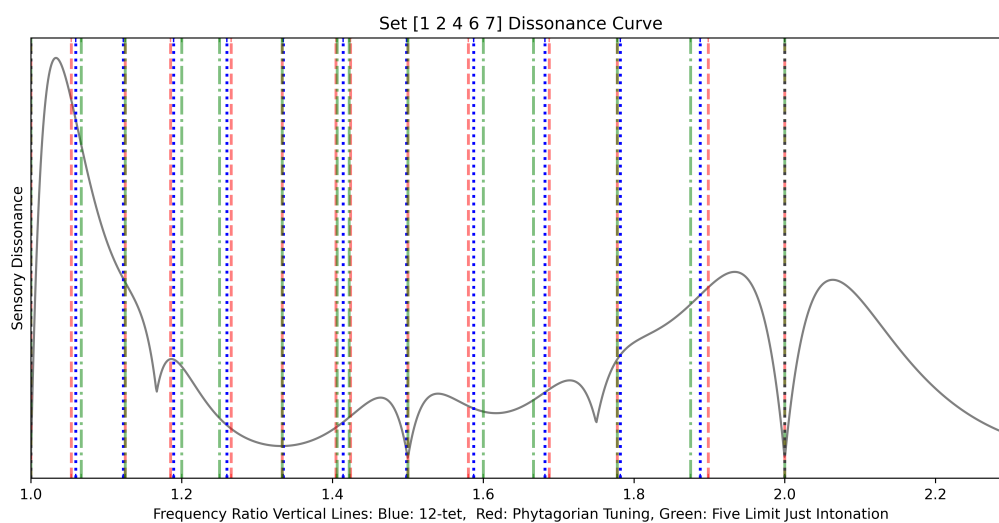


Figure 3.28: Dissonance Curve of Partial 1,2,4,6,7

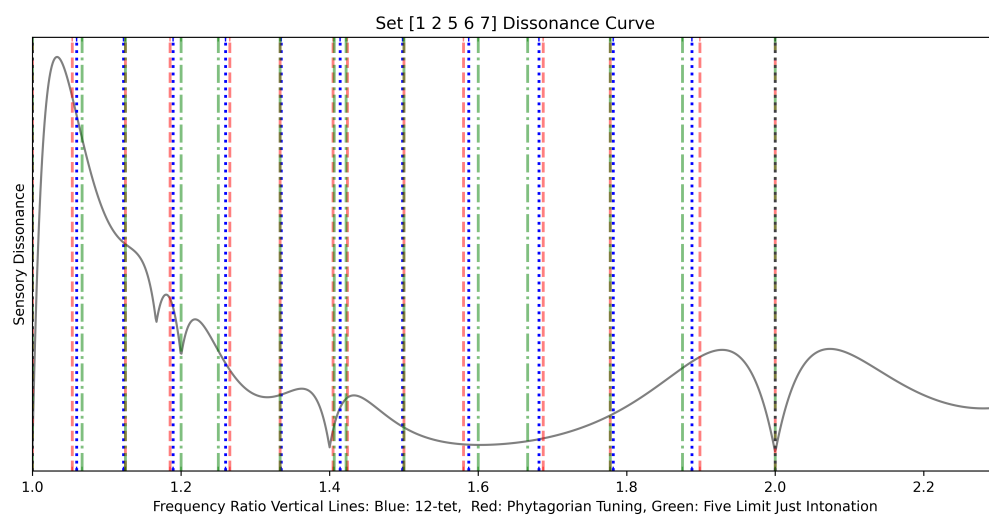


Figure 3.29: Dissonance Curve of Partial 1,2,5,6,7

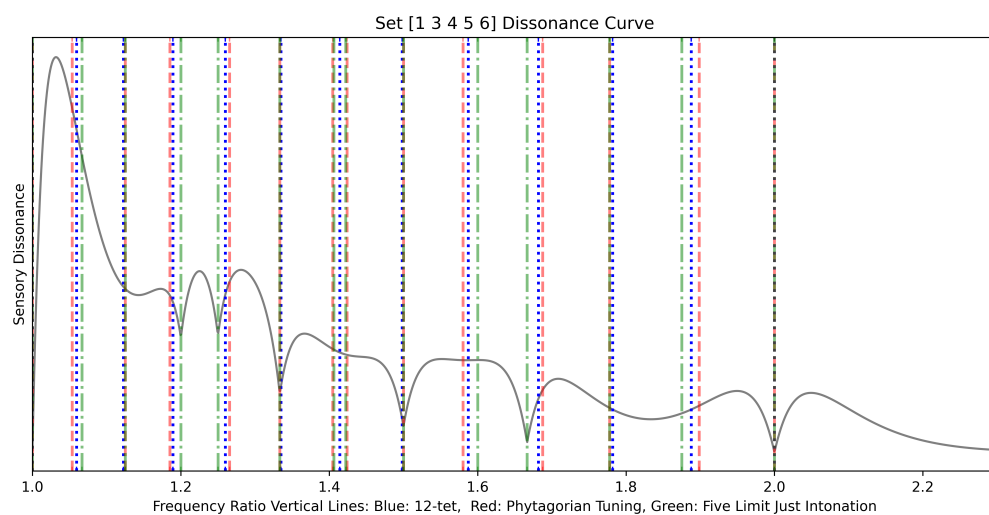


Figure 3.30: Dissonance Curve of Partial 1,3,4,5,6

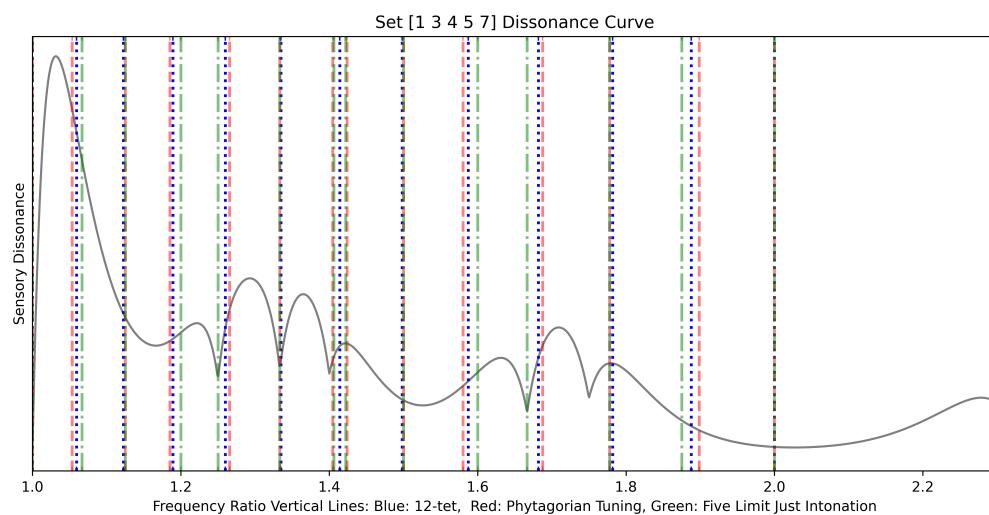


Figure 3.31: Dissonance Curve of Partial 1,3,4,5,7

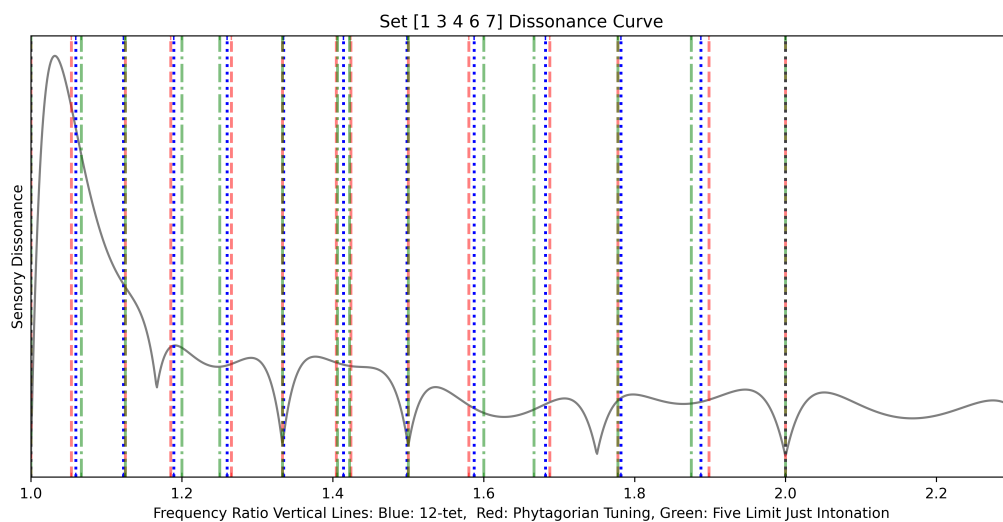


Figure 3.32: Dissonance Curve of Partial 1,3,4,6,7

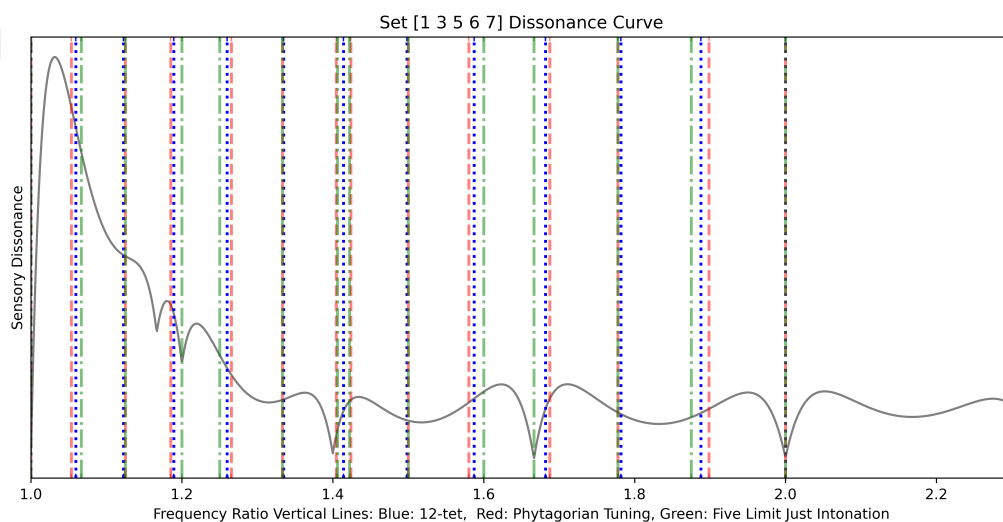


Figure 3.33: Dissonance Curve of Partial 1,3,5,6,7

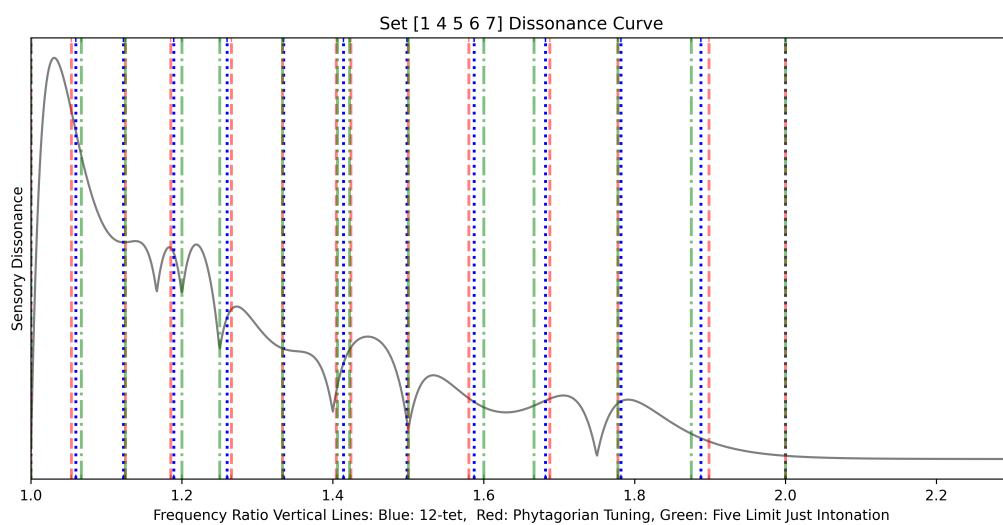


Figure 3.34: Dissonance Curve of Partial 1,4,5,6,7

3.2.2.3 6-Partial subsets

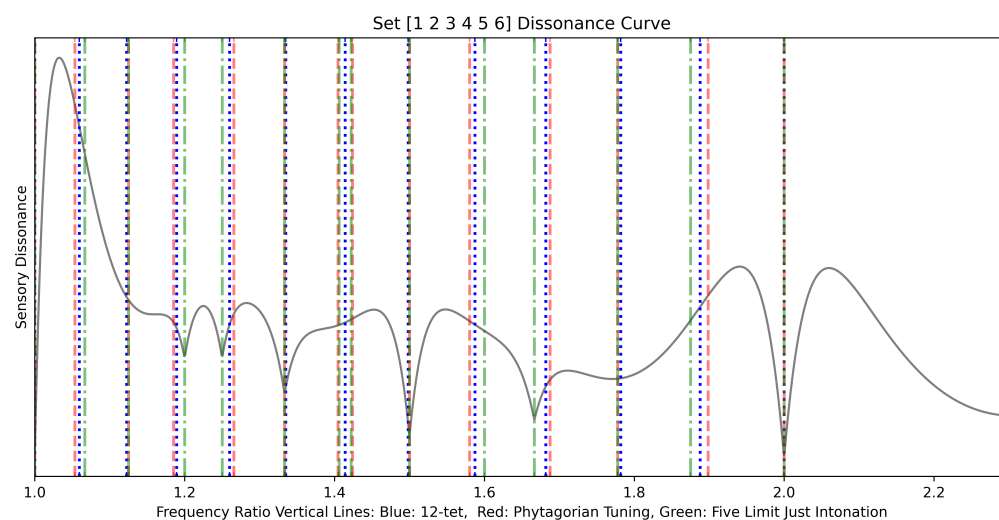


Figure 3.35: Dissonance Curve of Partial 1,2,3,4,5,6

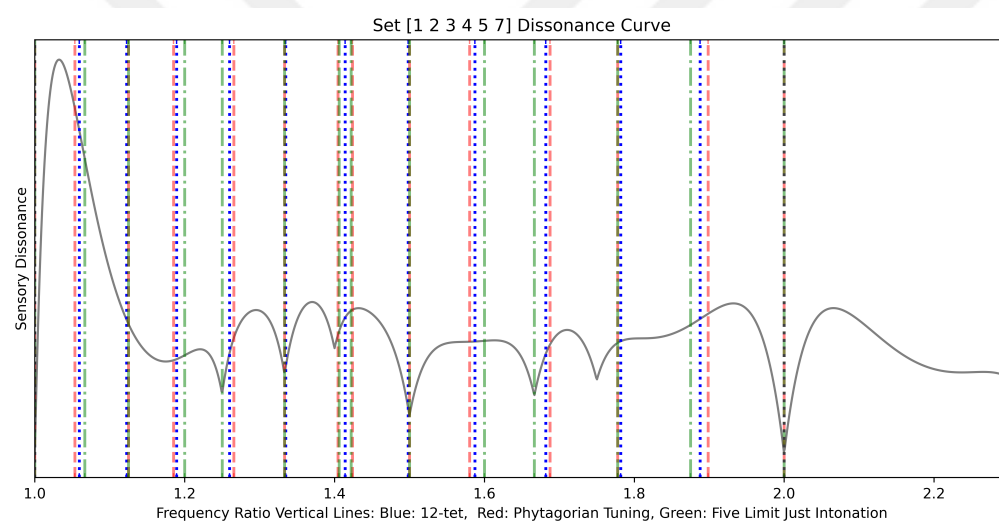


Figure 3.36: Dissonance Curve of Partial 1,2,3,4,5,7

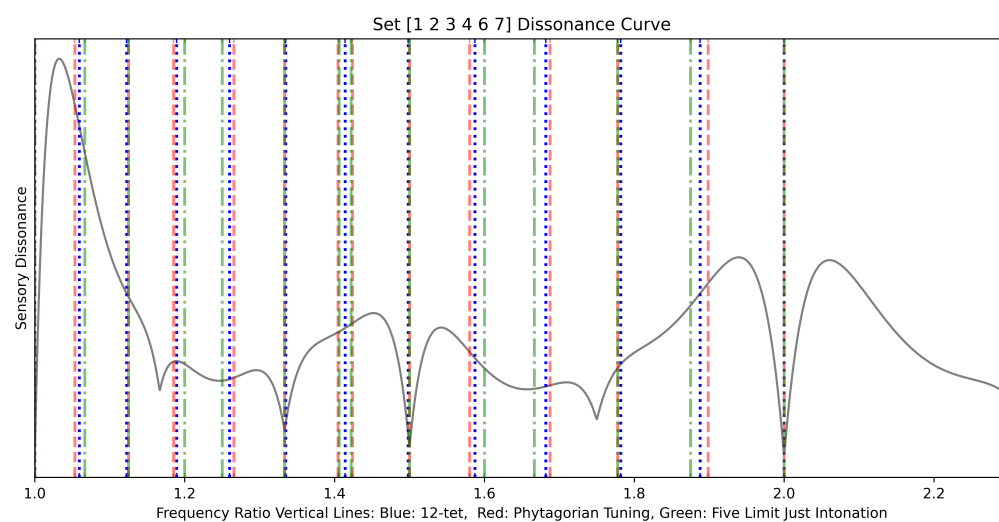


Figure 3.37: Dissonance Curve of Partial 1,2,3,4,,6,7

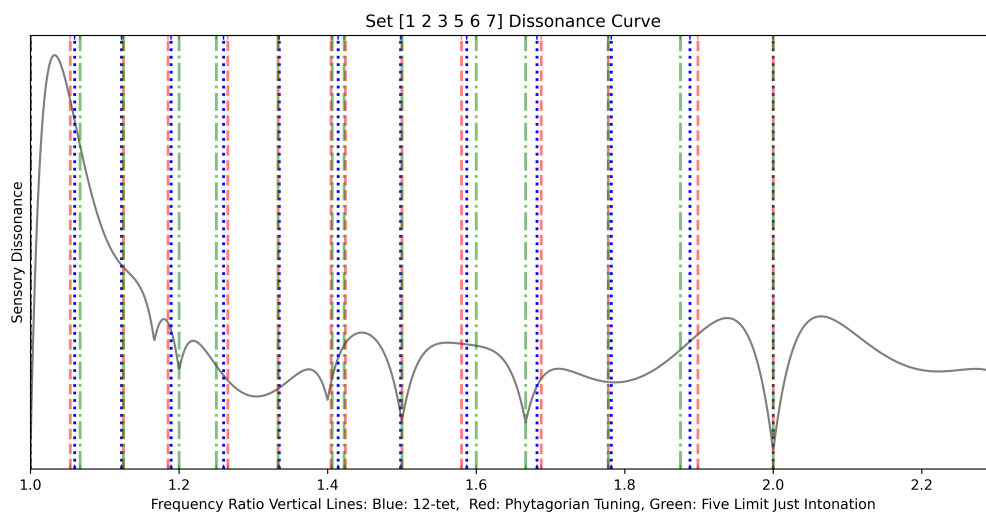


Figure 3.38: Dissonance Curve of Partial 1,2,3,5,6,7

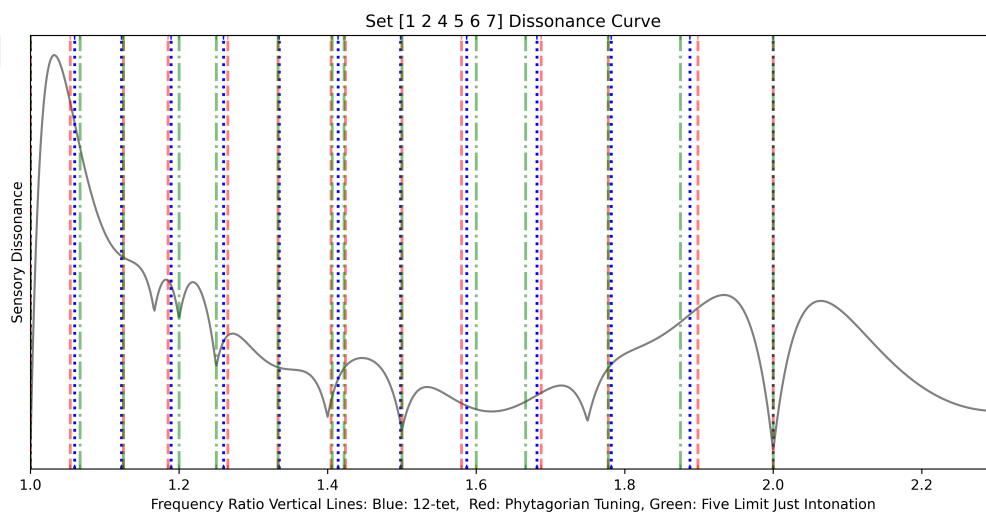


Figure 3.39: Dissonance Curve of Partial 1,2,4,5,6,7

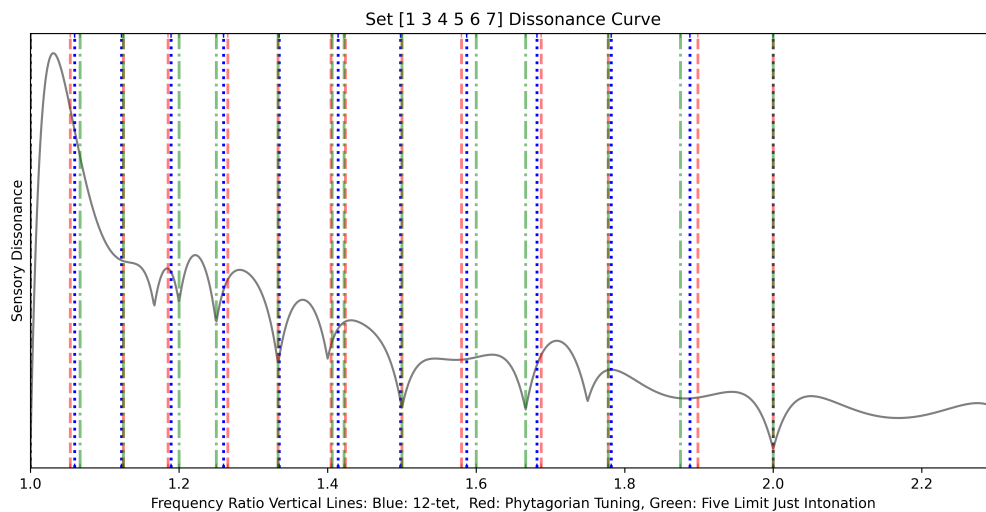


Figure 3.40: Dissonance Curve of Partial 1,3,4,5,6,7

4. CONCLUSION

4.1 General Outcomes

Since two different concepts are tested in this research, the results should be considered separately. But experimenting over the sensory dissonance curves and calculations has some general outcomes regardless of the concepts of experimentation. The first obvious aspect for all generations and tests is the relationship between the number of partials and the total sensory dissonance. Due to the nature of the original formulation, if the number of partials increases, total sensory dissonance is also increased. This creates an imbalance of comparison between timbres with different number partials. A possible attempt to eliminate this imbalance is creating a mechanism for normalizing the sensory dissonance value in accordance with the number of partials since the formula calculates all partial combinations. This can be considered as reducing the relativity aspect of the sensory dissonance and making it a more catalog measuring between different tones.

Second general extraction from the tests is possible new mechanisms for timbre analysis. Since the foundation of the method is calculating a parameter between 2 sine waves and then applying the calculation to all harmonic partial combinations, if another parameter besides sensory dissonance can be measured between 2 sine waves, then it can be measured for the whole timbre which can be decomposed to sine waves.

Hence the cumulative method, which starts from Helmholtz's introduction and continues with Sethares's and Haluska's complex calculations, can be applied to other concepts besides sensory dissonance.

Test 1 showed that the envelope information weight has an effect on the total sensory dissonance since the curve has a lower mean compared to the pure amplitude weight information. Since the partial numbers of three timbres with envelope information and the partial number of the timbre with no envelope information in the same epoch is the same, the number of the combinations for the partials sensory dissonance is the same. In this sense, it can be considered that the envelope information has an effect on the sensory dissonance. Secondly, if the amplitude values of partials remain the same, but

the envelope information differs, the shape of the sensory dissonance curve for an octave remains the same, but with a lower total sensory dissonance. It is actually accurate with the fact that envelope information does not weight directly the calculation of the partial but affects the amount of amplitude weight that goes into the calculation. It can be seen in Epoch 1 and Epoch 2. Remaining Epochs are generated with various amplitude information for each timbre and this created a palette of sensory dissonance curves for each timbre. This shows that with the addition of envelope information to the amplitude information, a timbre can be individualized for a tone system in regard to sensory dissonance. Also, with the information of the values which establish the envelope information, that timbre can be used as a model for additive synthesis or a created timbre can be analyzed for the sensory dissonance curve with its complex nature. On the other hand, the main local minimas for the curves remained same since the ratios 1.33 and 1.50 which are roughly the perfect fourth and fifth, are same in all generations. But for lesser local minimas, there are small changes for other regions. For example, in Epoch 6, Envelope 2 has a distinctive difference in the ratio near the minor second or in Epoch 7, Envelope 1 and 3 have differences near the major second and minor third regions.

Test 2 showed that the frequency ratios of partials and their distribution drastically affect the sensory dissonance curve's shape. Some of the partial combinations create lower sensory dissonances for some frequency ratios. There are many different combinations in the test. In this sense, the outcome of the test can be considered as a databank for timbre selection or creation processes in accordance with the sensory dissonance.

4.2 Musical Outcomes and Spectral Strategies for Additive Synthesis

The results of the two tests can be considered as a form of data for additive synthesis strategies which use sine waves as building blocks. Since the mentality behind the basic additive synthesis can be described as combining sine waves in order to create musical timbres, the concept of sensory dissonance can be regarded as a relevant parameter for this process. The purpose of monitoring the sensory dissonance for synthesized timbres can be contextualized with the nature of harmonic beating. If the harmonic beating between two pure sine waves create a fluctuation in the amplitude of the combination, complex tones with more partials create complex fluctuations in

the combined tone. This complex fluctuation results with a disturbance in the perception of the tone and this can be considered as the sensory dissonance of that tone. Hence, when a sound is created with the additive synthesis methods, the timbre of the synthesized sound will have complex fluctuations in the perception of its pitch information. In this sense, reducing this fluctuation can be considered as the optimizing the resolution of the pitch perception for that timbre. The results of the tests are used accordingly to establish a set of strategies for additive synthesis.

4.2.1 Strategy 1: equilibrium of sensory dissonance and number of partials

The main principle of the additive synthesis strategies in accordance with the sensory dissonance can be described as such that if the number of partials in a timbre is increased, the total sensory dissonance of two tones with that timbre is also increased, since the total energy of the spectrum is increased. The mentality behind establishing these strategies is increasing the harmonic quality and enriching the spectral identity of the tone while keeping the pitch resolution of that timbre high. In this sense, reducing the total sensory dissonance of a timbre is a way of approaching this purpose. But additionally, reducing the sensory dissonance of two tones distanced in a specific musical interval with that timbre is also a way of thinking for such task. In this sense, upcoming strategies are established with the regard of reducing the sensory dissonance occurring in specific intervals with same timbre.

4.2.2 Strategy 2: lowering the sensory dissonance of a timbre for two complex tones distanced in specific intervals in a tone system with envelope design

In the light of the Test 1 and its results, it can be observed that the total sensory dissonance of a timbre can be reduced with the partial envelope information. This is also relevant for each partial combination. The fundamental principle behind this reduction is reducing the energy and duration of partials by applying an envelope to its amplitude over time. This process can serve to the control over the weight of the partials. In other words, if there is a known effect of a specific partial to a timbre, this effect can be controlled with an envelope applied to that partial. This method has two advantages. First one is the control over the effects of partials. Secondly, having an envelope for each partial provides a backbone for additive sound synthesis by extending the aesthetic complexity of a timbre. This extension can enhance and enrich

the spectral components of the synthesized sounds while providing a mechanism for optimizing the resolution in pitch perception of that timbre.

4.2.3 Strategy 3: lowering the sensory dissonance of a timbre for two complex tones distanced in specific intervals in a tone system with harmonic partial distribution

In the Strategy 2, there is the saying “known effect of a partial”. This can be described as an effect of a specific partial to the sensory dissonance occurring between 2 complex tones with the same timbre. The question arises from this description that what kind of effect is this. Test 2 aims to cover this question. It can be observed that two tones played with the same timbre do not have same amount of harmonic beating occurring between these tones for all intervals in an octave. There are many minimum points for sensory dissonance at specific intervals on the graphs. The ratio data tested in the test 2 shows these intervals with lesser harmonic beatings compared to the rest of the intervals. Table 4.1 shows the abbreviations of the intervals.

Interval Symbol	5-Limit Just Intonation Name
m2	Minor Second
M2	Major Second
m3	Minor Third
M3	Major Third
P4	Perfect Fourth
D5	Diminished Fifth
TT/ET	Equal Temperament's Tritone
A4	Augmented Fourth
P5	Perfect Fifth
m6	Minor Sixth
M6	Major Sixth
m7	Minor Seventh
M7	Major Seventh
O	Octave

Table 4.1: 5-Limit Just Intonation Intervals and Abbreviations

Table 4.2 is representing all of the harmonic partial combinations tested in the test 2 and relevant minimums of the intervals.

Number of	Ratios	Intervals with Lower Sensory Dissonance
4	[1,2,3,4]	O, P4, P5
4	[1,2,4,5]	O, M3
4	[1,3,5,6]	m3, M6, O
4	[1,5,6,7]	m3, near(D5), between(M2, m3)
4	[1,3,4,5]	M3, P4, M6
4	[1,2,5,6]	m3, O
4	[1,3,5,7]	near(D5), M6
4	[1,2,4,6]	P5, O
5	[1,2,3,4,5]	M3, P4, P5, M6
5	[1,2,3,4,6]	P4, P5, O
5	[1,2,3,4,7]	P4, P5, between(M6, m7), O
5	[1,2,3,5,6]	m3, P5, M6, O
5	[1,2,3,5,7]	near(D5), P5, M6, O
5	[1,2,3,6,7]	between(M2, m3), P5, O
5	[1,2,4,5,6]	m3, M3, P5, O
5	[1,2,4,5,7]	M3, near(D5), between(M6, m7), O
5	[1,2,4,6,7]	between(M2, m3), P5, between(M6, m7), O
5	[1,2,5,6,7]	between(M2, m3), m3, near(D5), O
5	[1,3,4,5,6]	m3, M3, P4, P5, M6, O
5	[1,3,4,5,7]	M3, P4, near(D5), M6, between(M6, m7)
5	[1,3,4,6,7]	between(M2, m3), P4, P5, between(M6, m7), O
5	[1,3,5,6,7]	between(M2, m3), m3, near(D5), M6, O
5	[1,4,5,6,7]	between(M2, m3), m3, P4, near(D5), P5, between(M6, m7), O
6	[1,2,3,4,5,6]	m3, M3, P4, P5, M6, O
6	[1,2,3,4,5,7]	M3, P4, near(D5), P5, M6, between(M6, m7), O
6	[1,2,3,4,6,7]	between(M2, m3), P4, P5, between(M6, m7), O
6	[1,2,3,5,6,7]	between(M2, m3), m3, near(D5), P5, M6, O
6	[1,2,4,5,6,7]	between(M2, m3), m3, M3, near(d5), P5, between(M6, m7), O
6	[1,3,4,5,6,7]	between(M2, m3), m3, M3, P4, near(d5), P5, M6, between(M6, m7), O

Table 4.2: Lower Total Sensory Dissonances in 5-Limit Just Intonation Intervals
for Different Partial Distribution

In the Table 4.2, the mentioned intervals are representing the minimums in an octave range on the sensory dissonance curve. As it can be seen, different partial combinations result with different minimums in an octave range for sensory dissonance curve. The

limit was 7th partial in the Test 2. This limit actually determines the range of intervals. For example, there are no minor second, major second, minor seventh and major seventh intervals. In order to have minimums on these intervals the partials above the 7th one should be included, or the integer ratios of partials should be replaced with relevant non-integer ratios. In this sense, the partial combinations in the table 4.2 can be used for timbre synthesis with the awareness of intervals which have lesser harmonic beating. This method can be extended for other tone systems as well. In appendix A, there is a general sensory dissonance curve graph for Turkish maqams.

In a more detailed inspection, the timbre with 1,3,5,7th partial and the one with 1,2,3,5,7th partial shows that the addition of second partial results with addition of minimums on perfect fifth and octave. Another example is the timbre with 1,5,6,7th partial and the one with 1,2,5,6,7th partial. The addition of second partial can be seen here as well but, the result is the addition of a minimum for only the octave interval. In this sense, partial selection can be considered as a process which does not depend only on the partial type but the superposition of all partials. Hence, a further investigation of this interdependence is crucial for future research. Another deduction from the test is the usage of timbres 1,2,3,4,5,6 and 1,3,4,5,6, that they are efficient to reduce the sensory dissonance on them when pentatonic scale is played with them. Consequently, the strategies above can be used for establishing an additive synthesis methodology and the process of sound synthesis can have these methods to extend the possibilities of tone systems and timbre designs.

4.3 Future Research

For further research six concentration points are deduced:

- 1) More partial combination data for test 2
- 2) Testing non-integer partial ratios and evaluating harmonic entropy
- 3) Working on sound recordings with audio feature extraction concepts
- 4) Sonification of the timbres with envelope information and audience tests
- 5) Custom partial distribution for custom tone systems.
- 6) Correlation with N-limit Just Intonation





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