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.

A sound spectrum is a representation of a sound - usually a short sample of a sound - in terms of the amount of vibration at each individual frequency. It is usually presented as a graph of either power or pressure as a function of frequency. The power or pressure is measured in decibels and the frequency is measured in vibrations per second (or Hertz, abbreviation Hz) or thousands of vibrations per second (kilohertz, abbreviation kHz). The decibel (dB) is a logarithmic unit used to describe a ratio.

A vibrating object produces sound. The vibrations of the object create molecular motions and pressure oscillations in the air. Woodwind instruments, such as a flute, have a column of air. When a player blows air across the hole in the side of the head joint, causes airflow patterns at the edge of the lip plate to alternate rapidly. The alternation causes the air in the tube to resonate. Waves reflect back and forth in the column of air, creating the tone of the flute. The lowest note can be played when all the tone holes are closed and the column is at its maximum length. Brass instruments are the oldest among instruments. Air is blown through the mouthpiece by vibrating the lips, which will reach the instrument's bell. The air is reflected back toward the mouthpiece where it is modified by the vibration. This vibration decides the pitch of the sound produced. The waves bounce back and forth and the sound and color of a brass instrument is produced. The sound of a musical instrument consists of a fundamental frequency plus other higher frequencies (overtones) that form the harmonic series. Each instrument has a unique sound depending on how much of the other frequencies are present in each note.

The harmonic series may be described by the Fourier series, which is a sum of trigonometric functions (sine and cosine). In the case of waves, the harmonics are represented by sine functions. Characterization of each harmonic with its amplitudes and frequencies is equivalent of having the complete sound spectrum for a musical note. Decomposition of music sound into its harmonics may be performed by obtaining the Fourier Transform of the wave. This mathematical transformation produces the set of amplitudes and frequencies. A numerical technique called "Fast Fourier Transform" was applied by using the Matlab software.

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.

Data

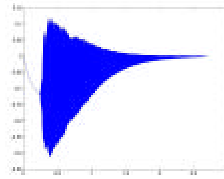

Fig. 1 Wave Signal of D (Flute)

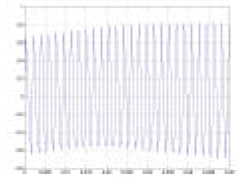

Fig. 2 Portion of the Wave Signal of D (Flute), using an extended time scale

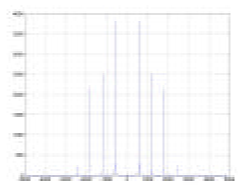

Fig. 3 Sound spectrum of the frequency and amplitudes of D (Flute)

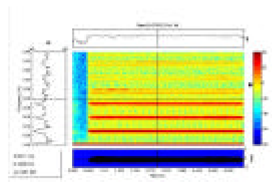

Fig. 4: Spectrogram of D in Flute

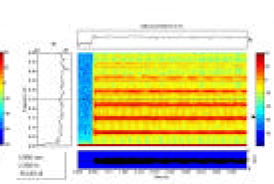

Fig. 5 Spectrogram of D in Trumpet

Tables

Table 1: Frequency and amplitudes of the Flute

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	0.0329				
		2153	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
						3395.2	0.02171

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	0.20782	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 form 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.

References

Alan Simpson (2000). Microsoft Access 2000. New York: Sybex. book

Bo Melin (1999). The Matlab Handbook. New York: Addison – Wessely. Book

Aldo E. Briano, Domingo Rodríguez. Musical Wave Creator. Computer Research Conference 2001.

Halliday, Resnick, Walker (1997). Fundamentals of Physics Extended. New York: John Wiley and Son's. book

Harmony Central. (2000); Physical Modeling Synthesis ; http://www.harmony-central.com/Synth/Articles/Physical_Modeling/ (10/25/00)

Paul A. Tiper (1997). Physics for scientists and engineers. New York: W.H. Company. book

Pompeu University. (2000); Current Perspectives in the Digital Synthesis of Musical Sounds; http://www.iua.upi.es/~xserra/arucies/current (10/16/00)

Psb Speakers International. (2000); The Frequencies - And Sound - of Music; http://www.psbspeakers.com/frequenciesOfMusic.html (10/12/00)

University of South Wales. (2000); How do Woodwind Instruments Work?; http://www.phys.unsw.edu.au/~jw/woodwind.html (10/16/00)

University of South Wales. (2000); What is a Sound Spectrum?; http://www.phys.unsw.edu.au/~jw/sound.spectrum.html (10/16/00)

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