2001

Comparison of three different pipe organs using fast fourier analysis

James Yuzuru Kioka
San Jose State University

COMPARISON OF THREE DIFFERENT PIPE ORGANS USING FAST FOURIER ANALYSIS

A Thesis
Presented to
The Faculty of the Department of Physics
San Jose State University

In Partial Fulfillment
Of the Requirements for the Degree
Master of Science

By
James Yuzuru Kioka
May, 2001
Adviser: Dr. Brian Holmes

UMI Number: 1403979

UMI Microform 1403979

Bell & Howell Information and Learning Company
300 North Zeeb Road
P.O. Box 1346
Ann Arbor, MI 48106-1346

APPROVED FOR THE DEPARTMENT OF PHYSICS

Dr. Brian Holmes, Professor of Physics

Dr. Karamjeet Arya, Professor of Physics

Dr. Brian Belet, Professor of School of Music and Dance

APPROVED FOR THE UNIVERSITY

Acknowledgements

The author's thanks are due to Professor Brian Holmes for his continued help and encouragement; also to Dr. Brian Belet for his generous advise.

The facts in this paper could not have been obtained without the information provided by many people, whom it is impossible to acknowledge separately; the author is especially grateful to Dr. Arthur and Jane Sato for proofreading and editing my manuscript and my wife Tomoko Kioka for financial and mental support and Dr. Robert Kanzo Kioka for continuous help and pray.

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CHAPTER 1: Introduction

1.1 Pipe Organs

The organ occupies a high position among human inventions. Many consider the pipe organ to be the most perfect of all musical instruments. Composer Amadeus Mozart was so fascinated by the pipe organ that he called it "The King of Musical Instruments." The solemn dignified sounds of a pipe organ can captivate large audiences for hours.

To quantitatively determine what factors contribute to the unique sounds of a pipe organ and how they differ from those of other musical instruments is challenging. Characterizing the sounds of pipe organs is difficult because there are many different types of pipes in each organ and many variations built into the pipe organs by each manufacturer. In this investigation, two types of pipes (Principal and Gedackt) and three organ manufacturers (Moller, Schantz and Schuke-Berialin) were studied.

The three pipe organs selected for this study were from three locations in two countries (United States of America and Germany). The Moller organ was recorded at the San Iku Gakuin Junior College located in Chiba, Japan. The Schuke-Berialin organ was recorded at the Amanuma Seventh-day Adventist Church in Tokyo, Japan. The Schantz organ was recorded at the First United Methodist Church in Campbell, California.

The main characteristics of sound are relative amplitude and frequency. In The Acoustic Foundation of Music, Backus explains that tonal quality is what enables us to distinguish one tone from others of the same frequency and volume.[1] Musical instruments produce complex tones that are mixtures of simple tones of various amplitudes and frequencies. Several simple tones making up a complex tone are called partial tones or simply partials. If the partials of a tone are integral multiples 1, 2, 3... of the fundamental frequency, then those partials are called harmonics.[1]

1.2 Purpose of the Study

This study on tonal quality has two purposes. The first purpose is to compare the spectra between the Principal pipes and Gedeckt pipes. The second purpose is to identify the spectrum differences between the organ pipes made by three organ manufacturers in the United States and Germany: the Moller (American), the Schantz (American), and the Schuke-Berialin (German).

Tonal quality depends primarily on the relative amplitudes of the harmonics.[1] To quantify the sound spectra, the fast Fourier transformation was applied to all signals. This yielded a series of harmonics expressed as a power spectrum. The power spectrum was then transformed into a weighted harmonic spectrum that expresses the harmonics relative to the fundamental harmonic.

1.3 Literature Review

The tonal quality of organ pipes depends on several factors such as the air jet, shape of the pipes, the wall materials of organ pipes, and more. The mechanism of sound production in organ pipes driven by air jets has been widely studied.[20,21,22] The harmonic generation in organ flue pipes is well understood.[23] The shape of the pipes determines harmonic generation.

Theoretically, since Principal pipes belong to the group of open pipes, all harmonics are expected to be present.[1,12,13] Principal pipes tend to have bright sounds. On the other hand, Gedackt pipes are closed at one end, so they belong to the group of stopped pipes. Since Gedackt pipes have strong odd-numbered resonance peaks, even-numbered harmonics are expected to appear less in their spectrum as compared to the spectrum of Principal pipes. Consequently, Gedackt pipes tend to have hollow sounds. However, the even numbered harmonics are weak, rather than being absent.[1,12,14] Since, theoretically, the even-numbered harmonics in the spectrum of Gedackt pipe are suppressed, it was anticipated that the tonal quality differences between the Principal and Gedackt pipes only resulted from the difference in amplitudes of even harmonics. Thus significant amplitude differences at even harmonics in the spectra of Principal pipes are expected.

The investigated pipe organs can be categorized into two different groups: the baroque or German organ and the modern or American organ. The Schuke-Berialin was a baroque organ, and the Moller and the Schantz were modern organs.

W. Lottermoser investigated the differences between baroque organs and modern organs in order to reconstruct baroque organs destroyed in World War II. According to his results, the open flue pipes in baroque organs tend to have less sound at a lower frequency than the modern organs.[16] Significant amplitude differences were expected between the American (Moller and Schantz) and the German (Schuke-Berialin) Principal and Gedackt pipes.

N. Thompson-Allen studied on the effect of climate upon organ tones. Significant differences in tonal quality were found between sounds recorded in March versus sounds recorded in August. The sounds of organ pipe had higher frequencies in each harmonic and brighter sounds in August compared to those in March.[16] Many higher numbered harmonics (greater than the tenth harmonic) were missing in March.[16]

1.4 The Structure of Organ Pipes

In this study, major stopped and open organ pipes were investigated. Stopped pipes have one end closed, whereas open pipes are open at both ends.[2] Likewise, the Principal organ pipes were selected because they represent one of the major open pipes. Figures 1-1-1, 1-1-2, 1-1-3 show several characteristic modes of vibration of a Principal pipe and the corresponding modes for Gedackt pipes. The boundary condition for an open end is a pressure node, or a displacement antinode. The Gedackt organ pipes were selected because they are one of the major stopped pipes.

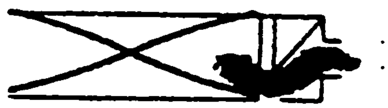


Figure 1-1-1. First harmonic of an open pipe (Principal pipe).

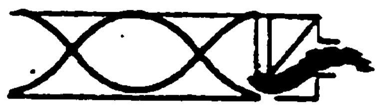


Figure 1-1-2. Second harmonic of an open pipe (Principal pipe).

Figure 1-1-3. Third harmonic of an open pipe (Principal pipe).

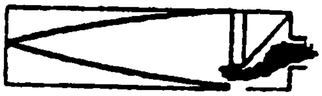


Figure 1-1-4. First harmonic of a closed pipe (Gedackt pipe).

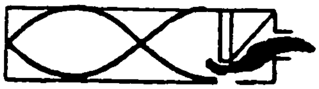


Figure 1-1-5. Third harmonic of a closed pipe (Gedackt pipe).

Figure 1-1-6. Fifth harmonic of closed pipe (Gedackt pipe).

1.5 The Principal Pipes

Principal pipes comprise the most important voice in the modern pipe organ, because their firm and supporting qualities form the backbone in the tonal structure of the organ. They are used throughout the range of audible pitches without changing tonal character. Principal pipes most often have a high percentage of tin (60 to 75 percent), "because it provides a fresher sound, and because Principal pipes are often mounted in the front, where appearance is important".[2]

1.6 The Gedackt Pipes

The Gedackt pipe is a major form of stopped pipes. The tonal character of Gedackt pipes is hollow because even numbered harmonics are suppressed. For Gedackt pipes, "both wood and tin-lead alloys have been used as materials, chiefly and generally with a low tin content (30 percent)" .[3]

1.7 Organ Pipe Materials

The influence of organ pipe materials on its tonal quality has long been a topic of controversy between organ builders and scientists. Organ builders believe that the materials used in organ pipes significantly affect their tonal quality. For example, wood pipes produce tones described as woody, warm, and mellow.[3] Metal pipes with a high percentage of lead[3] produce tones generally described as solid, foundational, and massive. If the metal has a high percentage of tin and the walls are thin, the tonal quality of the organ considered keen, stringy, biting, or incisive. Descriptive terms used to describe timbre are indefinite and lead observers to regard as valid conclusions about the effect of materials on tonal quality, even in the absence of objective bases for those conclusions.[4]

On the other hand, scientists have found that the materials of organ pipes only slightly affect their tonal quality. According to The Acoustical Foundations of Music, "as in the woodwinds, recent work has further shown that the vibration of the walls of the organ pipe when sounding do not affect the internal standing wave, nor do they radiate sufficient sound to be heard".[1] In addition, two scientists C. P. Boner and R. B. Newman studied the effect of wall material on the steady-state acoustic spectrum of flue pipes and concluded that cylinder material has a negligible effect on the generation and emission of sound.[4] Moreover, Backus explained that the most compelling reason for the use of the usual tin-lead mixture is the ease with which it may be worked and the pipe voiced.[1]

1.8 Structure of Paper

This paper is organized into seven chapters. The first chapter explains the purpose of the study and describes the Principal and Gedackt organ pipes. In the second chapter, the fast Fourier transformation and its algorithms are explained. In the third chapter, the digital signal processing is introduced. In the fourth chapter, the experimental method is explained. In the fifth chapter, the experimental results from the two types of pipes made by three manufacturers are reported as spectra and numerical data. In the sixth chapter, differences in tonal quality between the two types of organ pipes from the three organ manufacturers are discussed. In the seventh chapter, the conclusion is given.

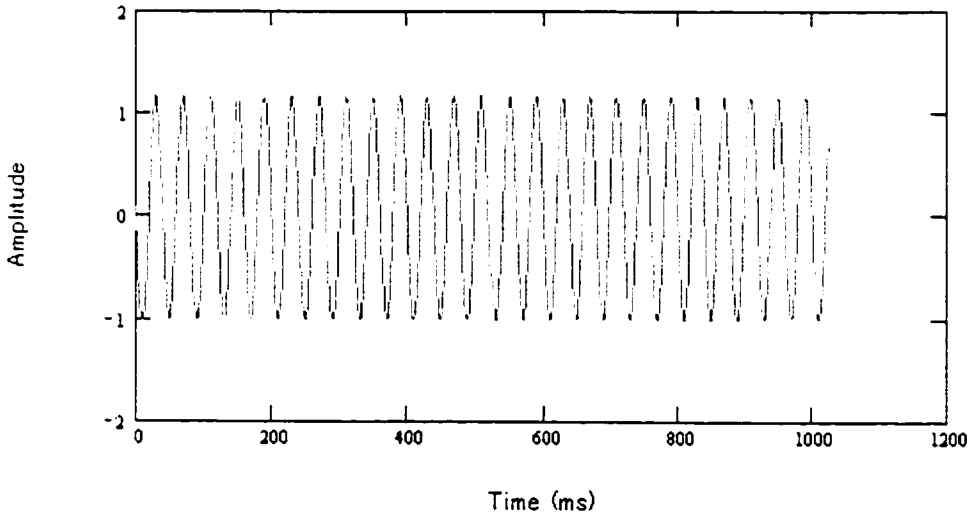
CHAPTER 2: Introduction of the Fast Fourier Transformation

Digital frequency analyses is based on mathematical calculation schemes rather than on the use of a band pass filter. The input to a digital frequency analyzer consists of a series of numbers. Such a series of numbers can be obtained from the original signal by analog-to-digital conversion. The digital signal processing results can be presented graphically as a frequency spectrum. In this study, the Fast Fourier Transformation (FFT) was used to obtain frequency spectra.

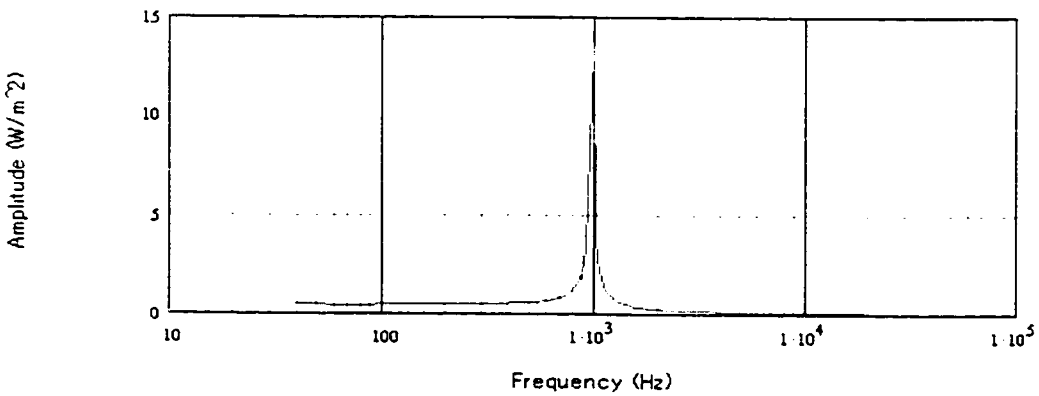
2.1 Introduction of Fourier Transformation

The Fourier transformation was first introduced by the French mathematician, Joseph Baron de Fourier (1768-1830). The Fourier transformation is based on the idea that "every periodical function can be expressed as a combination of trigonometric functions."[5] Through this idea of Fourier is widely accepted by scientists today, at the beginning of the nineteenth century, Fourier's idea was regarded as sensational and rejected by most scientists, even the very famous French mathematician, Lagrange.

The Fourier transformation can transform an original signal into a spectrum as shown in Figure 2-1.



(a) Waveform of 1000Hz



(b) Spectrum of 1000Hz

Figure 2-1. (a) Waves of 1000Hz and (b) Spectrum of 1000 (Spectrum obtained by fast Fourier transformation)

The Fourier spectrum analysis resembles the methods shown in recognition processes of the human ear. According to study by Nakajima, the human ear processes the sounds by performing spectral analysis.[6]

The Fourier series representation has the mathematical form:

$$g(t) = A_o + A_1 \cos(2\pi\ t/T) + \ldots + A_2 \cos(4\ \pi\ t/T) + \ldots$$

$$\ldots + B_1 \sin\ (2\pi\ t/T) + \ldots + B_2 \sin(4\pi\ t/T) + \ldots$$

$$+ \sum_{n=1}^{\infty} A_n \cos 2\pi \frac{nt}{T} + \sum_{n=1}^{\infty} B_n \sin 2\pi \frac{nt}{T} \quad . \tag{2-1}$$

where t is time, T is a period, and n is an integer. The lowest frequency terms $A_1 \cos(2\pi t/T)$ and $B_1 \sin(2\pi t/T)$ are called the fundamental components. $A_n \cos(2\pi n t/T)$ and $B_n \sin(2\pi n t/T)$ are called higher harmonic oscillation components.[7] The coefficients A_o, A_n, and B_n are called the Fourier coefficients. The Fourier coefficients indicate how cosine and sine components mix in the original signal. These coefficients are also called amplitudes. The process of determining the coefficients A_o, A_n, and B_n for a specific function G(t) is referred to as a Fourier analysis. In order to determine the amplitudes of the frequencies, the following integration must be performed:

$$Ao = \frac{1}{T}\int_0^T G(t)\,dt \quad . \tag{2-2}$$

$$An = \frac{2}{T}\int_0^T G(t)\cos 2\pi \frac{nt}{T}\,dt \quad . \tag{2-3}$$

$$Bn = \frac{2}{T}\int_0^T G(t)\sin\left(2\pi\frac{nt}{T}\right)dt \ . \qquad (2\text{-}4)$$

where T is the period, n is an integer, and t is time.[8]

By expressing the Fourier series in terms of an amplitude, cosine function, and phase, equation (2-1) can be simplified as following:

$$g(t) = C_o + \sum_{n=1}^{\infty} C_n \cos\left[2\pi\frac{nt}{T} - \phi_n\right] \ . \qquad (2\text{-}5)$$

where $C_o = A_o$, amplitude $C_n = \sqrt{(A_n^2 + B_n^2)}$, and phase $\phi_n = \tan^{-1}(B_n / A_n)$.

When the Fourier series is expressed as a complex numerical function, calculation of Fourier coefficients is simpler than calculation of the Fourier coefficients from sine and cosine functions. To achieve this, Euler's formula is used in order to express the Fourier series as a complex numerical function.

Euler's formula is described as follows:

$$\text{Exp}(i\,\theta) = \cos\theta + i\sin\theta \ . \qquad (2\text{-}6)$$

Substituting the Euler's formula into Equation (2-5), then Equation (2-5) can be expressed cosine and sine functions as those complex quantities:

$$g(t) = C_o + \sum_{n=1}^{\infty} C_n \cos\left[2\pi \frac{nt}{T} - \phi_n\right]$$

$$= C_o + \sum_{n=1}^{\infty} C_n \frac{\left[\left[\exp\frac{i2\pi nt}{T} - i\phi_n\right] + \exp\left[\frac{-i2\pi nt}{T} + i\phi_n\right]\right]}{2}$$

$$= C_o + \left[\sum_{n=1}^{\infty} \frac{C_n}{2}\left[\exp - i\phi_n \quad \exp\frac{i2\pi nt}{T}\right] + \sum_{n=1}^{\infty} \frac{C_n}{2}\left[\exp i\phi_n \quad \exp\frac{-i2\pi nt}{T}\right]\right].$$

(2-7)

When new constants G_n and G_{-n} are defined as follows:

$$G_n = \frac{C_n}{2} \quad \exp - i\phi_n \quad , \qquad (2\text{-}8)$$

$$G_{-n} = \frac{C_n}{2} \quad \exp\ i\phi_n \quad , \qquad (2\text{-}9)$$

then the Fourier series can be rewritten as this:

$$g(t) = \sum_{n=-\infty}^{\infty} G_n \quad \exp\frac{i2\pi nt}{T} \quad . \qquad (G_o = A_o) \qquad (2\text{-}10)$$

Equation (2-10) is called the complex Fourier expansion. Equation (2-10) only represents the characteristics of a periodical signal.

The equation for the Fourier coefficients is:

$$G_n = \frac{1}{T} \cdot \int_{-\frac{T}{2}}^{\frac{T}{2}} g(t) \cdot \exp \frac{-i2\pi nt}{T} \, dt \,. \qquad (2\text{-}11)$$

When the signal does not have a period when the period is hard to find, then the period T is assumed to be infinitely long. Thus Equation (2-11) can be rewritten as following:

$$G_n = \lim_{T \to \infty} \frac{1}{T} \cdot \int_{-\frac{T}{2}}^{\frac{T}{2}} g(t) \exp \frac{-i2\pi nt}{T} \, dt \,. \qquad (2\text{-}12)$$

In Equation (2-12), when the period is set to some finite value, then n/T represents the n th harmonic frequency. Higher harmonic frequency, f_n, and frequency difference, δf, between adjacent harmonic frequencies are defined as follows:

$$f_n = \frac{n}{T}, \qquad (2\text{-}13)$$

$$\delta f = \frac{1}{T}. \qquad (2\text{-}14)$$

If Equation (2-13) and (2-14) are substituted into Equation (2-12), this new equation is derived:

$$G_n = \lim_{T \to \infty} \left[\delta f \left[\int_{-\frac{T}{2}}^{\frac{T}{2}} g(t) \exp\left[- i2\pi f_n t\right] dt \right] \right] . \tag{2-15}$$

When a period T is assumed to have an infinitely long value, then δf (shown in Figure 2-2) becomes very small. Thus, the discrete spectrum can be shown as a function of frequency as a continuous variable. Therefore, f_n and δf can be rewritten as f and df.

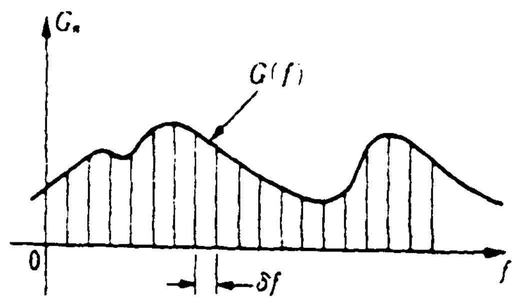


Figure 2-2. For the infinitely long period T, the discrete spectrum G_n can be shown as a continuous spectrum G(f).

Hence, the equation for Fourier coefficients, whether the signal is periodic or not, has following representation, called the Fourier transformation:

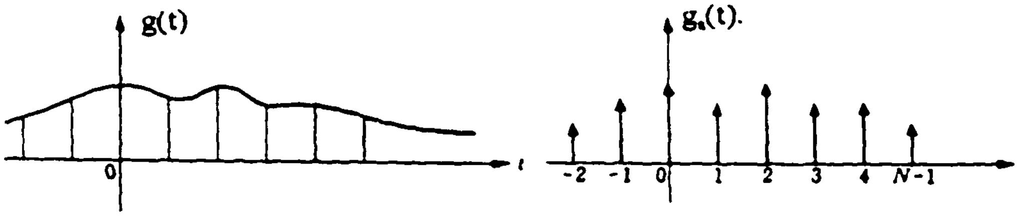
$$G(f) = \int_{-\infty}^{\infty} g(t) \exp(-i2\pi ft)\, dt . \tag{2-16}$$

2-2 Discrete Fourier Transformation

After sampling, a signal is no longer continuous. For such a discrete signal, a new Fourier Transformation is introduced which is called the discrete Fourier Transformation (DFT). For the sampled signal $g_s(t)$, the equation of the Fourier Transformation G(f) can be expressed as:

$$G(f) = \int_{-\infty}^{\infty} g_s(t) \cdot e^{(-i2\pi ft)} dt . \tag{2-17}$$

For signal $g_s(t)$, as shown in the Figure 2-3 (b), the value of signal $g_a(t)$ will be 0 except at $t = n\tau$. Thus, $g_s(t)e^{-i2\pi ft}$ is also zero when n=N-1.



((a) (b)

Figure 2-3. (a) Continuous signal g(t) and (b) sampled signal $g_s(t)$.

If follows that the Fourier Transformation can be rewritten as a summation of function $g_s(t)$ at $t = n\tau$:

$$G(f) = \sum_{n=-\infty}^{\infty} g_s(n\tau)\, e^{-i2\pi fn\tau} . \tag{2-18}$$

However, at $t = n\tau$, the value of continuous signal g(t) and sampled signal $g_s(t)$ are the same. Therefore, $g_s(t)$ is replaced with g(t) and the Fourier transformation can be expressed as:

$$G(f) = \sum_{n=-\infty}^{\infty} g(n\tau)\, e^{-i2\pi fn\tau} \quad (2\text{-}19)$$

This is the equation of a DFT for an infinite number of data points.

In equation (2-19), of primary importance is the f in $\exp^{(-i2\pi fn)}$. Since the period was set at infinity in the Fourier transformation, f became continuous. However, in order to execute the Fourier transformation with a computer, the finite period of the wave such as shown in Figure 2-3 (a) has to be chosen and treated as a single period.

Assuming that the signal is chosen and sampled from a continuous signal is as shown in Figure 2-4.

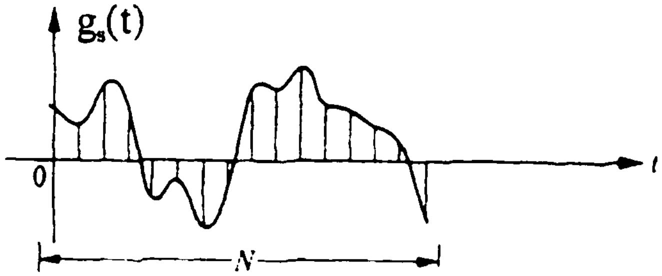


Figure 2-4. N sampled signal

Since the period of the wave is the sampling period multiplied by the total number of data points N ($T = \tau N$), its fundamental frequency is $1/(\tau N)$. The rest of the frequencies, which are integral multiples of the fundamental frequency, can be written as $k/(\tau N)$. Here k represents an integral multiple of the fundamental frequency. By substituting k/(τ N) into f, the Fourier transformation becomes discrete and data is finite. In order to simplify the DFT, τ can be set at 1 second. Thus DFT can be written as:

$$G(k/N) = \sum_{n=0}^{N-1} g(n) \exp\frac{-i2\pi kn}{N} \quad . \tag{2-20}$$

The sampled signal is finite and can be represented by N (from G(0) to G(N-1)), discrete Fourier spectrum of sampled signal, $G_s(k/N)$, can be written as $G_s(k)$ and DFT further rewritten as

$$G(k) = \sum_{n=0}^{N-1} g(n) \exp\frac{-i2\pi kn}{N} \quad . \tag{2-21}$$

In order to simplify the process of DFT calculation, a new factor is introduced, called the twiddle factor.[9] The twiddle factor is defined as follows:

$$W = \exp(-i2\,\pi/N). \tag{2-22}$$

From this the following equations thus:

$$W_N^{nk} = \exp(-i2nk\,\pi/N), \tag{2-23}$$

$$W_N^{-nk} = \exp(\,i2nk\,\pi/N). \tag{2-24}$$

For N = 8, W_8^{nk} can be drawn as follow:

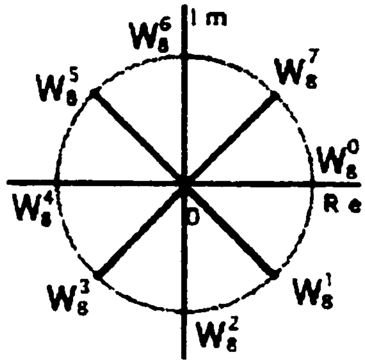


Figure 2-5. Twiddle Factor expressed as a unit circle.

The vertical axis is imaginary and horizontal axis is real. This circle has a radius of 1 and it was divided by 8. From Figure 2-5, it is easy to find value of W_8^{nk} .

For example, W_8^1 = Real part + iImaginary part = cos $(-2\pi/8)$ + isin$(-2\pi/8)$ = 1/SQR(2) - i1/SQR(2). If N = 16, then the circle will have sixteen segments.

Finally, by using the twiddle factor, DFT has the following representation:

$$G(k) = \sum_{n=0}^{N-1} g(n)\ W_N^{nk} \quad . \qquad (2\text{-}25)$$

2-3 Fast Fourier Transformation

In order to execute DFT calculations by computer, the number of DFT calculations must be reduced by an algorithm called the Fast Fourier transformation. This algorithm was first introduced by J.W.Cooley and J.W.Tukey in 1965.[1] Before the invention of the FFT, scientists believed the computer needs N^2 calculations in the DFT calculation in order to obtain the spectrum of signal G(k). The invention of the FFT algorithm reduced the number of calculations from N^2 to N log(N). For example, if N = 1024, the number of the DFT calculations will be 1,040,000. Using the FFT algorithm, it can be reduced from 1,040,000 to about 10,000.

Their algorithm is explained by using the twiddle factor and DFT equation when N = 8. The DFT representation is expressed as:

$$G(k/8) = \sum_{n=0}^{7} g(n)\ W_8^{nk} \quad . \tag{2-26}$$

Each DFT calculation requires a multiplication in its calculation, therefore, there would be 8^2 calculations. The Equation (2-26) can be shown as a Table 2-1.

	$g(0)$	$g(1)$	$g(2)$	$g(3)$	$g(4)$	$g(5)$	$g(6)$	$g(7)$
$G(0/8)$	W^0	W^0	W^0	W^0	W^0	W^0	W^0	W^0
$G(1/8)$	W^0	W^1	W^2	W^3	W^4	W^5	W^6	W^7
$G(2/8)$	W^0	W^2	W^4	W^6	W^8	W^{10}	W^{12}	W^{14}
$G(3/8)$	W^0	W^3	W^6	W^9	W^{12}	W^{15}	W^{18}	W^{21}
$G(4/8)$	W^0	W^4	W^8	W^{12}	W^{16}	W^{20}	W^{24}	W^{28}
$G(5/8)$	W^0	W^5	W^{10}	W^{15}	W^{20}	W^{25}	W^{30}	W^{35}
$G(6/8)$	W^0	W^6	W^{12}	W^{18}	W^{24}	W^{30}	W^{36}	W^{42}
$G(7/8)$	W^0	W^7	W^{14}	W^{21}	W^{28}	W^{35}	W^{42}	W^{49}

Table 2-1. Table of the twiddle factor

However, the twiddle factor rotates repeatedly over the same course, which means the same values are repeated over and over.

So just as 0° and 360° are the same, $W^0 = W^8$, $W^1 = W^9$, and so on. This simplifies the Table 2-1 to become the table of the twiddle factor as shown in Table 2-2.

	$g(0)$	$g(1)$	$g(2)$	$g(3)$	$g(4)$	$g(5)$	$g(6)$	$g(7)$
$G(0/8)$	W^0	W^0	W^0	W^0	W^0	W^0	W^0	W^0
$G(1/8)$	W^0	W^1	W^2	W^3	W^4	W^5	W^6	W^7
$G(2/8)$	W^0	W^2	W^4	W^6	W^0	W^2	W^4	W^6
$G(3/8)$	W^0	W^3	W^6	W^1	W^4	W^7	W^2	W^5
$G(4/8)$	W^0	W^4	W^0	W^4	W^0	W^4	W^0	W^4
$G(5/8)$	W^0	W^5	W^2	W^7	W^4	W^1	W^6	W^3
$G(6/8)$	W^0	W^6	W^4	W^2	W^0	W^6	W^4	W^2
$G(7/8)$	W^0	W^7	W^6	W^5	W^4	W^3	W^2	W^1

Table 2-2. Simplified the table of the twiddle factor

The exponents were reduced to only eight groups - the numbers from 0 to 7. Further reduction is possible if Table 2-2 is divided into odd and even values of n, the DFT representation can be written as equation (2-27), and the Table of the twiddle factor will be separated into two tables: Table 2-3 (a) and Table 2-3 (b).

$$G(k/8) = \sum_{n=0}^{\frac{8}{2}-1} g(2n)\, W_{\frac{8}{2}}^{k2n} + \sum_{n=0}^{\frac{8}{2}-1} g(2n+1)\, W_{\frac{8}{2}}^{k(2n+1)} \quad . \tag{2-27}$$

Even

	$g(0)$	$g(2)$	$g(4)$	$g(6)$
$G(0/8)$	W^0	W^0	W^0	W^0
$G(1/8)$	W^0	W^2	W^4	W^6
$G(2/8)$	W^0	W^4	W^0	W^4
$G(3/8)$	W^0	W^6	W^4	W^2
$G(4/8)$	W^0	W^0	W^0	W^0
$G(5/8)$	W^0	W^2	W^4	W^6
$G(6/8)$	W^0	W^4	W^0	W^4
$G(7/8)$	W^0	W^6	W^4	W^2

(a)

Odd

	$g(1)$	$g(3)$	$g(5)$	$g(7)$
$G(0/8)$	W^0	W^0	W^0	W^0
$G(1/8)$	W^1	W^3	W^5	W^7
$G(2/8)$	W^2	W^6	W^2	W^6
$G(3/8)$	W^3	W^1	W^7	W^5
$G(4/8)$	W^4	W^4	W^4	W^4
$G(5/8)$	W^5	W^7	W^1	W^3
$G(6/8)$	W^6	W^2	W^6	W^2
$G(7/8)$	W^7	W^5	W^3	W^1

(b)

Table 2-3. Even (a) and Odd (b) group of twiddle factor

By defining the even group as g(2n) = p(n) and the odd group as g(2n+1) = q(n), the equation (2-27) can be expressed as:

$$G(k/8) = \left[\sum_{n=0}^{\frac{8}{2}-1} p(n)\, W_{\frac{8}{2}}^{2nk} + W_{\frac{8}{2}}^{k} \cdot \sum_{n=0}^{\frac{8}{2}-1} q(n)\, W_{\frac{8}{2}}^{2nk} \right] . \qquad (2\text{-}28)$$

By moving the twiddle factor $W_{8/2}^{k}$ outside the summation, the same representation of the twiddle factor is valid for both even and odd numbers of n in Equation 2-28. The following is the table of even and odd groups of n.

Even group

	$p(0)$	$p(1)$	$p(2)$	$p(3)$
$G(0/8)$	W^0	W^0	W^0	W^0
$G(1/8)$	W^0	W^2	W^4	W^6
$G(2/8)$	W^0	W^4	W^0	W^4
$G(3/8)$	W^0	W^6	W^4	W^2
$G(4/8)$	W^0	W^0	W^0	W^0
$G(5/8)$	W^0	W^2	W^4	W^6
$G(6/8)$	W^0	W^4	W^0	W^4
$G(7/8)$	W^0	W^6	W^4	W^2

(a)

W^k

Odd group

	$q(0)$	$q(1)$	$q(2)$	$q(3)$
$G(0/8)$	W^0	W^0	W^0	W^0
$G(1/8)$	W^0	W^2	W^4	W^6
$G(2/8)$	W^0	W^4	W^0	W^4
$G(3/8)$	W^0	W^6	W^4	W^2
$G(4/8)$	W^0	W^0	W^0	W^0
$G(5/8)$	W^0	W^2	W^4	W^6
$G(6/8)$	W^0	W^4	W^0	W^4
$G(7/8)$	W^0	W^6	W^4	W^2

(b)

Table 2-4. Even (a) and Odd (b) group of the twiddle factor

The tables for the even and odd groups are now the same when the top half is multiplied. The results can be used for the bottom half. With sixteen calculations for the even group, sixteen calculations for odd group, and calculations of the twiddle factor with the odd group, there are thirty-six total calculations (16 + 16 + 4 = 36).

Reduction of the number of calculations is possible by again dividing the values of n in p(n) and q(n) into odd and even, so that the total number of operations can be reduced to 24. This is how the FFT works for N = 8 DFT.

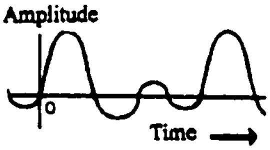
By repeatedly halving the number of values, the total number of calculations can be dramatically reduced. For this method to work, the number of data points must have the form of 2^n. In this study, the number of data points was 1024.

CHAPTER 3: Digital Signal Processing

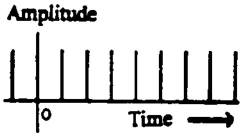
The audio signals must be sampled and digitized before executing the Fourier transformation on a computer.

3-1. Sampling Theorem

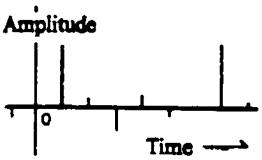
Sampling is the process of converting a continuous analog signal into discrete amplitudes at specified sampling intervals. As shown in Figure 3-1 below, in order to do sampling, a continuous signal is multiplied by a modulation signal, which is a set of impulse function separated by the sampling interval τ.



(a) Original Signal



(b) Unit impulse function

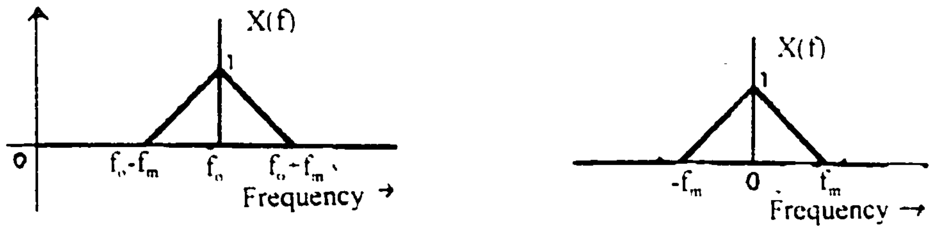


(c) Sampled signal

Figure 3-1. Sampling process: modulating a continuous signal with a unit impulse function.

The optimum sampling interval τ is determined from the input signal frequency content using the Nyquist sampling theorem. This theorem states that "A continuous input signal with frequency bandwidth limited to f f_m (where f is frequency of the input signal and f_m is the maximum frequency contained in its spectrum), can be reconstructed accurately from a sampled signal, provided the sampling rate is greater than twice the input bandwidth".[9] The sampling rate, f_S (samples per second), is the reciprocal of the sampling interval ($f_s=1/\tau$). Determining the sampling rate is important throughout the signal processing. This is the key to efficient implementation of digital calculations.

A signal which has a triangular shaped spectrum is shown in Figure 3-2 (a). For convenience, the center of the spectrum was shifted so that the spectrum is in the range $-f_m$ f f_m as shown in Figure 3-2 (b).



(a) (b)

Figure 3-2. Spectrum centered at f_o (a) center of spectrum shifted to $f = 0$.

When the input signal is sampled with sampling rate f_s, the spectrum $X_s(f)$ of the sampled signal will appear as shown in Figure 3-3.

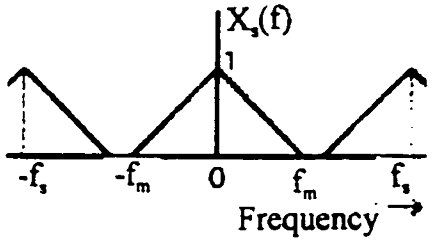


Figure 3-3. Output spectrum of signal after the sampling at sampling rate f_s.

When the sampling rate is $f_S < 2f$, the adjacent spectra overlap, distorting the output signal so that it looks as shown in Figure 3-4. The overlap is referred to as the aliased output spectrum or aliasing. The condition of the sampling theorem must be met when the signal is sampled in order to avoid distorting the spectrum. This criteria determines the choice of sampling rate f_s .

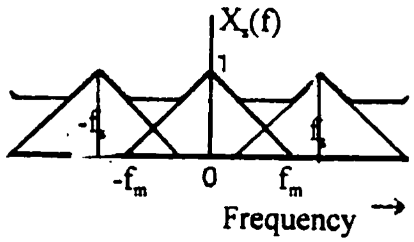


Figure 3-4. Output signal spectrum for f_s f_m.

In order to cut input frequencies above the sampling rate, usually, an anti-alias filter is used, such as the filter already incorporated in the mini disk recorder. In this study, the sampling rate was 40 KHz, corresponding to a sampling interval of 25 microseconds.

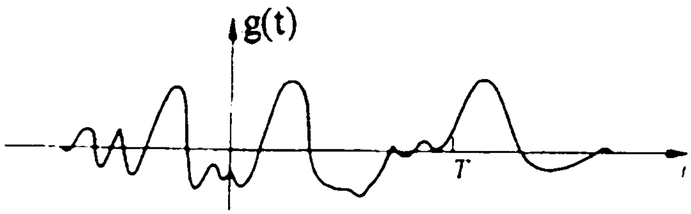
3-2. Hamming Window

The input to an FFT is not an infinite-time signal as in a continuous Fourier transform. A FFT can only handle a section (a truncated version) of a signal. In order to obtain such a segmented signal, a continuous signal is truncated by multiplying it by a special function called *temporal window function*, or, more simply, *temporal window*. The temporal window function can control the time interval of each truncated signal; the time interval is called sampling time. One of the major window functions is the Rectangular window function.

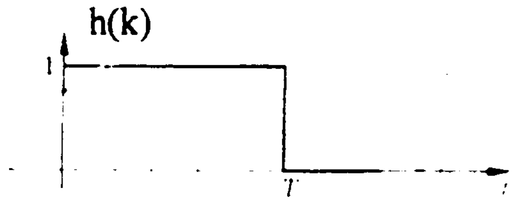
According to C.H. Chen, "The Fourier transform of a rectangular window is the sin(x)/x (or sinc) function, and the longer the rectangular window function, the narrower the main lobe (peak) of sinc".[10] Thus, for good frequency resolution, a long window is desired, but for good temporal resolution, a short window is desired.

For a DFT, the length of the rectangular function often set equal to one period or a multiple of the period of the input signal. However, if the time length of the rectangular window function is not equal to an integral number of periods of the input signal, spurious results will appear in the DFT output. Such spurious results are called leakage or noise. If the rectangular window is equal to an integral number of periods, then there is no disturbance of the spectrum.[7]

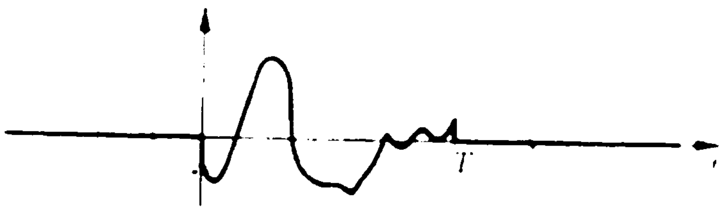
In a real system, it is very difficult to capture exactly one period or a multiple of periods of a signal because the FFT prefers a 2^N-point time domain sequence in order to shorten the time of calculation; therefore, sampling time will depend only on the total time length of a signal divided by 2^N data points.



(a) Original signal



(b) Rectangular window



(c) Sampled signal

Figure 3-5. Process of signal-cut by Rectangular window function

Therefore, when a Rectangular window function is used, leakage in the FFT output will usually result. It is better to use a window that has lower sidelobes (beginning point and end point of signal cut out) in the frequency domain to control leakage. The cost is a wider mainlobe, which decreases frequency resolution.

The window function should be selected for two characteristics. First, to reduce the effect of side lobe multiplication, the side lobes in the Fourier transform of the window function should be significantly smaller than those of the Rectangular window function's Fourier transform. Second, the main lobe of the window function's Fourier transform should be sufficiently narrow so that important signal information is not lost. In this research, Hamming window function h(k) was chosen. Its equation is the following:

$$h(k) = 0.54 - 0.46\cos(2\pi k / N-1), \qquad (k = 0, 1, \ldots, N-1) \qquad (3\text{-}1)$$

where k is an index of sampling points and N is the number of sampled data points.[10]

The Hamming window was derived from a generalized window function w(k):

$$w(k) = \alpha + (1-\alpha)\cos(2\pi k/n-1). \qquad (3\text{-}2)$$

For $\alpha = 1$ then this wave function is simply *Rectangular window function.* For $\alpha = 0.5$, this function is called *Hanning window function* and for $\alpha = 0.54$, this function is called *Hamming window function.*[11] According to the figure, the most effective window function to minimize the leakage is the Hamming window. The constant $\alpha = 0.54$ was solved from a generalized wave function in order to have the highest sidelobe level to be –42 dB.[1]

Window Function	Shape	Maximum Level of Sidelobe (dB)
Rectangular		-13
Triangle		-26
Sine function		-23
Hanning		-32
Hamming		-42

Table 3-1. A List of Window Functions

The constant α =0.54 was solved from a generalized wave function in order to have the highest sidelobe level to be -42 dB.[1] For comparison, the power spectrum of 1000Hz transformed through Rectangular window and Hamming window are plotted by using Mathcad 8.0 and given below (Figure 3-6). It is clear that Hamming window has lower sidelobes than rectangular window.

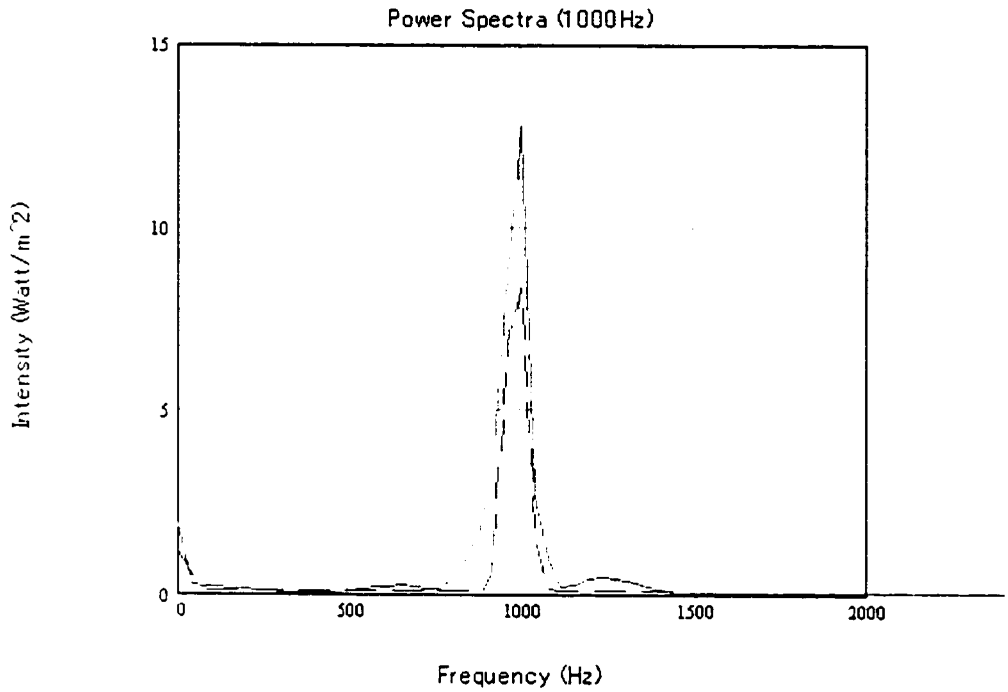


Figure 3-6. Spectra written by Rectangular window and Hamming window

Where dot line is spectrum of 1000 Hz which was given by the Hamming window and solid line is spectrum of 1000 Hz which was given by the Rectangular window.

CHAPTER 4: Methodology of the Study

4.1 Apparatus

In this study, a mini-disk recorder (Sony MZ-R5ST) and condenser microphone (AKG C1000S) were used to record the sounds of organ pipes. The frequency responses for both the mini-disk recorder and microphone were given in the operating instructions by the manufacture; nonetheless, the frequency characteristics of the equipment were analyzed to check the accuracy of the manufacture's information. In order to obtain the frequency response for the equipment, a function generator (TRIO AG-203 CR Oscillator) and voltmeter (Kenwood VT-171 AC Voltmeter) were used.

The frequency and sound pressure level of the function generator were set to 1000 Hz and -20dB respectively. Then the level of amplitude was fixed. Sixteen frequencies were randomly chosen between 20 Hz to 20000 Hz. The recording level of the mini-disk recorder was set to a fixed value (about five in its scale) then each signal was recorded for ten seconds. After all the signals were recorded, a digital voltmeter was connected to the output of the mini-disk recorder and set to show the sound pressure level. Subsequently, the sound pressure level of each signal was recorded and plotted on a graph using Lotus 1-2-3 Version 98. Next the graph of the frequency responses obtained and then compared with the manufacturers' information. According to the operating instructions, the frequency response of the mini-disk recorder should be flat to ± 0.5 dB over 5Hz ~ 20,000 Hz, and the obtained result shows that frequency response of mini-disk recorder flat to ± 0.3 dB over 20Hz ~ 20,000Hz.

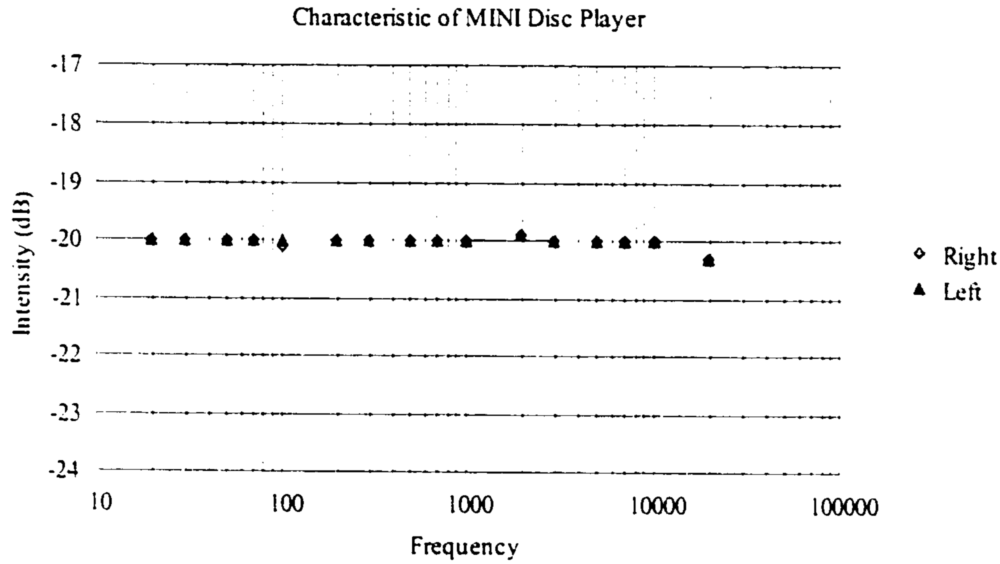


Figure 4-1 Characteristic Response of MINI DISC Recorder

For the microphone, the frequency characteristic was provided in the manual. (See Appendix A)

4-2 Procedure

An electret condenser microphone (AKG C1000 S) was mounted on a tripod set in front of the organ pipes. The distance between organ pipes and microphone was set to about 1 meter in order to prevent the microphone from catching much ambient hall noise. The output of the microphone was fed to a mini-disc (MD) recorder. The recording level of the MD was set to a fixed value (about Level five) throughout the recording sessions. The MD can convert the analog signals to digitized signals and record them; however, there was no equipment to transfer those digitized signals from MD to the computer, so an analog to digital converter was used. The discs were played into the National Instruments analog to digital converter (DAQ-516) which was installed in the computer (NEC READY 9619), and analog signals were converted to digitized signals and transformed into text files. Every pitch from C4 to C6 of the Principal and Gedackt pipes were recorded. For each note, the MD recorder was started and allowed to record the initial transient. Then the tone was played for 10 seconds. Every note was recorded three times. Twenty-five Principal pipes and Gedackt pipes for each organ were recorded.

The first set of recordings was taken at San-Iku Gakuin Japan Missionary College in Japan. This pipe organ was built by Moller Company.

Then second set of recordings was done at Amanuma Seventh Day Adventist Church in Tokyo, Japan. This pipe organ was made by Schuke-Berialin Company.

The third set of recordings was done at the First United Methodist Church in Campbell, California. The pipe organ was built by the Schantz Company. The procedure slightly differed from the procedure used in Japan because of the structure of the organ. All the pipes were in a loft where there was not enough space to put a microphone, so the microphone was attached to the one end of a 2.5 meters long steel pipe and held at about 1 meter from the pipes.

Data was analyzed using a t-test (See Appendix B) to assess differences between Principal and Gedackt pipes and differences among pipes of different organ manufacturers. The hypothesis in this study was that there was no differences between the spectra of the different organ pipes. To assess the difference between the tonal quality of organ pipes, we subtracted the average relative amplitudes of the harmonics of the Schantz and the Moller from those of the Schuke-Berialin. The difference between the Moller and the Schantz organs was obtained similarly. Results were considered significant at the 95% level of probability.

CHAPTER 5: RESULTS

Principal and Gedackt pipes were recorded for three different organs for 25 notes ranging from C4 to C6. Spectra were obtained using Virtual Bench from National Instruments. Once spectra were obtained, they were transformed into weighted spectra.

5.1. The Principal Pipes

The weighted spectra of Principal pipes are shown in Figure 5-1 through 5-3, and numerical values are given in Table 5-1 through 5-3. All the amplitudes are given as fractions of the amplitude of the fundamental harmonic. Also, the standard deviations for each harmonic are given, reflecting the variation of the amplitudes from C4 to C6.

In this study, because of limitations in our equipment, only the first eight harmonics were examined. All eight harmonics are present in the spectra of Principal pipes as shown in the figures 5-1, 5-2, and 5-3.

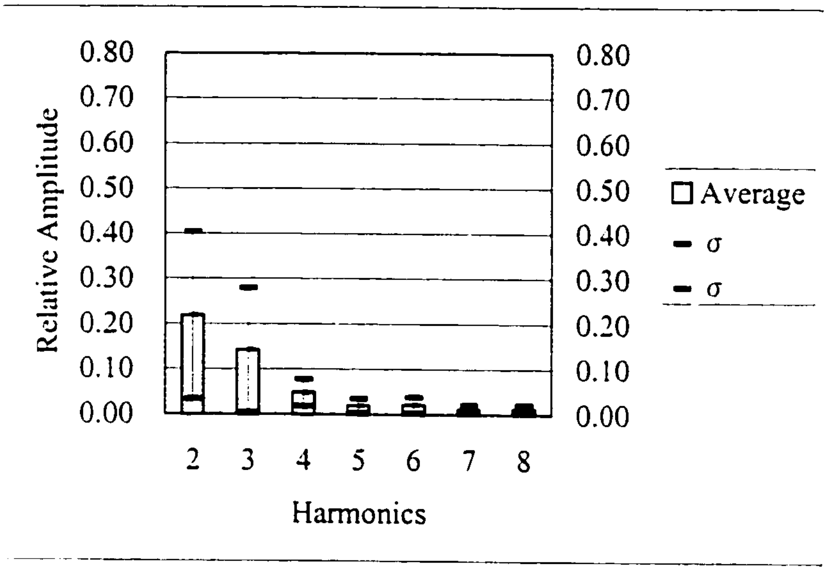


Figure 5-1 Spectrum of the Moller organ's Principal pipes

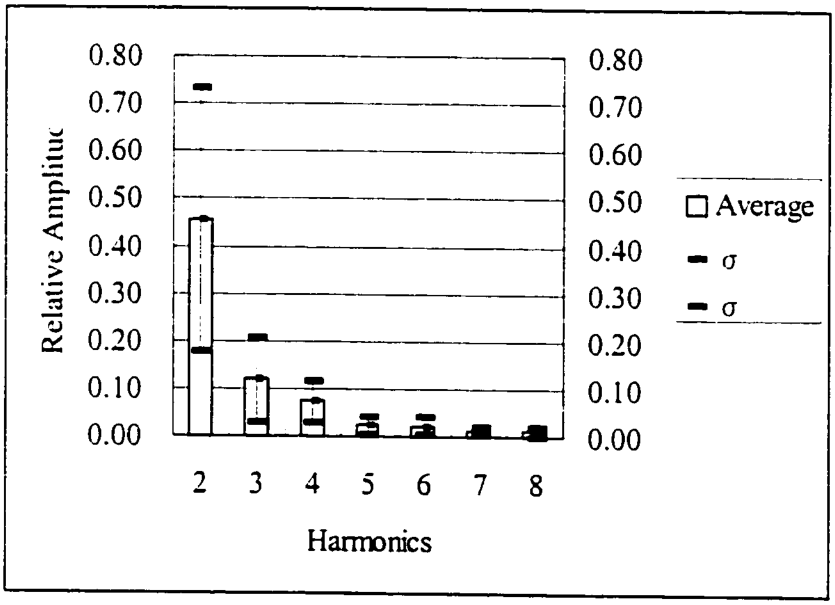


Figure 5-2 Spectrum of the Schantz organ's Principal pipes

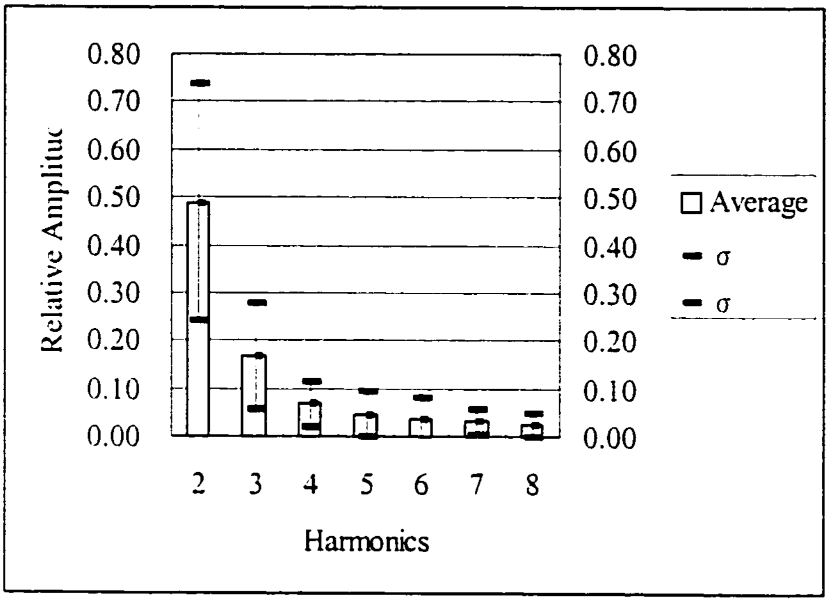


Figure 5-3 Spectrum of the Schuke-Berialin organ's Principal pipes

MOLLER	2ND	3RD	4TH	5TH	6TH	7TH	8TH
C4	0.0541	0.5619	0.0804	0.0058	0.0533	0.0250	0.0303
C4#	0.1556	0.5184	0.0219	0.0163	0.0166	0.0261	0.0082
D4	0.2370	0.0695	0.0841	0.0435	0.0160	0.0346	0.0330
D4#	0.0981	0.2456	0.0368	0.0142	0.0306	0.0073	0.0271
E4	0.3344	0.1974	0.0447	0.0069	0.0109	0.0026	0.0068
F4	0.1300	0.0763	0.0232	0.0107	0.0183	0.0127	0.0030
F4#	0.1018	0.0993	0.0248	0.0217	0.0099	0.0114	0.0143
G4	0.1555	0.0805	0.0148	0.0025	0.0179	0.0037	0.0077
G4#	0.0874	0.0799	0.0326	0.0022	0.0011	0.0196	0.0026
A4	0.1374	0.2129	0.0674	0.0367	0.0380	0.0081	0.0149
A4#	0.0611	0.0680	0.0108	0.0336	0.0263	0.0117	0.0126
B4	0.1018	0.0688	0.0584	0.0130	0.0181	0.0060	0.0159
C5	0.1415	0.1578	0.0428	0.0041	0.0251	0.0059	0.0184
C5#	0.0348	0.1254	0.0189	0.0138	0.0158	0.0062	0.0063
D5	0.2925	0.1126	0.0703	0.0202	0.0192	0.0035	0.0062
D5#	0.1628	0.1882	0.1158	0.0351	0.0191	0.0112	0.0235
E5	0.5046	0.0364	0.0712	0.0197	0.0018	0.0157	0.0231
F5	0.2888	0.0389	0.0634	0.0094	0.0057	0.0038	0.0091
F5#	0.5614	0.0816	0.0814	0.0347	0.0115	0.0034	0.0068
G5	0.8198	0.2584	0.0891	0.0572	0.0740	0.0337	0.0040
G5#	0.2003	0.0608	0.0047	0.0090	0.0121	0.0029	0.0048
A5	0.3810	0.0484	0.0504	0.0033	0.0167	0.0116	0.0029
A5#	0.0576	0.0181	0.0567	0.0443	0.0137	0.0131	0.0079
B5	0.2603	0.1399	0.0518	0.0302	0.0531	0.0141	0.0135
C6	0.1294	0.0317	0.0030	0.0079	0.0055	0.0081	0.0064
Average	0.2196	0.1431	0.0488	0.0198	0.0212	0.0121	0.0124
σ	0.1852	0.1372	0.0296	0.0154	0.0172	0.0092	0.0089

Table 5-1 Relative Spectra of the Moller organ's Principal pipes

SCHANTZ	2ND	3RD	4TH	5TH	6TH	7TH	8TH
C4	0.2820	0.1829	0.0261	0.0129	0.0097	0.0065	0.0038
C4#	0.1698	0.1025	0.0397	0.0156	0.0155	0.0076	0.0057
D4	0.3772	0.2119	0.0682	0.0109	0.0082	0.0085	0.0060
D4#	0.3343	0.3085	0.1367	0.0114	0.0231	0.0160	0.0112
E4	0.1765	0.1739	0.0407	0.0175	0.0167	0.0078	0.0072
F4	0.2415	0.2106	0.0570	0.0093	0.0216	0.0031	0.0119
F4#	0.2366	0.0605	0.0758	0.0144	0.0031	0.0064	0.0064
G4	0.7583	0.2014	0.1619	0.0502	0.0370	0.0165	0.0202
G4#	0.8446	0.1497	0.1331	0.0301	0.0492	0.0329	0.0122
A4	0.3342	0.1177	0.0939	0.0215	0.0356	0.0156	0.0139
A4#	0.4649	0.0369	0.0477	0.0188	0.0122	0.0108	0.0122
B4	0.3438	0.0582	0.0243	0.0166	0.0203	0.0146	0.0048
C5	0.2770	0.0236	0.0427	0.0092	0.0123	0.0158	0.0470
C5#	0.5403	0.0890	0.1187	0.0321	0.0222	0.0052	0.0051
D5	0.9906	0.0931	0.0677	0.0286	0.0225	0.0066	0.0214
D5#	0.0237	0.0885	0.0185	0.0140	0.0108	0.0094	0.0123
E5	0.4217	0.0383	0.0399	0.0179	0.0237	0.0123	0.0106
F5	0.9709	0.3754	0.1621	0.0937	0.0969	0.0117	0.0081
F5#	0.4340	0.0396	0.0284	0.0218	0.0025	0.0094	0.0035
G5	0.6832	0.0446	0.0887	0.0284	0.0231	0.0441	0.0051
G5#	0.0940	0.0600	0.0707	0.0339	0.0118	0.0174	0.0052
A5	0.7253	0.1313	0.0177	0.0307	0.0360	0.0218	0.0049
A5#	0.4981	0.0220	0.0650	0.0214	0.0142	0.0143	0.0084
B5	0.9229	0.0566	0.0735	0.0067	0.0131	0.0124	0.0146
C6	0.2476	0.0797	0.1169	0.0275	0.0290	0.0099	0.0107
Average	0.4557	0.1182	0.0726	0.0238	0.0228	0.0135	0.0109
Σ	0.2793	0.0904	0.0438	0.0176	0.0191	0.0089	0.0089

Table 5-2 Relative spectra of the Schantz organ's Principal pipes

SCHUKE	2ND	3RD	4TH	5TH	6TH	7TH	8TH
C4	0.3091	0.1122	0.0350	0.0082	0.0128	0.0220	0.0129
C4#	0.4831	0.2537	0.0595	0.0498	0.0121	0.0126	0.0286
D4	0.4122	0.1430	0.0625	0.0061	0.0398	0.0237	0.0175
D4#	0.6444	0.2117	0.1286	0.0150	0.0496	0.0151	0.0155
E4	0.3845	0.1446	0.0367	0.0126	0.0271	0.0148	0.0118
F4	0.7220	0.2059	0.1695	0.0506	0.0575	0.0403	0.0595
F4#	0.5908	0.3111	0.0522	0.0110	0.0117	0.0535	0.0025
G4	0.4571	0.0889	0.0391	0.0169	0.0102	0.0134	0.0065
G4#	0.6973	0.2293	0.0593	0.0465	0.0096	0.0244	0.0161
A4	0.0367	0.2057	0.0723	0.0131	0.0316	0.0390	0.0143
A4#	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
B4	0.9065	0.1305	0.0369	0.0511	0.0249	0.0231	0.0091
C5	0.5842	0.0747	0.0957	0.0485	0.0145	0.0369	0.0054
C5#	0.3000	0.0103	0.0051	0.0105	0.0165	0.0136	0.0133
D5	0.8855	0.1991	0.0263	0.0611	0.0477	0.0215	0.0262
D5#	0.6325	0.5217	0.1931	0.1876	0.2155	0.1381	0.1183
E5	0.7210	0.3027	0.0534	0.0769	0.0839	0.0373	0.0214
F5	0.8764	0.1855	0.0847	0.0473	0.0580	0.0578	0.0405
F5#	0.3211	0.1485	0.0262	0.0384	0.0278	0.0210	0.0126
G5	0.3140	0.0610	0.0231	0.0163	0.0185	0.0245	0.0159
G5#	0.2898	0.1592	0.0777	0.0293	0.0200	0.0296	0.0225
A5	0.3289	0.0843	0.1082	0.1614	0.0267	0.0307	0.0698
A5#	0.3636	0.0775	0.0567	0.0348	0.0157	0.0039	0.0120
B5	0.3098	0.0918	0.0793	0.0193	0.0196	0.0195	0.0042
C6	0.1823	0.0596	0.0668	0.1009	0.0812	0.0340	0.0190
Average	0.4897	0.1672	0.0687	0.0464	0.0389	0.0313	0.0240
Σ	0.2335	0.1086	0.0450	0.0462	0.0433	0.0262	0.0258

Table 5-3 Relative spectra of the Schuke-Berialin organ's Principal pipes

5.2. The Gedackt Pipes

The spectra of the Gedackt pipes are shown in Figure 5-4 through 5-6, and numerical values are given in Table 5-4 through 5-6.

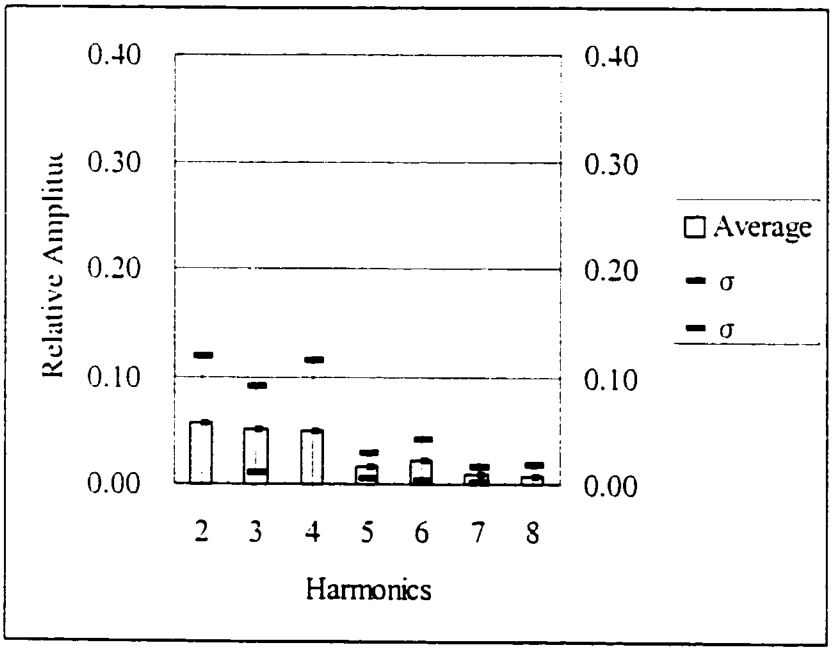


Figure 5-4 Spectrum of the Moller organ's Gedackt pipes

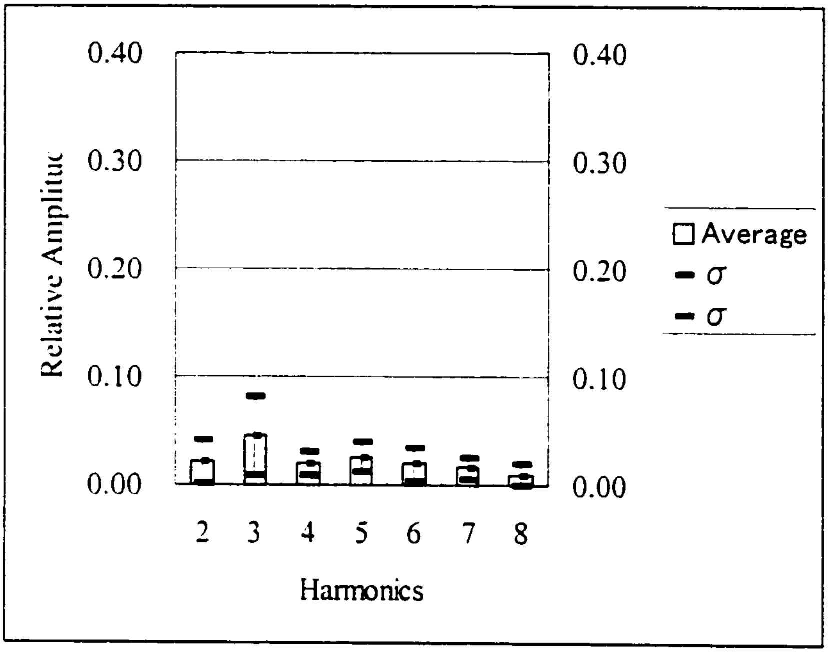


Table 5-5 Spectrum of the Schantz organ's Gedackt pipes

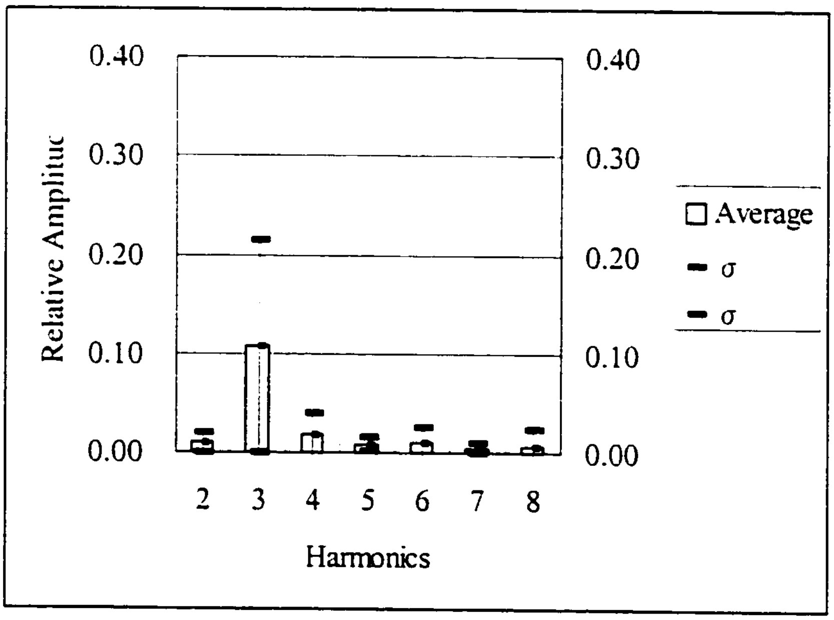


Table 5-6 Spectrum of the Schuke-Berialin organ's Gedackt pipes

MOLLER	2ND	3RD	4^{TH}	5TH	6TH	7TH	8TH
C4	0.0168	0.1831	0.0216	0.0198	0.0343	0.0114	0.0112
C4#	0.0450	0.1326	0.0377	0.0070	0.0614	0.0092	0.0207
D4	0.0265	0.1128	0.0719	0.0209	0.0069	0.0084	0.0032
D4#	0.0218	0.0776	0.0262	0.0083	0.0273	0.0071	0.0053
E4	0.0124	0.0612	0.0521	0.0059	0.0172	0.0056	0.0046
F4	0.0343	0.0231	0.0491	0.0057	0.0091	0.0053	0.0016
F4#	0.0090	0.0367	0.0280	0.0058	0.0147	0.0039	0.0052
G4	0.0223	0.0522	0.0256	0.0160	0.0162	0.0110	0.0027
G4#	0.0235	0.0528	0.0392	0.0132	0.0245	0.0027	0.0020
A4	0.0193	0.0268	0.0054	0.0088	0.0172	0.0021	0.0022
A4#	0.0243	0.0262	0.0151	0.0087	0.0239	0.0033	0.0021
B4	0.0338	0.0224	0.0444	0.0127	0.0216	0.0027	0.0024
C5	0.0278	0.0706	0.0052	0.0144	0.0063	0.0048	0.0034
C5#	0.0561	0.0436	0.0571	0.0127	0.0358	0.0089	0.0036
D5	0.0321	0.0371	0.0096	0.0023	0.0116	0.0031	0.0020
D5#	0.0143	0.0118	0.0377	0.0049	0.0024	0.0040	0.0073
E5	0.0527	0.0393	0.0399	0.0271	0.0029	0.0131	0.0140
F5	0.1141	0.0126	0.0568	0.0269	0.0431	0.0306	0.0160
F5#	0.2311	0.0195	0.3487	0.0394	0.0285	0.0193	0.0421
G5	0.0888	0.0216	0.0225	0.0187	0.0046	0.0163	0.0052
G5#	0.1599	0.0256	0.1035	0.0180	0.0104	0.0073	0.0078
A5	0.0149	0.0234	0.0154	0.0289	0.0020	0.0045	0.0031
A5#	0.0255	0.0298	0.0122	0.0207	0.0231	0.0056	0.0020
B5	0.2076	0.0644	0.0704	0.0414	0.0869	0.0321	0.0257
C6	0.1175	0.0758	0.0254	0.0418	0.0383	0.0070	0.0063
Average	0.0573	0.0513	0.0488	0.0172	0.0228	0.0092	0.0081
Σ	0.0618	0.0408	0.0667	0.0116	0.0197	0.0079	0.0095

Table 5-4 Relative spectra of the Moller organ's Gedackt pipes

SCHANTZ	2ND	3RD	4TH	5TH	6TH	7TH	8TH
C4	0.0085	0.0245	0.0056	0.0154	0.0162	0.0057	0.0013
C4#	0.0077	0.0369	0.0038	0.0148	0.0038	0.0069	0.0031
D4	0.0150	0.0070	0.0089	0.0204	0.0080	0.0103	0.0035
D4#	0.0465	0.0803	0.0385	0.0397	0.0590	0.0286	0.0100
E4	0.0085	0.1216	0.0233	0.0179	0.0049	0.0153	0.0086
F4	0.0149	0.0665	0.0044	0.0098	0.0060	0.0109	0.0032
F4#	0.0094	0.0242	0.0047	0.0218	0.0091	0.0128	0.0029
G4	0.0080	0.0567	0.0099	0.0561	0.0102	0.0142	0.0050
G4#	0.0108	0.0606	0.0195	0.0219	0.0323	0.0246	0.0503
A4	0.0082	0.0507	0.0226	0.0138	0.0240	0.0138	0.0055
A4#	0.0066	0.0515	0.0199	0.0225	0.0281	0.0300	0.0071
B4	0.0113	0.1407	0.0349	0.0312	0.0379	0.0441	0.0087
C5	0.0289	0.0970	0.0216	0.0426	0.0510	0.0386	0.0105
C5#	0.0266	0.0765	0.0171	0.0222	0.0329	0.0110	0.0049
D5	0.0196	0.0468	0.0122	0.0188	0.0173	0.0090	0.0063
D5#	0.0251	0.0295	0.0496	0.0253	0.0284	0.0065	0.0165
E5	0.0163	0.0073	0.0145	0.0225	0.0069	0.0146	0.0049
F5	0.0206	0.0271	0.0091	0.0179	0.0096	0.0125	0.0034
F5#	0.0215	0.0117	0.0305	0.0214	0.0403	0.0049	0.0066
G5	0.1002	0.0142	0.0252	0.0694	0.0148	0.0128	0.0289
G5#	0.0180	0.0243	0.0279	0.0380	0.0110	0.0103	0.0113
A5	0.0069	0.0247	0.0156	0.0164	0.0058	0.0052	0.0086
A5#	0.0416	0.0148	0.0236	0.0127	0.0107	0.0079	0.0145
B5	0.0389	0.0272	0.0233	0.0251	0.0109	0.0234	0.0110
C6	0.0173	0.0134	0.0245	0.0313	0.0050	0.0159	0.0050
Average	0.0215	0.0454	0.0196	0.0260	0.0194	0.0156	0.0097
Σ	0.0199	0.0356	0.0114	0.0140	0.0154	0.0103	0.0102

Table 5-5 Relative spectra of the Schantz organ's Gedackt pipes

SCHUKE	2ND	3RD	4TH	5TH	6TH	7TH	8TH
C4	0.0084	0.2024	0.0312	0.0045	0.0047	0.0172	0.0102
C4#	0.0058	0.2273	0.0053	0.0044	0.0037	0.0061	0.0047
D4	0.0028	0.0926	0.0054	0.0024	0.0019	0.0042	0.0050
D4#	0.0194	0.4499	0.0181	0.0120	0.0075	0.0052	0.0075
E4	0.0100	0.1276	0.0011	0.0009	0.0058	0.0019	0.0024
F4	0.0074	0.2016	0.0130	0.0095	0.0040	0.0045	0.0035
F4#	0.0111	0.1725	0.0094	0.0041	0.0025	0.0018	0.0050
G4	0.0256	0.2882	0.0488	0.0262	0.0129	0.0239	0.0910
G4#	0.0015	0.0342	0.0008	0.0015	0.0007	0.0006	0.0005
A4	0.0081	0.0949	0.0021	0.0022	0.0019	0.0024	0.0016
A4#	0.0183	0.1265	0.0252	0.0156	0.0202	0.0026	0.0071
B4	0.0199	0.0556	0.0099	0.0039	0.0032	0.0020	0.0032
C5	0.0034	0.0411	0.0042	0.0021	0.0025	0.0012	0.0011
C5#	0.0045	0.0135	0.0029	0.0058	0.0022	0.0095	0.0015
D5	0.0012	0.0277	0.0028	0.0029	0.0075	0.0023	0.0010
D5#	0.0409	0.0411	0.0082	0.0043	0.0065	0.0027	0.0054
E5	0.0148	0.1575	0.0019	0.0106	0.0152	0.0069	0.0034
F5	0.0028	0.0309	0.0024	0.0006	0.0019	0.0012	0.0014
F5#	0.0052	0.0350	0.0017	0.0079	0.0020	0.0044	0.0009
G5	0.0192	0.0227	0.0686	0.0174	0.0031	0.0091	0.0048
G5#	0.0060	0.1647	0.0788	0.0177	0.0848	0.0032	0.0056
A5	0.0040	0.0341	0.0306	0.0226	0.0208	0.0053	0.0021
A5#	0.0035	0.0073	0.0094	0.0046	0.0116	0.0014	0.0016
B5	0.0051	0.0212	0.0232	0.0114	0.0063	0.0012	0.0012
C6	0.0076	0.0055	0.0366	0.0061	0.0063	0.0025	0.0022
Average	0.0103	0.1070	0.0177	0.0081	0.0096	0.0049	0.0070
Σ	0.0093	0.1074	0.0213	0.0070	0.0166	0.0054	0.0177

Table 5-6. Relative spectra of the Schuke-Berialin organ's Gedackt pipes

CHAPTER 6: DISCUSSION

This discussion consists of three sections. In the first section, the spectrum of each pipe and the spectra differences between the Principal pipes and the Gedackt pipes are examined for each of the three pipe organs. The second section examines differences between the three organ manufacturers' Principal pipes and Gedackt pipes. The third section examines the standing waves, temperature, and characteristic sound radiation of the pipes which may affect the sound quality of the pipe organs.

6.1. The Variation of the Harmonics with Different Shape of Pipes.

6.1.1. Comparison of the Moller Organ's Principal and Gedackt pipes.

The significant differences in amplitudes between the spectrum of the Principal pipes and the Gedackt pipes were found at the second and third harmonics. For the second harmonic, the average of amplitude of the Principal pipes was $16.23 \pm 16.95\%$ stronger than that of the Gedackt pipes. For the third harmonic, the average of amplitude of the Principal pipes was $9.18 \pm 11.16\%$ stronger than the Gedackt pipes. For the fourth through eighth harmonics, there was no significant difference in the amplitudes.

For the Moller organ, the significant amplitude differences were found at second and third harmonics. By subtracting the average amplitude of the Gedackt pipes from the Principal pipes, the Principal pipes had stronger amplitudes than that of Gedackt pipes. But there was no significant amplitude difference in the other harmonics.

6.1.2 Comparison of the Schantz Organ's Principal and Gedackt pipes.

The significant amplitude differences between the Principal pipes and the Gedackt pipes were found at the second, third, and fourth harmonics. For the second harmonic, the average of amplitude of the Principal was 43.43 $\pm$ 27.60 % stronger than the Gedackt. For the third harmonic, the Principal was 7.28 $\pm$ 9.34 % stronger than the Gedackt. Finally, for the fourth harmonic, the Principal was 5.30 $\pm$ 4.67 % stronger than that of the Gedackt pipes. There was no significant amplitude difference in the fifth through the eighth harmonics.

For the Schantz organ, the significant amplitude differences between the Principal pipes and the Gedackt pipes were found at the second, third, and fourth harmonic. By subtracting the average amplitudes of Gedackt pipes from the Principal pipes, the Principal pipes had stronger amplitudes than that of the Gedackt pipes. But there was no significant amplitude difference in the other harmonics.

6.1.3 Comparison of the Schuke-Berialin Organ's Principal pipes and Gedackt pipes

The significant amplitude differences were found in the all harmonics. The largest difference was found at the second harmonic. The Principal was 47.98$\pm$24.68% stronger than that of the Gedackt pipes. The spectrum of the Principal pipes had stronger relative amplitudes than the Gedackt pipes.

For the Schuck organ, the significant amplitude differences were found in all harmonics. By subtracting the average amplitudes of Gedackt from the Principal pipes, Principal pipes had stronger amplitudes in all harmonics.

6.2 The Difference in spectrum for Different Pipe Organ Manufactures

6.2.1. The Principal Pipes

In this section, the characteristic tonal quality differences between the three different manufacturer's Principal pipes are examined. The significant amplitude differences between the Schuke-Berialin and the Schantz, the Schuke-Berialin and the Moller, and the Moller and the Schantz pipes are listed in Table 6-1. The positive sign (+) indicates that the first named organ was stronger. For example, the first column indicates that the Principal pipes of the Schuke-Berialin pipe organ has significantly stronger at the fifth, seventh, and eighth harmonics. In addition, the Schuke-Berialin pipe organ has stronger relative amplitudes than those of the Schantz (this was confirmed by subtracting the average amplitude of the Schantz organ from the Schuke-Berialin organ).

HARMONICS	SCHUKE VS. SCHANTZ	SCHUKE VS. MOLLER	MOLLER VS. SCHANTZ
2		+	+
3			
4			
5	+	+	
6			
7	+	+	
8	+	+	

Table 6-1. Tonal quality differences of Principal pipes

A significant amplitude difference between the Principal pipes of the Schuke-Berialin and the Schantz organs were found at the fifth, seventh, and eighth harmonics. The Schuke-Berialin's amplitude of the fifth harmonic was 2.15% ± 4.84%, the seventh harmonic was 17.0% ± 28.3%, and the eighth harmonic of the Schuke-Berialin was 1.26% ± 2.77% stronger than that of the Schantz organ. The average of harmonics showed that the Schuke-Berialin organ have stronger higher harmonics, such as the fifth, seventh, and eighth harmonics. The significant amplitude differences between the Schuke-Berialin and the Moller principal pipes were found at the second, fifth, seventh, and eighth harmonics. The Schuke-Berialin organ has stronger relative amplitude than does the Moller organ.

The average difference between the Schuke-Berialin and Moller Principal pipes at the second harmonic was 26.35 ± 30.74%, at the fifth harmonic was 2.71 ± 4.96%, at the seventh harmonic was 1.92 ± 2.82% and at the eighth harmonic was 1.16 ± 2.69%. A significant amplitude difference between the Moller organ and the Schantz organ Principal pipes was found at the second harmonic. The Schantz has a stronger amplitude at the second harmonic than does the Moller organ. The average difference between the Moller organ and the Schantz organ was 22.92 ± 29.23% at the second harmonic.

6.2.2. The Gedackt pipes

In this section, the characteristic spectra differences between three manufacturers' Gedackt pipes were examined and shown in Table 6-2. The positive (+) or negative (–)

signs indicate that there was a significant difference in the strength of a harmonic. The positive sign (+) indicates that the first named organ was stronger and negative sign (–) indicates that it was weaker.

HARMONICS	SCHUKE VS. SCHANTZ	SCHUKE VS. MOLLER	MOLLER VS. SCHANTZ
2	-	-	+
3	+	+	
4		-	+
5	-	-	-
6		-	
7	-	-	-
8		-	

Table 6-2. Tonal quality differences of Gedackt pipes.

Significant relative amplitude differences between the Schuke-Berialin and the Schantz were found at the second, third, fifth, and seventh harmonics. The Schuke-Berialin's third harmonic was $6.16 \pm 10.74\%$ stronger than that of the Schantz. On the other hand, the amplitudes of the Schuke-Berialin were weaker at the second, fifth, and seventh harmonics were $-1.12 \pm 2.05\%$ for the second harmonic, $-1.79 \pm 1.19\%$ for the fifth harmonic, and $-1.07 \pm 1.29\%$ for the seventh harmonic.

A significant amplitude difference between the Schuke-Berialin and the Moller organ was found in all harmonics. The Schuke-Berialin had stronger harmonics at the third harmonic with a difference of $5.57 \pm 10.02\%$. On the contrary, all other harmonics were weaker than that of the Moller with these differences: -4.70 $\pm$ 6.47% for the second harmonic, -3.12 $\pm$ 7.16% for the fourth harmonic, -9.13 $\pm$ 1.22% for the fifth harmonic, -1.32 $\pm$ 2.81% for the sixth, -4.24 $\pm$ 9.15% for the seventh, and −1.10 $\pm$ 2.12% for the eighth harmonics.

Significant relative amplitude differences between the Moller organ and the Schantz organ were found at the second, fourth, fifth, and eighth harmonics. At both the second and the fourth harmonics, the Moller organ had stronger relative amplitudes than the Schantz organ. The average difference was 3.58 $\pm$ 5.99% at the second harmonic and 2.92 $\pm$ 6.55% for the fourth harmonic. On the other hand, at the fifth and seventh harmonics, the Moller organ had weaker amplitudes than that of the Schantz organ with an average difference of −0.88 $\pm$ 1.75% at the fifth harmonic and −0.64 $\pm$ 1.39% at the seventh harmonic.

6.3 Factors External to the Pipes

Several factors can affect the observed sound quality of the organ. One is the standing waves at the position of the microphone. If the standing waves form a pressure node at the position of the microphone, the intensity will be reduced, on the other hand, if the standing waves form antinode, the intensity will be increased. The standing waves can affect the spectrum, since the nodes and amplitudes of the different harmonics will not coincide. The standing waves depend on the structure of the space where the organ is located. Many scientists have worked on how the standing waves depend on the space in the building[12,15,16] and the position of the microphone.[17] For example, W. Lottermoser pressed three adjacent keys (such as C4, C4#, and D4) at the same time and used octave band filters to analyze the sound. This minimized the effect of the standing waves by averaging the spectra of the three tone clusters.[15]

Because of limitations in the equipment, Lottermoser's method could not be replicated. This method was modified by adding the intensities of three adjacent notes (such as C4, C4# and D4) and dividing the sum of those intensities by 3. All 24 notes from C4 to B5 (we excluded C5) on Moller organ's Principal and Gedackt pipes were modified. The results showed small standard deviations, and the significant amplitude differences between Principal and Gedackt pipes were found at the second, third, fifth, seventh, and eighth harmonic. For convenience, this method is called a cluster method.

Sundberg and Jansson used a different method to minimize the effect of the standing waves. Ten different positions were chosen and the sound of the pipe organ was recorded at each position. After the recording, the each harmonic was averaged over ten positions. Averaging the spectra at ten positions reduces the standard deviation in the harmonics caused by the standing waves. For convenience, this method is called a multiple position method.

To evaluate the significance of our results, results of our original method to those obtained using a multiple position method were compared. This investigation was performed in May, 2000 at First United Methodist Church at Campbell, California. The room temperature was 20℃. The microphone was moved to ten different locations as shown in Figure 6-2 and recorded from C4 to B4.

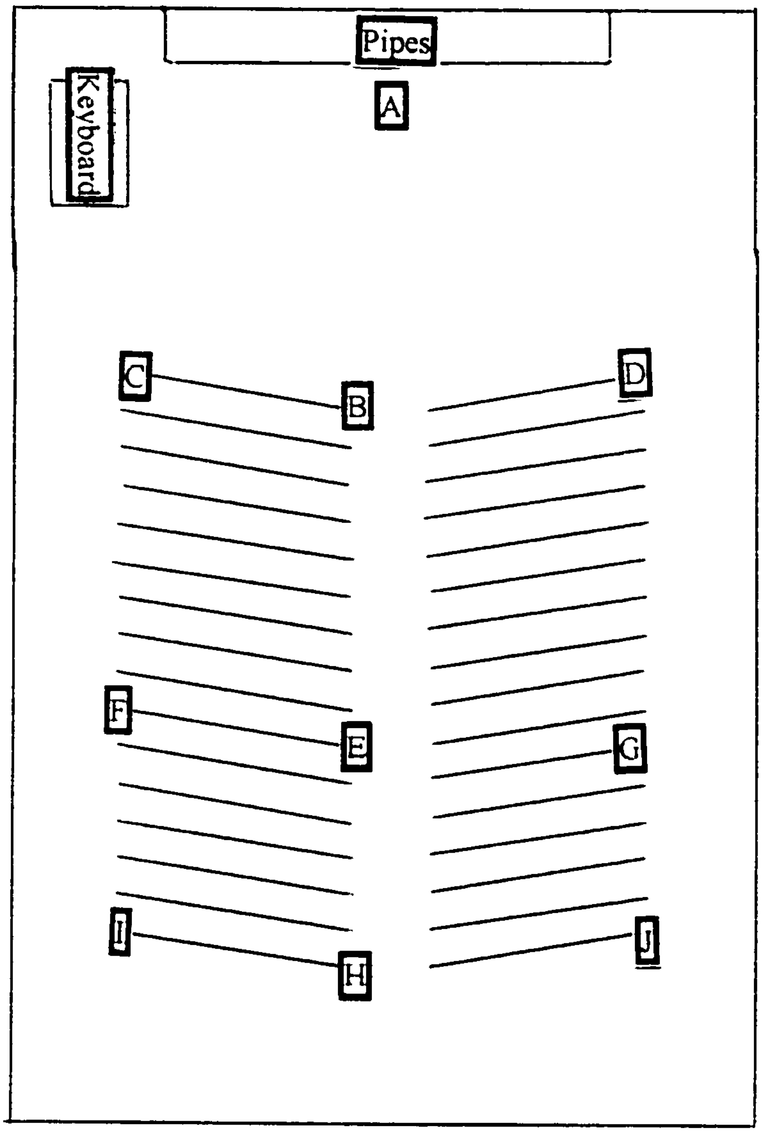


Figure 6-2. Appropriate ground plan of First United Methodist Church at Campbell, with positions (A, B, C, ...) at which sound measurements were made.

The spectra for the different locations were averaged and compared to the result of the original method. The numerical values of those results are shown in Table 6-4 and Table 6-5.

Notes	2nd	3rd	4th	5th	6th	7^{th}	8th
C4	0.1511	0.0738	0.0696	0.0303	0.0170	0.0111	0.0066
C4#	0.2316	0.1707	0.0388	0.0319	0.0135	0.0162	0.0147
D4	0.6181	0.0369	0.0667	0.0232	0.0159	0.0355	0.0052
D4#	0.6392	0.0425	0.0356	0.0154	0.0130	0.0131	0.0128
E4	0.4873	0.1219	0.1505	0.0310	0.0055	0.0130	0.0104
F4	0.1847	0.2304	0.1224	0.0125	0.0157	0.0337	0.0093
F4#	0.8410	0.5511	0.1840	0.0318	0.0577	0.0435	0.0218
G4	0.6038	0.1146	0.0621	0.0218	0.0093	0.0039	0.0018
G4#	0.3675	0.0436	0.0521	0.0565	0.0079	0.0135	0.0051
A4	0.4733	0.1151	0.0406	0.0083	0.0024	0.0036	0.0039
A4#	0.6965	0.1631	0.0972	0.0378	0.0258	0.0307	0.0077
B4	0.2915	0.0227	0.0364	0.0251	0.0067	0.0034	0.0193
Average	0.4655	0.1405	0.0797	0.0271	0.0159	0.0184	0.0099
Σ	0.2215	0.1439	0.0490	0.0128	0.0146	0.0138	0.0062

Table 6-4. The relative amplitudes and standard deviations for original method.

Notes	2nd	3rd	4th	5th	6th	7^{th}	8th
C4	0.3584	0.2044	0.0583	0.0267	0.0234	0.0109	0.0129
C4#	0.4074	0.2757	0.0644	0.0351	0.0222	0.0151	0.0115
D4	0.5402	0.2229	0.1326	0.0300	0.0412	0.0234	0.0111
D4#	0.6400	0.2056	0.0617	0.0190	0.0300	0.0142	0.0176
E4	0.5408	0.1900	0.1136	0.0305	0.0237	0.0191	0.0121
F4	0.4180	0.1709	0.0872	0.0114	0.0272	0.0151	0.0102
F4#	0.5224	0.2644	0.1140	0.0312	0.0238	0.0389	0.0186
G4	0.3606	0.1783	0.0456	0.0232	0.0215	0.0154	0.0109
G4#	0.3576	0.0748	0.0900	0.0291	0.0235	0.0221	0.0167
A4	0.4117	0.2861	0.0826	0.0337	0.0289	0.0213	0.0148
A4#	0.4903	0.0809	0.0696	0.0385	0.0133	0.0136	0.0059
B4	0.4047	0.0861	0.0600	0.0326	0.0156	0.0142	0.0179
Average	0.4543	0.1867	0.0816	0.0284	0.0245	0.0186	0.0134
σ	0.0907	0.0738	0.0268	0.0075	0.0071	0.0075	0.0038

Table 6-5. The relative amplitude and standard deviations for the multiple position method.

The average results were quite close to those of the original method. The strength of the relative amplitude at each harmonic in the multiple position method was about the same as the results obtained by original method. We found significant amplitude difference only at the eighth harmonic. However, the average standard deviations in the spectrum of the multiple position method was about 53% less than those in the original method.

According to Fletcher and Rossing, Principal pipes and Gedackt pipes differ in how they radiate the sound.[18] For Gedackt pipes, the radiation is relatively simple because there is only a single source, the mouth of the pipe. On the other hand, Principal pipes have two coherent sources, the mouth and the open end. For Principal pipes, these two coherent sources are acoustically in phase for odd harmonics and out of phase for even harmonics. We studied how this phenomenon might influence our results. We placed our microphone 50 centimeters higher than the original position and compared the results to the original position for Principal pipes.

The results are shown in Tables 6-4 and 6-6.

Notes	2	3	4	5	6	7	8
C4	0.3222	0.1003	0.0189	0.0145	0.0065	0.0065	0.0025
C4#	0.5247	0.4704	0.0853	0.0474	0.0602	0.0088	0.0166
D4	0.7545	0.1507	0.0141	0.0299	0.0299	0.0353	0.0104
D4#	0.5543	0.1983	0.1115	0.0286	0.0544	0.0179	0.0030
E4	0.9622	0.1845	0.0846	0.0144	0.0062	0.0148	0.0115
F4	0.4304	0.0660	0.0229	0.0197	0.0209	0.0037	0.0037
F4#	0.2910	0.1893	0.0419	0.0706	0.0308	0.0097	0.0046
G4	0.4336	0.1412	0.1135	0.0082	0.0319	0.0312	0.0046
G4#	0.6102	0.1227	0.0763	0.0140	0.0091	0.0203	0.0069
A4	0.0321	0.0519	0.0668	0.0395	0.0074	0.0038	0.0006
A4#	0.3225	0.0616	0.0046	0.0086	0.0054	0.0083	0.0040
B4	0.3486	0.1361	0.0264	0.0260	0.0043	0.0094	0.0029
C5	0.2079	0.0293	0.0844	0.0204	0.0094	0.0012	0.0040
Average	0.4457	0.1463	0.0578	0.0263	0.0213	0.0132	0.0058
σ	0.2413	0.1118	0.0380	0.0177	0.0191	0.0105	0.0045

Table 6-6. Average amplitudes and standard deviations from C4 to B4 for 50 centimeters higher position than the original position.

In comparison, no significant amplitude difference between the original and the 50 centimeters higher position was found. The standard deviations in Table 6-6 are quite closer to the standard deviations in Table 6-4, therefore, the variations in the harmonics probably due to the standing waves. The results showed that effect of the standing waves is more important than the effect of this phenomenon.

Another factor to consider is room temperature. The Schuke-Berialin pipe organ was recorded in early September, when the room temperature was 25.5 °C. The Schantz pipe organ was recorded in late December, when the room temperature was 12 °C.

The frequency shifts observed were shown in Table 6-3.

Pitch	Estimated frequency based on A4 440 Hz	Schuke (P)	Schuke (G)	Moller (P)	Moller (G)	Schantz (P)	Schantz (G)
C4	261.63	264.10	264.40	265.80	265.70	257.60	257.40

Table 6-3. Frequencies of the recorded sound of C4(Hz).
(P = Principal pipe, G = Gedackt pipe).

In order to examine the frequency shift by temperature, the organ pipe (Principal C4) of the Moller was selected. The sound was recorded at two different temperatures. The frequencies of C4 were 263.00 Hz at 24 °C and 265.80 Hz at

30.2 °C. Theoretically, the frequency difference should be 3.10 ± 0.22 Hz, not far from the actual frequency difference, 2.80 Hz.

According Hiroyuki Mochizuki, who is the tuner of the Schuke-Berialin pipe organ, C4 was tuned to 261.63 Hz (based on A4, 440Hz at 20 °C). Since the audiences feel most comfortable at temperatures between 20°C and 25 °C , organ pipes are usually tuned in that temperature range. However, the actual frequency of C4 was 264.1Hz.

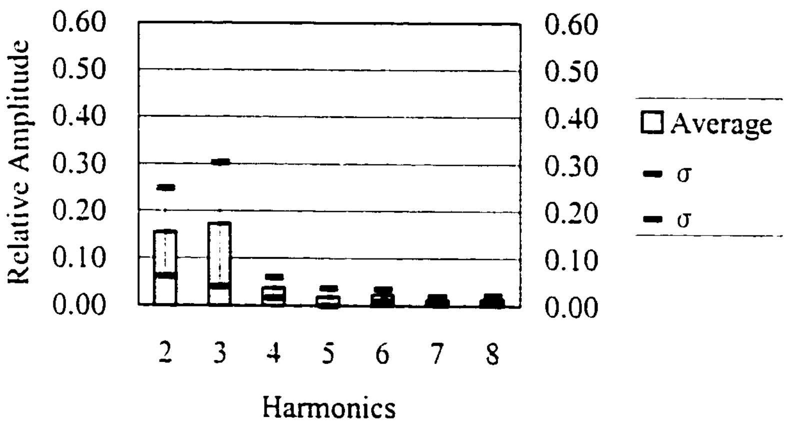
Mary Ann Gee, who is the organist at First United Methodist Church, told us that the Schantz pipe organ was tuned to 261.63 Hz (based on A4 440Hz at 20°C); however, the actual frequency was 257.6Hz for the Schantz pipe organ.

Theoretically, the frequency changes of the C4 for the Schuke-Berialin should be 2.46 ± 0.22 Hz higher than 261.63 Hz, 3.58 ± 0.22 Hz lower for the Schantz. In this investigation, the actual frequency changes for the Schuke-Berialin was 2.47 Hz and for the Schantz was 4.03 Hz, about the same for the Schuke-Berialin organ and a little higher than expected for the Schantz organ.

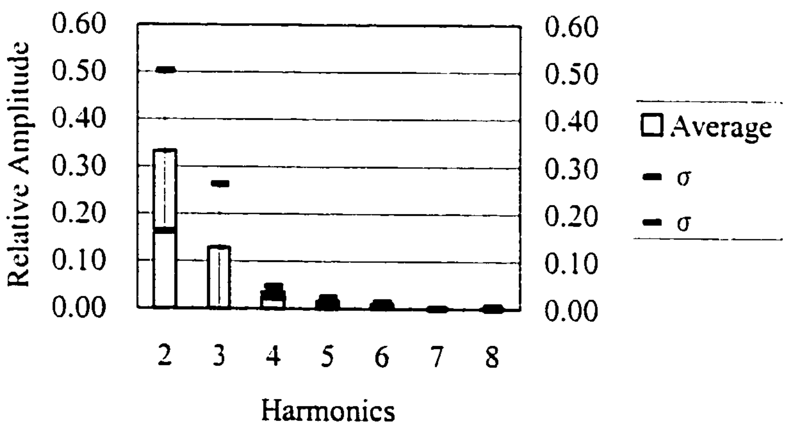
The higher harmonics may disappear from the spectrum at lower temperatures, reducing the brightness of the sound. N. Thompson investigated the effect of climate upon organ tone. He recorded all the C's of each stops (from C2 to C7) and nine chorus reed stops and four flue pipes were selected. His measurements were taken from a pipe organ in March (20.89 °C) and August (30.89 °C). He found that many higher harmonics above the sixth in the spectra of flue stops were missing in March, confirming the impression that the organ sounds brighter in August than March.[16] The results of investigation of the flue pipes over C4 to C6 range were quite impressed one.

In this research, the Moller's principal pipes from C4 to B4 were chosen, and the spectra at temperature of 30.2°C and 24 °C were examined to see if this effect could be verified.

For example, the spectra difference at C4 were shown in the Figure 6-1 (a) and (b).



(a) Spectrum of C4 of Principal pipe at 30.2 °C



(b) Spectrum of C4 of Principal pipe at 24 °C

Figure 6-1. The Spectrum of Principal C4 at 24 °C (a) and 30.2 °C (b)

Significant amplitude differences were found in sixth, seventh and eighth harmonics in the averaged spectrum of C4 to B4. Because of limitations in computer, the harmonics above the eighth harmonic were not examined.

CHAPTER 7: Conclusion

This study indicates that the harmonics in the spectrum of Principal pipes are not always stronger than those in the spectrum of Gedackt pipes. For example, significant relative amplitude differences between Principal and Gedackt pipes, both made by the Moller organ manufacturer, were found at the second and third harmonics. No significant relative amplitude difference was found at other harmonics. The tonal quality differences between Principal and Gedackt pipes was not solely due to relative amplitude differences in even harmonics, but also in relative amplitude differences in the odd harmonics.

Next comparison was made between the American (Moller and Schantz) and the German (Schuke-Berialin) Principal pipes. Also, comparison was made between the American and German Gedackt pipes.

Significant relative amplitude differences between American and German Principal pipes were found at the fifth, seventh, and eighth harmonics. German Principal pipes have stronger amplitudes than those of American pipes. Significant relative amplitude differences between the American and German Gedackt pipes were found at the second, third, fifth, and seventh harmonics. Except for the third harmonic, American Gedackt pipes have stronger amplitudes than the German Gedackt pipes.

Each organ had a characteristic tonal quality. However, the sample size was too small to generalize the characteristic tonal quality of each rank. Only two octaves of notes (C4 to C6) were recorded and, not all notes in each rank. Thus it is difficult to generalize the tonal quality in each rank, since there are more than two octaves in each pipe organ.

External factors, such as the standing waves and temperature, strongly influence the sound of organ pipes. Standing waves produce large standard deviations in each harmonic. Large standard deviation in the harmonic will make it difficult to find the significant relative amplitude differences between two spectra.

Due to the limitations of the equipment used, there were several limitations in this investigation. For example, spectrum analyzer cannot handle the calculation of the harmonic amplitude higher than the eighth harmonic. Therefore, the eighth harmonic was the highest harmonics to examine. In further investigations, a better spectrum analyzer could expand this investigation to include higher harmonics. Then more detailed tonal qualities of each pipe organ could be obtained. Since the tonal quality of sound depends mainly on the relative amplitudes of the harmonics.

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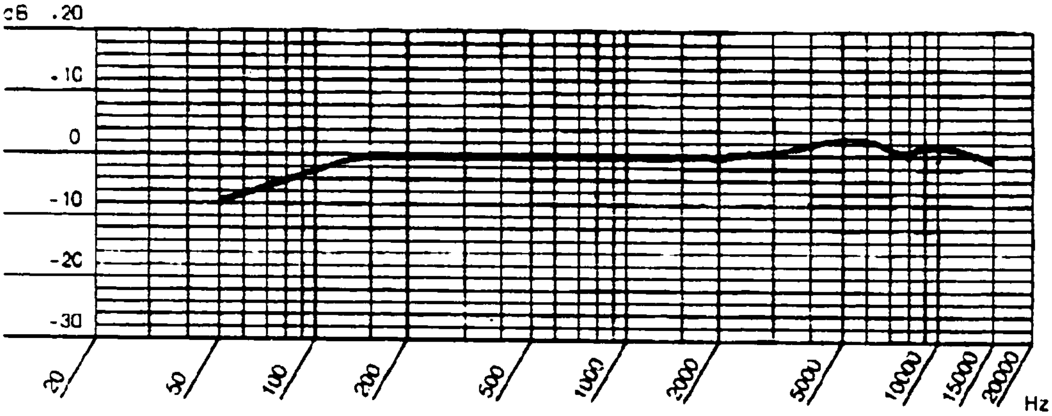
APPENDIX A



Characteristic frequency response of the microphone (AKG C1000S)

APPENDIX B

T – test

A test of significance that assumes the sample standard deviation is different from the population standard deviation. The level of confidence that a particular value is different from the null hypothesis value is derived from a t distribution rather than a normal distribution. The t distribution is wider than the normal distribution and the unobserved normal distribution. As the size of the sample increases, the t distribution approaches the shape of the normal distribution.

Standard error can be qualified by the degree of freedom. The degrees of freedom are related to how much data are being examined and how many things are estimated with that data.