Introduction

The aim of this project is to explore the capabilities and the limitations of the Hammond Organ in imitating pipe organ tones through both theoretical and practical researches and experiments.

Hammond Organ was the first electronic musical instrument invented as an organ without employing pipes although it took a few years for the inventor Laurens Hammond to be approved by the American Federal Trade Commission to call his instrument an organ. The Hammond Organ produces many pipe-organ-like tones without using pre-recorded pipe organ sounds other than by combining its unique harmonic drawbars, which consist of sine waves of different pitches. The tones are generated on the principle of additive synthesis, which is the method of adding component sine waves to the fundamental to construct a complex wave of given spectral characteristics.

Although the Hammond Organ is a versatile instrument, which produces numerous different sounds including distinctive novelty tones, the focus is on the aspect of imitating pipe organ tones, which was the original purpose of the instrument. If the Hammond Organ's initial purpose was to substitute the pipe organ, is the instrument capable of fully imitating the pipe organ sounds? If not, to what extent is the instrument capable of, and what are the limitations? If the Hammond Organ successfully produces tones which are almost identical to those produced by the pipe organ, how is this achieved? In search for the answers to these questions, an investigation has been undertaken.

The investigation has been undertaken mainly on the subject of imitating tones produced by pipe organ on the Hammond Organ.

First, the tone generation of the Hammond Organ is explained. Then, it is compared with the pipe organ in order to identify the common aspects and differences. Sound production of the pipe organ and various types of stops are studied. Then the timbres of tones produced by individual stops and combined stops are analysed in order to recreate the tones on the Hammond Organ. There are more than a hundred different pipe organ stops although the number of stops that an organ can employ depends on the size of the instrument. However, in this study, fourteen individual pipe organ stops and eight different combinations of stops are selected for the analysis and synthesis.

The second part of the study is to attempt imitations of tones produced by the pipe organ on the Hammond Organ. Based on the preceding research, various approaches to synthesise the tones produced by the pipe organ stops are experimented on the Hammond Organ. From the experiments, how the tones are synthesised on the Hammond Organ is summarised. In order to determine whether or not the tones are successfully imitated on the Hammond Organ, and whether the tones of the Hammond Organ perceived as pipe organ tones are psychoacoustic illusion, the synthesised tones are examined by human perception.

Finally, the outcome of the project is evaluated including the capabilities and the limitations of the Hammond Organ in imitating pipe organ tones, and the overall verdict of the instrument as a substitute for the pipe organ.

Chapter 1:

What is the Hammond Organ?

1.1 Introduction to the Hammond Organ

As the name suggests, Hammond Organ was invented for the purpose of substituting the expensive pipe organ, which also requires considerable amount of space. Since the tone was electronically generated without employing pipes it was not approved to be called an organ. The claim by the inventor Laurens Hammond was challenged and through a crucial test it was human ears, which gave him an authority to call his instrument an organ. However, it is possible to create pipe organ sounds although the instrument neither employ pipes nor produce tones using pre-recorded pipe organ sound stored as "pre-sets".
Primarily, the tones were generated by tonewheels, which produced sine waves of different pitches. Tonewheels driven by a motor generate sine waves by turning at a controlled speed to produce musical pitches. Teeth on the rim of the wheel disturb the electromagnetic field in a nearby magnet and the circuitry with which it is connected[1]. This disturbance is in nature of a sinusoidal wave. However, this mechanism is now replaced with digitally simulated tonewheels.
Sine waves generated by tonewheels are combined to form sounds of different timbre by adding harmonic components using Hammond Organ stops called harmonic drawbars. Each drawbar consists of sine waves of different pitches which correspond to those of pipe organ stops. The available pitches of Hammond Organ and pipe organ stops are referred to as the fundamentals and harmonics of C. In the same manner, the pipe organ produces sound by combining different stops although a single stops alone could be used. The difference is that each Hammond Organ stop (drawbar) consists of a pure tone, or a sinusoidal wave, while each single pipe organ stop contains harmonics in most cases. Thereby Hammond Organ enables the user to custom-build a waveform within a limit.

1.2 Harmonic drawbars

Harmonic drawbars, often called tonebars, are the basis of creating Hammond Organ sound. Each drawbar consists of sinusoidal waves of different pitches and there are typically nine drawbars for each manual. There are approximately 253,000,000 possible combinations of sound produced by them.[2] As shown in figure 1, pulling a drawbar out increases the volume in incremental steps from 0 (no volume) to 8 (maximum). Pushing the drawbar in decreases the volume of that drawbar.[3] However, each increment of a drawbar varies depending on the pitch of the drawbar. The lower the pitch is, the wider the steps of increments are, thus the lower the pitch of a drawbar is, the higher the overall amplitude is. For instance, experiments proved that if the master

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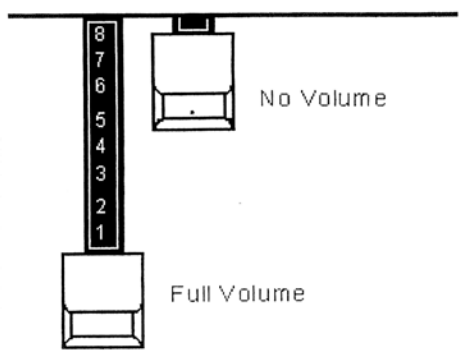
[1] Stevens, I., *Dictionary of Hammond Organ Stops* (New York: Schirmer, 1961) P. 2
[2] Hammond XB-1 Drawbar Keyboard Quick Features Guide (n.p.: Hammond Suzuki, n.d.) P.9
[3] *An Introduction to Drawbars* [http://www.hammond-organ.com/product_support/drawbars.htm]

volume is MID-HIGH, the increment of the 8’ drawbar in dBu is larger than that of the 1’ drawbar. From 2 to 3 in drawbar steps, there is approximately 5-7dBu increase for the 8’ drawbar and there is approximately 4dBu increase for the 1’ drawbar. From 7 to 8 in drawbar steps, there is approximately 3dBu increase for the 8’ drawbar, while there is approximately 2dBu increase for the 1’ drawbar. This also indicates that the overall amplitude of low-pitched drawbars is higher than that of high-pitched ones. Furthermore, smaller-numbered increment of drawbar steps increase/decrease large number of amplitude, compared to large-numbered ones. For instance, between 1 and 2 in drawbar steps the difference in amplitude is larger than between 7 and 8.

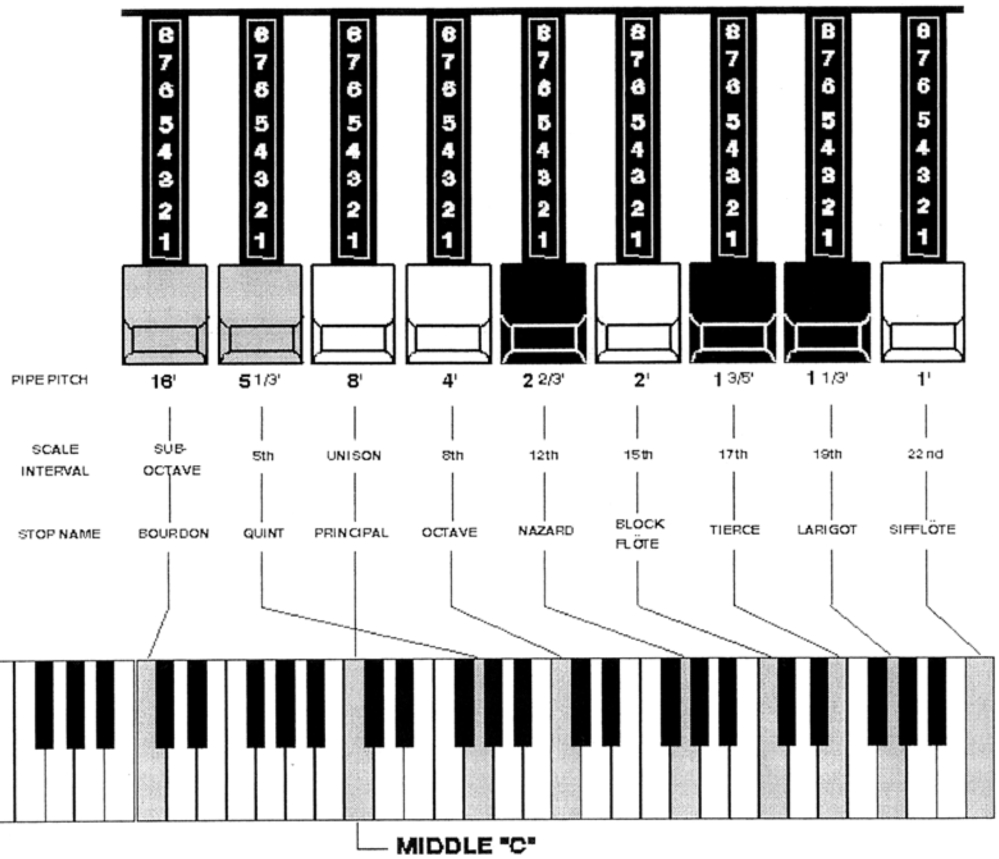
Figure 1. volume of drawbars[4]



Each drawbar is marked with a number followed by a footage mark, which refers to the pitch of the corresponding length of pipe of the pipe organ. The 8’ register is normally considered to be the fundamental. Since the frequency of oscillation in a pipe is inversely proportional to its length, the footage makings on the upper harmonics are 8/2 = 4, 8/3 = 2 2/3, 8/4 = 2, 8/5 = 1 3/5, 8/6 = 1 1/3 and 8/8 = 1. The seventh harmonic is normally omitted, as it is significantly out of tune with a note on the equally tempered scale.[5] Frequencies of harmonic components added by drawbars correspond to the pitches of notes on the equally tempered scale, rather than to the natural harmonic series. This means that only one oscillator frequency is required for each note in the scale, the drawbars being used to add them in different combinations.[6] Figure 2 shows how each drawbar relates to the manual when middle C is played.

[4] Figure from *An Introduction to Drawbars*
[5] Campbell, M., Greated, C., *The Musician’s Guide to Acoustics* (London: Dent, 1987) P. 504
[6] Campbell, Greated, *Musician’s guide* P. 504

Figure 2. The pitches of drawbars[7]



As it is clearly indicated in Figure 2, drawbars 16', 8', 4, 2' and 1' are octave sounding. Referring to the chart given in appendix A, each of them also represents the fundamental tone. For instance, the fundamental of the 8' registration series is 8' and the others excluding 16' are octave intervals of its harmonics. Drawbars 5 1/3', 2 2/3', 1 3/5', and 1 1/3' are harmonics of other intervals. They are essential in adding richness to timbres. Presence of these harmonics defines the characters of complex tones produced by reed, horn and string instruments. In addition, drawbars 16' and 5 1/3' may be used for "sub-octave" effects. 16' is the sub-octave of 8' and 5 1/3' is the sub-octave of 2 2/3'. These could be used when the 8' registration series is lowered by one octave or to add depth to the tones.

The following is the descriptions of how each drawbar contributes to construction of tones. The chart of the harmonic drawbars in relation to natural harmonics of the Hammond Organ, which is given in Appendix A, may be referred to.

[7] Figure from *An Introduction to Drawbars*

16' – Adds depth to any tone. Adds density and thickness to the tone when it is strong, and clarifies the tones adding more tonal dimension when it is soft. The fundamental of 16' registration series.

5 1/3' – Adds the third harmonic of 16' registration series. It contributes either a dull metallic sound or some inharmonic effect. It creates brass-like timbre when it is strong and creates reed-like or string-like timbres when it is weak.[8]

8' – The fundamental of 8' registration series and the second harmonic of 16' series. Adds intense tone when strong. More complete statement of pitch and enhancing all of the harmonics added.[9] Contains the tone whose pitch is unison to middle C on the manual.

4' – Adds the second harmonic to 8' registration series and the fourth harmonic to 16' series. Also the fundamental of 4' series. It conveys the effect of brightness (not brilliance) and clarity of pitch and timbre. Gives the exact sense of loudness and corroborates the 8' tones.[10] Gives penetration to all registrations in which it is strong. Adds the delicate brightness to all registrations when weak.[11]

2 2/3'– The third harmonic of 8' registration series and the sixth harmonic of 16' series. Adds some "quint-like" tones and a string-like effect. It contributes an essential woodwind colour if loud enough in proportion to its neighbouring harmonics, in other words, 4' and 2'.[12] Adds a little brightness but is not octave sounding. Thickens the tone markedly obscuring the pitch somewhat when strong. Adds a delicate piquancy to all orchestral imitations.[13]

2' – The fourth harmonic of 8' registration series and the eighth harmonic of 16' series. Also the second harmonic of 4' series. Adds brilliance to any tone combinations, and is an integral part of most 8' and 4' series. It conveys string-like and reed-like timbres. Adds great penetration and brilliance when strong. Adds mild brilliance and clean pitch definition when weak.[14]

1 3/5' – The fifth harmonic 8' registration series and the tenth harmonic of 16' series. Adds an acute quality to any tone unless kept in a soft volume. This drawbar furnishes much of the essential string-like or reed-like timbre. Also adds horn-like timbre. It is not particularly woodwind-like, but should be included at a soft volume. Brings somewhat "inharmonic" and sharp effects, although not truly dissonant when it is strong. May be sharp yet adds another dimension to tones when weak.[15]

[8] Stevens, *Dictionary* P. 10
[9] Stevens, *Dictionary* P. 10
[10] Stevens, *Dictionary* P. 10
[11] Stevens, *Dictionary* P.10
[12] Stevens, *Dictionary* P. 11
[13] Stevens, *Dictionary* P. 11
[14] Stevens, *Dictionary* P. 11
[15] Stevens, *Dictionary* P. 11

1 1/3' – The sixth harmonic of 8' registration series and the twelfth harmonic of 16' series. Also the third harmonic of 4' series. The octave of the 2 2/3' drawbar, hence has the similar tonal effect. It brings a brilliant keenness and string-like effect in some combinations if used strong. Has a tinsel-like effect, without brilliance when it is weak.[16]

1' – Adds the eighth harmonic to 8' registration series, the sixteenth harmonic to 16' series and the fourth harmonic to 4' series. Adds great brilliance especially when it is strong. It adds a glittering, high pitched timbre, which is essential for brilliant tones such as trumpet tones.

1.3 Other functions, which may be used

There are additional functions on the Hammond Organ, which may be used to add definitions and characters to the transients of the tones created with the Drawbars. These are namely, "reverb", "attack time" and "sustain" functions.
"Reverb" adds artificial reverberation to a tone to create more atmospheric effects.
"Attack time" determines either slow ("Slow Attack") or instantaneous attack ("No Attack") at the start of the transient.
"Sustain" determines the release time of a tone after the key is released. There are four levels of sustain: no sustain, short, mid and long. These are achieved by choosing an appropriate pre-set function button.

<u>Chapter 2:</u>

[16] Stevens, *Dictionary* P. 11

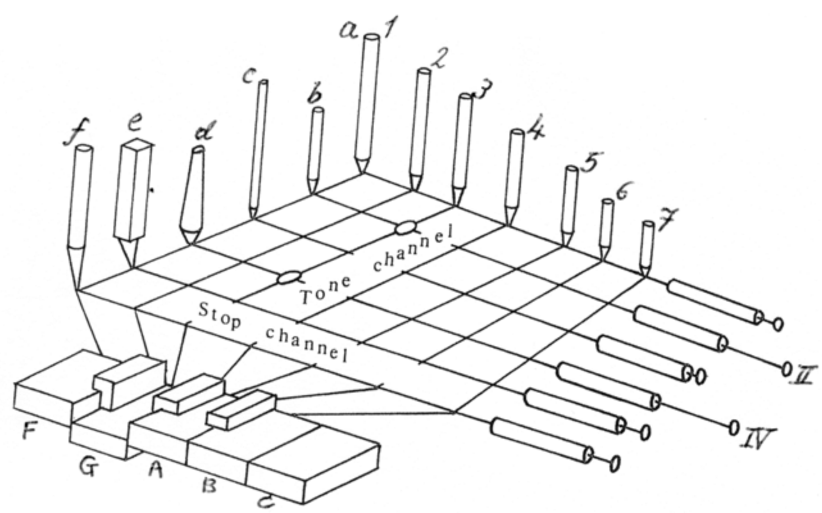
The tone production of the pipe organ

2.1 Introduction to the pipe organ

The pipe organ may be classified under wind instruments, as it uses the same mechanism of sound generation. Obviously, the pipes are the basis of the sound of the instrument. Tones produced by pipes vary according to their length, diameter, shapes and materials. However, there are two different types of pipes. Flue pipes use the oscillation of air stream to produce sound in the manner the flute establishes the vibrating air column. Reed pipes use vibration reeds, which are often made of metal.
In essence the instrument comprises a number of ranks of pipes, each having a different shape and timbre. Each rank is made up of a set of pipes having different size and pitch. The connections form a matrix, as shown in figure 3, so that air is channelled to a given pipe only when both its tone channel and its stop channel have been activated.[17]

Figure 3. The matrix representation of relation of the pipe organ stops and the pipes [18]

When a note G is played and the stops *II* and *IV* are in use, pipes *b* and *d* of length *3* are sounded simultaneously.



Each rank is operated by a drawstop. When a drawstop is withdrawn, the pipes of a given rank with their pallet valve open will sound.[19] The drawstops on an organ are shared out amongst a number of manuals (keyboards), each of which consists of 61 keys, with the pedalboard. The most important manual of the organ is the Great organ, which contains many louder stops and stops to be combined together to create louder sound.

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[17] Campbell, Greated, *Musician's guide* P. 461
[18] Figure from Campbell, Greated, *Musician's guide* P. 460
[19] Campbell, Greated, *Musician's guide* P. 462

Stop name is given according to the character of the tone a pipe produces. The footage marking indicates the pitch of the stop. Since the frequency of oscillation in the pipe is inversely proportional to its length, the higher the pitch is, the smaller the footage number becomes. An organ stop which has the same frequency values on the piano is marked 8'. The pitch of a 4' stop is an octave higher and the pitch of a 16' stop is an octave lower than an 8' stop. This is due to halving the length of a pipe doubles the frequency and doubling the length halves the frequency, as the frequency ratio of an octave is 2:1. However, footage marking is used as a terminology to describe the pitch, not the actual length of a pipe, hence a stop containing a stopped 4' pipe is labelled 8', in other words, the description of the pitch is based on the length of an open pipe, not a stopped pipe, whose frequency is half of an open pipe of the same length.

2.2 Tone production – timbral additive synthesis

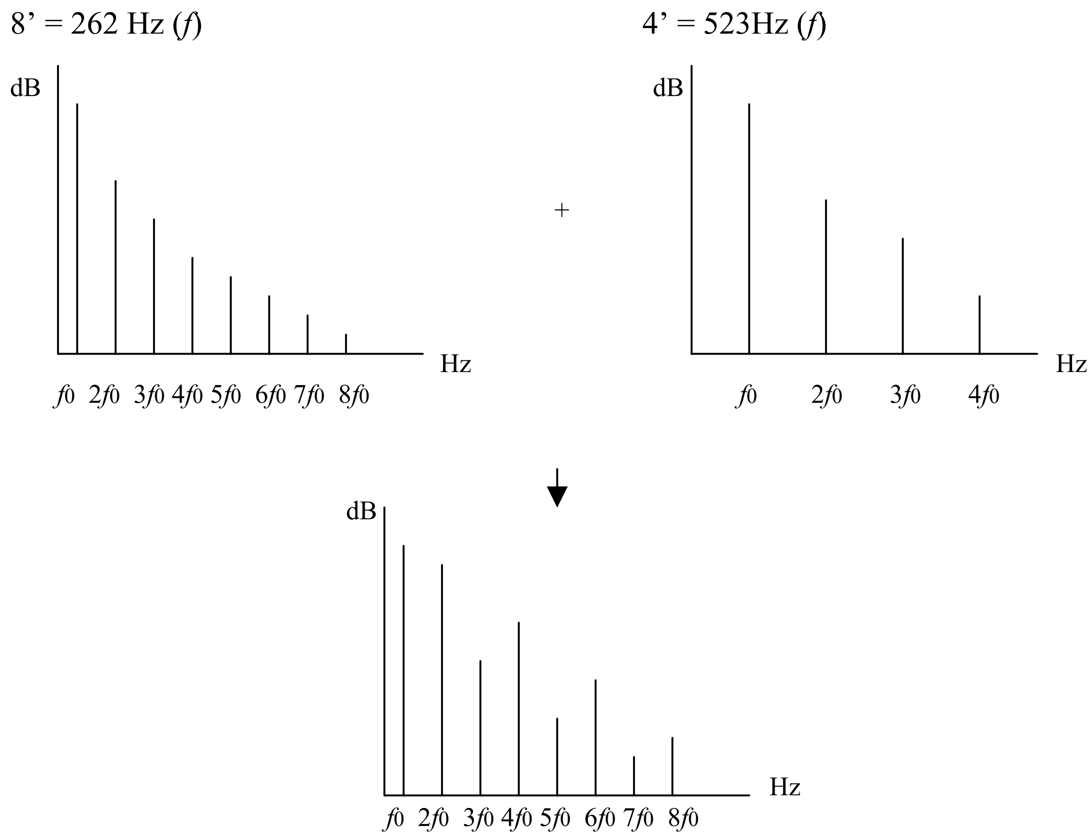
In fact, the pipe organ is one of the earliest acoustic timbral synthesisers, whose production of sound is based on the principle of harmonic additive synthesis. The stops of the pipe organ provide the means for adding harmonics together.[20] Although some 8' stops are used alone as solo stops, most stops are voiced to combine with other stops. Variations in timbre can be achieved by combining different stops, which is usually based upon 8' stops on the manuals and 16' stops for foot pedals. The timbral variations are manipulated by reinforcing the natural harmonics of the 8' harmonic series on the manuals. The following equation relates the footage of a stop to the member of the 8' natural harmonic series which its f_0 reinforces.[21]

$$\text{Stop footage} = 8/N \qquad \text{where } N = \text{harmonic number}$$

For example, the third harmonic is reinforced by a stop of 8/3 = 2 2/3'. However, tones produced by single pipe organ stops contain harmonics. Therefore, for instance, the addition of a 4' stop to a foundation 8' stop will enhance not only the second harmonic of the 8' stop, but also all other even harmonics,[22] as shown in figure 4. The odd harmonics of the 8' pipe are not members of the harmonic series of the 4' pipe.

Figure 4. Spectrum showing when two tones of pipes pitched 8' and 4' are added together

[20] Howard, D. M., Angus, J., *Acoustics and Psychoacoustics* (Oxford: Focal Press, 2001) P. 226
[21] Howard, Angus, *Acoustics* P. 226
[22] Howard, Angus, *Acoustics* P. 227



In general, when a stop is added, whose f_0 is set to reinforce a member (n = 1, 2, 3, 4….) of the natural harmonic series at 8' pitch on the manuals, it enhances the (2n,3 n, 4n….) also.[23] Those stops, which reinforce other harmonics, are called mutation stops. They do not produce a sound corresponding to the key depressed. Foundation stops are those which gives tones corresponding to the key depressed. On the manual, the 8' stops and on the foot pedals the 16' stops are foundation stops. The 4' on the manual and the 8' on the foot pedals are called "octave stops", and the 16' on the manual and the 32' on the pedal are called "double stops" or "sub-bass".[24]

The method of adding harmonic partials by combining pipe organ stops of different pitches to reinforce harmonics is employed by the tone construction of the Hammond Organ, which uses the drawbars of the same pitches used on pipe organ stops. However, drawbars of the Hammond Organ do not contain harmonics, therefore reinforcement of harmonic partials may be achieved by increasing the volume of drawbars of the appropriate harmonic number.

Chapter 3:

[23] Howard, Angus, *Acoustics* P.227
[24] Broadhouse, J., The Organ Viewed from *within a Practical Handbook on the Mechanism of the Organ* (London: Reeves, 1914) P. 50

Tone analysis of pipe organ stops

3.1 Types of pipe organ stops

The tones of pipe organ stops fall into four different classes, which are diapason, flute, strings and reeds. The categories of organ stops are grouped as follows:

Type of pipe		*tone family*
Flue pipe	—	Diapason flute strings
Reed pipe	—	reeds

Flue pipe stops

Flue pipes use the oscillation of air stream to produce the sound in the manner the flute establish the vibrating air column. Referring to the diagram in the figure 5-a, flue is a slit-like gap between the languid, which is the metal (wood) plate that divides the body of a pipe from the bottom part, and the bottom lip of the mouth. Air escapes from the foot through the flue, blows across the mouth and vibrates either side of the top lip to produce sound.[25] Flue pipes are either made of metal or wood. Wood pipes are usually square in shape. There are three tone families of flue pipes, which are: Diapason family, flute family and strings family.

- **Diapason family**: The Diapason is considered to be the most important foundation tone of the organ, whose sound is distinctive to the instrument. The family includes the Diapason 16' and 8', principal 4', twelfth 2 2/3', fifteenth 2' and compound stops known as mixtures. It combines fundamental tone with harmonic development to create louder and more brilliant choruses with overtones enhanced.
- **Flute family**: Flute stops have relatively low harmonic development, thus produce soft tones. There are four types of flute stops: open, stopped, harmonic and stopped harmonic. Stopped flute only produces odd harmonics and harmonic flute uses the principle of overblown flute to produce its octave and harmonics.[26]
- **Strings family**: Strings stops produce tones with highly developed upper harmonics.

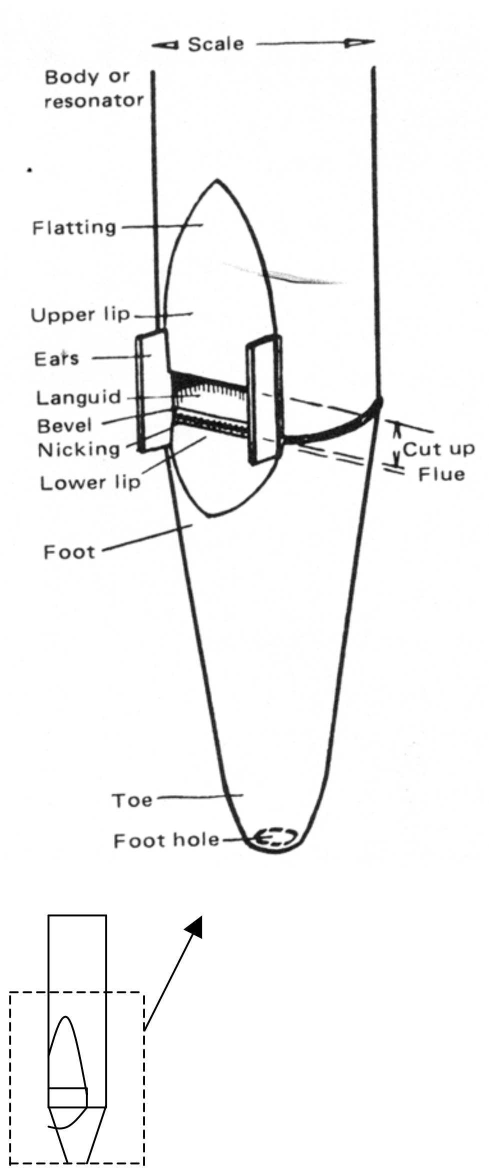
Reed pipe stops

[25] Norman, J., *The Organs of Britain* (Newton Abbot: David & Charles, 1984) P. 131
[26] Goode, J. C., *Pipe Organ Registration* (New York: Abingdon Press,1964) P. 16

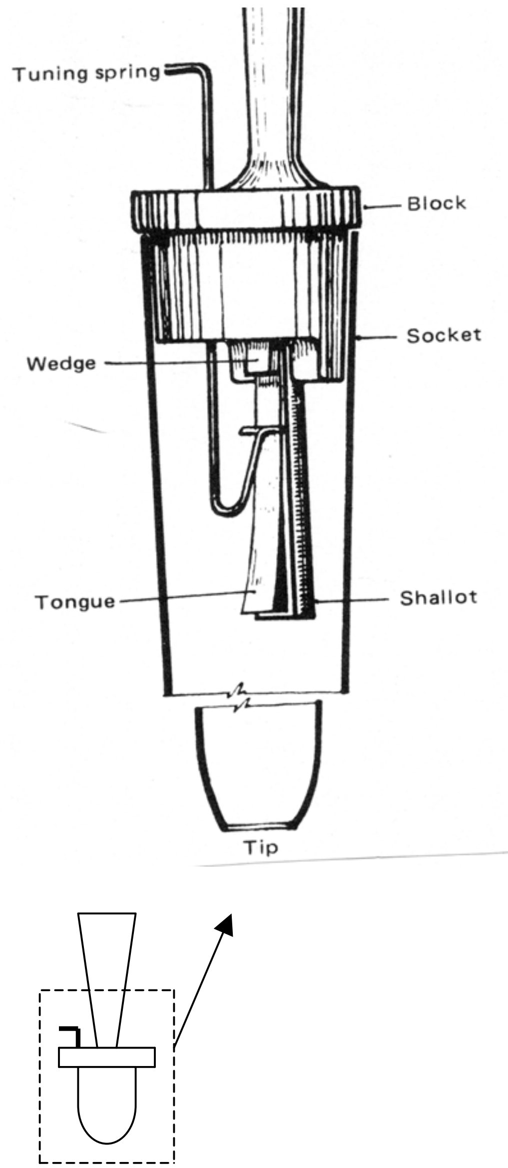
Reed pipes use vibrating reeds, which is often made of metal, to produce sound. Wind sets the reeds called the tongue, shown in figure 5-b, into vibration and the pipe acts as a resonator, which amplifies the original note and converts it into musical tone. Tones produced by reed pipes are classified as the reed family.

- **Reed family**: There are two types of reed stops: chorus and solo reeds. Chorus reeds form the equivalent of the brass of an orchestra, adding power and richness.[27] Solo reeds are imitative in quality and have poor blending qualities.

Figure 5 a. A flue pipe[28]



b. A reed pipe[29]



3.2 Pipe organ stops selected for the investigation

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[27] Goode, *Pipe Organ Registration* P. 30
[28] Figure from Norman, *The Organs of Britain* P. 17
[29] Figure from Norman, *The Organs of Britain* P. 17

From more than a hundred different stops, the number of stops an organ can employ depends on the size of the instrument. However, the pipes can be added or replaced with ones of different types.
In this investigation, a variety of individual stops and combinations of stops are selected for analysis and synthesis. These are listed as follows:

<u>Individual stops</u>
Open Diapason 8’
Stopped Diapason 8’
Principal 4’
Flute 4’
Twelfth 2 2/3’
Fifteenth 2’
Tierce 1 3/5’
Dulciana 8’
Trumpet 8’
Cremona 8’
Hautboy 8’ (from C_2)
Clarion 4’
Sesquialtera (Mixture) V
Cornet II

<u>Combination of stops</u>
Open Diapason 8’ + Principal 4’ + Fifteenth 2’
Open Diapason 8’ + Principal 4’ + Twelfth 2 2/3’ + Fifteenth 2’
Open Diapason 8’ + Principal 4’ + Twelfth 2 2/3’ + Fifteenth 2’ + Tierce 1 3/5’+ Sesquialtera V
Open Diapason 8’ + Principal 4’ + Fifteenth 2’ + Cornet II
Open Diapason 8’ + Flute 4’
Stopped Diapason 8’ + Flute 4’
Dulciana 8’ + Principal 4’
Open Diapason 8’ + Clarion 4’

The tones were first recorded, which is the initial sound source of the observation. The organ used for the recording is the Thomas Griffin organ built in 1743 at St. Helen’s church, Bishopsgate, London. The organ consists of three manuals, which are Swell, Great and Choir, and foot pedals. The number of stops for three manuals is 24 in total – nine stops for Swell, ten stops for Great and five stops for Choir. The organ uses “Mark Lindley Temperament for Bach”, which is 1/12 Pythagorean comma with the 1.9 cents narrower fifth and the 3.3 cents wider major third. The frequencies of the temperament are given in a following table.

Table 1. Frequencies of the Mark Lindley temperament and the equal temperament

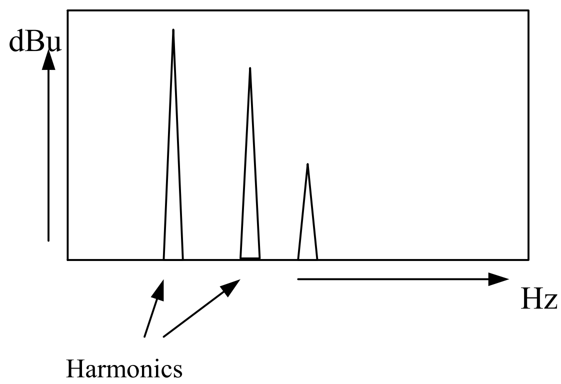
	Mark Lindley for Bach (Hz)	Equal Temperament (Hz)
C	262.42	261.63
C#	277.06	277.18
D	293.96	293.66
D#	311.48	311.12
E	329.3	329.63
F	350.41	349.23
F#	369.66	369.99
G	392.79	392
G#	415.31	415.3
A	440	440
Bb	467.22	493.88
B	493.21	523.25

Listed below is the equipment used for the recording.

- a portable DAT recorder
- an AKG414 capacitor microphone
- a pair of headphones
- an XLR cable

The microphone was secured on a short-boom stand and placed 3-4 metres away from the organ so that the level of the organ sound were at maximum and the noise level was minimised. Once the recording level was adjusted on the DAT recorder, a set of notes for each stop was recorded. The notes played are: Eb_1, Bb_1, F_2, middle C, G_3, and D_4 in ascending order. A few takes of each note were recorded. However, there is a low frequency noise throughout the recording, which could not be avoided. Most successful take of each sample recorded on DAT was then digitally transferred onto Pro Tools. Each sample, which consists of six notes was converted into and saved as an audio file for use on Spectra Foo, a spectrum analysing programme. On Spectra Foo, a spectrum of a tone appears on the spectragraph, which gives frequency domain, as shown in figure 6.

Figure 6. Spectragraph (frequency domain)



Frequencies of harmonic partials on the Spectragraph can be read and harmonic numbers are identified from the readings. The settings for the Spectragraph window are listed as follows:

Frequency range: approx.60 – 19.86Hz
Power range: -46 dBu ~ max
Show traces of average spectrum
Settling time: 0.358 seconds
Average mode: logarithmic
Resolution: continuous
Accumulation mode: white noise is flat

3.3 The descriptions and the tone analyses of the pipe organ stops

Tones produced by pipe organ stops have different characteristics. Various factors such as pipe length, type of pipe and voicing, determine the timbre. In order to create imitations on the Hammond Organ, the tones are analysed in three major areas: frequency and amplitude of each harmonic, and transient. First, each harmonic number is identified by its frequency. Secondly, amplitude of each harmonic is measured. Transient of tones produced by organ pipes is also determined by the types of pipe. Tones produced by flue pipes have relatively long attack time, while tones of reed pipes have rather instantaneous attack. Since the Hammond Organ does not cater flexible tuning systems and the equal temperament is used for synthesis, temperament of the organ used for recording or any discrepancies caused by the tuning of the organ are not taken into consideration for synthesis on the Hammond Organ.
The following is the classification of the organ stops used for analysis and synthesis, together with the stops equivalent to Hammond Organ drawbars.

Table 2. The classification of the selected organ stops

Name of stop	Pitch	Rank	Type of pipe	Tone family
Open Diapason	8’		Flue	Diapason
Stopped Diapason	8’		Flue	Flute
Principal	4’		Flue	Diapason
Fifteenth	2’		Flue	Diapason
Twelfth	2 2/3’		Flue	Diapason
Tierce	1 3/5’		Flue	Diapason
Flute	4’		Flue	Flute
Dulciana	8’		Flue	Strings
Trumpet	8’		Reed	Reed (chorus)
Cremona	8’		Reed	Reed (solo)
Hautboy	8’		Reed	Reed (chorus)
Clarion	4’		Reed	Reed (chorus)
Bourdon	16’		Flue	Diapason
Quint	5 1/3’		Flue	Diapason
Larigot	1 1/3’		Flue	Diapason
Sifflöte	1’		Flue	Diapason
Sesquialtera		V	Flue	Diapason
Cornet		II	Flue	Diapason

The following is the description and analyses of the stops listed above.

- ***Open Diapason***

A foundation stop of the Diapason family. The pitch is 8’ and its tone stands between flute and strings, yet independent. Also called Principal 8’.

Frequency spectra analyses

Referring to the spectra given in Appendix C pages VII – IX, the second harmonic is prominent and the fundamental is the second strongest partial. The higher the frequencies of harmonic partials are, the weaker they become. There are average of five harmonic partials present, and the fifth partial is absent in notes of higher pitch.

- ***Stopped Diapason***

A stop which is more appropriately described as a stopped flute. However, the pitch is 8’ and the 4’ stop is called Nason Flute.

Frequency spectra analyses

Referring to the spectra given in Appendix C pages X - XII, only two harmonic partials are present, which are the fundamental and the third. Since this is a stopped pipe, even harmonics are absent. The fundamental is strong and notes of higher range only contain the fundamental.

- ***Principal***

The octave Open Diapason. The 4' Diapason on the manual is called Principal as it forms the basis of tuning.

Frequency spectra analyses

Referring to the spectra given in Appendix C pages XIII – XV, four harmonic partials are present at Eb_1, and there are three partials present in other notes. The fundamental and the second harmonics are the strongest and most of the partials become weaker at higher frequencies.

- ***Twelfth (Nazard)***

A mutation stop of 2 2/3' pitch, which is the 12th note above the unison. It represents the third harmonic of the Diapason harmonic series. The most important mutation stop, which is thought to bind the octave and the superoctave.

Frequency spectra analyses

Referring to the spectra given in Appendix C pages XVI – XVIII, three to four harmonics are present. The fundamental and the second harmonics are strong. One of them is stronger than the other in most cases, however, at C_3, both have more or less the same amplitude.

- ***Fifteenth (Block Flöte)***

The superoctave Open Diapason of 2' pitch. (The 15th note above the unison). An integral part of the Diapason chorus. The power of the stop reaches maximum between tenor C and treble C.[30] Adds brightness to Diapason tones.

Frequency spectra analyses

Referring to the spectra given in Appendix C pages XIX – XXI, average of three harmonic partials are present. The fundamental and the second harmonic are strong. Only the fundamental is present at G_3 and D_4.

- ***Tierce***

The fifth partial tone of the natural harmonic series and the 17th note above the unison, whose pitch is 1 3/5'. Produces a flute-like tone and adds reed-like characteristic when combined with other stops.

Frequency spectra analyses

Referring to the spectra given in Appendix C pages XXII – XXIV, there are two or three harmonics present. The third harmonic is present at Eb_1. At D_4, only the fundamental is present. The fundamental is strong.

- ***Bourdon***

A stopped pipe of 16' pitch. A sub-bass of the Diapason family.

- ***Quint***

A sub-mutation stop whose pitch is 5 1/3' and the fifth above the unison. A part of the harmonic series of 16''

[30] Bonavia-Hunt, N. A., *Modern Organ Stops* (London: Musical Opinion, 1923) P. 29

- ***Larigot***

A stop whose pitch is 1 1/3' and the sixth partial of the natural harmonic series. Often one of the mixture ranks (19th).

- ***Sifflöte***

A small flue pipe of 1' pitch. Often one of the mixture ranks (22nd), rather than an independent stop.

- ***Flute*** A 4' stop which produces a soft tone without harmonic development.

Frequency spectra analyses

Referring to the spectra given in Appendix C pages XXXI – XXXIII, the tones contain only the fundamental in most cases. Two harmonics are present at Eb_1 and Bb_1. Since even harmonics are absent, this is assumed to be a stopped pipe. It could be compared to the spectra of Stopped Diapason 8', which is also a stopped pipe of the flute family. However, the pitch of Stopped Diapason is an octave lower than Flute 4', which is probably the reason why it is not called "flute". This Flute 4' stop may be more appropriately called "Nason Flute".

- ***Dulciana***

A stop of the strings family. Has a slightly nasal or string quality in most cases. Has a sweet, silvery and cantabile quality.[31]

Frequency spectra analyses

Referring to the spectra given in Appendix C pages XXXIV – XXXVI, two or three harmonics are present. The fundamental is strong, although the spectra of this stop seem to be irregular.

- ***Trumpet***

A stop of the reed family. The tone is brilliant and loud just as the orchestral trumpet. One of the normal chorus reed stops. This stop is characterised by its capacity to create a chorus. It can be also used as a solo stop.

Frequency spectra analyses

Uses reed pipes. The tones are rich in overtones like the orchestral trumpet (see Appendix B page III), thus produces brilliant timbre. Referring to the spectra given in Appendix C pages XXXVII – XXXIX, the spectra from note to note. At D_4, only seven partials are present. The fundamental is weaker than other partials in most cases. Upper harmonic partials such as the sixth and the seventh seem to be the strongest in general. The second and the third are also strong in most cases.

- ***Cremona***

A bright and coarse toned clarinet, which is falsely named after the German Krummhorn. It is one of the solo reed stops. However, the treble tone of the stop is said to be considerably clearer compared to the bass tone.

Frequency spectra analyses

Referring to the spectra given in Appendix C pages XL – XLII, odd harmonics are reasonably strong. Even harmonics are present yet rather weak, like the orchestral

[31] Sumner, W. L., *The Organ* (London: Macdonald and Jane's, 1973) P.308

clarinet (refer to Appendix B page IV). This is more significant in upper notes. This is probably why the tone of Cremona is described as "bright clarinet".

- ***Hautboy***

It is also called "Oboe". The stop does not blend well with other flue stops. The tone is between an oboe and a small-scaled horn.

Frequency spectra analyses

Referring to the spectra given in Appendix C pages XLIII – XLIV, the spectra of Hautboy, or oboe, resemble of those of its prototype, although the more imitative stop is called an "Orchestral Oboe". Like the acoustic oboe (see Appendix B page V), the third harmonic and the neighbouring partials are stronger than the fundamental.

- ***Clarion***

A 4' reed stop. An octave Trumpet.

Frequency spectra analyses

As it is described as "an octave trumpet", the spectra of Clarion are very similar to those of Trumpet 8' (refer to the spectra given in Appendix C pages XLV – XLVII). The fundamental is more or less strong.

- ***Mixture*** – Also called "harmonics". This stop is a part of the harmonic content of the flue chorus, which is used to add brilliance to the organ tone. A Mixture normally contains three to five ranks of pipes and typically consists of octave and fifth sounding ranks, such as 15th, 19th, 22nd, 26th and 29th. Stops such as 1 1/3' (19th) and 1' (22nd) are often replaced as part of a mixture stop. Mixtures supply to an organ a tonal quality in the chorus which can be obtained in no other way and is distinctive to the instrument.[32] Mixtures give depth to the treble, brilliance in the middle of the compass and definition to the bass, and act as a bridge between the fluework and chorus reedwork of the organ, binding the whole tone mass together.[33] Mixture stops are marked with the number of ranks in Roman numbering, not the footage mark. For instance, three ranks means mixture of three pipes sound simultaneously for each key played. "Sesquialtera" and "Cornet" are types of mixture stops.

Sesquialtera V

A stop which consists of five ranks of flue pipes. It gives a reed-like tone to the chorus and can be an ingredient of a bright solo. Originally a stop with two ranks of Twelfth and Tierce, giving an interval of a major sixth.[34]

Frequency spectra analyses

The tones are rich in overtones, as the stop is used for adding brilliance to the Diapason chorus. Referring to the spectra given in Appendix C pages XXV – XXVII, the stop is rich in upper harmonics. Analysing from the frequencies of harmonic partials, the stop may contain five of the following pipes: 12th, 15th, 17th,19th, 22nd, 24th and 26th (in intervals to the unison).

[32] Sumner, *The Organ* P. 316
[33] Sumner, *The Organ* P. 317
[34] Sumner, *The Organ* P. 323

Cornet II

A mixture stop made of several ranks of flue pipes. The cornet usually includes 2 2/3', 2' and 1 3/5', and 8' and 4' if of five ranks. These combine to give a reed-like single tone colour.

<u>Frequency spectra analyses</u>

This stop consists of two ranks of pipes, which, from frequency analysis, seem to be 2 2/3' and 1 3/5'. This may also be called "Sesquialtera", which is traditionally more appropriate for this stop. Referring to the spectra given in Appendix C pages XXVIII – XXX, there are average of four frequency partials present, which seem to be the fundamental and the second partials of each 2 2/3'- and 1 3/5'- pitched pipes, although at Eb_1 and Bb_1 the pitch is an octave higher.

The following are analyses of the selected combinations of stops.

- ***Open Diapason 8' + Principal 4' + Fifteenth 2'***

<u>Frequency spectra analyses</u>

Referring to the spectra given in Appendix C pages XLVIII – L, the second, the fourth and the eighth partials are enhanced. The third and the sixth partials are weak and the fifth and the seventh partials are absent.

- ***Open Diapason 8' + Principal 4' + Twelfth 2 2/3' + Fifteenth 2'***

<u>Frequency spectra analyses</u>

Referring to the spectra given in Appendix C pages LI – LIII, the second, the third, the fourth, the sixth and the eighth partials are enhanced. The second, the third and the fourth are strong and the fifth is weak. The seventh is absent.

- ***Stopped Diapason 8' + Principal 4' + Twelfth 2 2/3' + Fifteenth 2' + Tierce 1 3/5' + Sesquialtera V***

<u>Frequency spectra analyses</u>

Referring to the spectra given in Appendix C pages LIV – LVI, the tones are rich in enhanced upper harmonics. The second, the fourth, the fifth, the sixth and the eighth partials are enhanced and the seventh is absent. The second is prominent.

- ***Open Diapason 8' + Principal 4' + Fifteenth 2' + Cornet II***

<u>Frequency spectra analyses</u>

Referring to the spectra given in Appendix C pages LVII – LIX, at Eb_1 and Bb_1 the third is weak and the fifth is absent. From F_2 to D_4 the second, the third, the fourth, the fifth and the sixth partials are enhanced. The second and the fourth are strong.

- ***Open Diapason 8' + Flute 4'***

<u>Frequency spectra analyses</u>

Referring to the spectra given in Appendix C pages LX – LXII, at Eb_1 and Bb_1 the second and the sixth are enhanced by the 4' stop. The second is enhanced in all notes and is the strongest partial.

- ***Stopped Diapason 8' + Flute 4'***

<u>Frequency spectra analyses</u>

Referring to the spectra given in Appendix C pages LXIII – LXV, it is quite apparent that the combination of the two stopped flute stops give straightforward spectra, which is literally the addition of the spectra of each stop. The fundamental is considerably strong. The second and the sixth partials are enhanced.

- ***Dulciana 8' + Principal 4'***

Frequency spectra analyses

Referring to the spectra given in Appendix C pages LXVI - LXVIII, the tone is rich in overtones at lower notes. Even numbered harmonics are enhanced. The second harmonic is strong although the fundamental is stronger in lower notes.

- ***Open Diapason 8' + Clarion 4'***

Frequency spectra analyses

Referring to the spectra given in Appendix C pages LXIX - LXXI, the second, the fourth and the sixth partials are enhanced. The second is strong.

Transient analysis

All stops other than Trumpet 8', Cremona 8', Hautboy 8' and Clarion 4' use flue pipes. Thus create a noise of air stream entering into the pipes at the beginning of the transient and the attack of the tones is slow.
Trumpet 8', Cremona 8', Hautboy 8' and Clarion 4' use reed pipes, whose excitation of the air column is different from that of flue pipes. The Attack is almost instantaneous.

<u>**Chapter 4:**</u>

Synthesis on the Hammond Organ

4.1 Sound synthesis on the Hammond Organ

Imitations of the tones produced by pipe organ stops are created on the Hammond Organ using various functions available. The Hammond Organ normally contains two manuals with 61 keys on each manual, however, the Hammond XB-1 single manual keyboard is used for this project. The equal temperament is used for synthesis, whose frequencies are given in Table 1. Functions of the Hammond Organ and the areas of synthesis relate as follows.

Function *Areas of synthesis*

Drawbars --------- harmonic partials
Attack time ------- transient (attack)
Sustain ------------- transient (release)
Reverb* -------------- reverberation

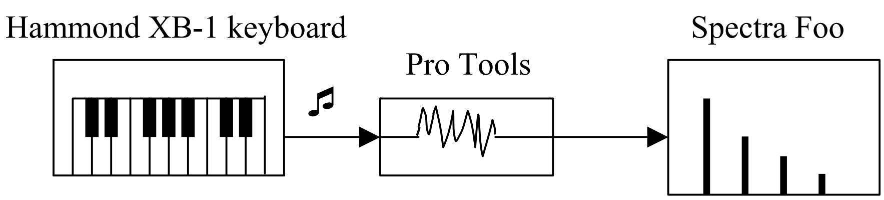
*Note that this functions is optional

Spectra define the timbre of the tone, and attack time and release time are the start and the end of the tone envelope.

First, spectra of each stop, which are considered to be most typical, are selected. Then harmonic number and amplitude of each partial are identified and measured. Secondly, they are transferred to the drawbars. The harmonic numbers of harmonic partials are applied to the relevant drawbars given on the chart in appendix A accordingly. For instance, if the 8' drawbar is used as the fundamental, the second harmonic is the 4' drawbar, and if the 4' drawbar is the fundamental, the second partial is the 2' drawbar. Amplitude of each partial is determined by adjusting the volume of the drawbar, as explained in Chapter 1.
Then the synthesised tones are observed using Spectra Foo and drawbar settings are amended where necessary. The equipment used are: the Hammond XB-1 keyboard, Pro Tools (audio editing programme) and Spectra Foo, which are connected as shown in a following diagram.

Figure 7. The set-up of the equipment

Synthesised tones are recorded on to Pro Tools for analysis on Spectra Foo



The spectra of the synthesised tones are available in appendices D and E. As spectra of tones produced by organ pipes differ from note to note, alternative drawbar settings are considered for some of the synthesised tone on the Hammond Organ. In order to furnish with more realistic tonal effects, medium length reverberation has been added to the synthesised tones.

The following are the outcome of the synthesis experiments. Amplitude of each setting is given in drawbar increment number.

- ***Open Diapason 8'*** (Appendix D pages LXXIII – LXXV))

Used spectra – Bb, G, D

Drawbar settings

Pitch:	**8'**	**4'**	**2 2/3'**	**2'**	**1 3/5'**	**1 1/3'**	**1'**
Harmonic no.	1	2	3	4	5	6	8
Amplitude:	5	8	5	4	2	0	0

Other functions used
Attack – "Slow Attack"

Capability
It is possible to add harmonics using the drawbars, as the pipe organ tones contain no more than five harmonics on average.

Limitations
The starting transient is different from that of the real tone.

- ***Stopped Diapason 8'*** (Appendix D pages LXXVI – LXXVIII)

Used spectra – C, Bb

Drawbar settings

Pitch:	**8'**	**4'**	**2 2/3'**	**2'**	**1 3/5'**	**1 1/3'**	**1'**
Harmonic no.	1	2	3	4	5	6	8
Amplitude:	7	0	4	0	0	0	0

Other functions used
Attack – "Slow Attack"

Capability
It is possible to synthesise the tones of this stop, as there are average of two harmonics, which are the fundamental and the third harmonics. It is possible to transfer them to the Hammond Organ drawbars.

Limitations

The starting transient is different from that of the real tone.

– ***Principal 4'*** (Appendix D pages LXXIX – LXXXI)

Used spectra – Eb, F

Drawbar settings

Pitch:	**8'**	**4'**	**2 2/3'**	**2'**	**1 3/5'**	**1 1/3'**	**1'**
Harmonic no.	N/A	1	N/A	2	N/A	3	4
Amplitude:	0	7	0	7	0	3	1

Other functions used
Attack – "Slow Attack"

Capability

It is possible to synthesise the tone of this stop using the Hammond Organ drawbars, as there are average of four harmonics.

Limitations

– ***Twelfth 2 2/3'*** (Appendix D pages LXXXII – LXXXIV)

Used spectra – Eb, C

Drawbar settings

Pitch:	**8'**	**4'**	**2 2/3'**	**2'**	**1 3/5'**	**1 1/3'**	**1'**
Harmonic no.	N/A	N/A	1	N/A	N/A	2	N/A
Amplitude:	0	0	4	0	0	6	0

Alternative drawbar settings

Pitch:	**8'**	**4'**	**2 2/3'**	**2'**	**1 3/5'**	**1 1/3'**	**1'**
Harmonic no.	N/A	N/A	1	N/A	N/A	2	N/A
Amplitude:	0	0	6	0	0	5	0

Other functions used
Attack – "Slow Attack"

Capability

The third and the fourth harmonics of the pipe organ tones are very weak, hence it is possible to imitate the tones without sounding remarkably different.

Limitations

It is not possible to add the third and the fourth harmonics for more resemblance.

– ***Fifteenth 2'*** (Appendix D pages LXXXV – LXXXVII)

Used spectra – Bb, C

Drawbar settings

Pitch:	**8'**	**4'**	**2 2/3'**	**2'**	**1 3/5'**	**1 1/3'**	**1'**
Harmonic no.	N/A	N/A	N/A	1	N/A	N/A	2
Amplitude:	0	0	0	7	0	0	4

Other functions used

Attack – "Slow Attack"

Capability

The third and the fourth harmonics of the pipe organ tones are very weak, hence it is possible to imitate without sounding remarkably different.

Limitations

It is not possible to add the third and the fourth harmonics for more resemblance.

– ***Tierce 1 3/5'*** (Appendix D pages LXXXVIII – XC)

Used spectra – C

Drawbar settings

Pitch:	**8'**	**4'**	**2 2/3'**	**2'**	**1 3/5'**	**1 1/3'**	**1'**
Harmonic no.	N/A	N/A	N/A	N/A	1	N/A	N/A
Amplitude:	0	0	0	0	7	0	0

Other functions used

Attack – "Slow Attack"

Capability

It is reasonable to synthesise the tone of Tierce 1 3/5' when a note consists of only the fundamental partial, as it is impossible to add more harmonics to the tone on the Hammond Organ.

Limitations

It is impossible to add any partials other than the fundamental.

– ***Flute 4'*** (Appendix D pages XCVII – XCIX)

Used spectra – Bb, C

Drawbar settings

Pitch:	**8'**	**4'**	**2 2/3'**	**2'**	**1 3/5'**	**1 1/3'**	**1'**
Harmonic no.	N/A	1	N/A	2	N/A	3	4
Amplitude:	0	5	0	0	0	2	0

Other functions used

Attack – "Slow Attack"

Capability

It is possible to synthesise the tone of this stop, as there are average of two harmonics, which are the fundamental and the third harmonics. It is possible to transfer them using the drawbars.

Limitations

The starting transient is not imitated.

– ***Dulciana 8'*** (Appendix D pages C – CII)

Used spectra – Eb, C, G, D

Drawbar settings

Pitch:	**8'**	**4'**	**2 2/3'**	**2'**	**1 3/5'**	**1 1/3'**	**1'**
Harmonic no.	1	2	3	4	5	7	8
Amplitude:	5	2	4	1	0	0	0

Alternative drawbar settings

Pitch:	**8'**	**4'**	**2 2/3'**	**2'**	**1 3/5'**	**1 1/3'**	**1'**
Harmonic no.	1	2	3	4	5	6	8
Amplitude:	3	5	1	1	0	0	0

Other functions used

Attack – "Slow Attack"

Capability

It is possible to add harmonics using the drawbars, as the pipe organ tones contain no more than four harmonics on average.

Limitations

The spectra differ by note. Hence it is necessary to consider an alternative setting.

– ***Trumpet 8'*** (Appendix D pages CIII – CV)

Used spectra – Eb, F, C, G

Drawbar settings

Pitch:	**8'**	**4'**	**2 2/3'**	**2'**	**1 3/5'**	**1 1/3'**	**1'**
Harmonic no.	1	2	3	4	5	7	8
Amplitude:	6	7	8	7	3	4	5

Other functions used
Attack – "No Attack"

Capability

It is more capable of imitating high notes such as G_3 and D_4.

Limitations

It is impossible to add upper harmonics above the eighth.

– ***Cremona 8'*** (Appendix D pages CVI – CVIII)

Used spectra – Bb, F, C, G, D

Drawbar settings

Pitch:	**8'**	**4'**	**2 2/3'**	**2'**	**1 3/5'**	**1 1/3'**	**1'**
Harmonic no.	1	2	3	4	5	7	8
Amplitude:	4	2	6	2	4	2	1

Other functions used
Attack – "No Attack"

Capability

It is possible to imitate tones of upper notes such as G_3 and D_4, as the tones rarely contains upper harmonics above the eighth.

Limitations

The imitations of lower notes are not as similar to the real tones, as the pipe organ tones contain upper harmonics above the eighth.

– ***Hautboy 8'*** (Appendix D pages CIX – CX)

Used spectra – F,G

Drawbar settings

Pitch:	**8'**	**4'**	**2 2/3'**	**2'**	**1 3/5'**	**1 1/3'**	**1'**
Harmonic no.	1	2	3	4	5	7	8
Amplitude:	4	6	8	6	5	3	1

Other functions used
Attack – "No Attack"

Capability

It seems possible to imitate the spectra of Hautboy 8', as this stop rarely contains overtones of the ninth or above.

Limitations

Upper harmonic partials above the eighth present in F_2 and C_3 of the real tones do not exist on the Hammond Organ.

– ***Clarion 4'*** (Appendix D pages CXI – CXIII)

Used spectra – Eb, F, C, G, D

Drawbar settings 1

Pitch:	**8'**	**4'**	**2 2/3'**	**2'**	**1 3/5'**	**1 1/3'**	**1'**
Harmonic no.	N/A	1	N/A	2	N/A	3	4
Amplitude:	0	6	0	6	0	4	4

Other functions used
Attack – "No Attack"

Capability

It is not impossible to imitate higher-pitched tones, as the pipe organ tones contain fewer upper harmonic partials.

Limitations

Up to only fourth harmonic partials are added, hence it is not possible to create tones of lower notes, which are rich in upper harmonics.

– ***Sesquialtera V*** (Appendix D page XCI – XCIII)

Used spectra – Eb, F, C, G

Drawbar settings

Pitch:	**8'**	**4'**	**2 2/3'**	**2'**	**1 3/5'**	**1 1/3'**	**1'**
Amplitude:	0	0	3	6	5	6	8

Other functions used
Attack – "Slow Attack"

Capability

It is possible to create strong sixth and eighth partials.

Limitations

The harmonic partials which may be added are limited, as there are more partials above the eighth partial. The spectra of this stop differ from note to note and it is not possible to create an overall imitation of this stop.

– ***Cornet II*** (Appendix D pages XCIV – XCVI)

Used spectra – F, C

Drawbar settings

Pitch:	**8'**	**4'**	**2 2/3'**	**2'**	**1 3/5'**	**1 1/3'**	**1'**
Amplitude:	0	0	5	0	4	2	0

Other functions used
Attack – "Slow Attack"

Capability

It is possible to add three harmonic partials.

Limitations

The fourth partial, which is the second harmonic of the 1 3/5' pipe, is not added.

– ***Open Diapason 8' + Principal 4' + Fifteenth 2'*** (Appendix D pages CXIV – CXVI)

Used spectra – Eb, Bb, F

Drawbar settings

Pitch:	**8'**	**4'**	**2 2/3'**	**2'**	**1 3/5'**	**1 1/3'**	**1'**
Harmonic no.	1	2	3	4	5	7	8
Amplitude:	6	8	3	6	0	3	6

Other functions used
Attack – "Slow Attack"

Capability

The pitches of the drawbars correspond to the harmonics of the pipe organ tones.

Limitations

The spectra of the pipe organ tones seem rather irregular and the entire spectra cannot be imitated across the whole manual of the Hammond Organ. The twelfth partial is not added.

– ***Open Diapason 8' + Principal 4' + Twelfth 2 2/3' + Fifteenth 2'*** (Appendix D pages CXVII – CXIX)

Used spectra – Eb, Bb, F,C

Drawbar settings

Pitch:	**8'**	**4'**	**2 2/3'**	**2'**	**1 3/5'**	**1 1/3'**	**1'**
Harmonic no.	1	2	3	4	5	7	8
Amplitude:	6	8	6	7	2	3	3

Other functions used
Attack – "Slow Attack"

Capability

The pitches of the drawbars correspond to the most of the harmonics of the pipe organ tones.

Limitations

The spectra of the pipe organ tones seem rather irregular and the entire spectra cannot be imitated across the whole manual of the Hammond Organ. Upper harmonic partials above the eighth are not added.

– ***Stopped Diapason 8' + Principal 4' + Twelfth 2 2/3' + Fifteenth 2' + Tierce 1 3/5' + Sesquialtera V*** (Appendix D pages CXX – CXXII)

Used spectra – Eb, Bb, C, G, D

Drawbar settings

Pitch:	**8'**	**4'**	**2 2/3'**	**2'**	**1 3/5'**	**1 1/3'**	**1'**
Harmonic no.	1	2	3	4	5	6	8
Amplitude:	6	8	4	7	5	6	8

Alternative drawbar settings

Pitch:	**8'**	**4'**	**2 2/3'**	**2'**	**1 3/5'**	**1 1/3'**	**1'**
Harmonic no.	1	2	3	4	5	7	8
Amplitude:	4	8	4	7	8	6	7

Other functions used
Attack – "Slow Attack"

Capability

It is possible to add harmonics up to the eighth harmonics, as the pitches of the drawbars correspond to the harmonics of the pipe organ tones within the range.

Limitations

It is not possible to add harmonic partials above the eighth.

– ***Open Diapason 8' + Principal 4' + Fifteenth 2' + Cornet II*** (Appendix D pages CXXIII – CXXV)

Used spectra – F,C

Drawbar settings

Pitch:	**8'**	**4'**	**2 2/3'**	**2'**	**1 3/5'**	**1 1/3'**	**1'**
Harmonic no.	1	2	3	4	5	7	8
Amplitude:	4	8	6	8	6	6	5

Alternative drawbar settings

Pitch:	**8'**	**4'**	**2 2/3'**	**2'**	**1 3/5'**	**1 1/3'**	**1'**
Harmonic no.	1	2	3	4	5	6	8
Amplitude:	7	6	3	7	0	5	8

Other functions used
Attack – "Slow Attack"

Capability

It is possible to add harmonics up to the eighth harmonics, as the pitches of the drawbars correspond to the harmonics of the pipe organ tones within the range.

Limitations

The spectra differ from note to note, particularly at Eb_1 and Bb_1 are different from the rest. Different settings may be necessary. The tenth and the twelfth partials are not added.

– ***Open Diapason 8' + Flute 4'*** (Appendix D pages CXXVI – CXXVIII)

Used spectra – Eb, Bb, G

Drawbar settings

Pitch:	**8'**	**4'**	**2 2/3'**	**2'**	**1 3/5'**	**1 1/3'**	**1'**
Harmonic no.	1	2	3	4	5	6	8
Amplitude:	6	8	4	3	1	3	0

Other functions used
Attack – "Slow Attack"

Capability

The pitches of the drawbars correspond to the harmonics of the pipe organ tones.

Limitations

The spectra of this stop differ from note to note and it is not possible to create an overall imitation of this stop.

– ***Stopped Diapason 8' + Flute 4'*** (Appendix D pages CXXIX – CXXXI)

Used spectra – Eb, Bb, C

Drawbar settings

Pitch:	**8'**	**4'**	**2 2/3'**	**2'**	**1 3/5'**	**1 1/3'**	**1'**
Harmonic no.	1	2	3	4	5	7	8
Amplitude:	7	6	4	0	0	3	0

Other functions used
Attack – "Slow Attack"

Capability

It is quite literally an addition of the two stopped flute stops, which is easily imitated.

Limitations

It is not possible to fully imitate the starting transient.

– ***Dulciana 8' + Principal 4'*** (Appendix D pages CXXXII – CXXXIV)

Used spectra – F, C, D

Drawbar settings 1

Pitch:	**8'**	**4'**	**2 2/3'**	**2'**	**1 3/5'**	**1 1/3'**	**1'**
Harmonic no.	1	2	3	4	5	7	8
Amplitude:	5	7	0	6	0	3	0

Other functions used

Attack – "Slow Attack"

Capability

The pitches of the drawbars correspond to the harmonics of the pipe organ tones.

Limitations

The spectra of this stop differ from note to note and it is not possible to create an overall imitation of this stop.

– ***Open Diapason 8' + Clarion 4'*** (Appendix D pages CXXXV – CXXXVII)

Used spectra – F, C, G, D

Drawbar settings

Pitch:	**8'**	**4'**	**2 2/3'**	**2'**	**1 3/5'**	**1 1/3'**	**1'**
Harmonic no.	1	2	3	4	5	7	8
Amplitude:	6	8	2	4	0	5	5

Other functions used

Attack – "No Attack"

Capability

It is not impossible to imitate higher-pitched tones, as the pipe organ tones contain fewer upper harmonic partials.

Limitations

Lower notes of the real tones contain many upper partials, which are not added to synthesised tones using the drawbars.

4.2 Comparison with other similar data

A similar study has been already done and numerous Hammond Organ drawbar settings for pipe organ stops are listed in "Dictionary of Hammond Organ Stops" by Irwin Stevens. Although my investigation is not based on his data, the results of my synthesis experimentation are compared to his translation of drawbar settings.

Open Diapason 8'

Stevens's settings have strong fundamentals. There are three of his settings similar to the one described in this report, which are: 7644 321, 7674 000 and 8742 000 [35] (from 8' to 1').

Stopped Diapason 8'

Stevens's setting 6020 000[36] (from 8' to 1') for this stop is rather softer than the setting in this report.

Principal 4'

The setting 0405 042[37] (from8' to 1') is the closest to the one in this report.

Twelfth 2 2/3'

The first setting in this report 0040 060 (from 8' to 1') is found in Stevens's book under "brilliant" Twelfth[38], and the second setting 0060 050 (from 8' to 1') is also found in his book under "bright" Twelfth[39].

Fifteenth 2'

Stevens's settings 0006 003 and 0006 004[40] (from 8' to 1') are similar to the setting in this report.

Tierce 1 3/5'

Stevens's book also has the same setting as the one in this report.

Sesquialtera V

0056 566 (from 8' to 1') under Mixture V[41] is similar to the one in this report.

Cornet II

0040 300 (from 8' to 1') under Sesquialtera II[42] is similar to the one in this report.

Flute 4'

Stevens's setting 0200 010[43] (from 8' to 1') for this stop is rather softer than the setting in this report.

Dulciana 8'

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[35] Stevens, *Dictionary* P. 75
[36] Stevens, *Dictionary* P. 97
[37] Stevens, *Dictionary* P. 77
[38] Stevens, *Dictionary* P. 80
[39] Stevens, *Dictionary* P. 80
[40] Stevens, *Dictionary* P. 65
[41] Stevens, *Dictionary* P. 73
[42] Stevens, *Dictionary* P. 78
[43] Stevens, *Dictionary* P. 93

2211 000 and 3211 000[44] (from 8' to 1') are similar to the ones in this report.

Trumpet 8'

6787 642 and 6678 246[45] (from 8' to 1') are similar to the one in this report. Stevens describes the former setting as one of the "round-toned" Trumpet, and the latter "moderate"

Cremona 8'

7162 321[46] (from 8' to 1') is the closest to the one in this report.

Hautboy 8'

4675 430 [47](from 8' to 1') is similar to the one in this report, which is found under "Oboe Horn" in Stevens's book.

Clarion 4'

0606 054[48] (from 8' to 1') is similar to the one in this report.

Stevens explains that combinations of the stops may be achieved by adding the increment numbers given in drawbar settings[49]. For instance, a combination of a stop *A* with the drawbar setting 6543 100 and a stop *B* with 0804 022 will be 6847 122 (from 8' to 1'), according to his approach. He explains that this method is more appropriate, as it is easier than considering settings for almost infinite number of combinations. His "addition" method is also compared to the settings for the combinations of stops given in this report.

Open Diapason 8' + Principal 4' + Fifteenth 2'

If three stops are simply added together, the drawbar setting for this combination will be 5858 235 (from 8' to 1'), which is not exceedingly different from the setting in this report.

Open Diapason 8' + Principal 4' + Twelfth 2 2/3' + Fifteenth 2'

If the four stops are added, the setting will be 5888 285 (from 8' to 1'), and the sixth partial (1 1/3') will be very strong.

Open Diapason 8' + Principal 4' + Twelfth 2 2/3' + Fifteenth 2' + Tierce 1 3/5' + Sesquialtera V

The addition will be 5888 888 (from 8' to 1'), which will have a very strong third partial (2 2/3').

Open Diapason 8' + Principal 4' + Fifteenth 2' + Cornet II

5888 635 (from 8' to 1'), if the four stops are added, which will have the weaker sixth partial (1 1/3').

Open Diapason 8' + Flute 4'

If the two stops are added, the setting will be 5854 220 (from 8' to 1'), which is similar to the setting in his report.

Stopped Diapason 8' + Flute 4'

If the two stops are added, the setting will be 7520 020 (from 8' to 1'), which is similar to the setting in this report.

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44 Stevens, *Dictionary* P. 63
45 Stevens, *Dictionary* P. 134
46 Stevens, *Dictionary* P. 122
47 Stevens, *Dictionary* P. 129
48 Stevens, *Dictionary* P. 121
49 Stevens, *Dictionary* P. 13

Dulciana 8' + Principal 4'

The addition of the two stops will be 5847 031 (from 8' to 1'), which is similar to the setting in this report, yet with a rather strong third (2 2/3').

Open Diapason 8' +Clarion 4'

The addition of the two stops will be 5858 244 (from 8' to 1'), which will have the stronger third (2 2/3') and fourth (2') partials.

4.3 The results of the listening tests

In order to observe how the synthesised tones are perceived and to what extent psychoacoustic theories of the synthesis apply to the human perception, listening tests have been undertaken. The methodology of the test is as follows:

1. For each question, two organ tones are played in sequence. One is a synthesised tone, the other is a pipe organ tone. One tone contains two musical notes in fifth played in succession. The pitches of two tones are the same. First part of the test is low – mid range notes and the second part of the test is the mid-high range notes. Across each one to three questions, one synthesised tone is compared to different pipe organ tones. One of them corresponds to the synthesised tone. Hammond Organ tones of randomly combined drawbars are also compared to the selected real pipe organ tones.

2. A participant (listener) determines how similar (or different) the two tones are on a scale of 1 to 4, where 1 represents "very similar" and 4 represents "different".

There are 20 participants of various musical backgrounds. The tests have been undertaken between 10^{th} and 17^{th} May 2004.

<u>The results</u>

- *Synthesised tones vs real organ tones*

Open Diapason 8'
- Low-mid note range: 60% of the participants identified that the synthesised tone was either similar or very similar.
- Mid-high note range: 90% perceived as either similar or very similar. None of the participants found them different.

Trumpet 8'
- Low-mid note range: only 10% perceived as either similar or very similar. 80% identified as different.
- Mid-high note range: 55% found them either similar or very similar.

Cremona 8'
- Low-Mid note range: 60% perceived as either similar or slightly different. One in five participants identified as very similar.
- Mid-high note range: 55% found that the two tones were either very similar or similar. 60% found them either similar or slightly different.

Hautboy 8'

- Low-Mid note range: 75% perceived them as either slightly different or different.
- Mid-high note range: 65% perceived either similar or slightly different. 45% found them either similar or very similar.

Open Diapason 8' + Principal 4' + Fifteenth 2' (Combination 1)

- Low-Mid note range: 75% identified that the two tones were either similar or very similar.
- Mid-high note range: 55% found them either similar or very similar. Two in five participants perceived them as slightly different. 75% perceived that the synthesised tone was also similar to the real pipe organ tone of the Combination 2 (Open Diapason 8' + Principal 4' + Twelfth 2 2/3' + Fifteenth 2').

Open Diapason 8' + Principal 4' + Twelfth 2 2/3' + Fifteenth 2' (Combination 2)

- Low-Mid note range: 55% identified as either similar or very similar.
- Mid-high note range: 70% identified as either similar or very similar. None perceived as different.

Open Diapason 8' + Principal 4' + Twelfth 2 2/3' + Fifteenth 2' + Tierce 1 3/5' + Sesquialtera V (Combination 3)

- Low-Mid note range: 75% perceived them as either slightly different or different.
- Mid-high note range: 65% found them either slightly different or different, with 45% finding them slightly different.

Open Diapason 8' + Principal 4' + Fifteenth 2' + Cornet II (Combination 4)

- Low-Mid note range: 75% perceived as either slightly different or different.
- Mid-high note range: 65% found them as either similar or slightly different. 55% identified as either similar or very similar.

Open Diapason 8' + Flute 4' (Combination 5)

- Low-Mid note range: 85% identified as either similar or very similar, with three in five participants finding the two tones very similar.
- Mid-high note range: 85% identified as either similar or very similar, with 55% finding them very similar.

Stopped Diapason 8' + Flute 4' (Combination 6)

- Low-Mid note range: 4 in 5 participants identified the two tones as either very similar or similar, with three in five finding them very similar. Over 60% found the synthesised tone was also similar to the real tone of the combination 5 (Open Diapason 8' + Flute 4').
- Mid-high note range: 70% identified as either very similar or similar, with 45% finding them very similar. Over 60% found the synthesised tone was also similar to the real tone of the combination 5 (Open Diapason 8' + Flute 4').

Dulciana 8' + Principal 4' (Combination 7)

- Low-Mid note range: 70% identified them either very similar or similar. One in four perceived as slightly different. 60% found the synthesised tone was also similar to the real tone of the combination 5 (Open Diapason 8' + Flute 4').
- Mid-high note range: Half of the participants identified the two tones either very similar or similar. Two in five found them slightly similar.

Open Diapason 8' + Clarion 4' (Combination 8)

- Low-Mid note range: 85% perceived the two tones as different.
- Mid-high note range: 65% found them either slightly different or different.

The graph representations of the above stops/combinations (excludes Open Diapason 8') are shown in figures 8-a and b.

- *Random Hammond Organ tones vs real pipe organ tones*

Open Diapason 8' + Principal 4' + Fifteenth 2' (Combination 1)

- Low-Mid note range: 85% perceived that the real tone of this combination was either similar to or slightly different from the random tone.

Open Diapason 8' + Principal 4' + Twelfth 2 2/3' + Fifteenth 2' (Combination 2)

- Low-Mid note range: 70% perceived that the real tone of this combination was either similar to or slightly different from the random tone.
- Mid-High note range: 55% perceived that the real tone of this combination was either slightly different or different from the random tone.

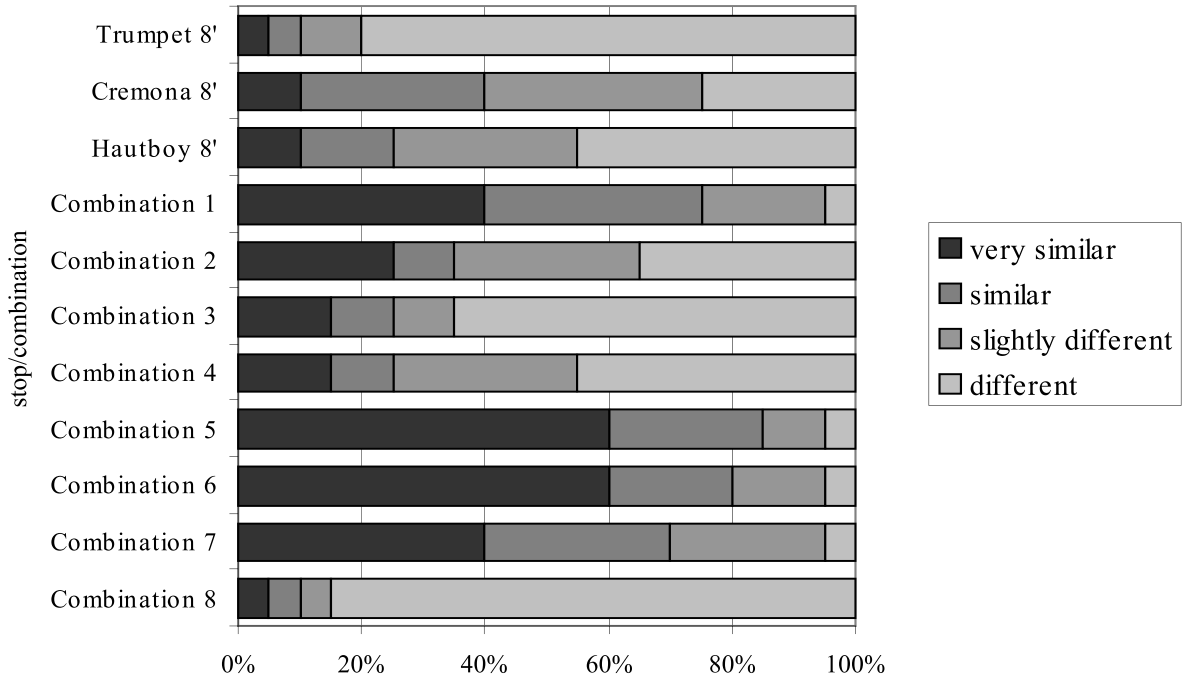
Open Diapason 8' + Principal 4' + Twelfth 2 2/3' + Fifteenth 2' + Tierce 1 3/5' + Sesquialtera V (Combination 3)

- Low-Mid note range: 85% perceived that the real tone of this combination was either slightly different or different from the random tone.
- Mid-High note range: 85% perceived that the real tone of this combination was either slightly different or different from the random tone.

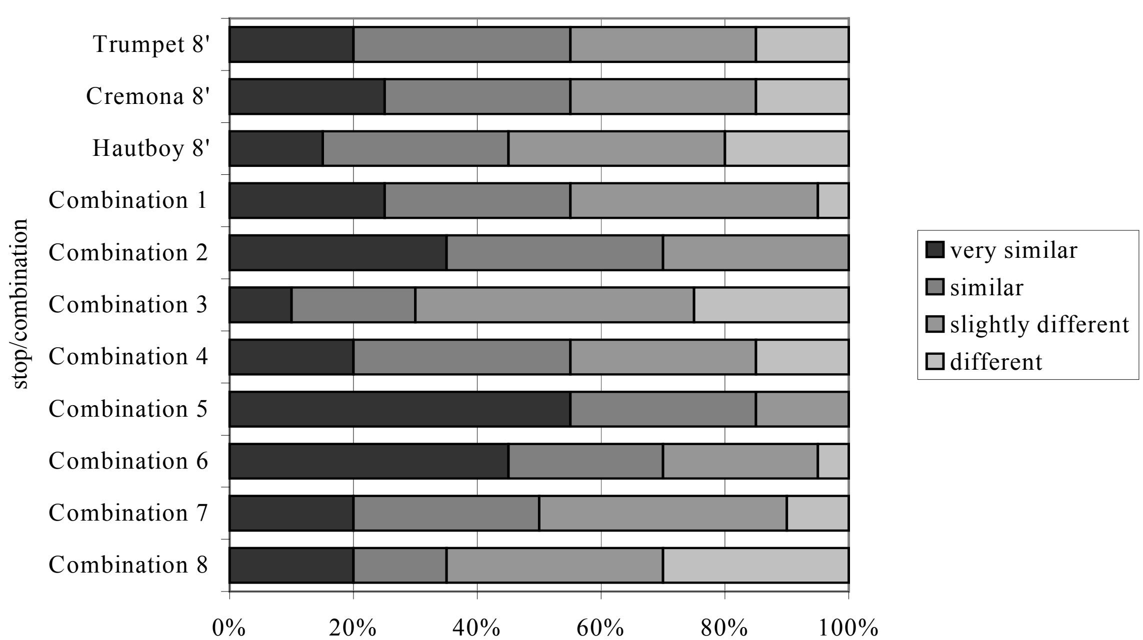
Open Diapason 8' + Principal 4' + Fifteenth 2' + Cornet II (Combination 4)

- Low-Mid note range: Three in five participants perceived that the real tone of this combination was either slightly different or different from the random tone.

Figure 8 - a. The graph of the listening test results (low-mid note ranges)



b. The graph of the listening test results (mid-high note ranges)



From the outcome of the listening tests, the reed stops and the combinations whose tones contain many upper harmonics were perceived as different from the synthesised tones. This is apparently due to that the synthesised tones do not contain harmonics above the eighth. The tones of combinations such as "Stopped Diapason 8' + Flute 4'" were perceived as similar to the synthesised tones, due to their simpler spectra with no harmonics above the eighth. However, the difference of the starting transient between the two tones might have caused them being perceived rather differently in some cases. This is because a musical tone is perceived as a whole, including the transients. The attack is an important feature of a tone produced by a musical instrument, since the starting transient is a crucial role in providing the brain with clues to identify the instrument.[50] However, the decay transient (which occurs at the end of the tone) is less important a feature of the tone characteristic.[51]

The tones which the majority found different contain either irrelevant spectra or transient, or the both. The tones of musical instruments are perceived as a whole. The tones without appropriate transients are difficult to identify.

In general, more participants identified the two tones similar in mid-high tones than in low-mid tones. This may be due to upper harmonic partials becoming too weak to be audible, in addition to the human perception experiencing difficulties identifying high-frequency partials.

The results also proved that the Hammond Organ is not an instrument which is able to produce any pipe organ tones by randomly combining the drawbars.

[50] Campbell, Greated, *The Musician's Guide* P. 142
[51] Campbell, Greated, *The Musician's Guide* P. 158

Chapter 5:

Evaluation and conclusion

5.1 The capabilities and the limitations of the Hammond Organ in imitating pipe organ tones

It is possible to imitate certain tones produced by the pipe organ stops on the Hammond Organ. It is also possible to imitate simpler spectra, as long as there are corresponding drawbar pitches.

The capabilities

- √ It is possible to imitate tones which contains harmonics of up to the 8^{th} partial, provided the fundamental is 8' pitch; it is possible to imitate tones whose spectra are simpler, for instance, tones produced by stops such as Stopped Diapason 8' and Flute 4' contain the fundamental and the third partials, and there are drawbars which corresponds to these harmonics.
- √ The pitches of the Hammond Organ drawbars correspond to those of both foundation and mutation stops of the pipe organ.
- √ It is possible to imitate combinations of Diapason family and flute family, as all the prominent harmonic partials are added by using corresponding drawbars.
- √ It is possible to create combinations of stops on the Hammond Organ by adding drawbar increment numbers given in drawbar settings of required individual stops.
- √ Since each harmonic partial is added separately using individual drawbars, this enables the player to adjust the volume of harmonic components according to the requirements or preference.[52]

Limitations

- × It is, in most cases, difficult to imitate tones produced by reed stops and combinations with reed stops. Tones produced by reed stops normally contain harmonics above the 8^{th}, which do not exist on the Hammond Organ.
- × The Hammond Organ does not have functions to imitate different types of transients of musical instruments.
- × The Hammond Organ does not cater for synthesis mapping, which is a particular range on the manual where a synthesised tone with a specific spectrum is applied. Therefore, it is not possible to imitate an entire range of a pipe organ tone whose spectra differ from note to note.
- × It is not possible to add harmonic partials of higher pitched stops such as Fifteenth 2' and Tierce 1 3/5', as there is no drawbars whose pitches correspond to those of upper harmonics.

[52] Stevens, *Dictionary* P.28

× It is not possible to imitate combinations which contains many prominent upper harmonics, such as the combination Open Diapason 8’ + Principal 4’ + Twelfth 2 2/3’ + Fifteenth 2’ + Tierce 1 3/5’ + Sesquialtera V.

5.2 How the results may be used

From the analyses of the spectra of the selected pipe organ tones, it is understood that spectra of a tone differ from note to note, according to the pitch in most cases. Since the Hammond Organ does not cater for synthesis mapping system, it may be appropriate to imitate specific spectra, which seem most common. Alternatively, a spectra of tones of mid-range notes may be imitated, as high-pitched notes may be able to deceive human perception, as it is increasingly difficult for human ears to recognise higher pitched harmonics.

As explained in Chapter 4, originally in “Dictionary of Hammond Organ Stops” by Irwin Stevens, creating combinations of stops on the Hammond Organ may be achieved by adding drawbar increment numbers of required individual stops. This method may enable the player to create any combinations, provided the drawbar settings of the required stops are known.

The Hammond Organ also has drawbars pitched as 16’ and 5 1/3’. They may be used effectively when it is required to synthesise 16’stops (whose name begins with “Contra” or “Double”). For instance, Double Diapason 16’ is an octave lower than Open Diapason 8’. The synthesis method applied to Open Diapason 8’ is transformed from 8’ series to 16’ series, as shown below.

Open Diapason 8’

Pitch:	**16’**	**5 1/3’**	**8’**	**4’**	**2 2/3’**	**2’**	**1 3/5’**	**1 1/3’**	**1’**
Harmonic no.	N/A	N/A	1	2	3	4	5	7	8
Amplitude:	0	0	6	8	6	4	0	0	0

↓

Double Open Diapason 16’

Pitch:	**16’**	**5 1/3’**	**8’**	**4’**	**2 2/3’**	**2’**	**1 3/5’**	**1 1/3’**	**1’**
Harmonic no.	1	3	2	4	6	8	10	12	16
Amplitude:	6	6	8	4	0	0	0	0	0

5.3 Conclusion

From the outcome of the study, it is observed and understood what are the requirements for synthesis. If a crucial requirement is not met, it is not possible to create an imitation. From the limitations, rather than the capabilities, absent requirements for synthesising particular organ tones are identified. For instance, even though the synthesised flue pipe tones have identical spectra to those of real flue pipe tones, the tone is barely recognisable if the starting transient is not imitated. This suggests that it is difficult to identify a tone without the transients. Therefore it is understood that the starting transient contributes towards our perception of the tone as a whole. It is also studied that which note range that a specific spectrum could be applied for synthesis. In most cases, spectra of a tone vary according to the pitch of a note. As a general rule, spectra of low-mid-range notes were chosen. As the results, a synthesised tone may sound similar within a specific range on the Hammond Organ manual, yet different outside this range. For instance, if a tone was imitated based upon a spectrum of middle C, the synthesised tone may sound similar from the fifths below middle C to the fifths above on the Hammond Organ, but may sound different outside this range, due to lower and higher pitched notes containing different spectra. However, if the Hammond Organ catered for synthesis mapping system, a synthesised tone for lower notes might have been applied to a low note range on the Hammond Organ manual. The same manner applied to mid- and high-range notes. This might have enabled the synthesised tones sound more similar throughout the whole manual.

In terms of using the Hammond Organ as an additive synthesiser to imitate pipe organ tones, there are capabilities and limitations. This is transformed to be advantages and disadvantages of using the instrument as a "pipe organ synthesiser". The instrument is useful to imitate tones of flute and Diapason families. On the other hand, it is not suitable to imitate brilliant sounding tones, which are rich in upper harmonics above the eighth, or tones produced by reed stops or combinations involved with reed stops, such as the combination of Open Diapason 8' and Clarion 4'. However, the overall verdict of the Hammond Organ as an electronic <u>organ</u> is – it is capable of imitating pipe organ tones, Diapason tones in particular, within limits. With all things considered, the tones of the pipe organ are represented by its distinctive "Diapason" tones.

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