

A Musical Signal Analyst

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Abstract

Sounds are created by instruments, but can they be made on the computer? Sounds are created by a vibrating object that causes molecular motions and pressure oscillations in the air. Each wave signal is composed of many different fundamental harmonics and certain overtones. Each instrument produces numerous frequencies. On a computer, sound may be created. This is done by using several mathematical formulas and functions.

The purpose of this investigation was to analyze a wave signal to the fullest. A couple of musical notes played by the trumpet and the flute were recorded. Using the Fast Fourier Transform, the waves were decomposed into their basic harmonics, and proved to be periodic. The frequencies and overtones of each instrument were compared and reconstructed artificially. Each wave signal underwent a spectrogram. A spectrogram is a function, which enables a person to view the wave's characteristics (meaning where the intensity was and how it relates to its sound as a function of time). A simple user-friendly program was created to give the viewer an in-depth view and analysis of a wave signal.

Introduction

Sound is a longitudinal wave moving through air. It consists of alternate areas of high and low pressures, compressions, and refractions. A sound wave is characterized by its velocity, frequency, wavelength, and amplitude just as any other periodic wave. At any point in the air, near the source of sound, molecules move back and forward, and the air pressure varies up and down by very small amounts. The number of variations per second is called the frequency, measured in cycles per second or Hertz (Hz). The pitch of a note is almost entirely determined by the frequency: high frequency for high pitch and vice versa. The frequency of a sound wave is a measure of the number of waves passing a given point in one second. The distance

between two successive crests of the wave is the wavelength. This is the shortest distance between points where the wave pattern repeats itself. The product of the wavelength by the frequency is the speed of propagation of the wave. Two waves with the same frequency may have different wavelength or amplitude. Amplitude is the maximum displacement from the rest or equilibrium position. The greater the amplitude of the wave, the harder the molecules strike the eardrum and the louder the sound that is perceived.

Sound moves forward in a straight line when traveling through a medium having uniform density. Like light, however, sound is subject to refraction, which bends sound waves from their original path. The excellent reception of sound downwind and the poor reception upwind are also due to refraction. Sound is also governed by reflection, obeying the fundamental law that the angle of incidence equals the angle of reflection. An echo is the result of reflection of sound. A megaphone is a funnel-like tube that forms a beam of sound waves by reflecting some of the diverging rays from the sides of the tube. A similar tube can gather sound waves if the large end is pointed at the source of the sound; an ear trumpet is such a device.

Sound is also subject to diffraction and interference. If sound from a single source reaches a listener by two different paths—one direct and the other reflected—the two sounds may reinforce one another; but if they are out of phase they may interfere, so that the resultant sound is actually less intense than the direct sound without reflection. Interference paths are different for sounds of different frequencies, so that interference produces distortion in complex sounds. Two sounds of different frequencies may combine to produce a third sound, the frequency of which is equal to the sum or difference of the original two frequencies.

Data

Fig. 5 Spectrogram
of D in Trumnet

Matlab is an advanced interactive software package specially designed for scientific and engineering computations. It integrates graphic illustrations with precise numerical calculations, and is a powerful, easy to use, and comprehensive tool for performing all kind of computations and scientific data visualization.

FLUTE							
E	E	F	F	G	G	A	A
Frequency (Hz)	Amplitude	Frequency (Hz)	Amplitude	Frequency (Hz)	Amplitude	Frequency (Hz)	Amplitude
346.8	0.7165	357	1.3121	411.3	0.83467	459.7	0.95223
669.4	0.06514	726	0.0475	798.4	0.04037	911.3	0.16439
1008.1	0.12097	1094	0.0256	1201.6	0.08995	1362.9	0.15199
1701.6	0.05273	1440	0.0768	1604.8	0.04653	1814.5	0.04653
		1786 2153	0.0329 0.0217				
B	B	C	C	D	D	E	E
Frequency (Hz)	Amplitude	Frequency (Hz)	Amplitude	Frequency (Hz)	Amplitude	Frequency (Hz)	Amplitude
508.1	0.70409	544.4	0.65972	604.8	0.50558	669.4	0.3505
1024.2	0.13337	1085.8	0.0932	1201.6	0.26985	1346.8	0.21524
1524.2	0.20161	1627.3	0.15168	1814.5	0.21402	2040.3	0.08995
2040.3	0.04653	2157.3	0.02741	2427.4	0.2171	2701.6	0.04653

Table 2: Frequency and amplitudes of the trumpet

TRUMPET							
E	E	F	F	G	G	A	A
Frequency	Amplitude	Frequency	Amplitude	Frequency	Amplitude	Frequency	Amplitude
346.8	0.20161	362.9	0.18921	411.3	0.12097	459.7	0.26985
685.5	0.29782	717.7	0.14578	814.5	0.15819	911.3	0.183
1008.1	0.046553	1088.7	0.19541	1217.7	0.06514	1395.2	0.28846
1362.9	0.15819	1443.5	0.05893	1637.1	0.06514	1830.6	0.08995
1717.7	0.09615	1814.5	0.08995			2282.3	0.05893
2056.5	0.04032	2185.5	0.05893				
2395.2	0.05893	2540.3	0.0432				
B	B	C	C	D	D	E	E
Frequency	Amplitude	Frequency	Amplitude	Frequency	Amplitude	Frequency	Amplitude
508.1	0.36911	535.7	0.15899	604.8	0.29467	669.4	0.23263
1024.2	0.13337	1077.2	0.26133	1217.7	0.31328	1346.8	0.3629
1524.2	0.16439	1618.7	0.13706	1814.5	0.22643	2024.2	0.12717
2040.3	0.10236	2160.1	0.07858	2427.4	0.07754	2733.9	0.01551
2540.3	0.05273	2701.6	0.03472				

Discussion

This project, which is a continuation of a previous one, was divided into two parts: the analysis of a musical sound and the synthesis of it using mathematical tools and a computer.

In the analysis section, the musical notes: E, F, G, A, B, C, D, E were played on the transversal flute and a trumpet and the sounds were recorded and transferred into the computer. The sound spectrum of each note was separated into its natural harmonics. A Pentium III computer and a program written in the Matlab environment were used to obtain all the frequencies and amplitudes of each tone.

Plots of the wave signal, amplitude vs. time (Fig. 1 and Fig. 2), and of the sound spectrum, the normalized amplitude vs. frequency (Fig. 3), were plotted for each musical note. Graph samples for D (Re) are presented for the discussion.

In figure 2, the characteristic sound wave of D is plotted in an extended time scale. It is clearly demonstrated from this graph that this is a periodic wave.

The sound spectrum has the expected shape, with the maximum value at the first harmonic, and smaller values at the overtones. Reading of the amplitudes and frequencies of each harmonics were done, and tabulated

in Table 1 after normalizing the y-axis (amplitude) by the maximum spike.

The natural frequencies of each harmonic are not independent; they should follow the characteristic values of the Fourier sine series. The lowest frequency, the one that identify the note is called the fundamental frequency f and all other (overtones) increase in pitch and decrease amplitude. Analyzing the sound spectrum of D in the flute (Table 1), it is found that the fundamental frequency, f , is 604.8 Hz. This means that the air in the flute is vibrating at a pattern that repeats 604.8 times a second, or once every $1/604.8$ seconds. This time interval is called the period T .

Higher frequencies harmonics (overtones) are characteristic of the specific instrument and will depend on the make of it and on the expertise of the individual player. Thus, the complete sound spectrum of one note will not be the same for different players even when they use the same instrument.

A spectrogram was done to each of the musical notes produced. It is composed of three dimensions: time, frequency, and amplitude. Spectrograms are a collection of spectra. Spectrum refers to various wavelengths and shows amplitude or intensity. The spectrograms are used mainly for periodic signals in order to get more reliable results. These spectrograms were done to get an inside view of the waves and its intensity and amplitude of the frequencies at any point of the signal. The flute and trumpet graphs were compared and led to an important conclusion. Both instruments have certain frequencies in common which create the tune needed for that note. The trumpet's harmonics show to have more amplitude than those of the flute, which is the cause of the specific tones produced. The flute has its main amplitude in its fundamental frequency, while its overtones are less meaningful. These characteristics lead to the bright trumpet sound and to the sweet flute sound. This analysis is easily seen in Figure 4 vs. Figure 5.

The synthesis of a sound note, using mathematical formulation, once the frequencies and amplitudes are known, consists of the proper combination of the harmonics. This was done for every note with a program in Matlab and using a sum of sine function with the proper frequencies and amplitudes.

The sound produced was similar to the original but not exactly equal, because very small overtones were neglected.

Once every note was synthesized, combinations of notes may be programmed and songs could be “mathematically” produced and digitally played. To make the artificial sounds friendlier to the user, an application for Windows using a program called Access was done. The program uses visual concepts such as buttons or objects to create applications. Visual Programming is a new, easy, and very effective tool. People without previous programming experience can learn it. In Visual Programming the creation of databases, forms, and queries were done relatively fast. The interface in Access is an application, which can be used for analysis or as an educational tool. Any user may easily view the differences of the flute and the trumpet harmonic’s.

This study has a number of future projections. First of all, every instrument of an orchestra should be studied, analyzed, and reproduced artificially, trying to create a virtual mathematical orchestra. Extra research with other equipment can be used to try to create the sounds as real as possible. Decomposition of 2 instruments at the simultaneously can be also implemented in this project.

Conclusions

The following conclusions were reached based on the results gathered throughout the experimentation. They are shown below in the following bulleted phrases.

A sound signal:

- Is a periodic function.
- May be separated into its basic harmonics by using the Fourier transform.
- May be mathematically reconstructed and digitally played.

The flute and the trumpet:

- Are composed of the same fundamental frequencies.
- Have certain overtones in common though the trumpet has more.
- The trumpet’s harmonics (after the fundamental) have more intensity and amplitude than those of the flute; this characterizes the color and sound of the trumpet.

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