ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE ENGINEERING AND TECHNOLOGY

INVESTIGATION OF TIMBRAL QUALITIES OF GUITAR USING WAVELET ANALYSIS

M.Sc. THESIS

Şafak EKMEN

Department of Electrical Engineering

Electrical Engineering Programme

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GİTARIN TINISAL ÖZELLİKLERİNİN DALGACIK ANALİZİ KULLANILARAK ARAŞTIRILMASI

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TEMMUZ 2020

Şafak Ekmen, a M.Sc. student of İTU Graduate School of Science Engineering and Technology student ID 504151094, successfully defended the thesis entitled "INVESTIGATION OF TIMBRAL QUALITIES OF GUITAR USING WAVELET ANALYSIS", which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

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To VDE, Safiye-Hüseyin EKMEN and Sakine SARITEPE,

FOREWORD

First, I would like to thank my advisor Prof. Dr. Serhat ŞEKER for the interest he gave on my project and the time he managed to spare from his non-human level busy schedule.

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ABBREVIATIONS

CWT	: Continuous Wavelet Transform
DWT	: Discrete Wavelet Transform
FEM	: Finite Element Method
MRA	: Multiresolution Analysis
STFT	: Short Time Fourier Transform
WPT	: Wavelet Packet Transform

SYMBOLS

t	: Time
f	: Frequency
Δt	: Time resolution
Δf	: Frequency resolution
Ψ	: Mother Wavelet
$\psi_{(a,b)}$	: Wavelet
ω	: Radial frequency
s	: Scale
f_0	: Base frequency
C_ψ	: Admissibility condition
V	: Vector space
V_1, V_2	: Vector subspace
p^2	: Time Bandwidth
γ	: Symmetry parameter

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INVESTIGATION OF TIMBRAL QUALITIES OF GUITAR USING WAVELET ANALYSIS

SUMMARY

This study presents a practical and accurate technique using the power of wavelet analysis for investigating timbral qualities of classical guitars. Work includes complete work frame from the experimental procedure through capturing the data with piezoelectric film sensors, which have not been widely applied for this type of application, to the analysis of captured information. Aim is to present a study for more objective evaluation of guitars that is suitable for performing by the different parties of the field; from instrument makers and designers to the quality control engineers and end users. It is believed that with the right improvements and modifications, system presented in this thesis can be used for detailed cataloging of different guitars and their timbral characteristics, which in turn can be used in range of areas such as music information retrieval, guitar research and development and probably even for genuity testing of the guitars. Structure of this study as follows: first understanding the concept that is being investigated, timbre is explored after the introduction. Properties of timbre and the studies that discovered these properties are reviewed. In the following chapter, wavelet theory, which is the backbone and most important aspect of this study is explained in a level that provides intuitive grasping of the concept, because the area is vast and ever improving. Then subject of the study that is guitar is presented through the studies of guitar analysis literature. Then, naturally comes the chapter that the experimental setup and procedure is explained as well as performed analysis and its results are presented with their interpretation and comments. Finally, conclusion of the study with a discussion is given.

Experiments was performed in the main studio of Istanbul Technical University/Center for Advance Studies in Music. A mass produced guitar that is described as a learning guitar by its production company and a luthier-made guitar were used. Procedure is done while a guitar player holding the guitar in a conventional playing position and plucking the strings with a pluck. A minor diatonic scale with addition of A minor chord at the end, both in open position and 5th position is played. Choice of the played scale was rather arbitrary whereas the choice of playing the scale in two position on the fingerboard is made to observe the effect of excitation epicenter on the finger board. Piezofilm sensors was used because of their wide frequency range, near-flat frequency response and low mass. Analysis were performed in MATLAB environment using Wavelet Toolbox. First Continuous Wavelet Transform is applied. Continuous Wavelet Transform is a highly computation heavy method for general applicability and the resolution of the results can be far more detailed than necessary for some applications in the area. For this reason, Wavelet Packet Transform is performed to present a more computationally inexpensive solution that provides adequate detail. Results show detailed presentation of harmonic and non-harmonic partials as well as time envelopes of them in a resolution that cannot be obtainable using Short Time Fourier Transform. Resolution of the results allow for objective

analysis on the timbre of a guitar as well as making comparison between the timbral properties of the two guitars.

GİTARLARIN TINISAL OZELLİKLERİNİN DALGACIK ANALİZİ KULLANILARAK ARAŞTIRILMASI

ÖZET

Bu çalışma, klasik gitarların tınısal özelliklerinin araştırılması için dalgacık analizinin gücünden faydalanarak, pratik ve keskin bir teknik önermektedir. Çalışma deney düzeneğinin hazırlanmasından, daha önce bu alanda yaygın şekilde kullanımı görülmeyen, piezofilm sensörler kullanılarak verinin elde edilmesi ve verinin analiz edilmesine kadar olan bütün süreçleri içermektedir. Amaç; alanda çalışan çalgı yapımcıları/tasarımcılarından kalite kontrol mühendisleri ve son kullanıcılara kadar olan geniş bir yelpazedeki tarafların, gitar sesini daha nesnel değerlendirebilmek için kullanabileceği bir çözüm sunmaktır. Doğru geliştirmeler veya kullanılacak alana göre gereken ayarlamalar yapılarak önerilen sistemin farklı uygulamalarda kullanılabileceğine inanılmaktadır. Örneğin, sistem farklı gitarların ve onların tınılarının sınıflandırılması için kullanılarak; müzik verisi edinimi, gitar araştırma-geliştirme ve hatta gitarların orijinallik testi alanlarına uygulanabilir.

Bu raporun içeriği şu şekilde yapılandırılmıştır: anlatılan yöntemlerin uygulanabilmesi için, araştırılan konu hakkında bilgi sahibi olma gerekliliği aşikar olduğundan, ilk önce tını kavramı ve bu kavramın özelliklerini araştıran çalışmalar, incelenmiş ve sunulmuştur. Takip eden bölümde, bu çalışmanın iskeleti ve en önemli yönü olduğundan, Dalgacık Analizi teorisi, alan çok geniş ve sürekli gelişmekte olduğundan, konu hakkında sezgisel bir kavramayı sağlayacak düzeyde açıklanmış ve bu teorinin müzikal işaret işleme uygulamalarında kullanımına ilişkin çalışmalar incelenmiştir. Sonrasında ise bu çalışmanın nesnesi olan gitarlar, gitar analizi hakkındaki literatürdeki çalışmalar aracılığıyla açıklanmıştır. Daha sonra, doğal olarak, deney kurulumu ve işleyişiyle beraber uygulanan analizler, sonuçları ve sonuçların değerlendirmesinin bulunduğu bölüm gelmektedir. Son olarak çalışmanın gözden geçirildiği ve ek argümanların sunulduğu bölüm vardır

Tını kavramının, tam kapsamlı bir tanımı olmamasına rağmen; mevcutta kabul edilen tanım ve üzerindeki çalışmalar, zamanla değişen özelliklerine atıfta bulunmakta ve insanın tınıyı algılayış şekli kullanılarak açıklamaktadır. Müzikal bir işaretin tınısının belirleyici özelliklerini, bileşenlerinin frekanslarının yanı sıra zamana bağlı özelliklerinin de önemli derecede etkilediği ve bu özelliklerin çok kısa zaman aralıklarında değiştiği belirtilmiştir. Bu nedenler tını kavramının karmaşık bir kavram olduğunu göstermenin yanı sıra dalgacık analizinin gerekliliğine de işaret etmektedir.

Mevcut literatürde bulunan yöntemlerin hepsinin avantaj ve dezavantajları vardır. Bu yönlerin, çalışmanın yapıldığı dönemdeki teknolojinin durumundan kaynaklandığı düşünülmektir. Ana dezavantajları özetle belirtmek gerekirse: deney düzeneklerinin kurulması ve işleyişlerinin uygulanması oldukça zordur. Bu zorluk nedeniyle de tınısal özellikleri, farklı gitar tasarımları ve yapımlarıyla eşleştirecek bir sınıflandırma kütüphanesi oluşturmak gerçekçi olamamaktadır. Ek olarak Fourier Analizi herhangi bir zaman-frekans saptaması sağlamamakta, Kısa Süreli Fourier Dönüşümünün ise

sağladığı çözünürlük, ayrıntılı bir analiz için yeterli olmamaktadır. Ancak belirtilmelidir ki önemli bir gösterge olan modal titreşim şekilleri ancak bahsedilen çalışmalardaki Sonlu Elemen Yöntemi, Sayısal Görüntü Korelasyonu ya da Chladni Şekilleri gibi yöntemlerle elde edilebilmektedir. Dolayısıyla bu tezde önerilen sistem oldukça pratik ve yüksek çözünürlüklü olmakla beraber, modal titreşim şekillerini elde edememektedir.

Çalışmanın deneyleri, İstanbul Teknik Üniversitesi/Müzik İleri Araştırmaları Merkezi'nin ana stüdyosuna gerçekleştirilmiştir. Denek olarak seri üretim ve üreticisi tarafından öğrenci gitarı olarak sınıflandırılan bir klasik gitar ve çalgı yapımcısı tarafından elle üretilmiş bir klasik gitar kullanılmıştır. Deney, çalan kişi, gitarı normal çalma pozisyonunda tutarken ve telleri bir pena ile uyarırken gerçekleştirilmiştir. Batı müziğindeki akordu ile La minör diyatonik dizisi, La minör akoru ile sonlandırılarak hem açık hem de 5. pozisyonda çalınmıştır. La minör dizinin seçilmesi rastgele denebilecekken, iki farklı pozisyonda çalınmasının nedeni gitar sapı farklı konumlardan uyarıldığında oluşacak sonuçları gözlemleyebilmek içindir. Oluşan titreşimi elde etmek için geniş bir frekans aralığı ve sabite yakın bir frekans cevabına sahip olan piezofilm sensörler kullanılmış ve bunlara deneye uygun olacak şekilde kablo ve çıkış eklentisi yapılmıştır. Ek olarak piezofilm sensörlerin kütlesi oldukça düşük olduğundan gitarların doğal frekansına olan etkilerinin ihmal edilebilmesine izin vermektedir.

Analizler MATLAB ortamında Wavelet Toolbox kullanılarak yapılmıştır. İlk olarak Sürekli Dalgacık Dönüşümü kullanılarak mümkün olan en yüksek çözünürlükteki sonuçlar elde edilmiştir. Daha sonra Sürekli Dalgacık Analizinin talep ettiği bilgisayar gücünün çok fazla olması ve elde edilen sonuçların çözünürlüğünün, birçok uygulamanın gerektirdiğinden daha fazla olmasına dayanarak; daha az hesaplama yükü gerektiren aynı zamanda da gereken ayrıntı seviyesini sağlayabileceğine inanılan Dalgacık Paket Dönüşümü, seçenek sunmak amacıyla uygulanmıştır. Sonuçlar, harmonik ve anharmonik frekanslardaki bileşenlerin Fourier Analizi yöntemleriyle ulaşılamayacak düzeyde elde edilebildiğini göstermiştir. Elde edilen çözünürlük, tek başına bir gitarın tınısal özelliklerinin yorumlanmasına olduğu kadar iki gitar arasında karşılaştırma yapılabilmesine de izin verecek seviyededir. Genel olarak gitarlarla ilgili şunlar gözlemlenmiştir: 1. Gitar daha sade bir tınıyla beraber kısa ve zayıf bir sese sahipken, 2. Gitar zengin, temiz bir tınıya ve daha dolgun ve tanımlanabilir bir sese sahiptir. Ek olarak, yüksek frekanslardaki birleşenlerinin sahip olduğu enerjinin yüksekliği nedeniyle, 2. Gitarın tınısının "parlak" olarak ifade edilen özelliğe sahip olduğu söylenebilmektedir. Dalgacık Paket Dönüşümü analizinin sonuçları ise, daha az bilgisayar gücü kullanılarak, anlık frekans değerleri hakkındaki detaylar dışında, benzer gözlemleri yapmaya izin veren bir seçenek olduğunu göstermiştir.

1. INTRODUCTION

Music fascinates us, it alters our emotions and how it does this, is rather magical. So, it is no wonder scientists tried to find inner workings and phenomenon underlying the process.

Pythagoras and his school first stated a relationship between numbers and rhythm and defined harmonic relationship between musical notes using numbers [1]. Helmholtz studied frequency content of musical tones and their relationship [2]. In addition, in the modern era, musical signal processing, along with the speech and image processing, is the main application area of digital signal processing research.

Instrument making is a traditionally empirical process, which relies on the ears of instrument makers and players ears. Most of the design approaches that are being used today was invented as back as 18th century by Anthony Torres Juredo [3]. One of the most established technique for studying characteristics of acoustic guitars is Chladni patterns [4]. Invented by physicist Ernst Chladni, technique is for determining the vibration modes of the plates made from different materials. After spreading a low density material in dust form on the plate in focus, it is excited by an external force and the patterns the dust creates is observed. It can be understood that this method is rather cumbersome. However second half of the last century possesses promising advancements for researching and testing the characteristics of the guitar such as digital image analysis, Finite Element Method (FEM) analysis and Fourier analysis with the different experimental procedures such as hammer and sine sweep excitation on a freely supported guitar. But, none of these techniques find a popular place among the independent instrument makers probably because they are either complex in theory or hard to implement which makes them hard to perform for large number of times. Therefore, completely constructing the instrument and evaluating by ear is still a wide choice. Moreover, when buying most audio equipment, one can reach the frequency response or can reach the full technical specifications which they can have a rough idea about the sound of the equipment. Main reasons of this is that there are considerable number of research on categorization (or mapping if you will) of the sound characteristics of these equipment to their design parameters. On the other hand, even though one can also obtain the full specifications of design and build of a music instrument, they still have hard time to imagine their projection to the resulting sound and playability of the particular model or design. Thus, most of the end users, especially the ones inexperienced or not the specialist in the topic still lean on reviews of others. It is not uncommon to came across questions like "Is this guitar have these characteristics?" or "Is this guitar have that characteristics which is important for that particular genre" or even questions about the sound and playability of almost same design but built in different countries or one is more economical then the others. On top of these, it is no secret that not everyone has the financial means of obtaining a carefully handmade instrument from a renowned luthier or obtaining a build that is well established. So, specifics of the characteristics become more and more important. At this point, it should be stated that the "sound characteristics" repeatedly used above can be defined as timbre which will be looked in detail later. Most of the constraints causing the mentioned shortcomings comes from timbre being a complex concept consists of multiple different phenomenon and being a concept can mostly be defined through the human perception of it.

This study presents a practical and accurate technique using the power of wavelet analysis for investigating timbral qualities of classical guitars. Work includes complete work frame from the experimental procedure through capturing the data with piezoelectric film sensors, which have not been widely applied for this type of application, to the analysis of captured information. Aim is to present a study for more objective evaluation of guitars that is suitable for performing by the different parties of the field; from instrument makers and designers to the quality control engineers and end users. It is believed that with the right improvements and modifications if needed, system presented in this thesis can be used for detailed cataloging of different guitars and their timbral characteristics which in turn can be used in wide range of areas such as music information retrieval, guitar research and development and probably even for genuity tests of the guitars.

Structure of this report is as follows: since it is obvious to first understanding the concept that is being investigated, timbre is explored at the next chapter. Properties of timbre and the studies that discovered these properties are reviewed. In the following chapter, Wavelet theory, which is the backbone and most important aspect of this study, is explained in a level that provides intuitive grasping of the concept, because the area is vast and ever improving. Then subject of the study that is guitar is presented through the studies of guitar analysis literature. Then, naturally comes the chapter that the experimental setup and procedure is explained as well as performed analysis and its results are presented with their interpretation and comments. Finally, conclusion of the study with a discussion is given.

2. TIMBRE

There is no exhaustive definition of timbre. One of the most used and accepted definition is by American National Standards Institute [5]; which points to the difference of two sounds having the equal loudness and pitch as they perceived by a listener. It attributes this difference to spectrum content as well as time-varying properties of both the signal as a whole and its frequency components.

Spectral content being the foundation for timbre, envelope of the components of the sound is also an important property needs to be considered. Much like any object, musical instrument have natural frequencies. These natural frequencies are the ones that the instrument vibrates on a partical level. If an instrument is excited with an equal or a harmonic of these frequencies. It results with sympathetic vibrations which have larger amplitude then other components. Natural frequencies are determined by build and material choice and they will be present in the radiating sound of the instrument independently from the content it is excited [6]. Thus, non-integer harmonics of a played pitch created by the acoustical qualities of the instrument and their amplitude ratios have an important effect on its timbre.

Study in [7] shows the effect of transients on an instruments timbre by investigating the recordings of wind instruments. It also presents that transients which occur in the first 10 ms of the signal have different contents from the steady state portion.

In [8] researchers investigate the different elements that affect timbre. The research is done by employing three methods: removing the attack and decay portions of the signal; altering the attack and release portions of the signal and taking some of the partials out of the signal. Results show that the transient portion of the signal is considerably important in the recognition of timbre.

Study [9] shows the effect of time differences between the frequency components of a tone. A listening experiment is conducted using stimuli which are combinations of the same two frequency components but altering the phase between them. Results demonstrate that different phase relationships between the partials is important for differentiating timbres.

Work in [10] researches for a compact criteria space for the recognition of timbre. Results present following properties of the sound signal as important factors for timbre recognition: distribution of energy among the frequency spectrum including inharmonic partials; amount of energy in the attack time that is resulted from high frequency and low amplitude; phase relationship between the transient portions of the high frequency components and variation of frequency with time.

3. WAVELET THEORY

Although traces of Wavelet theory can be followed back to the 1900s with Alfred Haar, the modern Wavelet theory can said to be started with Morlet [11]. After discovering a new technique, he then worked with Grosmann to strengthen the foundations of his findings. The word "Wavelet" was first used in their 1984 paper. Meyer, already working on the theory, developed orthogonality of the wavelets. Mallat, in his 1986 paper, presented the "Multiresolution Analysis" by studying the previous literature and connecting the dots that are different techniques which are now considered as part of wavelet theory. In 1987, Daubechies constructed a new wavelet family which is now highly popular and rightfully named "Daubechies Wavelet".

Mathematical transforms can be considered as looking same information with a different viewpoint [12]. This gives the ability to see some information that is present in the signal but not so obvious to see or work with. To define the transform operation and be able to make a smooth transition between different techniques, it is a good idea to first define the inner product. The inner product of two vectors or functions can be defined as:

$$\langle f, g\rangle = \int f(x) g^{*}(x) dx \tag{3.1}$$

Where the symbol "*" identifies the complex conjugate of $g(x)$. It is appropriate to begin the road with Fourier analysis and go to the wavelet. Fourier analysis is a technique of decomposing any finite energy periodic or non-periodic function with sine and cosine basis functions for expressing it in the frequency domain. Using the definition of inner product in equation (3.1), Fourier transform can be defined as:

$$\mathcal{F}\{x(t)\} = \langle x(t), e^{-j\omega t}\rangle = X(\omega) = \int_{-\infty}^{\infty} x(t) e^{-j\omega t}\, dt \tag{3.2}$$

As seen on the equation (3.2), Fourier transform is performed over complete duration of the signal at once [13]; as if it is a prism which white light passes through it decomposed to its color components. Thus, individual time information of the frequency components are not presented. To obtain this information, "Windowed

Fourier Transform" or "Short Time Fourier Transform (STFT)" is developed. That is computing the Fourier transform of the signal for the portions determined by a fixed and finite size window and decomposing that portion to sine and cosine functions which enables us to see components present only in that portion. Thus, giving a time information about the components. If we define the STFT by the same way we defined the Fourier transform in equation (3.2) using equation (3.1):

$$STFT_g(t,\omega) = \langle x(t), g^*(t)\rangle = \int_{-\infty}^{\infty} x(t) g^*(t-\tau) e^{-j\omega t}\, dt \tag{3.3}$$

The STFT processes the signal with a fixed size window with the dimensions Δt and Δf. The relationship of time and frequency [14], which can be thought as resolution, is restricted in practice which can be explained using Heisenberg's Uncertainty Principle; based on the equation (3.3) mathematical definitons of Δt and Δf are:

$$\Delta t^2 \cong \frac{\int_{-\infty}^{\infty} t^2 |g(t)|^2 dt}{\int |g(t)|^2\, dt} \tag{3.4}$$

$$\Delta f^2 \cong \frac{\int_{-\infty}^{\infty} f^2 |G(f)|^2 df}{\int |G(f)|^2\, df} \tag{3.5}$$

Applying Heisenberg's Uncertainty principle, the restriction of time frequency resolution is:

$$\Delta t \Delta f \ \geq \frac{1}{4\pi} \tag{3.6}$$

It is discovered [15] that instead of sines and cosines, when Gaussian window functions are used, equation (3.6) becomes an equality.

STFT has the disadvantage of using fixed size windows, because a real world sound signal consists of both low and high frequency components. A window with a fixed size lacks the accuracy either in low frequency or in high frequency components when it is too short in time or when the size is too long respectively. The first solution naturally comes to mind is the usage of varying sized windows. So, if we denote $\psi(t)$ to a window (basis) function with a variable size and interchange the window function in equation (3.3), we get:

$$\langle x(t), \psi(t)\rangle = \int_{-\infty}^{\infty} x(t)\psi(t)\, dt \tag{3.7}$$

Which is the basic definition of Continuous Wavelet Transform (CWT). We can define the window function as:

$$\psi_{a,b}(t) = \frac{1}{\sqrt{a}}\psi(\frac{t-a}{b}) \tag{3.8}$$

Where "a" is the scaling parameter and the "b" is the translation parameter that are used to modify window size and move the window respectively. The factor on the equation is added to normalize the wavelet function and create a unit "mother wavelet". The definition also shows that CWT transforms a time domain signal in to the time-scale plane, this creates the need to convert scale values to frequency values for a more intuitive analysis. Approximate calculation of frequency values from scale values can be made with the equation:

$$s \cong \frac{f}{f_0}$$

Where s is the scale value, f is the corresponding frequency and f_0 is the base frequency, which is the approximate center frequency of the basis function in the frequency domain. Using the equations (3.7) and (3.8), a more formal and detailed definition of CWT is:

$$CWT_{\psi_{a,b}} = \frac{1}{C_\psi}\int_{-\infty}^{\infty} x(t)\psi_{a,b}(t)dt \tag{3.9}$$

Here the term $\frac{1}{C_\psi}$ introduces a condition which is called admissibility condition. The admissibility condition is defined as:

$$C_\psi = \int_{\mathbb{R}} \frac{|\psi(\omega)|^2}{\omega} d\omega < \infty \tag{3.10}$$

To satisfy the admissibility condition, equality below must be satisfied

$$\psi(\omega = 0) = \int \psi(t)dt \tag{3.11}$$

Combined with the definition of CWT in equation (3.9) and definition of admissibility condition in equation (3.10); the equality in (3.11) tells that to perform CWT with a basis function, i.e. a basis function to be a wavelet, its total area in the time domain must be zero.

By looking at its fundamental form, it can be understood that the Continuous Wavelet Transform is computed for infinite number of translations. This results with impractical computation. Also, shifts of the wavelet with infinitely small intervals creates an overlap between successive windows and this creates a high degree of redundancy. To overcome this, scaling and translation parameters can be discretize. By this, one is still employing so to say CWT but its computed using discrete values. But even in this way, redundancy is still present and this makes the perfect inversion of transform impossible which is causing the phenomenon known as aliasing. True Discrete Wavelet Transform (DWT), is developed mainly with the studies of Meyer [16] and Mallat [17]. Meyer found the orthogonality of wavelets. Orthogonality can simply be defined as all of the basis functions of a vector space satisfying the following equality: let V_1 and V_2 are functions (or vectors) of a vector space V then,

$$\langle V_1, V_2 \rangle = 0$$

This allowed performing a wavelet transform with discrete parameters in a way that the transform is not redundant thus making perfect reconstruction possible when orthogonal wavelets are used. Meyer added that the analyzed signal can be decomposed in to orthonormal, that is orthogonal and normal to each other, vector subspaces if orthonormal wavelets is used. This way a signal can be analyzed to a desired level that can be thought as resolution, using sequence of wavelets that are scaled versions of the mother wavelet. Which making wavelets similar to low-pass and high pass filters, thus removing the necessity of tuning the parameters of wavelets according to particular analysis and consequently enabling the possibility of adaptive analysis. Meyer named this technique as Multi-Resolution Analysis (MRA).

Later Daubechies developed wavelets [18-20] that are compactly supported orthonormal wavelets with the highest number of vanishing points. In simple terms, Daubechies wavelets are zero outside of their defined time interval and have the highest time-frequency localization. Also, since they are orthonormal, they can be used in DWT and in MRA.

In MRA, sequential filters are applied to the output of the low pass filter in preceding level and the output of the high-pass filter is not being filtered again. This is a disadvantage of the technique when it is performed on signals that have information spread out through the whole frequency range of the signal, such as sound signals. Coifman, Meyer and Wickerhauser [21-23] introduced Wavelet Packet Transform (WPT) which filtering process applied also to the output of the high-pass filter at the preceding level and eliminating the aforementioned disadvantage. This creates a tree structured analyzing scheme. As a result, WPT got a place between CWT and MRA in the following sense: output of WPT can be perfectly constructed and computationally more efficient than Continuous Wavelet Transform but the resolution of WPT is lower than CWT whereas WPT is not at as efficient as Discrete Wavelet Transform while having a higher resolution. Figure 3.1 shows how mentioned transforms creates a grid on the time-frequency plane. It can be a good way to intuitively grasp the concept. Grey area in the graphics, implicates the overlap.

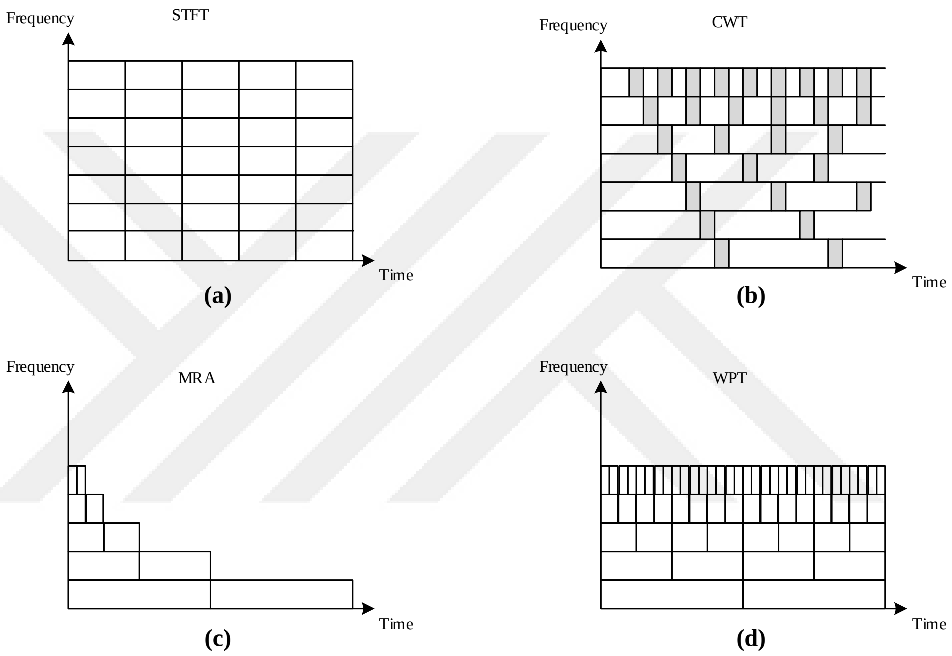

Figure 3.1: Grids on time frequency plane created by the windows of different transforms (a) STFT, (b) CWT, (c) MRA, (d) WPT.

3.1Applications of Wavelet Analysis to Musical Signal Processing

A survey of the application of wavelet analysis to musical signals, especially signals of musical instruments, is presented in this chapter. In an attempt to demonstrate suitability of wavelet analysis in this area as well as its preference over Short Time Fourier Transform, also to provide a review of literature on the topic.

In the study [24] why time-frequency analysis is required for musical analysis is explained as following: musical instrument sounds consist of sinusoids with different frequencies and these sinusoids have properties that changes with time, making them non-stationary. Moreover, in instrument sounds, partials get crowded in low frequency range as a result of body frequencies. Another characteristic of musical signals is that their frequency components are not distributed on a uniform scale, they rather distributed in a logarithmic scale of base 2 which is called an octave. Therefore, discretization of scaling and translation parameters of wavelet analysis using values that are powers of 2 is a logical choice. When a sequence of pitches played in a musical instrument, transitions between the notes have closely spaced frequencies much like the body vibrations. On top of all these reasons, musical signals have important information in sudden changes i.e. transients. These show that time-frequency analysis is required since Short Time Fourier Transform window has a fixed size and it is not adequate for separating closely spaced frequencies as well as accurately capturing information on a logarithmic scale. To demonstrate their statements, researchers perform wavelet analysis using Gabor wavelets. Same sequence of three notes is played on a piano, a flute and a guitar. Tuning of the parameters of the Gabor wavelet such as center frequency and frequency bandwidth is explained and performed according the lower most partials of played pitches. Presented results show that performance of the particular analysis is adequate for a detailed investigation.

To emphasize the aforementioned ability of performing wavelet analysis with a logarithmic grid, it is worth to mention that there are studies of wavelet transform is based on the model of the perception of ear [25].

Paper [26], makes the similar points about the non-stationary nature of the musical signals and time varying properties of the frequency component and adds that as a result of this phenomenon our pitch and timbre perception is the composition of temporal and spectral characteristics thus, any analysis of timbre requires time-frequency localization. Moreover, researchers state that empirical mode decompositions such as Wigner-Ville Decomposition and Hilbert-Huang Transform are more suitable for these applications since they are frequency parameter based whereas wavelet transforms are scale parameter based. To demonstrate their ideas, explained techniques are applied and results are compared. One point made in the paper should be emphasized since it is also one of the main arguments of this thesis. That is the musical signal processing research generally focused on the analysis at molecular levels so to speak. This is probably the result of having insights on the rather mystique process of musical composition is more fascinating or probably because the aim of providing help for the needs of composers. Whichever it be, it is clear that studies on the micro levels of musical signals is a less crowded area. Also, a comment can be made on the usage of mode decomposition techniques being more suitable; it is this author's opinion that they have more strict structures and are more complex to use then wavelet analysis and the difference of practicality is bigger than the amount of advantage they provide over wavelet analysis.

Paper [27] studies the application of wavelet transform for musical signal processing. Useful guidelines for employing wavelet transform are presented. Such as:

- Gabor and similar Gaussian-like windows has the maximum simultaneous concentration in time and frequency
- Complex mother wavelets are useful for analyzing audio signals because, Fourier Transform of these wavelets are zero for negative frequencies.
- In musical signals, analysis should be performed for 10 octaves minimum. Which is the average range of human ear.
- Usage of smoother wavelets reduces frequency leakage.

Study in [28] uses wavelet analysis for musical feature extraction, Discrete Wavelet Transform is applied to the groups of wind, string and percussive instruments. Based on the results, a recognition system using Artifical Neural Networks is built. Daubechies 2, Daubechies 5 and Symlet 2 wavelets are used to determine which one is more suitable and Daubechies 2 wavelet was chosen. It is reported that success of recognition is weak within the same family of instruments however high between different families.

Study [29] presents a musical signal model based on the insights obtained using complex continuous wavelet analysis. Presented model is a combination of sinusoids with the addition of a transient signal. To test the model a synthesized signal is compared with the original signal and the synthesized signal is reported to have a high quality.

4. ANALYSIS OF GUITARS

The version of the guitar we used today has six strings and the pitches these strings tuned are E2, A2, D3, G3, B3 and E4 with the frequencies of 82 Hz, 110 Hz, 147 Hz, 196 Hz, 247 Hz and 330 Hz respectively. Strings of guitar tied to tune heads at one end and to the bridge on the other end in a parallel position to each other. The classical guitars, such as the objects of this study, are acoustic instruments with nylon strings. The main energy of sound generated by guitar comes from the body [3]. If one trace the signal generated by the vibration of strings; it can be seen that vibrations of top plate, back plate and air cavity as well as their coupling contributes to the final sound radiating from the guitar with different weights and in different frequencies. Bracing, size and the choice of wood being the design parameters have the most effect on the final sound and how they being assembled coming second. When it comes to measuring and detecting those frequencies and vibration modes, different techniques and experimental setups are being used. Each designed for obtaining and thus pointing different qualities.

In [30] vibrational modes and modal shapes of classical guitar is obtained using holographic inframetry.

Finite Element Method (FEM) analysis used in paper [31] to research the parameters of guitar design before completely constructing it. Mechanical model of the guitar is developed. Vibration modes obtained by the FEM analysis is compared with different studies which the modes are measured with different techniques. It is stated that similar modes are obtained. Furthermore, based on the FEM analysis, effect of different design parameters investigated.

In study [32], resonance frequencies and modal vibrations of the guitar body (without neck attached to it) are investigated using Chladni patterns and accelerometers. Guitar bodies are supported with the maximum degree of freedom and excited with a mini-shaker. In [33], FEM analysis was performed and compared with the previous study.

In the study [34], on top of the FEM; measurements were done using accelerometers attached to sound board. As an excitation, hammer impact was applied to a freely supported guitar. Moreover a second measurement technique, called "Digital Image Correlation" was used. In this method, again a freely supported guitar excited acoustically with a sound source and resulting vibrations captured with high speed cameras. These captured images digitally processed using a software package. Fast Fourier Transform of the captured information is presented. Findings of all three methods are compared and high correlation between them is reported

Study in [35] investigates the effect of neck material and its attachment method to the vibrations of guitar body. Experiments were done using different guitars with using different excitation methods. Additional experiments were done on a single guitar with exciting the neck itself as well as neck attached to the body. For the measurements frequency response obtained using sine sweeps and processed using Fast Fourier Transform. Chladni patterns was used for obtaining modal shapes. High influence of neck on the vibrations of total guitar body is reported.

Paper [36] studies the transients of modal frequencies belong to the string, guitar body and the coupling of the two. The first of important differences in this study is that as an excitation method, plucking of the string was used. Main measurements were done by accelerometers and for analysis STFT is used which is the second important difference. It is stated that time-frequency techniques, which STFT belongs to, are more suitable in this type of applications since especially transients of the frequencies are important and frequencies of the obtained signal is close to each other. Additionally, for investigating its validity, measurements using microphones was performed and the comments was made on the results. The accelerometer results are compared with the synthesized sounds based on the mechanical models and it is reported that both confirm each other with a high degree. It can be understood that in this study, researchers are looking for a more practical, generally applicable and at the same time a more detailed experiment, measurement and analysis method for analyzing guitar sound.

Methods in the studies above have both their advantages and disadvantages probably due to the technology at the time of each study. Mainly, experiment setups are hard to install in some of them, it is hard to create a general catalog of the resonant frequencies because it is not practical to install those experimental setups for large number of times. Moreover, FFT doesn't provide any time-frequency localization while STFT has lower resolution and doesn't have the flexibility for analyzing sound signals. However model shapes of guitar bodies can only be obtain using holograms, digital image correlations and Chladni patterns, Also, FEM is the most efficient way of modelling them. The system proposed in this thesis not only demonstrates the application with the current and improved technology; it is argued that system proposed in this thesis provides a practical experiment method and accurate analysis thus enabling a realistic opportunity to create a catalog of resonant frequencies of different guitar designs and different production methods. However, it has the disadvantage of not obtaining modal shapes.

5. EXPERIMENT, ANALYSIS AND RESULTS

Experiments was performed in the main studio of Istanbul Technical University/Center for Advance Studies in Music. A mass produced guitar that is described as a learning guitar by its production company and a luthier-made guitar were used. Procedure is done while a guitar player holding the guitar in a conventional playing position and plucking the strings with a pluck. A photograph showing the player while holding the guitar is presented in figure 5.1. A minor diatonic scale with addition of A minor chord at the end, both in open position and 5th position is played. Choice of the played scale was rather arbitrary whereas the choice of playing the scale in two position on the fingerboard is made to observe the effect of excitation epicenter on the finger board. Each material is played at least for 5 times to obtain most consistent data.

Figure 5.1: Holding position during the esperiment.

Piezo film sensors, specifically two SDT-028K are used because the accelerometers used in the reported studies on the previous chapters have a narrower range of frequency response whereas, piezofilm sensors, as stated in their datasheet [37] have the frequency range between 10 Hz to 100 kHz. Piezoelectric film sensors consist of capacitive film and the vibrations of the surface that the film attached on creates pressure on the film and in turn the film creates electric potential as a result of the electrostatic field created by the movements of the electrons in the film. Moreover while accelerometers have considerable deviation from the flat frequency response [38], SDT-082K has an almost flat frequency response. Additionally, since SDT-082K has relatively lower mass compared to the other vibration sensors, its effect on the natural frequency response of the guitar body is negligible. The choice on the number of sensors used in the experiment is bounded by financial limits; two was the highest number of acquirable sensors within the limit. Sensors modified with cables having the gauge around 20 AWG to be able to place electrical end in a comfortable distance. For the connection to the amplifier system 6.35 mm TRS plug was soldered to the open ends of the cable. One sensor is placed next to the air cavity in a parallel fashion on the side that is between the air cavity and ground when guitar is held in playing position. Other sensor is placed right under and parallel to the bridge; that is the side between bridge and the end of the guitar body. Figure 5.2 shows the placement of sensors on one of the guitars. Sensor placement is based on the common points of modal vibrations that are observed on the studies which are again reported in the previous chapter. Common areas was the top and bottom sides of the bridge and a lung shaped area around the air cavity. Although intensity of vibrations on the top of the air cavity is bigger, placing the sensor on the bottom part could be more convenient because of the playing position. Sensors are attached using non-foam double sided tapes as recommended on their datasheet. While choosing the tape, not harming the coating on the wood but a tape that can safely carry the sensors is considered. It has been seen that the tape is not damaged the coating in both guitars. Additionally to obtain different samples, sound is captured using microphones and same material above is played in a higher speed for gathering data, which has the information of note transitions.

Figure 5.2: Placement of the sensors on the guitar body.

Sensors are connected to isolation transformers. Input impedance of the transformers are set to 1 MOhm as the minimum recommended value in the datasheets of the sensors. Output of the transformers are connected to commercial preamplifiers and signals recorded through an audio interface with 24 bit bit-depth and 44.1 kHz sampling rate. Signal flow of the experiment can be seen in figure 5.3.

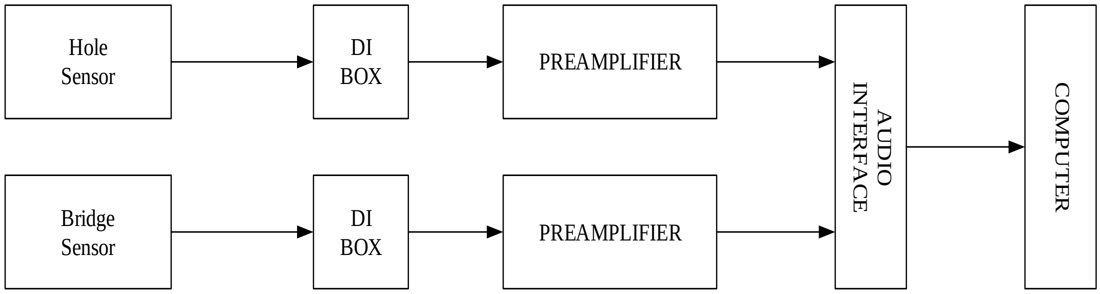

Figure 5.3: Signal flow of the experiment

5.1 Analysis and Results

Analyzing the complete database resulted from experiments would far exceed the time limitations of this study. Therefore, samples of A2, A3, A4 pitches at the both fingerboard positions and from the both of the sensors are selected. Choice was made with the purpose of covering the most of the frequency range of guitar while keeping the variables at minimum. Because priori knowledge about the researched properties is existed, first, continuous wavelet analysis performed for maximum resolution and to create reference point. Analysis were performed in MATLAB environment using Wavelet Toolbox. For the analyzing wavelet Analytic Morse Wavelet was chosen among the available wavelets in the toolbox [39]. Analytic Morse Wavelet is chosen because it has more tunable parameters according the needs of the application and by tuning parameters similar behavior to the other continuous wavelets can be obtained [40]. Approximate center frequency of the mother wavelet is tuned according to fundamental frequencies of the played pitches as well as expected harmonic and inharmonic partials of them. Time bandwidth parameter (p^2) that corresponds to width of the wavelet in the time domain and symmetry parameter (γ) that corresponds to distribitiuon around the peak frequency of wavelet tuned to 120 and to 3 respectively for best resolution within the computational limits of the used computer. 20 voices per octave was set for again the frequency resolution. To be able to present the 3D time-scale plots of the data obtained from the output of transform, energy of every scale is calculated and the first 100 scales that have the most energy are used for graphics. For more intuitive evaluation of the results, scale values are converted to approximate center frequencies. For convenience, only the graphics obtained from the analysis of the signals captured both from bridge and hole sensors of pitch A3 when played on both guitars in open position and in 5th position are presented in figure 5.4. Rest of the results can be found in Appendix A. For the rest of the text, the mass produced guitar will be referred as “Guitar 1” and the luthier-made guitar will be referred as “Guitar 2”.

Continuous Wavelet Transform is a highly computation heavy method for general applicability and the resolution of the results can be far more detailed than necessary for some applications in the area. For this reason, Wavelet Packet Transform is performed to present a more computationally inexpensive solution that provides adequate detail. WPT is computed for 10 levels which corresponds to a minimum frequency bandwidth of 32 Hz. For analyzing wavelet Daubechies wavelet with 4 vanishing moments is chosen because while the lower vanishing moments providing better time resolution, high vanishing moments (smoother wavelets) provide better frequency resolution. Since, WPT is not redundant and have lower resolution, output data was smaller than the CWT. This allowed the usage of first 125 frequencies that have the most energy in the graphics. In addition, because the resulting waveform is discrete due to resolution there were no need to present the graphics in 3D. Again, for convenience only the analysis of signals that are results of playing pitch A3 is presented in figure 5.5. Rest of the results of WPT can be found in Appendix A.

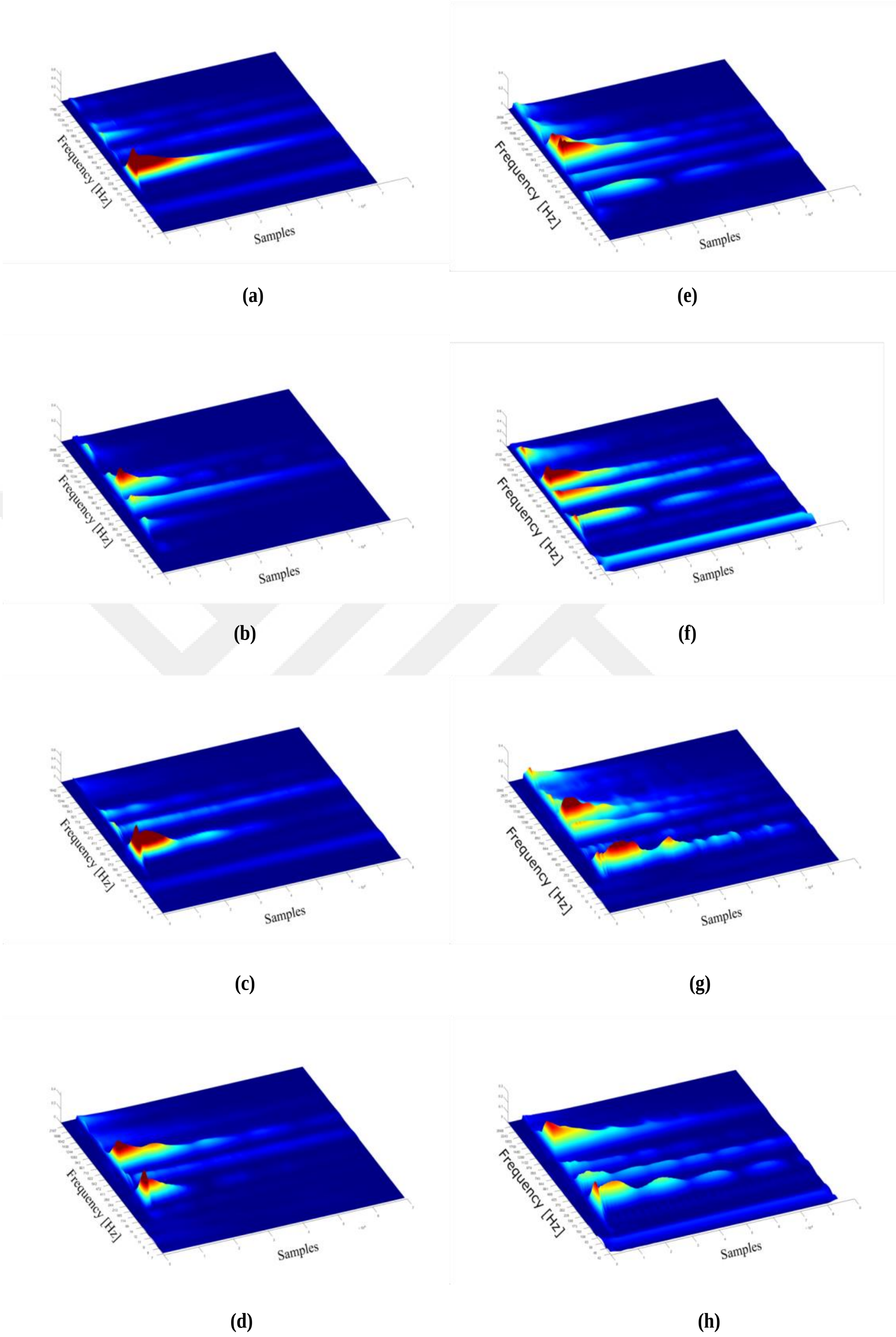

Figure 5.4: CWT results of pitch A3: (a) Guitar 1, open position, bridge (b) on Guitar 1, open position, hole (c) Guitar 1, 5th position, bridge (d) Guitar 1, 5th position, hole (e) Guitar 2, open position, bridge (f) Guitar 2, open position, hole (g) Guitar 2, 5th position, bridge (h) Guitar 2, 5th position, hole

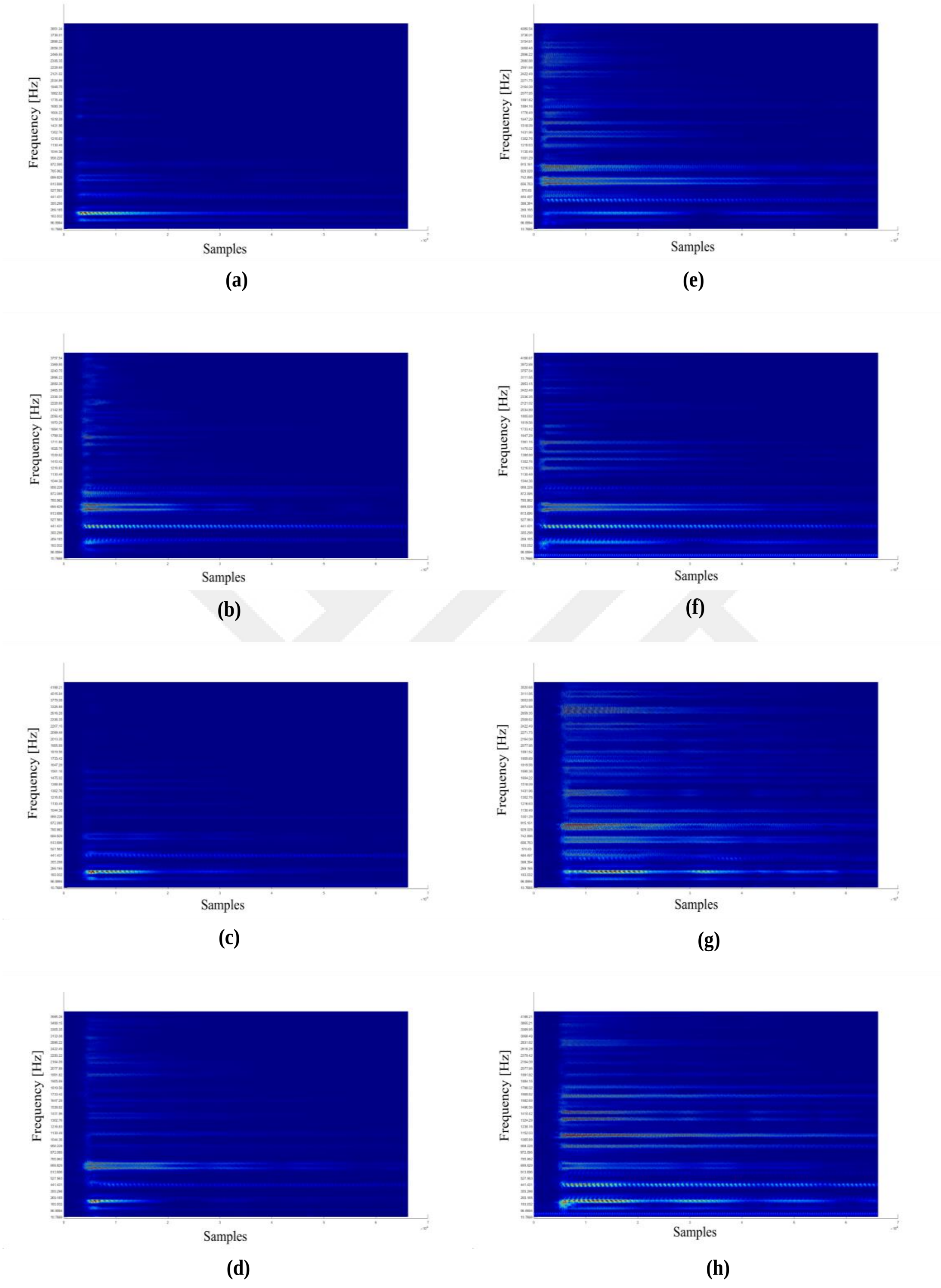

Figure 5.5: WPT results of pitch A3: (a) Guitar 1, open position, bridge (b) on Guitar 1, open position, hole (c) Guitar 1, 5th position, bridge (d) Guitar 1, 5th position, hole (e) Guitar 2, open position, bridge (f) Guitar 2, open position, hole (g) Guitar 2, 5th position, bridge (h) Guitar 2, 5th position, hole

Before making remarks on the guitars, it should be stated that results clearly support the superiority of wavelet analysis over Fourier and Short Time Fourier Transform. It can be seen by looking at graphics that localization at the low frequencies is in a degree that can't be reached using STFT. Partials as low as 30 Hz are observable. Also, wavelet analysis can more accurately present non-harmonic partials. For example, in the figure 5.4 partial with the frequency of 660 Hz can be seen even though it is not a harmonic partial of pitch A3 since, 660 Hz is not even multiply of 220 Hz. By comparing the graphics in figure 5.4(a) and 5.4(b) which belongs to pitch A3 being played on Guitar 1, in the same open position but from bridge and hole sensors respectively; it can be observed in figure 5.4(a) that most prominent higher partials of bridge portion are approximately at 660 Hz and 880 Hz and even these partials don't have a high energy ratio relative to the formant at 220 Hz whereas in figure 5.4(b) it can be seen that hole area of the guitar not only have larger number of more prominent higher partials which are at 440 Hz, 660 Hz, 880 Hz and 1760 Hz, energy intensity of these partials are higher than the partials in bridge area. One interesting evidence in the graphics is that the formant at 220 Hz has lower energy in hole area while the harmonic partial at 880 Hz having the most energy among the components. Considered that the signal has a more composite structure around the air cavity this shows the reaction between the back plate and top plate through the air coupling. If we investigate same aspects in Guitar 2 using figure 5.4(e) and 5.4(f), we can see that the frequency of partials as well as energy distribution among them is similar between hole and bridge area. A comparison can be make using this evaluations, That is the body vibrations are more homegenous in Guitar 2 when compared to Guitar 1. If we observe the difference of fingering postition using figures 5.4(a) and 5.4(c), figures 5.4(b) and 5.4(d) for Guitar 1; while the frequency location of partials almost similar there are slight differences between time envelopes. Same can be made for Guitar 2 using figures 5.4(e) and 5.4(g), 5.4(f) and 5.4(h). This implicates that effect of fingering position is close to none on the overall timbre of guitar. If we look at the time envelopes in all the graphics that belongs to Guitar 1, we can see that energy is spread around the center frequency towards the neighbor harmonics. Also, within the individual frequency components, energy is concentrated towards to attack portion which makes attack portion percieved more intense while making damping portion shorter. Another obsevartion is that the instantenous frequency of the formant matches to its tuning frequency almost instantly. If same aspects are investigated in Guitar 2, it can be seen that energy of partials is more concentrated on their center frequency while having a more even distrubution in the time envelope with the relatively low intensity in the attack portion and longer damping time. Also the steady state portion of the components are prominent in Guitar 2. However there is a distingushible time for instantaneous frequency to match its tuning frequency which can be explained by Guitar 1 much more older than Guitar 2 and the woods used in musical instrument need time to mature for reaching its ideal sound characteristic. An apperant observation that can be made using figures preseented in appendix A is that the frequency range of Guitar 1 is narrower with the highest partial being at around 3900 Hz and it is being around at 5900 Hz.

Using graphics in figure 5.5 and comparing them to their corresponding ones in figure 5.4 it is proved that the results of the Wavelet Packet Transform shows same aspects of the signals except for the details on instantaneous frequencies or instantaneous power. Therefore, it is adequate for making similar observations while having less computational load.

6. CONCLUSION AND DISCUSSION

In this study, investigation of the timbral qualities of classic guitars using wavelet analysis is presented. The aim was providing a more practical experiment procedure as well as more accurate analysis of the signals thanks to wavelet analysis. Experiments performed on two different guitars using piezoelectric film sensors for capturing vibrations. Results show detailed presentation of harmonic and non-harmonic partials as well as time envelopes of them in a resolution that can't be obtainable using Short Time Fourier Transform. This allows for objective analysis on the timbre of a guitar as well as making comparison between the timbral properties of the two guitars. To demonstrate this analysis, evaluation of all the graphics can be summarized as next. in Guitar 1 more partials are present around the hole then there are around the bridge. Also, difference of the number of partials between the two is considerably large. This implicates that the vibrations are heterogeneous over the body. Distribution of energy among the partials is not balanced with higher partials having the least energy. Also, synchronicity between the time envelopes of partials is considerably low while most prominent partials of the guitar having a very intense attack and correspondingly short attack time. Moreover, all the partials decrease to zero very rapidly which is the implication of low sustain characteristic. The overall frequency range of Guitar 1 goes up to around 3900Hz. In Guitar 2, while having more partials compared to Guitar 1 in every corresponding sound sample, energy is distributed more evenly among the partials with high synchronicity between the time envelopes of the partials. Attack time is longer in Guitar 2 and partials decrease to zero more slowly than Guitar 1. It is observed that amount and the frequency of partials almost same in the hole and in the bridge signals which shows that vibrations are homogenous over the body. Guitar 2 have partials up to 5900 Hz. It is seen that in Guitar 1, energy is spread around close frequencies whereas in Guitar 2 it is concentrated. In Guitar 2, time it takes for instantaneous frequency of the fundamental to match its tuned frequency is longer than Guitar 1; this could be due to Guitar 1 being older than Guitar 2 and it is known that wood takes time to mature. In general, it can be said that Guitar 1 has simpler timbre with low sustain and low definition while

Guitar 2 having richer, cleaner timbre with higher sustain and high definition. Also, Guitar 2 has more high frequency partials than Guitar 1, making its timbre what is called "bright". Because Continuous Wavelet Analysis is computationally too expensive; application of Wavelet Packet Transform is presented as a faster and less detailed but still having adequate time-frequency resolution analysis method for most of the applications in the area. Additionaly it should be noted that; conducting the experiments in a small or acoustically untreated room may cause interference of room resonances. Since MIAM Studio is both acoustically treated and big, this interferences did not occur in the experiments, but for other places, effect of room also needs to be examined.

Extend of the experiments and analysis is limited by the financial and time constraints. Author is well aware of that with its current state proposed methods is not completely ready for general usage but with the right improvements and additions such as; using more sensors that some of them on the back plate of guitar body can provide broader analysis, performing experiments at the each iterations of guitar making process makes the seeing effects of different design parameters on the final product possible which in turn can be used for guitar research and development. Performing the experiment and analysis on different guitars with the same design or on with different builds with the same design can make it usable for guitar quality test as well as for categorization of guitars and their sounds. Therefore, it is firmly believed that work frame suggested in this thesis initiates a powerful system for analyzing timbral qualities of guitars while undoubtedly contributing to the literature on the application of wavelet transform on micro level analysis of musical signals.

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APPENDIX

APPENDIX A: Remaining CWT and WPT Result Graphics

APPENDIX A

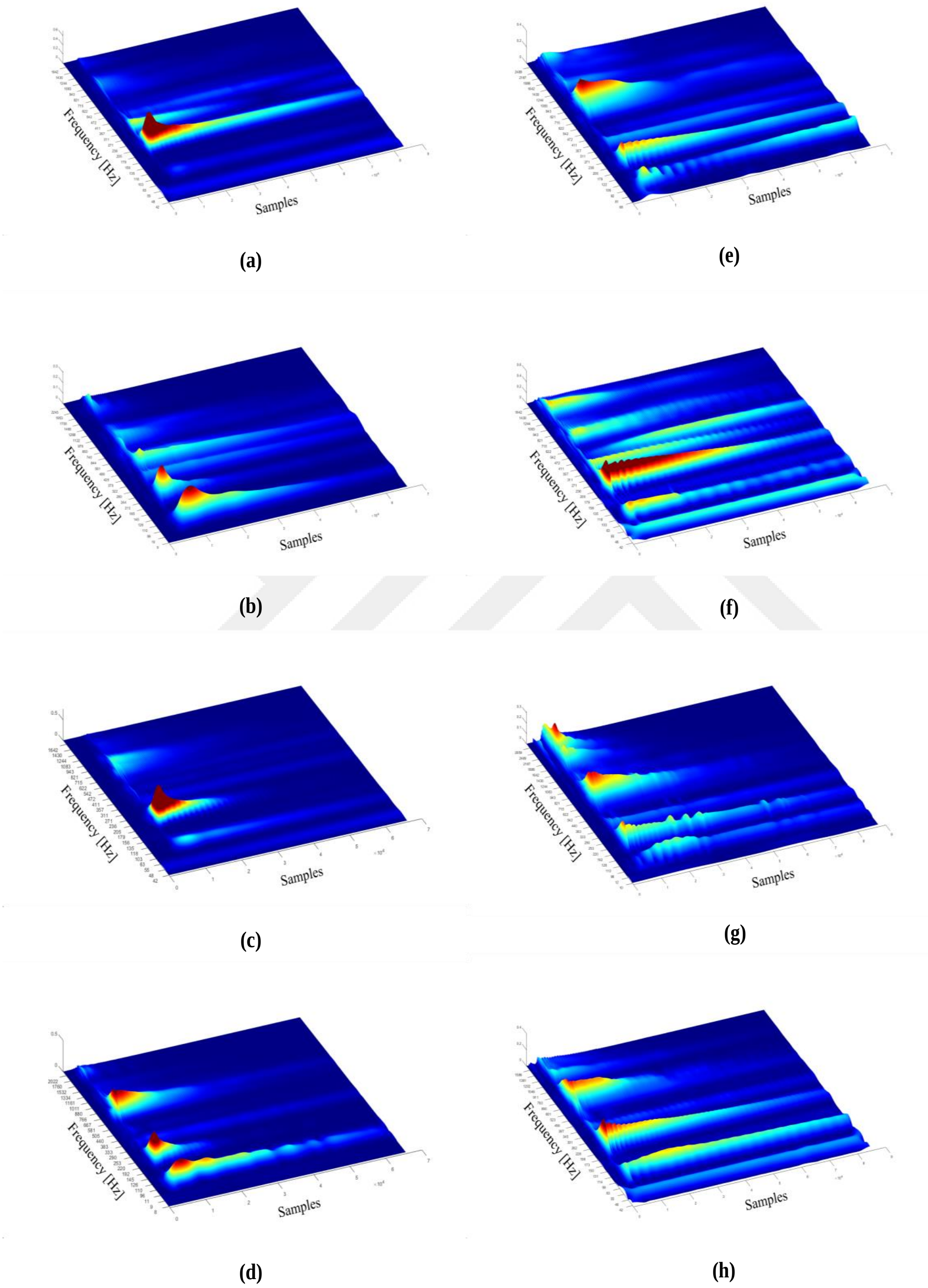

Fıgure A.1: CWT results of pitch A2: (a) Guitar 1, open position, bridge (b) on Guitar 1, open position, hole (c) Guitar 1, 5th position, bridge (d) Guitar 1, 5th position, hole (e) Guitar 2, open position, bridge (f) Guitar 2, open position, hole (g) Guitar 2, 5th position, bridge (h) Guitar 2, 5th position, hole

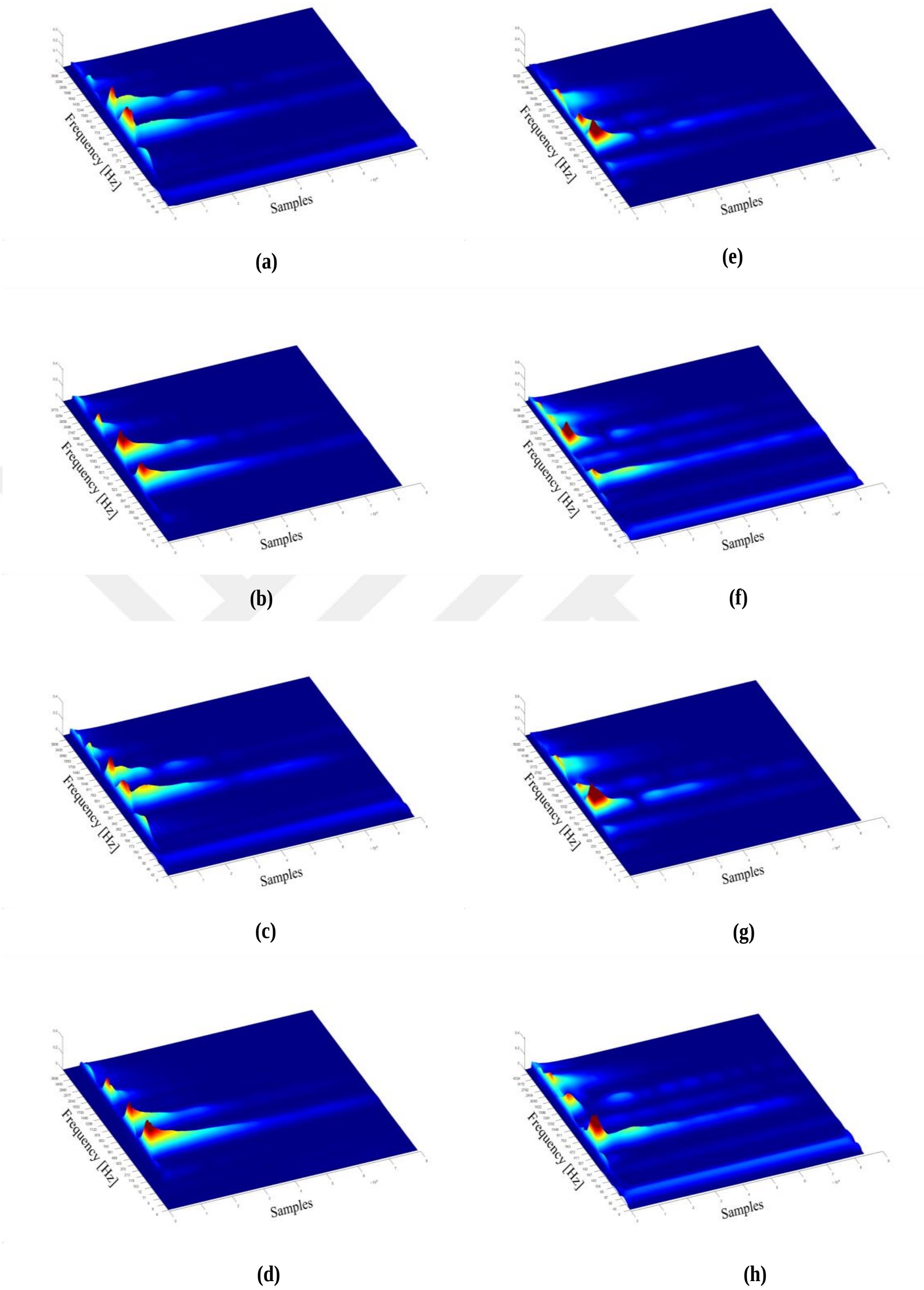

Figure A.2: CWT results of pitch A4: (a) Guitar 1, open position, bridge (b) on Guitar 1, open position, hole (c) Guitar 1, 5th position, bridge (d) Guitar 1, 5th position, hole (e) Guitar 2, open position, bridge (f) Guitar 2, open position, hole (g) Guitar 2, 5th position, bridge (h) Guitar 2, 5th position, hole

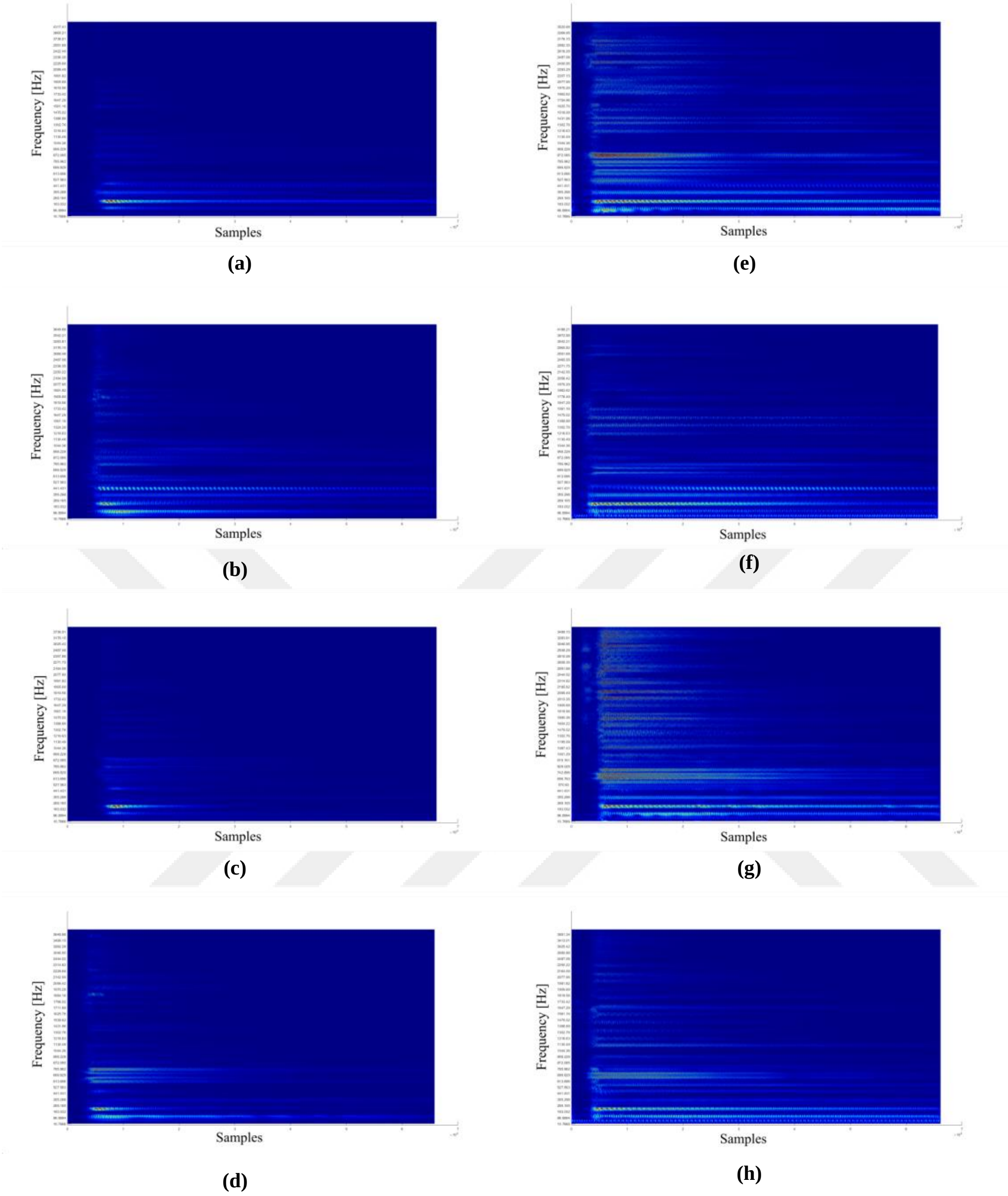

Fıgure A.3: WPT results of pitch A2: (a) Guitar 1, open position, bridge (b) on Guitar 1, open position, hole (c) Guitar 1, 5th position, bridge (d) Guitar 1, 5th position, hole (e) Guitar 2, open position, bridge (f) Guitar 2, open position, hole (g) Guitar 2, 5th position, bridge (h) Guitar 2, 5th position, hole

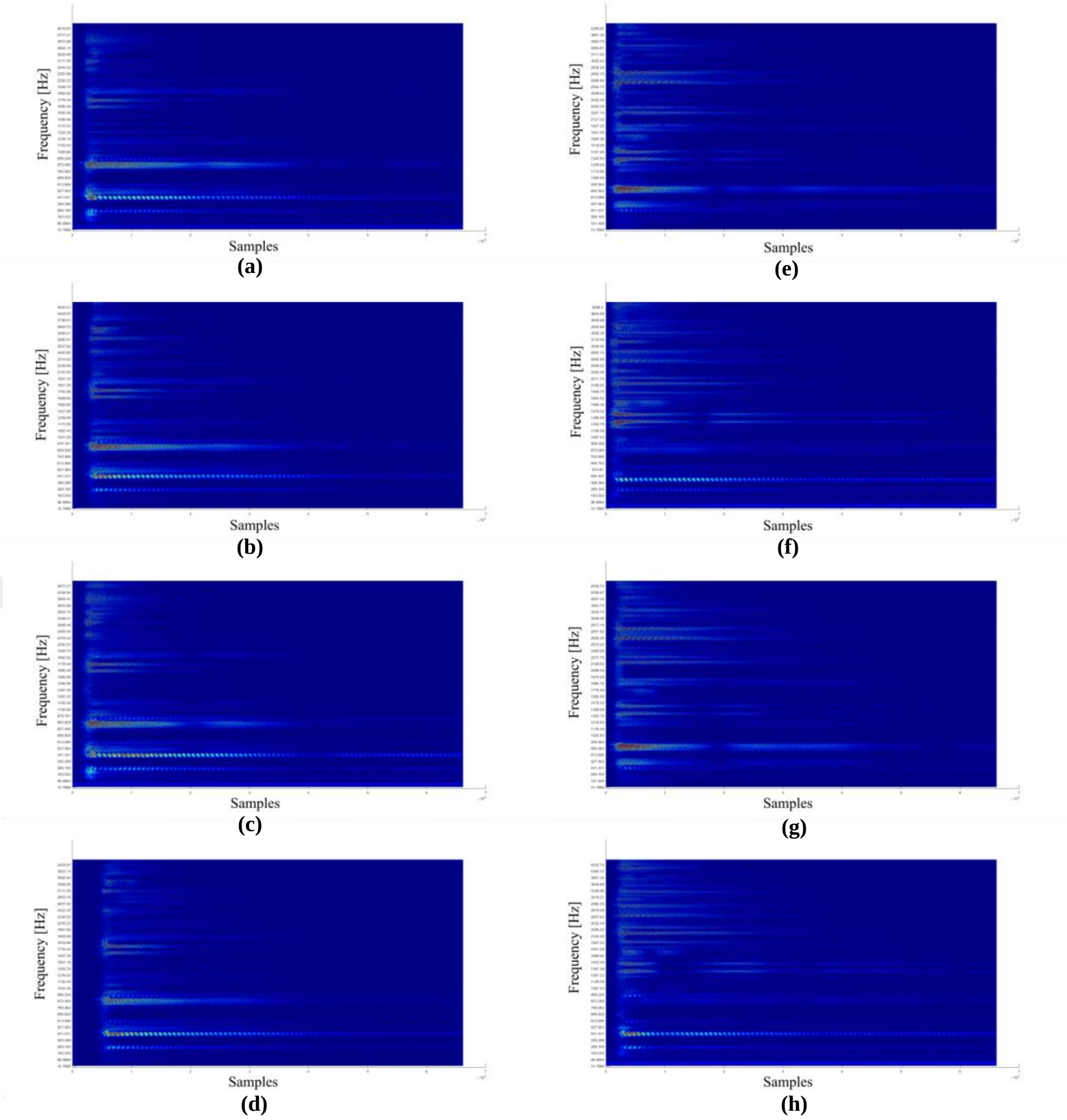

Fıgure A.4: WPT results of pitch A4: (a) Guitar 1, open position, bridge (b) on Guitar 1, open position, hole (c) Guitar 1, 5th position, bridge (d) Guitar 1, 5th position, hole (e) Guitar 2, open position, bridge (f) Guitar 2, open position, hole (g) Guitar 2, 5th position, bridge (h) Guitar 2, 5th position, hole

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