Article

Not peer-reviewed version

# Changes in Piano Waveforms from the Perspective of Physics and Deep Learning

Eunsung Jekal *, Younju Kim, Hyoeun Park, Juhyun Ku

Posted Date: 7 January 2025

doi: 10.20944/preprints202412.1866.v3

Keywords: Waveform; Piano; Wavelet Transform; Spectrogram Analysis

 doi:10.20944/preprints202412.1866.v3



*Article*

# Changes in Piano Waveforms from the Perspective of Physics and Deep Learning

**Eunsung Jekal [1,*], Younju Kim[2], Hyoeun Park[2,3,†] and Juhyun Ku[2,†]**

[1] Jekals LAB, Republic of Korea
[2] Ulsan Pianist Club, Republic of Korea
[3] Scala music institute, Republic of Korea
* Correspondence: everjekal@gmail.com
† These authors contributed equally to this work.

**Abstract:** In this study, we investigated whether it is possible to visually determine the difference in sound depending on the way in which a piano key is pressed through the use of spectrograms. It was found that, when the key is pressed hard, the high-frequency component is emphasized while, when it is pressed gently, the low-frequency component is more prominent. In addition, it was confirmed that the pattern of the spectrogram varies depending on the playing technique (e.g., staccato or legato), as well as whether or not the pedal is used. We attempted to analyze whether the pianist's touch or expressive power has an effect on the physical wave form and, furthermore, whether pianists are able to accurately infer the connection between the way they play and the resulting sound from the spectrogram.

**Keywords:** waveform; piano; wavelet transform, spectrogram analysis

## 1. Introduction

Pianists and scientists approach the principle of how a piano sounds from different perspectives. Pianists mainly explain these sounds from an artistic, sensory, or empirical perspective, while scientists explain them from a physical, acoustic, or engineering perspective [1]. A pianist's view, which focuses on an artistic perspective, is mainly focused on their performance experience and the expressive power of the sound. Therefore, they understand the piano's sound by linking it with the emotional elements of tone, touch, pedaling, and performance [2,3]; for example, it is emphasized that the tone changes depending on the pressure and speed of the finger. Pianists see the sound of the piano as an artistic tool, rather than a simple mechanical reaction, through which musical emotions are conveyed [4,5]. Therefore, it is argued that the sound of the piano depends on how the player presses on the keys (e.g., in terms of speed, intensity, touch sensation), which depends on the player's skill and interpretation [6]. For example, a performer may say that even the same note can create a completely different nuance, depending on how the sound is made [7]. In addition, pianists recognize that certain pianos (e.g., Steinway, Yamaha) produce a unique sound, which they see as a result of the design of the instrument itself and its interaction with the performer [8,9].

However, scientists analyze piano sound from physical, engineering, and acoustic perspectives [10]. According to physical principles, the sound of a piano begins when a hammer strikes a string and generates vibrations. These vibrations are amplified through the soundboard, which are then transmitted into the air and heard in the ears. Therefore, the pitch of a note is determined by the length, thickness, and tension of the piano strings. The magnitude of the sound also depends on the hammer's strength and hitting speed. To add acoustic analysis to this, the sound of a piano consists of a combination of fundamental frequencies and harmonics. Scientists describe tone as the characteristics of the distribution of sound and resonance, which is an attempt to objectively express a pianist's sensory explanation. Therefore, even when designing a piano, we focus on creating specific tone and

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 7 January 2025 doi:10.20944/preprints202412.1866.v3



sound characteristics from a mechanical perspective; for example, through studying the strength of felt used in hammers or the effect of the material and structure of strings on sound.

**Table 1.** Differences between the key perspectives of pianists and physicists.

| Pianists | Physicists |
|---|---|
| Focus on the sensory elements and expressiveness of the performance. | Focus on the physical/mechanical principles of sound generation. |
| Explain that the sound differs by "touch" and "expression." | Explain the difference in sound according to the force, speed, and physical qualities. |

From a combined point of view, the perspectives of the pianist and the scientist are complementary. The pianist's experience provides qualitative insights into sound, which can inspire designers or scientists to improve their pianos. Meanwhile, scientific analysis helps to objectively explain the principles of piano sound and can help performers to understand the sound more deeply and develop their musical expression based on it. In conclusion, we can best understand the sound and attractiveness of pianos when artistic sense and scientific analysis are brought together.

### *1.1. History of Piano Timbre*

The development of pianos and their tone has undergone changes and growth throughout the centuries as a result of a combination of technological innovation and musical demands. This process has evolved the instrument's design, material, playing style, and acoustic characteristics [11].

First of all, the piano started with the piano forte, invented by Bartolomeo Cristofori in Italy in the early 18th century. Unlike the existing harpsichord, the piano was able to control the volume (thus producing soft and strong sounds) by playing the strings with a hammer, allowing the performer to play more expressively. The tone of these early pianos was also softer and more delicate, making them suitable for playing in small spaces [12]. Then, with the advent of the classical and romantic eras in the 18th and 19th centuries, the technological development of pianos and musical demand rapidly expanded [13].

With the introduction of iron frames in the 1820s, pianos were able to withstand the tension of larger strings, and their sound became louder and richer. The keyboard was also standardized from the existing 5–6 octaves to the current 88 keys (7 octaves) as a result of the response to romantic musicians (e.g., Chopin and Liszt), who required a wider range [11]. In the case of the material of the hammer, it was improved with wool felt, and the arrangement of strings transformed into a cross-string arrangement, providing a more resonant tone [14].

As a result of the above developments, the piano at this time gave off a powerful and rich sound, making it suitable for playing in large concert halls, and its breadth of musical expression allowed for nuances ranging from delicate tones to intense forte [12].

With industrialization and mass production in the 20th century, pianos became popular under the influence of the industrial revolution and technological advances. Regarding technical aspects, new materials such as steel strings, solid wood, and high-quality felt were commonly used, thus increasing the durability and sound quality of pianos. The upright piano (vertical piano) was also developed to increase spatial efficiency, leading pianos to become more popular for home use. There was also a change in tone, with the spread of popular music and jazz requiring tunes adapted to different music genres. The upright piano yielded a soft and warm tone, while the grand piano was characterized by a colorful and grand tone [15,16].

In the 21st century, digital technology contributed greatly to the development of pianos and their tone; in this line, digital and hybrid pianos are typical examples [13]. Digital pianos utilize electroacoustic technology to sample or synthesize piano tones for their effective reproduction. They are light in weight, do not require tuning, and offer a variety of tones and functions. Hybrid pianos

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 7 January 2025 doi:10.20944/preprints202412.1866.v3



combine the structure of an acoustic piano with digital technology, providing both traditional tone and modern functionality [17].

The latest digital pianos can precisely reproduce the sound of a real grand piano using high-quality sampling technology. Physical modeling provides a more natural sound through virtual generation of the sound of strings and resonators based on acoustic principles. At present, performers can utilize not only traditional acoustic pianos, but also various digital tones (e.g., electronic pianos, organs, and synthesizers), with technology having enabled the extensive customization of tones.

In conclusion, a wide range of musical genres—ranging from Bach, Beethoven, and Chopin to jazz, pop, and film music—have led to the development of the piano's tone. The performance environment has also required improvements in the volume and resonance performance of pianos, having expanded from small-scale salon performances to large concert halls. In terms of technological innovation, technological advances such as iron frames, digital sampling, and physical modeling have improved the quality and expressiveness of piano sounds. As such, the development of pianos and their tone has resulted from the interactions between music and technology. Early small and delicate tones developed into tones that are magnificent, rich, and suitable for various genres and environments. Through the introduction of digital technology and new materials, pianos can be expected to evolve and continue to provide more innovative tones.

### *1.2. The Principle of Piano Sound*

The way in which a piano makes sound basically follows the principle that strings vibrate and sound is transmitted into the air. Specifically, it is as follows:

The piano has several keys and, when the user presses a key with their finger, the hammer goes up and bounces the strings. Each key is connected to a string that produces a specific sound. Each time the keys are pressed, the strings bounce and the vibration begins [18].

There are also several hammers inside the piano, each of which is connected to a keyboard. When the keyboard is pressed, a hammer (or hammers) strikes the string and causes vibration. When a hammer hits a string, its sound volume and tone vary depending on its strength and speed. For example, hitting hard and fast makes a loud sound, while hitting slowly and pressing gently makes a small and soft sound [19].

When the hammer hits a string in this way, the string begins to vibrate quickly. As the frequencies of each note vary depending on the length, thickness, and material of the strings, each string makes a specific note. There are about 230 strings on a piano, which are arranged in order from low to high; in particular, long strings are used for low notes and short, thin strings are used for high notes [20].

As the sound produced by strings vibrating is a very microscopic sound wave, a resonant container is required for the sound to be heard well by humans. Inside the piano, there is a large wooden box called a resonant container, which amplifies the vibration of the strings, making them even louder. The resonant container diffuses the sound waves generated when strings vibrate, and makes the piano's sound richer and louder [21].

In addition, the piano has a pedal. There are usually three pedals, which affect the duration and characteristics of the sound. For example, the soft pedal (left pedal) softens the sound by weakening the hit on the strings, while the damper pedal (right pedal) keeps the strings ringing to make the sound last long. Finally, the sound adjustment pedal (center pedal) can fine-tune the length or tone of a sound.

In conclusion, the piano makes a sound when the player presses the keyboard and the hammers hit the strings, which are amplified by the resonator. In addition, the characteristics of the sound can be controlled using the piano's pedals.

The graph above visually depicts the waveform of sound waves, according to the characteristics of the sound:

In a loud sound (high amplitude) such as that shown in Figure 1(a), the amplitude of the waveform is large, indicating a more intense sound. On the other hand, in a small sound (low amplitude) such as that shown in Figure 1(b), the amplitude of the waveform is small, indicating a smooth and quiet

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 7 January 2025 doi:10.20944/preprints202412.1866.v3



sound. Figure 1(c) represents a high sound (high frequency), where the waveform repeats faster and corresponds to a high note. Meanwhile, low-frequency sounds, as shown in Figure 1(d), have a different waveform, which repeats slowly and corresponds to a low-pitched tone [22,23].

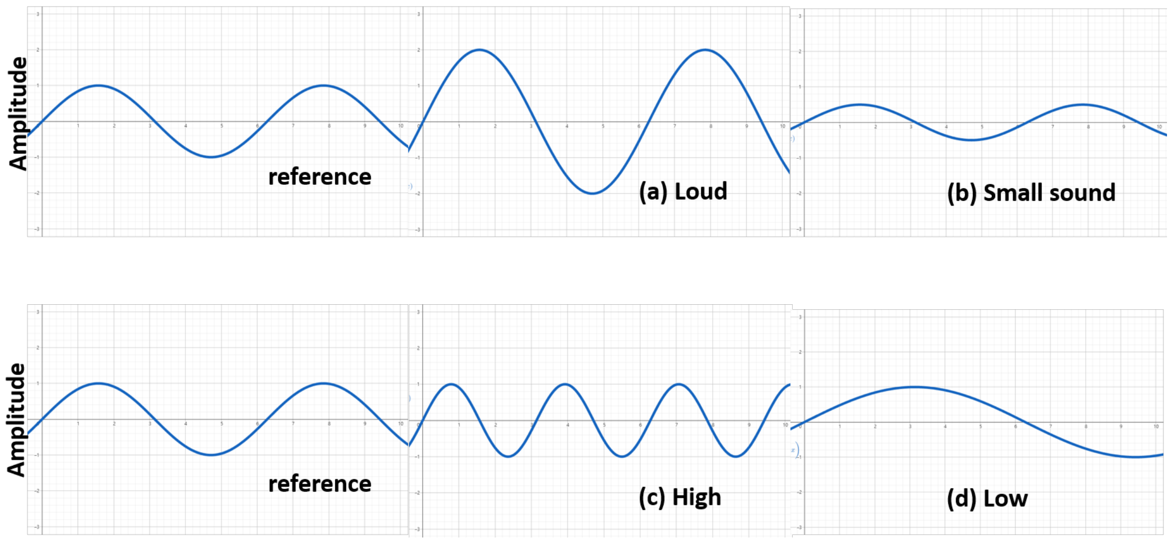


**Figure 1.** Change in sound according to waveform.

### *1.3. Piano Timbre Analysis from a Physical Point of View*

Physically analyzing piano tones is the process of numerically understanding and explaining the characteristics and principles of piano sound using acoustics, physics, and signal processing technology. To first analyze the physical properties of piano tones, we must understand and measure the following factors:

#### 1.3.1. Frequency

The piano notes consist of primary frequencies (basic notes) and several harmonics. The base frequency corresponds to the pitch associated with a particular key (e.g., that for A4 is 440 Hz), and the background sound is expressed as an integer multiple frequency of this base frequency. The characteristics of the tone depend on the strength and distribution of the frequencies [24].

#### 1.3.2. Amplitude

The amplitude indicates the magnitude of the sound wave, which determines the volume of the sound. On the piano, the amplitude depends on the strength of the player's playing [25].

#### 1.3.3. Time Domain

Piano sounds have characteristics that change over time, and the following factors are considered for their analysis: Attack: The part that quickly strengthens when the sound begins; Decay: The process of gradually decreasing the intensity of the sound; Sustain: A sound that is maintained for a certain period of time; Release: The process of sound disappearing completely [26].

#### 1.3.4. Resonance

Piano sounds include resonant effects, which are produced by resonators and strings. Resonance makes the sound richer, and resonance (e.g., sympathetic resonance) caused by the interactions of adjacent strings can also be analyzed [27].

The tone of a piano can be analyzed in the following manner. First, record the piano sound using a microphone and a spectrum analyzer, then analyze the frequency and amplitude. Recording with a high-quality microphone at this time can increase the accuracy of the sound data. The spectrum is then analyzed, and the intensity of the basic sounds and tones is visually identified by converting the

 doi:10.20944/preprints202412.1866.v3



sound into the frequency domain. This allows scientists to determine the frequency structure of the tone from a particular keyboard [28].

The Fourier Transform is typically used as a signal processing technique [29], in order to analyze the sound tone structure and energy distribution by converting signals from the Time Domain to the Frequency Domain. The results are represented in a spectral graph, which indicates the size of each frequency component. Spectrograms also enable dynamic analysis of changes in tone through visualizing the frequency distribution over time [24,30]; for example, to determine how the frequency components change while the sound persists or attenuates. A temporal characterization analysis is necessary to measure the amplitude change curve and analyze the temporal characteristics of the piano's sound. The attack, decay, sustain, and release stages of the sound are graphed, and the duration and amplitude change rate in each stage are calculated. In addition, resonance analysis measures the vibration from soundboards and strings, analyzes the effect of piano resonance on tone, and assesses the impact of the acoustic environment on tone through identifying how piano sound is reflected and absorbed in space [29].

Some examples of practical application of piano tone analysis in the above manner are as follows. First, in the field of acoustic modeling, a digital model based on the acoustic characteristics of a piano can be generated, allowing for mathematical simulation of the vibrations of strings and resonators through physical modeling. Modern digital pianos, for example, utilize this approach to reproduce the tones of actual pianos. Second, it can be used for piano design and tuning, where the results of the tone analysis are directly used for the design and tuning of pianos. This allows the length, thickness, and tension of the strings to be adjusted to implement a specific tone. In addition, the material and hitting strength of the hammer can be reflected in the design. Third, it is possible to analyze a certain performer's performance style [31], through quantitatively analyzing the influence of their performance style (e.g., strength control, pedaling) from sound data. In this way, the acoustic differences affected by how different performers press the same keyboard can be determined. In conclusion, the process of measuring and analyzing various factors, such as frequency, amplitude, temporal characteristics, and resonance, allows for physical analyses of piano tone. Such analysis plays a crucial role in piano design, digital acoustic modeling, and performance technique research, contributing to a deeper understanding of the acoustic beauty and technical principles of the piano [32].

## 2. Methods

### *2.1. Wave Function for Physical Analysis*

In sound wave analysis, the wave function is used as an important tool to mathematically express and analyze the physical properties of sound waves. Sound waves are essentially vibrations that are transmitted through a medium (e.g., air, water), and can be modeled using the wave function. Below, we explain how the wave function is used for sound wave analysis [33].

Wave functions are mathematical representations depending on the amplitude, frequency, phase, temporal, and spatial properties of sound waves. Generally, waves are expressed in the following way:

$$y(x,t) = Asin(kx - wt + \Phi), \tag{1}$$

where $y(x,t)$ is the value of the wave at the time $t$ and position $x$ (the magnitude of the wave); $A$ is the amplitude of the wave (corresponding to the volume of the sound); $k = \frac{2\pi}{\lambda}$ expresses the wavenumber, which is the reciprocal of the wavelength (per unit length); $\omega = 2\pi f$ denotes angular frequency, a value associated with the frequency; and $\Phi$ is the phase constant, indicating the initial position of the wave. This equation is in the form of a sinusoidal wave, representing a simple model of sound [34].

The use of wave functions in sound wave analysis is crucial, where sound wave analysis involves a process of understanding the physical and acoustic properties of sound waves through analyzing

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 7 January 2025 doi:10.20944/preprints202412.1866.v3



characteristics such as frequency, amplitude, and phase. Wave functions are used to perform these analyses in a quantitative and systematic manner [35]

Wave functions are transformed into frequency components via the Fourier Transform:

$$F(f) = \int_{-\infty}^{\infty} y(t)e^{-i2\pi ft}dt, \tag{2}$$

where $F(f)$ represents the spectral intensity of the sound wave at frequency $f$.

This allows us to evaluate the tone by checking the relative intensity of the associated frequency in the piano's sound.

However, as Fourier transform does not show how signals change over time, short-time Fourier transform (stft) or wavelet transform can be used to compensate for this problem. These methods are useful when analyzing how signals change over time, which is essential when identifying changes in frequency composition over time; for example, when analyzing melodies in music.

Figure 2 provides a schematic representation of the Fourier transform.

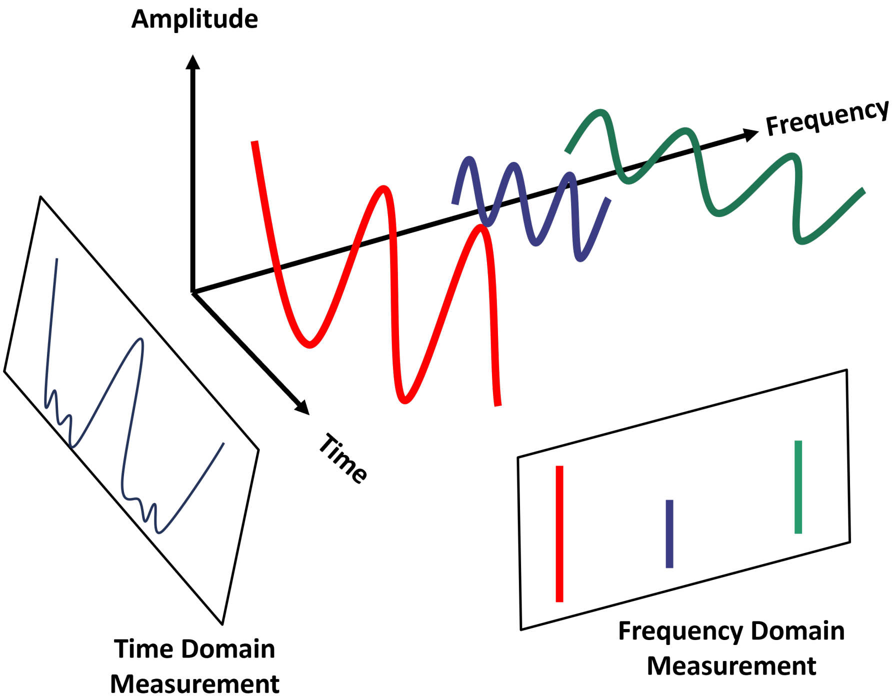


**Figure 2.** Schematic representation of the Fourier transform.

The Short-time Fourier Transform (STFT) is a very useful tool for analyzing signals in the time–frequency domain, which is utilized in musical analysis in various ways. STFT divides signals into short time intervals, and performs Fourier transformations on each interval to obtain time and frequency information simultaneously [36,37].

$$STFT(x(f))(\tau,\omega) = \int_{-\infty}^{\infty} x(t)\omega(t-\tau)e^{-j\omega t}dt. \tag{3}$$

The Wavelet Transform, on the other hand, is a time–frequency analysis technique that provides localized time–frequency information of signals in a different way than STFTs for the analysis of sound waves (e.g., audio signals). While STFT uses a fixed window size, the Wavelet Transform analyzes signals while adjusting the window size. This method is particularly powerful for analyzing audio, including abnormal signals (i.e., signals whose frequency components vary over time) or short events.

In other words, a Wavelet is a short "waveform"—a signal that is localized in terms of both frequency and time. The Wavelet Transform compares signals to "wavelet functions" at various scales and time locations. Then, at a small scale, we can see the detailed changes with high-frequency

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 7 January 2025 doi:10.20944/preprints202412.1866.v3



components while, at a large scale, we can see the overall structure of the signal with low-frequency components. Therefore, the Wavelet Transform allows for multi-resolution analysis of signals.

Based on the Wavelet Transform results, signals in a specific frequency band can be removed or emphasized, following which an inverse Wavelet Transform is possible. In addition, the multi-scale analysis of signals allows us to analyze the rhythmic structure, which can be well-utilized for the analysis of tone and acoustic features. In particular, the Wavelet Transform varies in time–frequency resolution, making it powerful for analyzing the abnormal characteristics of signals.

**Table 2.** Wavelet Transform versus STFT.

| | **Wavelet Transform** | **STFT** |
|---|---|---|
| Frequency resolution | High at low frequency, low at high frequency | Fixed frequency resolution |
| Time resolution | High at high frequency, low at low frequency | Fixed time resolution |
| Short event analysis | More effective | Relatively less effective |
| Calculation amount | Efficient | relatively computationally efficient |
| Application | Abnormal Signal Analysis, Compression, Noise Elimination | Rhythm, Spectrogram-Based Analysis |

The Wavelet Transform works like a zoom-enabled magnifying glass, capturing fine details in small areas or the overall outline of a signal in large areas. For this reason, the Wavelet Transform excels at analyzing sound waves with fluctuating time–frequency information.

### 2.2. Spectrogram Analysis

A Spectrogram is a tool that visualizes the time, frequency, and amplitude information of a sound at a glance. This allows us to see how the sound changes over time and how strongly a specific frequency band appears.

Data collection must first be conducted in order to analyze music using a Spectrogram. For example, in this study, high-sensitivity microphones were used to record piano sounds, and audio interfaces were used to obtain more accurate data.

Next, the recorded audio data are entered into certain software to generate the spectrogram. Representative software includes Praat, Sonic Visualizer, MATLAB, and Python; in this paper, we used Python.

In this way, we can analyze which frequency band appears strongly at a specific time in the spectrogram, in order to check the piano's harmonics, resonance, and tone change over time.

$$X[m,k] = \sum_{n=0}^{N-1} x[n] \cdot \omega[n - mR] \cdot e^{j\frac{2\pi}{N}kn}. \tag{4}$$

A window function $w(t)$ is used to highlight or limit specific time intervals in a signal. The selection of window functions affects time and frequency resolutions. Common window functions are as follows:

(1) Rectangular window

$$\omega(t) = 1(0 \leq t \leq T). \tag{5}$$

(2) Hamming Window

 doi:10.20944/preprints202412.1866.v3



$$\omega(t) = 0.54 - 0.46cos(\frac{2\pi t}{T}). \quad (6)$$

(3) Hanning Window:

$$\omega(t) = 0.5(1 - cos(\frac{2\pi t}{T})). \quad (7)$$

(4) Gaussian Window:

$$\omega(t) = e^{-\frac{t^2}{2\sigma^2}}. \quad (8)$$

In Figure 3, we provide the Python code used for spectrogram calculation.

```
import numpy as np
import matplotlib.pyplot as plt
from scipy.signal import spectrogram

# sample
fs = 1000  # frequency
t = np.arange(0, 2, 1/fs)  # time lable
x = np.sin(2*np.pi*50*t) + np.sin(2*np.pi*120*t)

#  Spectrogram calculation
f, t, Sxx = spectrogram(x, fs, nperseg=256, noverlap=128, window='hann')
plt.pcolormesh(t, f, 10 * np.log10(Sxx), shading='gouraud')
plt.ylabel('Frequency [Hz]')
plt.xlabel('Time [sec]')
plt.colorbar(label='Power [dB]')
plt.show()
```

**Figure 3.** Python code used for spectrogram calculation.

Using the obtained spectrograms, we can visually compare the differences in tone according to various piano models and playing methods. We can also evaluate the harmonious degree of the tone through checking the relationship between the fundamental frequency and the tone.

In addition, it is possible to diagnose defects as, if there is a problem with a specific part of the piano (e.g., string, hammer, soundboard), it may appear as an abnormal pattern in the spectrogram. For example, if the tone is murky, the low-frequency area will be emphasized and the high frequency tone will be weak or irregular.

As such, the spectrogram is a powerful tool that allows us to analyze sound objectively, away from simply listening to it. This allows us to study the tone of pianos, as well as various other instruments, more precisely.

### *2.3. Deep Learning Process*

We provide the code used for the sound wave prediction model below.

 doi:10.20944/preprints202412.1866.v3



```
import tensorflow as tf
from tensorflow.keras.models import Sequential
from tensorflow.keras.layers import LSTM, Dense

model = Sequential([
    LSTM(128, input_shape=(None, feature_dim), return_sequences=True),
    LSTM(64, return_sequences=False),
    Dense(32, activation='relu'),
    Dense(output_dim)
])

model.compile(optimizer='adam', loss='mse')
model.summary()
```

**Figure 4.** Deep learning python code for the sound wave prediction model.

Deep learning models can learn high-dimensional non-linear relationships directly from sound data. In particular, piano sound waves contain various elements, such as pitch, intensity, rhythm, and combinations of chords. Deep learning models can automatically analyze and learn these elements, enabling more flexible analysis than traditional signal processing methods.

Traditional methods required significant domain knowledge to derive the Mel-Frequency Cepstral Coefficient (MFCC), spectrogram, or high-dimensional properties. Deep learning approaches automatically extract features from raw audio data, thus reducing the process of designing features for manual tasks. Furthermore, deep learning models provide higher accuracy when compared to traditional analytical methods, making them robust for dealing with tasks that require fine distinctions, such as piano sound wave analyses (e.g., different touches on the same pitch). Through leveraging a large data set, the models can also learn the personal styles of performers, differences in piano, and environmental noise.

Notably, piano sound analysis can be performed in combination with score data or performance images, not just through analyzing audio data; for example,
(1) learning sound waves and sheet music at the same time → automatically turning the performance into sheet music (automatic writing).
(2) Learning video data → Analyzing the relationship between the player's hand movements and sound waves.
As such, deep learning overcomes the limitations of existing signal processing techniques, opening up great possibilities for piano sound analysis and related applications.

## 3. Results

The differences between spectrograms depending on the touch of the piano keys is mainly due to the strength and skill of the player, as well as the positions of the keys. A spectrogram is a graph that visually represents changes in the frequency of a sound over time, such that differences occur depending on how the keys are pressed. Some of the key elements are explained below.

First of all, the intensity of the sound varies depending on how hard or gently one presses the piano key, and the spectrum varies accordingly. When pressed hard, the high frequency component is more emphasized due to the strong strike, and the dynamic range of the sound is widened. Overall, the sound react more strongly, especially in the high frequency range. In the spectrogram, high frequency components are more prominent and strong peaks can be seen, as shown in Figure 5(b), while Figure 5(a) shows the standard 440 Hz sound. On the other hand, when pressed gently, the

 doi:10.20944/preprints202412.1866.v3



sound is relatively smoother and there are fewer high-frequency components. The lower frequency bands (lower frequency ranges) of the spectrum may appear to be stronger.

The second major element is articulation. Playing styles such as Staccato and Legato affect the duration and gradation of the sound. For instance, the staccato technique gives each note a short, distinct division. On the spectrogram, each note's duration is short, and the high-frequency component appears to drop quickly, as shown in Figure 5(c). Legato, on the other hand, uses smooth notes and, so, continuous frequency changes appear smoother in the spectrogram, and the connection between notes appears longer.

The third major element is the position on the keyboard. In Figure 5(e), we confirm that spectral differences occur between the Bass and Treble regions of the piano, which affect the frequency distribution in the spectrogram. The lower frequency band is emphasized when playing the bass keyboard, and the low frequency region is relatively prominent in the spectrogram. Meanwhile, high-frequency components are emphasized when playing high-pitched keys and, in the spectrogram, more energy is distributed in the high-frequency domain.

Finally, how the pedal is used is also highlighted in the graph component. The Sustain Pedal allows the sound to persist and multiple notes to ring at the same time. In this case, multiple frequencies overlap in the spectrogram, and we can see how the sound continues in a certain pattern, as shown in Figure 5(d) and (f). Without the pedal, the note disappears quickly and the spectrogram has a shorter negative duration, as shown in Figure 5(a).

In conclusion, the difference between spectrograms depending on how the piano keys are played greatly depends on the strength of the player, their playing technique, the position of the keys, and whether or not the pedals are used. These aspects allow for visual analysis of various characteristics of the sound.

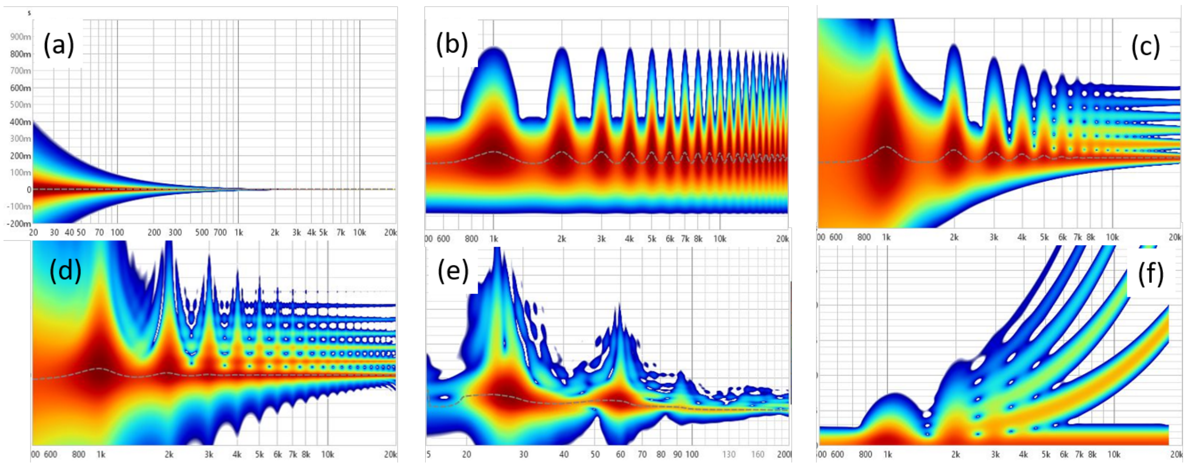


**Figure 5.** Spectrogram results depending on piano touch.

## 4. Discussion

In this study, we attempted to determine whether keyboard touch or expressive power—as pianists claim—directly bring about changes in physical waveforms. For this purpose, we introduced the most basic Fourier transform and used spectrograms for visual observation. As a result, it was found that the speed of pressing the key (strength), the acceleration, the position of the key, and the use of the pedal all had sensitive effects on the resulting spectrograms. What was surprising was the answer when we showed pianists the spectrograms and asked them: "How do you think you should play the piano for this graph to come out?" In particular, although pianists who had little information about how their music is expressed in the physical field were surveyed, most of them guessed exactly which spectrogram represented how they played. Some musicians gave different answers; however, in that case, they were more fascinated by the color than the shape of the wave. When conducting additional surveys, it may be necessary to show black and white-toned spectrograms, excluding color.

## 5. Limitation

Scientific perspectives and calculations in the musical field can help to improve a performer's performance or when designing a venue; however, it is insufficient for 'musical impression.' In addition to scientific principles, numerous exercises and personal technical aspects are required to draw the audience's impression, and the thoughts and attitudes of the performer may be the most important factor.

For example, when Horovitz returned to his home country for the first time in more than 50 years and played "Tromerai," the audience shed tears of emotion while watching him. Was this because Horovitz impressed the audience with his tremendous tone, or because of the sympathy of the audience who knew the details of Horovitz's life?

Therefore, while a scientific approach to music is essential for performers, they must be aware that it does not always lead to 'musical impression.'

## 6. Future Work

When working on this paper, the first goal was to determine whether the performer could analyze piano techniques or emotional expressions in the realm of science and, if possible, how the realm of science could help musicians. Players have learned that, through various techniques, fine movements or expressions can be represented sensitively in the wave graph. On the other hand, if they could understand music by looking at the wave graph, it can be questioned whether hearing-impaired people who could not hear music or those who were in an environment or situation where they could not hear music could also enjoy music through visual information. If the visual sense can give a lingering feeling of the same size as an emotion experienced when hearing music, it is expected that scientific technology may come a step closer to 'musical emotion.' In future research, we hope to determine the role of the scientist from the audience's point of view, rather than the performer's point of view. Of course, as shown in Figure 6, the best interaction between the performer and the audience is likely to exchange music as just music. However, even considering the basic tuning process, the role of a scientist who analyzes music in waveforms and delivers it is essential. Furthermore, as mentioned above, there is an audience that does not directly receive music. If performers wish to convey their musical impression to them, they will need a scientist as a mediator.

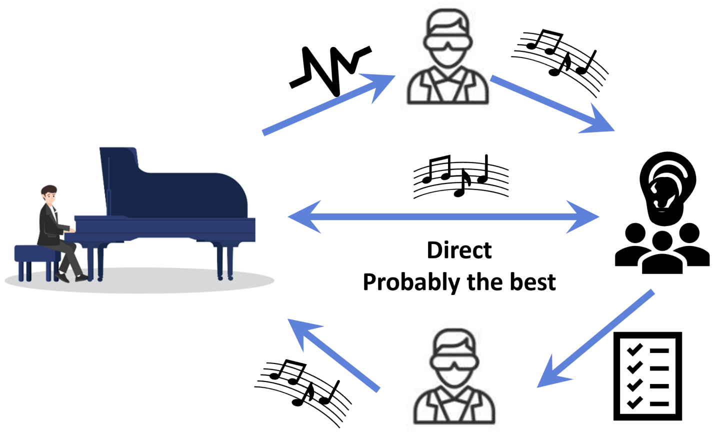


**Figure 6.** A schematic diagram of the relationships between the performer, the audience, and the scientist.

## Appendix A

The keys on the piano are divided into seven frequency ranges, called "octaves." Each octave exhibits a frequency spectrum twice as large as the previous one. On the piano, each octave is again divided into seven main keys, where each key plays a different note. In classical Western music, in particular, these notes are accompanied by the symbols C, D, E, F, G, A, and B. The frequencies are arranged to increase in alphabetical order. However, contrary to popular opinion, octaves usually start with C and end with B. As the convention was formed in this manner, the notes are listed semi-alphabetically. The number of cycles per unit time (usually the number of cycles per second) is the frequency of a note (f). Hertz (abbreviated Hz) is a unit of sound frequency, specified as one cycle per second. As a result, the wave's frequency is

$$\frac{6cycles}{0.0181seconds} = 331Hz = D4\#note. \tag{A1}$$

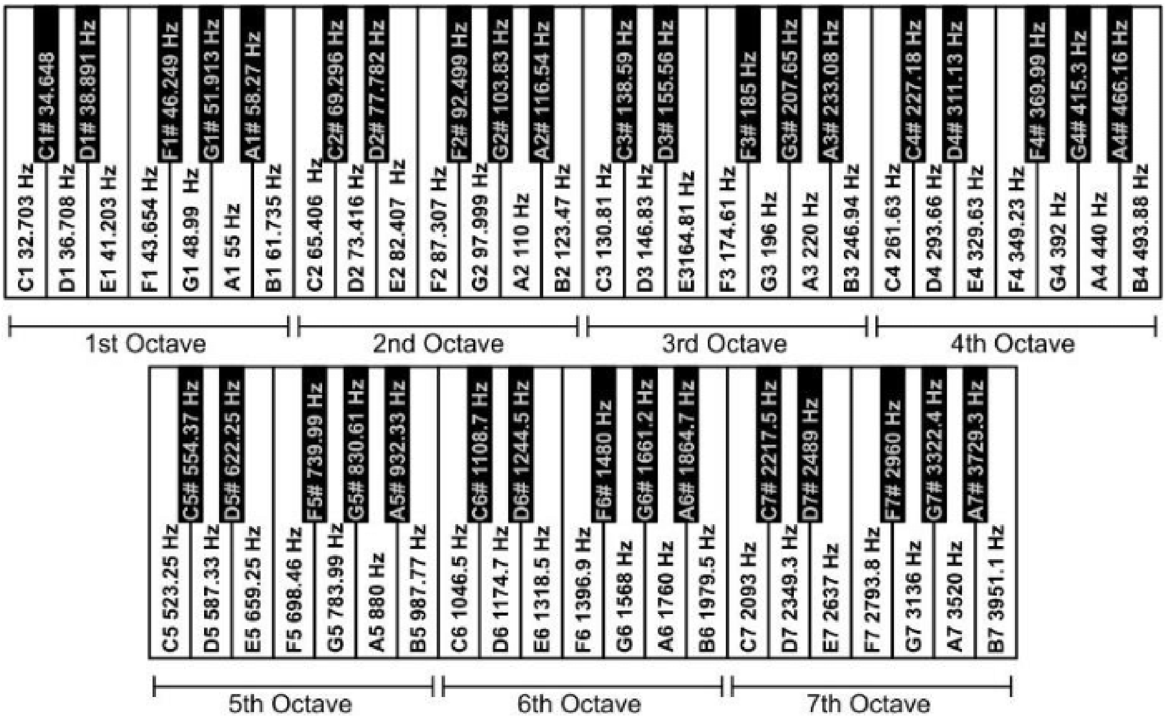


**Figure A1.** Piano's notes with their respective frequencies.

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 7 January 2025 doi:10.20944/preprints202412.1866.v3



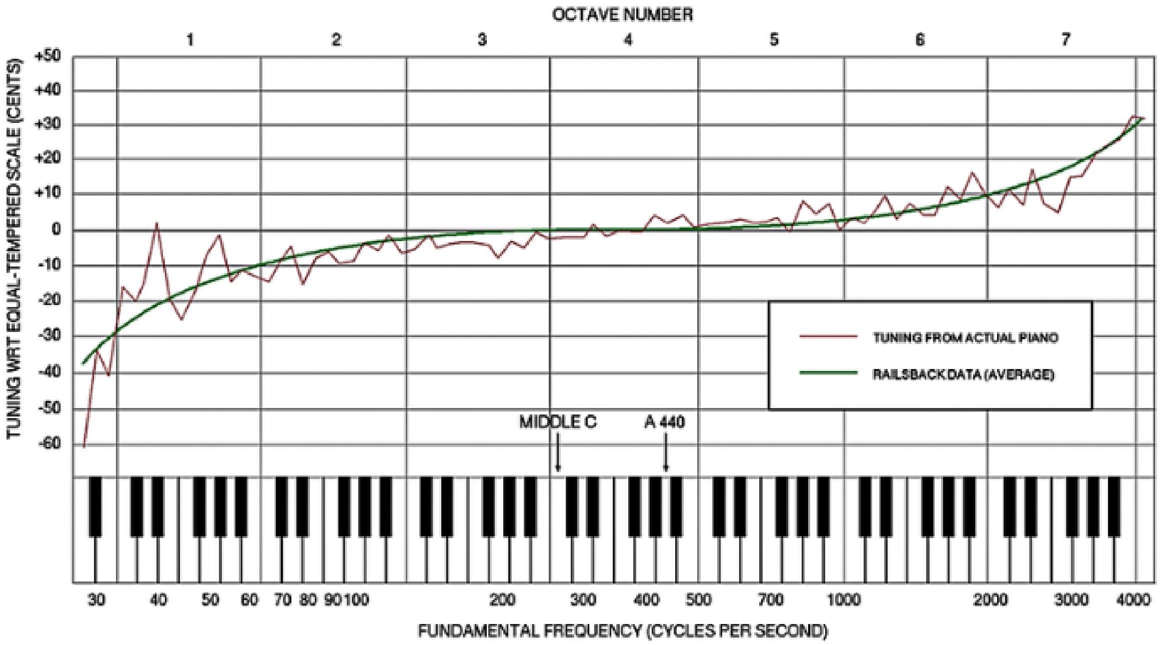


**Figure A2.** Typical tuning curve of a piano. The plot shows how much the fundamental frequency of each note deviates from the equal-tempered scale. The deviations are measured in cents, defined as 1/100 of a halftone which corresponds to a frequency ratio of $2^{1/1200} \approx 1.0005778$.

The cacophony varies across instruments, making it difficult to calculate the appropriate stretch using electronic tuning methods. More advanced tuning devices measure individual overtone spectra of all notes and correlate higher harmonics to calculate the required stretch. The latter method yields fairly good results and is increasingly being used by professional piano tuners; however, many musicians are still convinced that electronic tuning cannot compete with the high-quality auditory tuning of skilled piano tuners. In fact, when measuring the frequencies of an audibly well-tuned piano, we find that the tuning curves are not smooth. Rather, they exhibit negative to negative irregular fluctuations over the overall elasticity (see Figure 8). At first glance, one might expect that these fluctuations are randomly distributed and are caused by natural inaccuracies in human hearing. However, these fluctuations are probably not entirely random, instead reflecting—to some extent—the individual irregularities in the overtone spectrum of each instrument, which could play an important role in high-quality tuning. Perhaps our ears can find better compromises in the very complex space of the spectral lines than electronic tuning approaches.

## Appendix B

To visually evaluate the accuracy of the results, the score of the song played on the sample is shown in Figure A3. The song is called "Twinkle Twinkle Little Star", which is used for piano learners. The time signature of the music is 4/4, and the score is numbered with 12 beats. The score does not have a key signature, as the song is in C major.

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 7 January 2025 doi:10.20944/preprints202412.1866.v3




**Figure A3.** Sheet music of the song "Twinkle Twinkle Little Star" as an example.

## Appendix C

SIGVIEW is a real-time signal analysis application with various spectrum analysis tools, statistical features, and comprehensive graphical analysis methods for 2D and 3D graphics. SIGVIEW can analyze offline or live signals and provides a variety of analysis tools, allowing researchers to focus on the practical scientific analysis of phenomena, instead of learning to use the program.

Just like how a standard calculator processes numerical representations, SIGVIEW's embedded signal calculator facilitates combinations of signals or instruments through various arithmetic or signal analysis tasks. This tool can be used to perform various cross-spectrum analyses, such as adding or subtracting two signals or spectra.

Each change in the signal will cause the spectrum to be calculated again. A single spectrum will be calculated from the complete visible signal part of the source window. This is the default behavior, as shown in Figure 10.

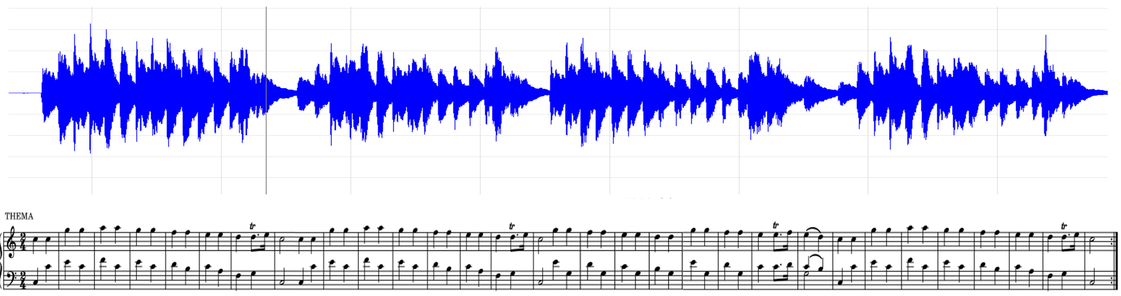


**Figure A4.** Spectral Analysis Defaults.

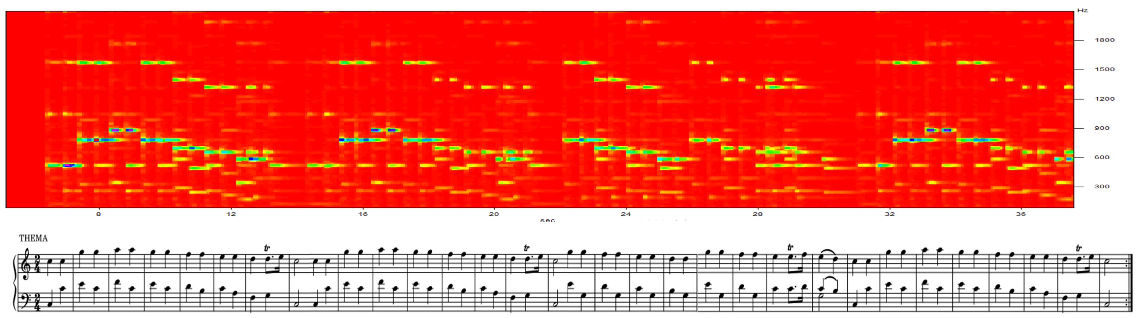


**Figure A5.** 2D signal filter.

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 7 January 2025 doi:10.20944/preprints202412.1866.v3



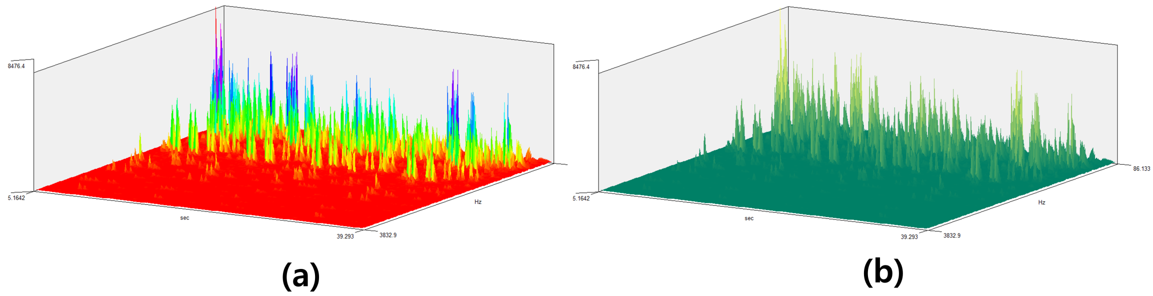


**Figure A6.** 3D signal filter: (a) Colored; and (b) single-tone type.

If one needs to apply a complex set of filters with different time/frequency ranges and amplitudes to the signals, the '3D signal filter' function can be used. The filter characteristics can be defined in three dimensions—namely, time, frequency, and amplitude—hence the term '3D.'

## Reference

1. Bank, B.; Avanzini, F.; Borin, G.; De Poli, G.; Fontana, F.; Rocchesso, D. Physically informed signal processing methods for piano sound synthesis: a research overview. *EURASIP journal on advances in signal processing* **2003**, *2003*, 1–12.
2. Bank, B.; Sujbert, L. Generation of longitudinal vibrations in piano strings: From physics to sound synthesis. *The Journal of the Acoustical Society of America* **2005**, *117*, 2268–2278.
3. Blackham, E.D. The physics of the piano. *Scientific american* **1965**, *213*, 88–99.
4. Giordano, N.J. *Physics of the Piano*; Oxford University Press, 2010.
5. Kochevitsky, G. *The art of piano playing: A scientific approach*; Alfred Music, 1995.
6. Kulcsár, D.; Fiala, P. A compact physics-based model of the piano. *Proceedingd of DAGA* **2016**.
7. Rauhala, J.; et al. *Physics-Based Parametric Synthesis of Inharmonic Piano Tones*; Helsinki University of Technology, 2007.
8. Simionato, R.; Fasciani, S.; Holm, S. Physics-informed differentiable method for piano modeling. *Frontiers in Signal Processing* **2024**, *3*, 1276748.
9. Stulov, A. Physical modelling of the piano string scale. *Applied Acoustics* **2008**, *69*, 977–984.
10. Xie, H. Physical Modeling of Piano Sound. *arXiv preprint arXiv:2409.03481* **2024**.
11. Wagner, E. History of the Piano Etude. *The American Music Teacher* **1959**, *9*.
12. Bartels, A. A HISTORY OF CLASS PIANO INSTRUCTION. *Music Journal* **1960**, *18*, 42.
13. Russo, M.; Robles-Linares, J.A. A Brief History of Piano Mechanics. In Proceedings of the Advances in Italian Mechanism Science: Proceedings of the 3rd International Conference of IFToMM Italy 3. Springer, 2021, pp. 11–19.
14. Newman, W.S. A Capsule History of the Piano. *The American Music Teacher* **1963**, *12*, 14.
15. HG. History of the Piano, 1948.
16. Russo, M.; Robles-Linares, J.A. A Brief History of Piano Action Mechanisms. *Advances in Historical Studies* **2020**, *9*, 312–329.
17. Tomes, S. *The Piano: A History in 100 Pieces*; Yale University Press, 2021.
18. Story, B.H. An overview of the physiology, physics and modeling of the sound source for vowels. *Acoustical Science and Technology* **2002**, *23*, 195–206.
19. Linder, C.J.; Erickson, G.L. A study of tertiary physics students' conceptualizations of sound. *International Journal of Science Education* **1989**, *11*, 491–501.
20. Bennet-Clark, H.C. Songs and the physics of sound production. *Cricket behavior and neurobiology* **1989**, pp. 227–261.
21. Josephs, J.J.; Slifkin, L. The physics of musical sound. *Physics Today* **1967**, *20*, 78–79.
22. Sataloff, J.; Sataloff, J. The Physics of Sound. 2. *Hearing Loss* **2005**, p. 2.
23. Daschewski, M.; Boehm, R.; Prager, J.; Kreutzbruck, M.; Harrer, A. Physics of thermo-acoustic sound generation. *Journal of applied Physics* **2013**, *114*.
24. Wever, E.G.; Bray, C.W. The nature of acoustic response: The relation between sound frequency and frequency of impulses in the auditory nerve. *Journal of experimental psychology* **1930**, *13*, 373.

25. Mellinger, D.K. Feature-Map Methods for Extracting Sound Frequency Modulation. In Proceedings of the Conference Record of the Twenty-Fifth Asilomar Conference on Signals, Systems & Computers. IEEE Computer Society, 1991, pp. 795–796.
26. Wood, J.C.; Buda, A.J.; Barry, D.T. Time-frequency transforms: a new approach to first heart sound frequency dynamics. *IEEE Transactions on Biomedical Engineering* **1992**, *39*, 730–740.
27. Hawk, B. Sound: Resonance as rhetorical. *Rhetoric Society Quarterly* **2018**, *48*, 315–323.
28. Flax, L.; Dragonette, L.; Überall, H. Theory of elastic resonance excitation by sound scattering. *The Journal of the Acoustical Society of America* **1978**, *63*, 723–731.
29. Bracewell, R.N. The fourier transform. *Scientific American* **1989**, *260*, 86–95.
30. Williams, E.G. *Fourier acoustics: sound radiation and nearfield acoustical holography*; Academic press, 1999.
31. Yoganathan, A.P.; Gupta, R.; Udwadia, F.E.; Wayen Miller, J.; Corcoran, W.H.; Sarma, R.; Johnson, J.L.; Bing, R.J. Use of the fast Fourier transform for frequency analysis of the first heart sound in normal man. *Medical and biological engineering* **1976**, *14*, 69–73.
32. Hornikx, M.; Waxler, R.; Forssén, J. The extended Fourier pseudospectral time-domain method for atmospheric sound propagation. *The Journal of the Acoustical Society of America* **2010**, *128*, 1632–1646.
33. Tohyama, M. *Waveform Analysis of Sound*; Springer, 2015.
34. Westervelt, P.J. Scattering of sound by sound. *The Journal of the Acoustical Society of America* **1957**, *29*, 199–203.
35. Dean III, L.W. Interactions between sound waves. *The Journal of the Acoustical Society of America* **1962**, *34*, 1039–1044.
36. Maas, T. Sound Analysis using STFT spectroscopy. *Bachelor Thesis, University of Bremen* **2011**, pp. 1–47.
37. Lee, J.Y. Sound and vibration signal analysis using improved short-time fourier representation. *International Journal of Automotive and Mechanical Engineering* **2013**, *7*, 811–819.