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Acoustical Analysis of a Desktop Personal Computer System

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Acoustical Analysis of a Desktop Personal Computer System

by

Matt Nantais

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ABSTRACT

This thesis investigates acoustical and psychoacoustical emissions of a desktop computer system by attempting to understand, measure, and attenuate computer noise. Five cooling fans were examined: the CPU fan, the GPU fan, the PSU fan, a rear case fan, and a front case fan. The fans were tested individually, outside of the computer then installed within. The fully operating computer was also tested. Attenuation techniques tested were: installing acoustic insulation, software modification, and hardware modification. After experimentation was performed, the following was determined: acoustic insulation did not appear to be a viable noise reduction technique; CPU fan software modification for the purpose of noise reduction is not effective but does reduce power use; and hardware modification was not a useful technique when the case fans were installed in the fully operating computer because they were overpowered by the other noise sources present.

DEDICATION

Dedicated to my mom and dad,

Leslie and Gary Nantais

who were the first to ever support me through this project and

who pushed me to keep moving forward and doing my best

in everything I have ever done

ACKNOWLEDGEMENTS

The author would like to acknowledge the contributions of support to me and this project made by some very special people: Val, I simply couldn't have done any of this without you and your support, you've always believed in me and have kept me going from day one; Jeff, you're the best friend I could have during these past years, your help and friendship are unmatched; my committee: Drs. Novak, Gaspar, Zamani, and Tam, your patience and understanding are very much appreciated; my fellow NVH-SQ Group members Helen Ule and Neb Radic, thanks again for your help and everything else along the way; my family, for your encouragement through the toughest of times; and my second family, the St. Gelais', I can never pay you back for everything you've given and shared with me.

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NOMENCLATURE

P – Sound Pressure (Pa)
P_{ref} – Reference Sound Pressure (20×10^{-6} Pa)
Pa   Pascal
W – Sound Power (W)
W_{ref} – Reference Sound Power (10^{-12} W)
W   Watts
SPL – Sound Pressure Level
L_P – Sound Pressure Level (dB)
SWL – Sound Power Level
L_W – Sound Power Level (dB)
dB – decibels (linear)
dBA – decibels (A-weighted)
f – Frequency (Hz)
s – Second
m   Metre
Hz – Hertz
N – Loudness (sone)
V – Volts
°C – degrees Celsius
AC – Alternating Current
DC – Direct Current
RPM – Revolutions per Minute
BPF – Blade Passing Frequency
CPU – Central Processing Unit
GPU – Graphics Processing Unit
PSU – Power Supply Unit
HDD – Hard Disk Drive
ODD – Optical Disk Drive
UPS – Uninterruptable Power Supply
LCD – Liquid Crystal Display
ISO – International Organization for Standardization
ANSI – American National Standards Institute
FFT – Fast Fourier Transform
AMD – Air Moving Device
PCM – Phase Change Material
FEP – Fluorinated Ethylene Propylene
AGP – Accelerated Graphics Port
ATX – Advanced Technology Extended (form factor specification)
PCI – Peripheral Component Interconnect
UBL – Upper Band Limit
CF – Centre Frequency
LBL – Lower Band Limit

CHAPTER I

INTRODUCTION

The contemporary retail market for personal computer systems is growing. Demand throughout the world is greater each year. Competition between manufacturers to supply personal computer systems and components to end-users is escalating. To be competitive manufacturers must ensure both increasing functionality of new personal computer systems and reduced costs and retail prices. This has led to consumer demand for a value-for-money product. A factor in determining value-for-money is perceived quality. Perceived quality is an important factor for many retail goods including personal computer systems. An area that has received attention in recent years is the human perception of sound, or sound quality. This area is applicable to the personal computer industry although it has not been priority for manufacturers. This thesis will investigate acoustical and psychoacoustical emissions of a desktop personal computer system.

1.1 Motivation

The motivation behind this thesis work is to understand, measure, and determine how to attenuate the unwanted acoustical and psychoacoustical emissions of a desktop personal computer system. In particular, the emissions from active cooling solutions were studied. This application of acoustical science has not been explored in great detail in available literature. Also, acoustics has not been a major concern for personal computer manufacturers until recently. For simplicity, the phrase “unwanted acoustical and psychoacoustical emissions of a desktop personal computer” is referred to as “computer noise”. This introduction provides the following: a brief overview of sound, acoustics, psychoacoustics, and noise, reasons why computer noise has been increasing over time, and why proper attenuation techniques are necessary — and thus why the issue of computer noise is now a significant concern for both consumers and manufacturers. At the end of this introductory chapter is a description of the primary goals of this thesis work, which relate to the motivation behind it, and the specific objectives needed to be accomplished in order to meet these goals.

1.2 Sound, Acoustics, Psychoacoustics, and Noise

A basic understanding of sound, acoustics, psychoacoustics, and noise is necessary in order to appreciate the issues discussed later. According to Everest, sound is defined as the wave motion in air, or other elastic media (this being a stimulus), and as that excitation of the hearing mechanism of the ear that results in the perception of sound, this being a sensation [1]. This definition is broken into two components, one physical and one psychological. Acoustics is the branch of science dealing with the physical characteristics of sound generation and propagation. Noise is a complex phenomenon that may best be described as unwanted sound. However, according to Everest, there are types of noise that in certain situations may have useful applications [1]. Examples include pink noise or white noise. For additional information regarding sound, acoustics, psychoacoustics, and noise, refer to Appendix A: Important Additional Acoustics Information.

Psychoacoustics is the branch of science dealing with the interaction between sound and the human auditory system. In other words, psychoacoustics deals with the human perception of sound [1], or perceived sound quality. There many different metrics that are used to measure and quantify sound quality, some of which have been standardised and some of which are used by manufacturers for their own purposes internally. The most common sound quality metric is loudness. Quantities such as sound pressure level and sound power level which can be determined in a very straightforward manner based on pressure waves. According to Defoe [2], loudness is a much more complex metric that is used to more accurately represent the perceived intensity of a sound.

1.3 History of Computers and Computer Processing

The increase in both general and specialised use of the personal computer is well known. This increase has lead to an understandable rise in the demand of computer performance requirements. In other words, more processing power for less cost is always being sought. The fundamental reason why there has been an increase of computer noise over time is because of the escalation of computer processing power since the invention of the integrated circuit board. This escalation was first predicted by Moore in his famous paper from 1965 [3].

> The complexity for minimum component costs has increased at a rate of roughly a factor of two per year. Certainly over the short term this rate can be expected to continue, if not increase. Over the longer term, the rate of increase is a bit more uncertain, although there is no reason to believe it will not remain nearly constant for at least ten years.

In 1965, Moore was able to make the empirical observation that the number of transistors on an integrated circuit for minimum cost doubles every two years [3]. This observation became known as Moore's Law. In the 40-plus years since its original inception, Moore's Law has proven remarkably accurate and according to Bondyopadhyay, "has come to refer to almost anything related to the semiconductor industry" [4]. This consistently exponential increase in computer processing power has lead to an increase in heat generation, also predicted by Moore.

1.4 Increased Heat Generation as a Result of Increased Computer Processing Power

As processing power has increased from one generation of central processing unit (CPU) to another, so has the associated heat generation. Gurrum et al. discussed how thermal issues are becoming more important because CPU performance is "becoming increasingly limited" due to the maximum heat that may be removed [5]. Due to the delicate nature of the circuitry within a CPU, heat must be removed so that the interior temperature does not reach a dangerous level. Heat is removed from a CPU by utilising a "cooling solution" mounted directly onto the motherboard and in direct contact with the CPU surface. Active and passive cooling solutions are discussed in greater detail in the next section.

The CPU is not the only source of heat generation within a computer system. Additional sources of significant heat generation include the power supply unit (PSU) and the graphics processing unit (GPU). The latter has become a much more prominent source in recent years due to the increased utilisation of the GPU now having the ability to support modern interactive games, complex engineering design applications, and entire home entertainment systems. The functions of a GPU require a great deal of processing power and, similarly to the CPU, lead to the production of greater amounts of heat, [6]. Heat generated by this source is removed by utilising a cooling solution mounted onto the GPU card and in direct contact with the GPU processor. Additional sources of heat that are not actively cooled include the hard disk drive (HDD), the optical disk drive (ODD), the motherboard, and any peripheral cards or drives that may be installed. Heat from these sources is also ultimately removed by the case fan.

1.5 Traditional Methods for Heat Removal – Active and Passive Cooling Solutions

A cooling solution is designed to facilitate the transfer of heat from a source to a sink. A passive cooling solution consists of a metallic heat sink and an active cooling solution is typically made up of a small axial-flow fan attached to metallic heat sink. A heat sink is made up of a number of thin cooling fins, and facilitates the transfer of heat from the two-dimensional circuit board by increasing the surface area for heat transfer. The fan in an active cooling solution creates a flow of air from within the computer case over the cooling fins. Thus, heat is transferred from the fins to the cooler air by convection. This is not the only configuration of active cooling. Another example is a radial-blower fan which brings airflow into a closed compartment containing the cooling fins. Warm air is then released directly into the environment surrounding the case. Since passive cooling solutions do not include fans, and thus do not produce sound, they are not an area for concern in this study.

Active cooling solutions are designed in many configurations and must meet two objectives: the cooling requirements of the particular component for which it is used; and any applicable form factor size restrictions. Form factors are simply specifications detailing the sizes, arrangements, and other technical parameters of the primary computer system components. Form factor restrictions are a very important and very limiting consideration in the design of active cooling solutions. These restrictions depend on the specification being followed (ATX or otherwise). Regardless of the specification, similar issues involving physical parameters arise. In the ATX Specification Version 2.2, see Figure 1-1, it is clear that the cooling solution for a GPU must be designed differently from that of a CPU since the form factor limitations are much more restrictive in terms of space available [7].

It should be noted that the cooling methods used by the CPU and GPU, although effective at removing heat from those components, only dissipate heat from the delicate circuitry to within the interior of the computer case. This heat must be removed from the case by an additional fan, mounted onto the interior of the case designed to remove warm air from within the interior of the computer case. This fan is intuitively referred to as a case fan. It is traditionally attached to the interior of the back side of the case. A similar fan may be installed elsewhere on the interior of the case to bring cooler air from the surroundings inside.

1.5.1 Advantages/Disadvantages of Active Cooling Solutions

The most important characteristic of active cooling solutions, and thus their advantages over passive cooling solutions, is their ability to achieve higher heat transfer rates. This prevents overheating and greatly reduces the likelihood of component failure. The main disadvantage, and primary focus of this work, is that active cooling solutions are noise sources within a computer that may dominate all other noise sources present. Also, active cooling solutions may become less efficient over time due to wear and are also responsible for bringing dust into a computer system, which may have negative effects. However, because they are vital to the proper operation of computers, active cooling solutions will continue to be widely used in the foreseeable future.

1.6 Noise Issues

Although there are different sources of noise within a computer, the focus of this work is on active cooling solutions. There are two reasons for this: first, because they are the dominant source of noise generation; and second, because noise generated by other mechanical components is much more difficult to test individually and to subsequently modify. For example, the HDD is definitely a source of noise within the computer. However, unlike cooling fans which operate at a relatively constant or easily adjustable velocity, the HDD operates sporadically, seeking information when needed, and its noise emissions may vary greatly during periods of heavy use versus periods of idle use. Noise testing of the HDD could be done in future experimental work by keeping the cooling fans operating at a constant speed. This would detail the emissions of the HDD by itself, but is beyond the scope of this thesis work.

1.6.1 Why is Noise a Problem?

Unwanted sound of any kind may be classified as noise [1]. Of course, the perception of noise is inherently subjective. A particular sound that one individual finds annoying and difficult to listen to may be classified as noise. However, to another person who does not have the same response, the same sound may be tolerable or easily ignored. In terms of personal computers, noise characteristics may be as varied as the components within the system itself. Anyone who has used a computer system has some appreciation of the common sounds made when staring up, operating for an extended period of time, and running an interactive game or intense graphical or numerical processing software. Computer noise may become more noticeable depending on the length of time one is using a computer or the number of computers operating in a particular area. Even if noise does not necessarily contribute to physical hearing loss or damage, it may be perceived as annoying and can lead to losses in productivity. Given the frequency of use and the extended periods of time countless people spend using a computer system, the relevance of computer noise is clear.

1.6.2 Locations

The locations of various noise sources within a desktop computer system are illustrated in Figure 1-1. Included are the CPU, GPU, PSU, HDD, and case fans. Even though a computer system must adhere to certain form factor specifications, the exact placement of each component is also dependent on the design of the computer case and the layout of the motherboard. Figure 1-1 illustrates the layout of the components on the interior of a desktop computer according to the ATX form factor, taken from the ATX Specification Version 2.2 [7].

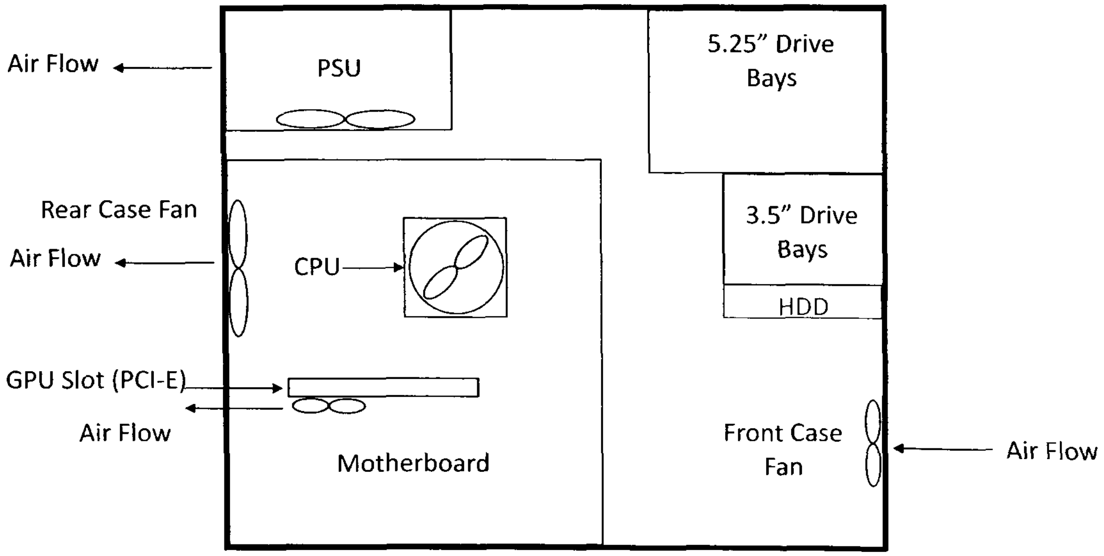

Figure 1-1: ATX Form Factor Specification for Desktop Personal Computers [7]

1.6.3 Possible Noise Reduction Techniques at the Source

There are several methods of reducing (attenuating) the acoustical and psychoacoustical emissions from a noise source. These methods are discussed in detail in Chapter 2. The most obvious solution is to simply eliminate the noise source entirely. This solution is not appropriate as it would not be possible to achieve the cooling rates required. Modifying the noise sources in such a way so as to reduce noise emissions has the potential to succeed. This may be done by slowing fan velocities during periods of idle use or by having them stop rotating periodically. Modifications may be executed through software installed on the computer system of interest.

Other solutions are to replace the original fans, or even entire cooling solutions, with aftermarket products that are designed to remove heat more effectively. These solutions may have superior build quality and may be constructed from materials with high thermal conductivity, resulting in higher heat transfer rates. The problem with these products is the additional cost to the user. CPU, GPU, and PSU manufacturers who are attempting to build competitive systems cannot necessarily afford the additional cost of higher quality active cooling solutions. If it is not possible to mitigate the source of noise itself, then acoustical emissions must be attenuated after they have already been generated. Several of these techniques exist and will be discussed in detail in Chapter 2.

1.7 Relevance to Consumers and Manufacturers

A modern computer system should produce noise emissions that are perceived as acceptable by users, without sacrificing functionality. The acoustical emissions of a product may indicate its perceived quality. Even if the components of a product operate correctly, the acoustical emissions of the product will not necessarily be perceived as acceptable to a consumer. This is the primary issue facing computer manufacturers. Computer noise is inherent, and is a result of the components used. As consumer demand for computer systems continues to increase and expand, so does the competition between manufacturers. Thus, the acceptability by consumers of computer noise is of key interest for manufacturers. The techniques employed in this thesis work may be used in the future as a method of comparing various systems or configurations. Utilising psychoacoustic metrics provides quantitative information about the qualitative nature of computer noise. The results presented will provide insight regarding the effectiveness of different methods of attenuating computer noise.

1.8 Goals, Objectives, and Contributions

The motivation behind this thesis work is to understand, measure, and attenuate computer noise, with an emphasis on the emissions from active cooling solutions. Thus, the primary goals of this thesis are as follows: to acquire knowledge about computer noise, testing standards, and measurement techniques; to perform a repeatable measurement procedure specifically for the purpose of measuring computer noise; and to be able to draw conclusions about a series of attenuation techniques in terms of their effectiveness for modifying the acoustical emissions of a desktop computer system. In order to accomplish these primary goals, a series of objectives for each are now given.

First, to gain an understanding of computer noise, a review of available literature regarding computer systems, axial-flow fans, noise attenuation techniques, and other applicable subject matter was completed and is presented in Chapter 2. Second, in order to measure computer noise, applicable acoustical measurement standards were reviewed and an understanding of the measurement equipment and environment was gained. Third, in order to determine the effectiveness of various attenuation techniques, an experimental methodology was developed to test and compare different acoustic scenarios and is presented in Chapter 3. Fourth, the methodology was implemented in an effort to learn about different attenuation techniques. The procedure of the experimental work is found in Chapter 4. The results of the experimentation performed are presented in Chapter 5. Finally, conclusions regarding the effectiveness or ineffectiveness of the attenuation techniques and recommendations for future research investigations are presented in Chapter 6.

The contributions to Engineering knowledge and practice that will be given by this thesis work are as follows: further the understanding of acoustical science in an area that is relatively unexplored; present an experimental methodology and procedure that may be duplicated, modified, and improved in the future; and to provide insight as to what techniques may be effective or ineffective at attenuating computer noise, and possible reasons why.

CHAPTER II

REVIEW OF LITERATURE

As stated in Chapter 1, the motivation of this thesis is to understand, measure, and determine how to attenuate computer noise. These noise emissions include, but are not limited to, those of active cooling solutions used within a computer. This review of literature will provide background information regarding the following: previous work done in the areas of understanding the noise generation mechanisms of axial-flow fans; previous experiments performed to measure the noise emissions from axial-flow fans and computer systems; techniques used to attenuate the noise emissions of axial-flow fans and computer systems; techniques used to improve heat transfer from computer systems; and finally, potential problems associated with modifying computer systems.

2.1 Progress in Integrated Circuits

The most concise explanation for the silicon revolution beginning in the last half of the twentieth century is found in Moore's paper from 1965, reprinted in 1998 [3]. Moore emphasised the importance of integrated electronics. In 1965 he was able to predict that integrated circuits would lead to home computers, automatic controls in automobiles, personal portable communications equipment, and advances in telecommunication capabilities. Moore commented on how integrated electronics were being used in military systems, the Apollo missions, and companies in the commercial computer field. He mentioned how integrated electronics systems demonstrate high reliability, reduced cost, and improved performance over systems made up of discrete components. Moore stated that more and more functions were being added to a single semiconductor substrate. An important concept of Moore's paper is the constant of number of components per integrated circuit for minimum cost. In simple circuits, the cost per component is inversely proportional to the number of components. However, there is a minimum cost per component which is dependent on the time in the evolution of the technology. In 1965, Moore stated that the minimum cost per component would be reached when 50 components were used per circuit. At the time, the rate of increase of complexity for minimum component cost was a factor of two per year. According to Moore, by 1975 the number of components per integrated circuit for minimum cost would be approximately 65,000. Moore was also able to predict the problem associated with the generation and removal of heat of tens of thousands of components in a single chip.

In 1975, Moore [8] wrote a follow-up to his earlier paper. He noted that the complexity of integrated circuits had approximately doubled every year since their introduction, cost per function has decreased by several orders of magnitude, and system performance and reliability had been improved. Moore stated that the rate of increase of complexity for minimum component cost was expected to change to a doubling every two years, rather than every year, by the end of the 1970s. Other authors such as Bondyopadhyay [4], have stated that Moore's prediction would have been more accurate to say 18 months, as opposed to two years. This discrepancy is common, but the concept behind Moore's Law remains. Also, Yazawa et al., [9] mention how Moore's Law has driven a reduction of component size and an increase in transistor count causing microprocessor power and heat generation to rise. According to Chu et al., [10] if present trends continue, there may be a billion or more transistors on a single microprocessor chip by 2010.

Chu et al., [10] mention how the applications of computers vary from those of personal systems such as playing games and watching movies for entertainment to those of highly complex systems supporting vital health, economic, scientific, and military activities. In many applications, computer failure would result in a major disruption of vital services and may even have life-threatening consequences. Thus, improving the reliability of computers is as important as improving storage capacity and processing speed [10]. Cooling and thermal management have played a key role in accommodating increases in power while maintaining component temperatures at levels which satisfy performance and reliability objectives.

2.2 Computer Noise is a Problem

Many papers discuss the problem of computer noise resulting from the use of cooling fans in active cooling solutions. Fitzgerald and Lauchle [11] stated that the use of modern (1983) personal computers was common in the workplace and growing at home. For proper operation and protection of internal components, computers incorporate cooling fans. The noise produced by small cooling fans dominates the overall noise generated by other electronic equipment [11]. Quinlan and Bent [12] mention that the dominant trend in physical design of electronic systems is the continuing rise in system heat dissipation. This trend is being driven by a rise in circuit density in addition to much smaller system size. A problem with this trend is an associated increase in computer noise. This is because these systems are cooled with air moving devices, and to remove excess heat, both faster moving fans as well as more fans are required. Huang [13] states that acoustic performance is becoming one of the major indices differentiating one manufacturer from another in terms of consumer products in which fans are used. Noise radiated by computer cooling fans is receiving increasing attention as the CPU power increases rapidly and the trend of slimmer packaging continues, [13, 14]. Miastkowski [15] mentions how many personal computer systems are loud enough to be distracting or annoying, especially if a work area is otherwise quiet and peaceful.

The main sources of noise are spinning components such as the hard drive, CPU fan, case cooling fans, and power supply fan(s). Also, fans and hard drives may produce vibration that may be magnified by the PC case. Chin [16] states that since personal computers are becoming more prevalent in the home and in home theatre setups, great attention has been paid to computer noise by both consumers and manufacturers. Spector et al., [17] mention that in general, complete quiet most of the time with sporadic interruption is more annoying than a slight noise all of the time, since it is usually easier to ignore a constant noise. Hodgson and Li, [18] point out that increasing concern about computer noise has led to increasing demand for overall quieter computer systems. The primary components being targeted for noise reduction are the cooling fans. Pastukhov and Maydanik [19] discuss the problem of increased levels of computers noise emissions as a direct result of the increase in the number of cooling fans needed as the amount of heat to be dissipated has also increased. The increase in noise may have an adverse effect on the user, and thus should be an important issue for manufacturers.

Getz [20] claims that computer noise is not only undesirable, but also detrimental to human health and well-being. The author makes reference to a study where it was suggested that noisy open offices may contribute to health problems such as heart disease and musculoskeletal problems. Getz claims that personal computer users and manufacturers are becoming more aware that low levels of computer noise are important factors for comfortable working and home environments. The most important issue in acoustic performance is how users perceive sound. The science of the human perception of sound is called psychoacoustics. For additional information regarding psychoacoustics refer to Appendix B.

Although the majority of the relevant literature deals with the topic of noise of axial-flow fans, there has been work done on specific noise sources within a computer. Work in the area of GPU cooling fan acoustical analysis has been done by Sun and Panigrahy [21], Novak et al.[22], Ule et al. [23], and Nantais et al. [6]. Work in the area of hard disk drive (HDD) acoustical analysis has been done by Choi et al. [24]. Research has been done using psychoacoustic analysis by [25], [26], [27], and [28]. A comprehensive analysis of the psychoacoustic metric of loudness was done by Defoe [2].

2.3 Noise Generation Mechanisms of Axial-Flow Fans

The primary focus of this thesis work is the noise generated by active cooling solutions within a personal computer system. These noise emissions are primarily due to the utilisation of axial-flow fans. The following will examine some of the research done that focused on understanding the noise generation mechanisms of axial-flow fans, and in particular, those used in personal computer systems.

2.3.1 Sources of Noise in Axial Flow Fans

One of the first investigations into the sources of noise in axial-flow fans was done by Sharland in 1964, [29]. He discusses various mechanisms of noise generation and that the strength of these mechanisms must relate to the physical parameters of the system. A detailed knowledge of the origin of noise is needed if it is not to become an operational limitation and also to provide the understanding on which attenuation methods may be based, [29]. These ideals apply to any situation where fan noise is a problem. Once the source and mechanism of noise is understood, then an effort may be put forth to attenuate the noise, addressing the particular physical parameters of that situation.

Sharland, [29] begins by stating that the sources of noise are largely dipole in nature, and that in turn, the noise originates from fluctuating forces exerted by the blades on the air as it passes through the fan. Both Baade, [30] and Hodgson and Li, [18] agree that the sound generated by a sub-sonic axial-flow fan is dipole in nature. For additional information regarding monopole, dipole, and quadrupole sources refer to Appendix B.

The general nature of fan noise is indicated by its frequency spectrum, [29] which is made up of two sets of components, broadband and discrete frequency peaks. This observation was also made by Maling, [31], who stated in a review of the control of noise generated by small air-moving devices that the two areas of concern are broadband noise generation and discrete frequency noise generation. These were also areas of concern for Mugridge and Morfey [32], who discussed experiments and theory related to sources of noise in axial-flow fans. Fitzgerald and Lauchle [11] stated that the acoustical frequency spectrum of axial-flow fans may be characterised by a broadband component on which is superimposed a series of discrete frequency peaks.

The two components' strengths vary with the characteristics of the fan under consideration. The noise from a fan with a very low tip speed will be almost entirely broadband whereas noise from a fan with a very high tip speed may be characterised by a discrete frequency peak [29]. In a system with varying fan speeds, both components must be examined in detail. In the results of a controlled experimental study of the noise emission of a typical model of computer cooling fan Hodgson and Li [18] concluded that the noise emissions are more tonal at maximum flow rate than at lower flow rates, where the noise becomes more broadband. Also, sound power level (SWL) increased with increasing fan voltage. This is intuitive because angular speed is proportional to voltage. Fitzgerald and Lauchle [11] noted that operation at a high static pressure rise results in sound that is far more broadband in nature. They stated that operation at a low static pressure rise results in sound that is mostly tonal in nature [11]. A static pressure rise is caused by sources of resistance such as the equipment being ventilated, heat sinks, or safety guards [31].

2.3.2 Broadband Components of Axial-Flow Fan Noise

The broadband component of the frequency spectrum is due to random fluctuating forces. There are three mechanisms by which these forces occur: the surface pressure field arising from a turbulent boundary layer; vorticity shedding from the surface of a body in a moving flow; and turbulent flow that impacts on the blade surface [29], which is the most significant contributor to the overall SWL.

Mugridge and Morfey [32] also stated that broadband noise is related to random fluctuations in blade loading, due to the interaction of the solid surfaces with an adjacent turbulent flow. The turbulent flow is generated in either the blade boundary layers, incidence on the blade surface, or from secondary flows, such as those from blade-tip clearances and duct boundary layers.

Quinlan and Bent [12] presented results from an investigation of the broadband sources of acoustic noise in small axial-flow fans. They indicated that secondary flows are the primary contributors to the broadband noise generated by small axial flow fans. In particular, flow unsteadiness associated with tip gap flows was identified as a primary source of high frequency broadband noise [12].. As air is forced through the tip gap, (space between the rotating blade tip and the stationary housing) the flow rolls up forming vortices at the blade tip. By convection, these vortices move into the blade passage. The likely radiation mechanisms are trailing edge scattering and radiation from free turbulence and/or boundary layers.

2.3.3 Discrete Frequency Component of Axial-Flow Fan Noise

The discrete frequency component of the frequency spectrum is due to non-random fluctuating forces. There are two mechanisms by which these forces occur: periodic excitation of an elemental area of air; and a periodically varying velocity field when the fan is operating in the vicinity of a solid obstacle in the flow [29]. The former occurs at a fixed point near the fan caused by a force fluctuation each time a blade passes by. Discrete frequency peaks occur at this, the fundamental blade passage frequency (BPF) and its harmonics. The BPF is the rotational frequency (in rotations per second) multiplied by the number of blades.

Mugridge and Morfey [32] claim that the discrete frequency component is due to periodic interaction of the fan blades with the fluctuating forces induced by an unsteady flow field. Three types of unsteady flow are potential and wake velocity fields of an adjacent blade row, and intake flow distortion. Flow distortion may occur due to: asymmetry in the duct around the fan, cross flow, obstructions in the inlet path. In each of these cases, the authors claim that acoustic radiation will occur at the BPF [32]. In addition to that at the BPF, acoustic radiation may occur at the angular frequency of the fan due to non-uniform rotor blade geometry or spacing [32]. This problem may be minor assuming high quality and repeatability of modern fan manufacturing techniques.

Fitzgerald and Lauchle [11] claimed that discrete frequency tones dominate the acoustic spectra at lower operating static pressure rises, which correspond to minimum blade loading with maximum air flow. They claimed that the discrete frequency component may reduce the acceptance of this equipment into working and living environments [11]. The authors drew conclusions about the discrete frequency noise radiated by small, subsonic, axial-flow fans; the maximum radiated amplitude of the discrete frequency noise occurs at high flow coefficients (minimum static pressure rise); the radiated directivity of the discrete frequency noise is uniform; and the primary source of the discrete frequency noise is the interaction of the fan blades with circumferentially non-uniform flow, which causes unsteady rotor blade loads. Figure 2-1 summarises the noise sources in subsonic axial-flow fans.

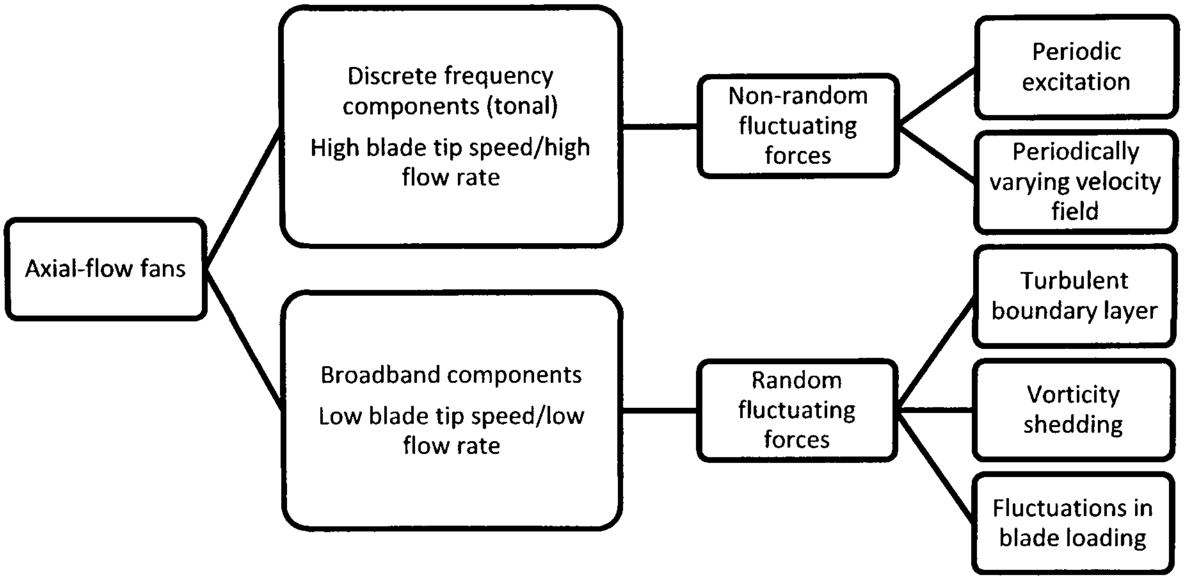

Figure 2-1: Summary of the Noise Sources in Subsonic Axial-Flow Fans

2.4 General Guidelines for Selection of an Axial-Flow Fan

A paper by Maling [31], titled "Historical developments in the control of noise generated by small air-moving devices," reviewed published information for understanding and controlling noise from axial-flow fans. His focus was on air-moving devices less than 30 cm in diameter, which encompasses the cooling fans that are used in personal computer systems. Useful descriptors for the noise emitted by fans and blowers include both A-weighted and octave or one-third octave band SWLs [31]. According to empirically derived formulae, the sound power emitted by an air-moving device is proportional to the square of the static pressure rise (P^2), the volume flow rate (Q) and also that it is proportional to the seventh power of the fan diameter (D^7) and to the fifth power of shaft rotational speed (N^5) [31]. These empirical equations do not take into account the number of fan blades or the particular fan design, but serve as a general guideline. Equation 1 shows the proportional relationship between sound power, static pressure rise, and volume flow rate. Equation 2 shows the proportional relationship between sound power, fan diameter, and shaft rotational speed.

$$W \propto P^2 \propto Q \tag{1}$$

$$W \propto D^7 \times N^5 \tag{2}$$

A third equation may be derived from Equation 2. If the blade tip speed (T) is equal to the radius of the fan multiplied by shaft rotational speed, then Equation 2 may be re-written.

$$\begin{gathered} W \propto D^2 \times D^5 \times N^5 \\ W \propto D^2 \times (32) \times \left(\frac{D \times N}{2}\right)^5 \\ W \propto 32 \times D^2 \times T^5 \end{gathered} \tag{3}$$

Equation 3 shows the proportional relationship between sound power, fan diameter, and blade tip speed.

Maling [31], provides a series of guidelines for the selection of air-moving devices used to ventilate small equipment. First, in accordance with Equation 1, a system should be designed to have the lowest possible static pressure rise (P) for the required volume flow rate (Q). This means that the device may have a low tip speed which results in a low noise level. Second, a fan should be selected such that it operates near its point of maximum static efficiency. Third, if the device operates away from its point of maximum static efficiency, it should be in the direction of higher airflow rate and lower static pressure rise. Fans may be unstable and very noisy when operating at low airflow rates and high static pressure rise. Fourth, a device should be selected that does not have high discrete frequency components in its frequency spectrum since they are more difficult to attenuate than broadband components and may be a source of greater annoyance [31]. Fifth, (in accordance with Equation 1) a device should be selected having the lowest tip speed and the largest diameter, after the other considerations have been followed.

2.5 Measuring Noise Emissions of an Axial-Flow Fan

In order to explain and justify the methods used in this thesis, it is important to understand what techniques have been implemented by researchers in the past. Maling [31] discussed a method that he developed in 1964 to measure sound power emitted by air-moving devices. He constructed a plenum box made of light-weight plastic film and performed measurements in a reverberant room. This was the origin of the ANSI S12.11-1987 standard for the measurement of noise emitted by small air-moving devices.

One area of progress discussed by Maling is that of measurement techniques. Maling [31] credited progress made in the understanding of noise generation by small air-moving devices to the establishment of the Technical Group on Computers and Business Equipment (TG/CBE), by the Institute of Noise Control Engineering of the U.S. A. (INCE). This group began an effort to develop a standard measurement method for the noise of small air-moving devices that could be applied to the computer and business equipment industry. At the INTER-NOISE 82 conference, a workshop entitled "Measurement of Noise from Fans for Cooling Electronics" was held. There, a number of papers were presented and it was ultimately decided that a single design for the aforementioned plenum box test apparatus was needed for consistent measurements of air-moving devices. A series of papers were presented at the INTER-NOISE 86 conference that detailed the results of evaluations of a standard test plenum box. This work led to the aforementioned ANSI S12.11-1987 standard. Denton and Bernhard, [33] based their 1989 study on the ANSI S12.11-1988 standard, which detailed a technique for the measurement of noise emitted by small air-moving devices.

The test facility used by Fitzgerald and Lauchle [11] consisted of a fan duct, an anechoic chamber, and apparatus for acoustic measurements. An anechoic chamber was used as it provided a free-field environment. Baseline data was collected in an effort to characterise the noise generated by the cooling fans at different operating conditions. The authors performed initial experiments using an on-axis microphone location. These produced very similar overall sound pressure results between similar fans (0.5 dB), as well as very similar frequency spectra (less than 2 dB differences in tonal levels).

Hodgson and Li [18] utilised the international standard, ISO 10302. This standard describes a method for measuring the noise emission of small fans using a fan test plenum and other experimental considerations such as characterising noise emissions in terms of SWLs, as determined using ISO 3745. This ISO standard calculates SWL using SPLs measured at 10 locations on an imaginary hemispherical surface surrounding the source, located above a reflecting plane in a hemi-anechoic environment.

INCE approved a recommended practice on air-moving device measurement in 1985. This practice is titled "Measurement of noise emitted by air-moving devices for cooling computer and business equipment." Several papers that presented results of evaluations done with this practice were presented in the conference proceedings year at Inter-noise '86.

A conference paper by Boggess [34], made comparisons between the INCE recommended practice for measuring fan noise to other techniques. One of the difficulties in measuring fan noise is how to mount and support the fan. The author claimed that many acoustic labs used a Mylar box to mount the fan, however, since there was no standard set in place, each lab may have had a different size, shape, and thickness of box. The INCE recommended a practice specifying a standard box and using ANSI S12.10 as a standard testing procedure. Another method used to measure fan noise is to suspend the fan with springs in free air and measure noise at various distances and locations. Boggess discovers that using the INCE box gives higher magnitude SWLs than older versions. Also, he finds that it is difficult to compare the free-field data from the suspended fan to that obtained when using the Mylar box.

This may be due to the fact that the freely suspended measurement is at a specific point, not an average, as is the case with the Mylar box [34]. He concluded that using the INCE recommended practice would "help stabilise" the testing procedures used and thus make it easier for different fans to be compared to one another. He cautions against comparing noise data taken using different methods and also against using data taken by a single point microphone location as it may be misleading [34].

A conference paper by Gresho [35], made comparisons of fan noise levels measured using the INCE recommended practice to noise levels measured in an operating environment. The author attempted to discover what the results will be using the INCE method as well as if those results can be correlated with the results from measurement in an application. He concluded that a fan measured as louder or quieter using the INCE plenum may not be the same when compared to being measured in the operating environment if the inlet and outlet conditions of the application are not duplicated [35]. In this case he is referring to the protective grill on the outlet side of the fan. Gresho recommends utilising an aerodynamically superior wire grill as opposed to a stamped grill. He states that the noise levels observed with a formed wire grill were very similar to those without a grill at all, except at high frequencies [35].

A conference paper by Lotz [36], described the newly-published INCE recommended practice for measuring noise levels from small fans. Lotz was the Chairman of the INCE Technical Group on Computer and Business Equipment. This recommended practice (RP) was developed from 1982-1986 by the INCE Technical Group on Computer and Business Equipment (TG/CBE). The scope of the group was "engineering aspects of noise control for computer and business equipment and for their typical operating environments, such as offices and computer rooms" [36]. Clearly, this group's work was very similar in scope to that of the work presented in this thesis. The focus of the group was on printers for office use and air-moving devices (AMDs) for cooling electronics.

A conference paper by Pei [37] described the INCE fan noise test procedure and its application. The author commented on how the two major sources of noise in modern office buildings are the environmental control systems and computer and other business equipment. The new INCE recommended practice would meet the need of engineers to standardise the testing procedure for small axial-flow fans commonly used to cool electronic equipment. The author concluded by stating that the INCE recommended practice may be used as a general noise test method for small air-moving devices that are used to cool computers and other business equipment.

Dunens and Radziunas [38] wrote a brief conference paper describing testing they performed in an effort to control noise emissions of two small air moving devices. Acoustic testing was done using the ISO 7779 (1988) Standard for Acoustics Measurement of Airborne Noise Emitted by Computer and Business Equipment.

2.6 Attenuating Noise Emissions of Axial-Flow Fans

Maling, [31] stated it is possible to significantly reduce the noise level of a computer cooling fan by operating fans at a low speed when temperatures are normal, and to increase the speed of the devices when the temperature of the air reaches a preset limit. This is contrary to Spector et al., [17] who stated that a constant noise is likely easier to ignore. Factors that determine the appropriate course of action include the frequency of how often the fan would need to increase in speed and the acoustical emissions during low speed and high speed operation. Maling also stated that attaching a computer cooling fan to ducts or other systems to be cooled can have a significant influence on the sound emitted by the device [31].

Fitzgerald and Lauchle [11] stated that the fluctuating forces experienced by an axial-flow fan may be removed or reduced in order to create a quieter axial-flow fan. They suggested that the reduction of discrete frequency noise may be done by decreasing the unsteady blade loads, which may be accomplished by improving the circumferential symmetry of the fan annulus, inlet, and outlet and by reducing the potential field of stationary objects in the fan annulus. Inlet flow conditions may be improved by adding a bell mouth; and using blade flow modifiers such as suction side serrations may reduce unsteady blade forces due to laminar separation and vortex shedding [11].

Huang [13] studied computer cooling fan noise in a theoretical sense, paying close attention on the radiation from the interaction between rotor blades and rotor struts. The author claimed that the large clearance-to-fin radius ratio of the plastic fan in such a small product makes an ideal source of noise generation mechanisms. His study focuses on the tonal noise of isolated computer cooling fans, which he stated to be the first step towards understanding the noise radiation of such cooling fans installed inside a computer chassis. He noted that a computer chassis is a confining environment and that reflection and scattering of sound by walls may alter noise radiation characteristics significantly. This means that the environment inside a computer is a source of noise which is not encountered in free space. Thus, efforts in silencing an isolated cooling fan would be useful.

Huang and Wang [14] investigated noise radiated by a typical computer cooling fan. They pointed out three primary sources of noise: inlet flow distortion; interaction of rotor blades with the struts that hold the motor; and the extra size of one strut carrying electrical wiring. Although there may be an abundance of knowledge about aeroacoustic phenomena, there has not yet been a detailed, systematic study on each component of the noise mechanism present in a specific type of cooling fan. Their study used a typical computer cooling fan sample and aimed to identify and quantify the exact source mechanisms in the fan assembly, and the directivity of the radiated sound.

Wang et al. [39] continued their examination of computer cooling fans with this work, which examined active tonal noise control for a small axial-flow fan. They hoped to globally eliminate the rotation-locked tones by applying a very simple destructive interference to a modified cooling fan with the number of struts equal to the number of rotor blades. The motivation for the study was to maximize the simplicity and the global effectiveness of the technique of destructive acoustic interference so that it might become economic enough to be applied in practice. The authors summarised the important mechanisms of fan noise in computer cooling fans: tip leakage flow, non-uniform inlet flow condition, and turbulent and/or separated flow condition on a rotor, trailing edge noise, and rotor-stator interaction. They mention how sound absorption is often the most reliable and effective measure of noise abatement, but unfortunately, not for un-ducted fan applications. Most work has been towards improving the flow conditions of the noise source mechanisms, such as the inlet flow uniformity and the reduction of the strength of wake interactions which depend on the distance between the rotor and stator blades. Other useful modifications were recommended such as a bell mouth to smooth out the inlet flow, downstream struts to reduce rotor-stator flow interactions, and correction of the cupped trailing edge to prevent flow separation and vortex shedding. The authors concluded that active acoustic interference demonstrates that the sound related to the rotation from a typical computer cooling fan can be significantly attenuated by a simple design.

Wang and Huang, [40] continued their examination of computer cooling fans with this work, this time attempting to suppress the drag noise globally by active noise control. Drag noise features a rotating dipole and thus it must be cancelled by a secondary source of the same nature. They attempt to do so by using a pair of loudspeakers located at right angles to each other on the fan rotational plane. Results show that the globally integrated sound power is reduced by about 13 dB. Several conclusions were made including a typical computer cooling fan is very noisy due to two major problems: the square frame which distorts inlet flow and the wide wire-carrying strut which is a powerful noise source [40].

2.7 Attenuating Noise Emissions of Computer Systems

The most obvious solution to attenuating the noise emissions of computer systems is to simply remove the components which are producing the unwanted sound. This cannot be done as the noise generating components are vital for system functionality. Several works provide suggestions that may be useful for attenuating noise emissions of computer systems.

Miastkowski [15] outlined steps that may be taken to reduce the noise of a computer system while also achieving adequate cooling. Moving the computer may reduce the problem; for example, placing the case on carpet or foam may reduce or eliminate any case vibration. Tightening the mounting screws may reduce vibration, as does using screws with polymer or rubber washers. Installing polymer gaskets on the fan housings may isolate their vibration from the case. Installing heat-sensitive case fans which use temperature sensors and slow down the fans when the internal case temperature drops. Alternatively, single-speed fans that are designed to produce low noise may be used. Upgrading to a low noise PSU that uses one larger (120 mm) fan that provides the same cooling ability as two smaller (80 or 90 mm) fans. Some power supply units even use controls to slow down or speed up the fan(s) depending on the case temperature. Upgrading to a low noise CPU cooling solution may both lower the heat of the processor, thus improving performance and reliability, and reduce noise by using a larger fan. Acoustic insulation may be installed on the interior of the computer case. The hard drive may be installed in an acoustic enclosure which deadens the sound it produces. A drive enclosure such as this would fit in one of the 5.25-inch drive bays.

Chin [16] discussed quiet personal computers that are fan-less. Two companies offer personal computers that have the processing power necessary for media heavy functions while producing very low noise emissions, due to their fan-less cases. Each system uses custom-designed heat pipes and a case that acts like a large heat sink. The only remaining major source of noise is the HDD. The computers were $2230 USD and $3750 USD respectively, and neither system is completely silent. When written in 2004, these would be considered expensive systems given the components they contained, ranging from 30 to 40 percent more expensive than comparable systems. According to Chin, the sound level ranged from 23 to 27 dBA at idle to much higher levels when the hard disk drive(s) are working, although the levels were significantly lower than typical desktop computers. This illustrates how a computer system can be made quieter, but at a greater cost than the average consumer may be willing to pay.

Spector et al. [17] gave solutions that mitigate the problem of computer noise. The authors claimed that reducing computer noise can actually be relatively cheap and easy, as the computer does not have to be made completely silent, just quiet enough for the ambient level of the environment. By utilising the correct equipment, overheating can be prevented while keeping the system quiet. Software may be used that can monitor internal temperature. Thus, any variation in temperature due to hardware changes made may be determined. The authors suggest replacing the PSU first, and getting one with a single 120 mm fan as opposed to two 80 mm fans. Next, they suggest replacing the case fan(s) with larger ones if possible, but definitely with higher quality fans. Then, the authors suggest upgrading the computer's hard drive with a modern one that uses a fluid dynamic bearing instead of a ball bearing. Additionally, the drive could be placed in a soundproof box which fits into the 5.25-inch bay. Next, they suggest replacing the CPU cooling solution. This can be difficult as it must be ensured that a replacement will fit in the computer case as well as being able to attach to the motherboard and CPU socket. Finally, the authors suggest replacing the fan attached to the video card.

2.8 Improving Heat Transfer of Computer Systems

As was stated earlier, the most direct reason for the increase in computer noise is the increased heat generation of a system, and the need for an increased heat transfer rate. Computer noise may then be examined as a heat transfer problem. There are many works that discus the problem of improving heat transfer in computer systems. Advantages of improving heat transfer are two-fold, both as an effort to reduce the load on the cooling solutions present in the computer system, thus reducing computer noise emissions, but also to improve the reliability of the delicate electronic components used by computer system.

Gurrum et al. [5] commented on how thermal issues are becoming increasingly important for high-end microelectronic chips whose performance is becoming limited by the maximum power that can be dissipated without exceeding the maximum junction temperature within. According to Pin-Chih and Wei-Keng [41] most electronic chips must operate with a junction temperature less than 100 ^{0}C. This is the reason why cooling solutions are employed, and is the primary source of the problem of computer noise.

Getz [20] presented an article that dealt with the issue of trade-offs between thermal management and acoustic emissions in high-performance computer systems. Getz dealt with the issue of power dissipation in personal computer systems becoming a much larger challenge for both mechanical and thermal engineers to deal with. The author claimed that increasing the performance of high-end computers is leading to more complex thermal design issues than ever before. One way of dealing approaching this problem is to over design the solution, meaning, assuming a worst-case condition where the largest possible heat sink and multiple cooling fans would be installed into the computer system. Unfortunately, this has the drawbacks of added cost and noise emissions. A second approach is to design a closed-loop system wherein cooling fans only operate to adequately cool the system in addition to an appropriate combination of heat sinks and fans. There is a trade-off in the thermal design of a computer system and it is between cost, heat, and noise. A passive cooling solution will be quiet, but one capable of dissipating the heat of high-performance systems would be massive and expensive. Adding a cooling fan to a heat sink reduces the overall cost and size of the cooling solution, but adds the noise source. The author recommended first determining an acceptable level of noise for an end user, and then designing a cooling solution wherein the fan does not generate noise in excess of this level. The author explained the complexities of determining acceptable acoustical levels, and also the relative nature of noticeable sound emissions. The author claims that the thermal load on a computer system can vary greatly, and thus stresses the importance of controlling the cooling fan's speed. Thus, to compensate for varying thermal loads, most computer systems use temperature-based fan control. A typical CPU's cooling solution uses forced-air convection to transfer energy that the processer dissipates to the air. Assuming that the area for heat transfer and the temperature of the incoming air are constant, the heat transfer efficiency varies directly with fan speed. As fan speed increases, the cooling solution's ability to transfer heat increases, and the heat sink's temperature decreases. The control system that manages the speed of the fan must also account for psychoacoustic effects. A system that turns the fan off and on may be distracting. Also, the human ear is more sensitive to the rate of change in sound levels than to actual sound levels. Thus, there needs to be some built-in control over the rate of change in sound levels. This could be done by controlling a fan's rate of change in angular speed. This must be done carefully so as not to exceed the maximum temperature of the CPU. Getz recommends measuring the temperature and adapting the fan speed multiple times per second for a high-performance PC.

There are four types of systems that are used to cool a computer: air-cooled, hybrid-cooled, liquid-cooled, or refrigeration-cooled [10]. The most common method for cooling a CPU is the air-cooled heat sink [5]. The base of the heat sink is in direct contact with the chip which is to be cooled. Gurrum et al. [5] discussed the process of heat transfer from the CPU to the environment in air-cooled systems. The components are the spreader plate, thermal interface, and the heat sink. The spreader plate is made of copper and is attached directly to the chip. Between the spreader plate and the heat sink is the thermal interface. Because of microscopic variations in either of the solid surfaces, a thermal interface material is used to ensure a perfect thermal contact. Types of interface material include a thermal pad, thermal grease, or a phase change material. Typically, the thermal resistance of the interface material is much less than that of either the spreader plate or the heat sink [5]. Fins that protrude from the base extend the surface area for heat transfer by convection. Air flow can be in one of two ways, either laterally through the fins or by impinging from the top. Additionally, heat pipes have been embedded into heat sinks to more effectively transfer the heat to other locations, where the heat transfers to the ambient air inside the computer case. A good summary of the design of heat pipes in general can be found in a paper by Mochizuki et al. [42].

These types of systems alone may not be enough to cool a system. In this case, a hybrid-cooling system may be employed where water-cooled heat exchangers may be used to cool air. Or, liquid-cooled cold plates may be installed on components to facilitate heat transfer further. In some larger server computer systems, a refrigeration-cooled system may be used. A system like this would employ a liquid-cooling system where the fluid utilised is a refrigerant which needs to be chilled outside of the computer system. This is much more complex and would only be for large computers that generate heat that cannot be removed by other means.

Saini [43] stated that the power dissipation of processors used in desktop computers has been steadily increasing with time and is expected to increase in the future. Due to chassis layout restrictions, it would be difficult to utilise a heat sink with a base area greater than 60 x 80 mm with a height of 50 mm. Also, airflow produced by a standard 60 mm fan is limited by fan speed which is, in turn, limited by noise constraints. Thus, there is a theoretical maximum heat transfer available given a cooling solution with these restrictions.

Kwang-Soo et al. [44] claimed that a traditional aluminum heat sink and cooling fan solution may not be sufficient for heat removal. They discuss the issue of the increasing heat transfer requirements of high-performance personal computers while the computer itself is becoming more compact. Yazawa et al. [9] discussed that while a reduction of component size and an increase in transistor count cause microprocessor power and heat generation to rise, performance and reliability constraints demand constant or decreasing chip temperatures.

Webb [45] claimed that the current, cost effective, active cooling of processors in desktop computers is nearing the end of its life because future, higher power, processors will require more heat transfer than what is available at present. Also, the author stated that as CPU power increases while size decreases, certain limitations arise such as heat sink area and height, fan size and speed, and allowable noise. When these limits are reached, a new method of heat removal will be required. Chang et al. [46] claimed that power dissipation for integrated circuit chips such as a CPU has been projected to be 100 W and that conventional air-cooling systems are reaching their limits. New technology may be need in the near future to alleviate these concerns. Pastukhov et al. [47] discussed the development of miniature heat pipes for use in cooling electronics components and the CPU of mobile personal computers.

Kwang-Soo et al. [44] stated that options such as super-conductive heat pipes or water cooled systems, both of which produce no noise emissions, should be considered. Their study proposed a cooling method capable of reducing noise emissions while at the same time meeting cooling performance requirements. They determined that a heat pipe cooling module had excellent thermal performance when the active cooling solution fan was operating below 2950 rpm. Thus, the heat pipe module could be applied to systems where low noise and high performance is required. It should be noted that since heat pipe technology relies on capillary movement, it is not significantly affected by effects due to gravity.

The cooling requirements of future processors could easily be met if all sides of the chip were available for heat transfer. [5]. Unfortunately, the chip must be connected to the computer and must also be protected from the environment in order for it to function. Thus, any thermal management solution and its performance are constrained by these requirements.

Indirect heat removal could be used to utilise a working fluid to transport heat from a hot source to a heat sink located elsewhere. Heat could then be dissipated from the heat sink by using air or water-cooling. Possible means of heat transport include a heat pipe or convection using a single-phase or two-phase fluid.

Tan and Tso [48] performed an experimental study on the cooling of mobile electronic devices using a heat storage unit filled with a phase change material (PCM). The benefit of a phase change material is that it has a high latent heat of melting. The problem in mobile electronic devices is that they are becoming smaller in size while becoming more densely packed with higher power dissipation from its components. This can lead to device malfunction and damage. Active cooling solutions such as those used in personal computers are not suitable for small electronic devices since they are bulky. So, a passive solution using a solid-liquid phase change material is used. The operation of a PCM is in three phases: first, the temperature of the solid PCM increases from the ambient temperature to its melting temperature; second, phase change occurs as the solid melts under a constant melting temperature; and third, the temperature of the liquid PCM increases as heat is continually supplied. Effective cooling can be achieved if the operation of the mobile device does not exceed the duration of phase 2. Also, the larger amount of PCM used, the longer the temperature of the device will remain stable. The use of PCM in personal computers may be possible.

Chang et al. [46] introduce a design approach for a liquid cooling system to be used in a personal computer system. It consists of a micro channel heat sink, liquid pump, and a heat rejecter. The micro channel block has 38 micro channels of 680 μm hydraulic diameters. Unfortunately, this system is not a passive one, and will produce noise emissions.

Valdez [49] discusses sealed for life, closed loop, liquid cooling units for desktop computers. He mentions that a computer process cooling solution needs to be highly reliable and also nearly invisible to the computer user. Liquid cooling may be used to offset the increased heat generation of new computers. These units must be sealed for the life of the computer, between five and seven years. A major problem with these solutions is evaporative loss, caused by either micro cracks or permeation. Loss of fluid means that the user must replenish the fluid occasionally, and thus is not ideal. Also, a tubing material must be selected that is both flexible and non-flammable. For instance, metals, which are non-permeable, are not very flexible, and are susceptible to corrosion. Polymers, which are flexible, do not resist permeation. Valdez [49] recommended the use of a material called fluorinated ethylene propylene (FEP) as it is inflammable, nearly impermeable, and flexible. Pastukhov and Maydanik [19] discussed the use of a passive cooling system using loop heat pipes.

The problem of cooling a personal computer system may not be entirely focused on the CPU. Sun and Panigrahy [21], discuss the thermal management of a computer graphics processing unit (GPU). Although the cards discussed are intended for use in a computer's Accelerated Graphics Port (AGP) peripheral slot, there should be no difference for modern cards designed for use in a computer's PCI-Express peripheral slot instead. The authors claim that cooling the central CPU is no longer the only major concern for the thermal management of a modern personal computer. The GPU is now becoming a much more important concern than in the past. This is because a high-end video card may dissipate even more heat than a CPU in the future and because a cooling solution for a peripheral card has a very restrictive form factor. A single-slot cooling solution has a height limit between 11-13 mm, whereas a CPU cooling solution may have a limit between 50-70 mm. The authors claimed that a passive cooling solution would not be sufficient to remove the heat from a card using 50-60 W of power, thus, an active solution must be used. The authors designed and performed a CFD analysis on an active cooling solution. They then built a prototype cooling solution based on their work and found that experimental results were within +-10% of the results predicted by the simulations.

Chu et al. [10] mentioned another method for cooling an entire computer called immersion cooling. It involves bringing liquid coolant in direct contact with the components to be cooled. However, a coolant that has a high thermal conductivity, absolutely zero electrical conductivity, and also is chemically suitable is difficult to find. The authors discussed some future challenges including: keeping the cost of cooling a computer system to a relatively small fraction of the total system cost; air cooling may not be sufficient to cool all computer systems in the future; more densely packed computer systems make cooling solutions much more difficult to implement as they may take up a great deal of space within a computer.

Gurrum et al. [5] stated that improvements in heat transfer from processors need to focus on removing heat from the chip to the motherboard and then to the ambient by way of heat spreaders or integrated liquid cooling. They stated that by doing so, it may be possible to reduce or even eliminate the active cooling solution.

2.9 Future Issues

Maling [31] concluded his paper with an examination of some key issues that may be addressed in future research. In the area of small axial-flow fans, he made several suggestions. First, work needs to be done to develop methods to better predict the sound produced due to environmental effects such as turbulent and non-uniform inlet airflow, and because of impedance. Second, work needs to continue to reduce the level of discrete frequency components. Third, methods should be developed to better predict and reduce structure-borne noise. This is sound that is transmitted into a structure and then re-radiated. Fourth, active noise control must be examined to reduce both the blade-passage tones as well broadband noise in systems that that contain many small air-moving devices. The total cost of an active noise control system must be considered and compared to that of a passive system which maintains the same noise reduction.

Quinlan and Bent [12] pointed out that progress in small air-moving device noise control has been limited by the lack of detailed information regarding underlying aeroacoustic process. This is especially true for broadband noise, which has not been studied to the degree that tonal noise has. They recommend that active noise control may be used to reduce noise emissions; however, all of the aeroacoustic processes have not yet been identified. Thus, application of active noise control may be useless. They emphasized that further detailed identification of all of the primary aeroacoustic process in small axial-flow fans is needed. They investigated the key source mechanisms. They mentioned that further study will be needed before it can be stated for certain that the relevant aeroacoustic mechanisms were trailing edge scattering and radiation from free turbulence and/or boundary layer radiation.

2.10 Computer Cooling Fans and Sound Quality

There has been significant work done involving the sound quality of computer cooling fans by the University of Windsor NVH-SQ Research Group. Novak [22], discusses how passive cooling solutions are no longer able to keep up with the required cooling rates required by modern graphics processing units. He mentions the importance of perceived quality with regards to the noise emissions of the cooling solutions and that sound quality metrics are applicable as they may provide quantitative values regarding human perception. Ule [50], performed a study to determine how increased blower fan speed affected acoustic emissions of a blower style fan used in a GPU cooling solution. Fan speed was controlled by adjusting the input voltage to the fan. Sound power was calculated based on sound pressure measurements. As expected, the increased fan speed led to both an increase in acoustic emissions as well as an increase in thermal performance. Nantais [6], wrote about the acoustic characteristics of three GPU cooling solutions and used the metric of loudness in addition to sound pressure and power levels. He determined that as the complexity of the design of the cooling solution is increased in an effort to increase cooling capacity, so do the values for both SPL and loudness, implying poorer acoustic performance. Defoe [51], examined the sound quality metric of loudness in great detail. He states that "it accounts for both the frequency-sensitivity of the ear as well as masking effects." He mentions how although there are standards in place regarding the use of loudness, it remains poorly understood despite being one of the most common sound quality metrics. Although loudness and other metrics may be used in engineering applications, there is certainly a void of understand when it comes to their meaning and use. Ule [52], discussed how varying heat sink fin distance from the cooling fan blade tip affects noise emissions of a GPU cooling solution. She included a sound quality analysis along with a discussion of the aeroacoustic phenomena present.

2.11 Analysis of Literature Review

There are some aspects to computer noise that have been explored in the available literature. The scope of this thesis work includes conducting an acoustic analysis of a desktop computer system in a similar manner to that of Hodgson and Li [18]. However, unlike their work, five sources of noise will be examined in detail. These are the CPU fan, the GPU fan, a rear case fan (case fan 1), a front case fan (case fan 2), and a PSU fan. In the literature examined, there was no mention of any acoustic analyses performed on all of the computer fans within a computer system, only individual ones, or multiple fans which all perform the same function, that is, are all used as CPU fans, case fans, or GPU fans. Methods for acoustical testing described in ISO 7779, ECMA 74 and ISO 3745 which provides experimental considerations such as characterising noise emissions in terms of SWLs. It should be noted however that the standards found do not explicitly mention techniques of sound quality measurement. There is definitely a lack of understanding (both in theory and in practice) with regards to how sound quality metrics should be applied in investigations involving emissions from small axial-flow fans.

Based on what may be absent from available literature, it is desirable to add to the work that has already been done. Thus, it is necessary for this work to accomplish two objectives thus far absent from available literature. The first is to derive an appropriate and repeatable test plan, perform acoustical measurements, and record results for testing done on all fans used within a computer system. The second is to further the understanding and use of sound quality metrics for the purpose of computer fan acoustical performance testing. As stated in Chapter 1, the motivation of this thesis is to understand, measure, and determine how to attenuate computer noise. Doing so accomplishes both of these objectives. It is hoped that the following work will provide insight for individuals both in the computer manufacturing industry as well as acousticians performing research investigations into sound quality phenomena.

CHAPTER III

EXPERIMENTAL METHODOLOGY & DETAILS

The literature review chapter discussed previous work done to understand, measure, and determine how to attenuate computer noise, and in particular, noise emissions of axial-flow fans used by active cooling solutions. This chapter details the experimental portion of this work. In particular, this chapter provides the following: a description of the applicable acoustical measurement standards; the measurement components; and the acoustical environment utilised. Also provided is an outline of the sets of results to be compared in the following chapters. This is done so that it may be understood why certain measurements are performed.

3.1 Focus

The focus of this experimental work is to achieve results that allow for accurate conclusions to be made about of the effectiveness of various noise control techniques. The three noise control techniques used in this thesis work are: the implementation of acoustic insulation within the desktop computer case; the implementation of software modification to a desktop personal computer system; and the implementation of hardware modification to the components of a desktop personal computer system. These three noise control techniques are all passive noise control methods. As stated in Chapter 2, the use of active noise control methods is not studied in the experimental thesis work. Although active noise control methods may have certain applications, they have not been implemented in any capacity that would make them available for widespread and user-friendly use in the personal computer industry. Passive noise control methods are much more readily available, inexpensive compared to the overall cost of a personal computer system, and far more user-friendly than active noise control methods. Thus, the remainder of this thesis work will only focus on the implementation and effectiveness of various passive noise control methods, as described above.

3.2 Acoustical Measurement Standards Associated with Measuring Axial-Flow Fan Noise

Methods for acoustical testing used in this thesis work are described in International Standard ISO 3745 [53]. This acoustics standard provides a description for the determination of SWLs of noise sources using sound pressure. The standard "specifies methods for measuring the SPLs on a measurement surface enveloping a noise source in anechoic and hemi-anechoic rooms" [53]. Measuring the SPLs on a surface is important as it allows for the determination of SWL or sound energy level of the noise source. The standard gives the requirements for the test environment, instrumentation, as well as measurement and calculation techniques to obtain the SWL or sound energy level of the noise source. The calculation of SWL in a hemi-anechoic room as described in ISO 3745 is shown in the following equations [53].

$$L_W = L_p + 10 * \log\left(\frac{S_2}{S_0}\right) + C_1 + C_2 \qquad (4)$$

Where,

$$C_1 = -10 * \log\left[\frac{B}{B_0} * \sqrt{\frac{313.15}{273.15 + \theta}}\right] \qquad (5)$$

And,

$$C_2 = -15 * \log\left[\frac{B}{B_0} * \left(\frac{296.15}{273.15 + \theta}\right)\right] \qquad (6)$$

In these equations: L_p is the surface SPL over the test hemisphere, in decibels; $S_2 = 2\pi r^2$ is the surface area of the test hemisphere (of radius r);$S_0 = 1\ \mathrm{m}^2$; B is the barometric pressure during the measurements, in Pascals; B_0 is the reference pressure, $1.01325 * 10^5$ Pa; and θ is the air temperature during the measurement, in degrees Celsius. For additional information regarding the background of acoustic equations, refer to Appendix A.

Also used in this thesis work is information found in ECMA International Standard ECMA-74 [54]. This ECMA Standard describes methods for measuring and reporting the noise emissions of technology and telecommunications equipment. The advantage of using ECMA-74 is that it is available for free.

3.3 Measurement Components

Table 3-1 lists the fans that were used for acoustical testing, and provides their diameters and number of blades. Table 3-2 lists the hardware components of the computer system that was used for the in-system measurements.

Table 3-3 lists the hardware and equipment that was used to conduct the acoustical measurements.

Table 3-1: Fans used for Acoustical Testing

Fan	Diameter (mm)	Blades
CPU	70	9
PSU	120	7
Case 1	120	7
Case 2	70	9
GPU	65	29

Table 3-2: Computer System Components

CPU	AMD Athlon 64 X2 3800+, Dual Core, S939
Motherboard	ASUS A8R-MVP ATX
HDD	Western Digital 250 GB, 7200 RPM, 16 MB
Memory	OCZ Performance PC3200, 2 GB, DDR400
PSU	OCZ Stealth X-Stream 500W
Optical Drive	Pioneer DVR-111D DVD+DL

Table 3-3: List of Measurement Equipment

Microphones	Microtech Gefell NC-MK231
Preamplifier	Microtech Gefell NC-MK203
Data Acquisition	01dB-Metravib Symphony interface
Laptop Computer	Windows® PC, running 01dB-Metravib dB-RTA
Hemi-anechoic room	Certified for frequencies above 200 Hz
Power Supply	Goodwill Instrument 12V DC power supply
Calibrator	Larson Davis CAL150, 94dB@1kHz

3.4 Acoustical Measurement Environment

Before details of the acoustical measurements performed are given, some definitions are needed to understand the techniques used. According to International Standard ISO 3754 [53] the following definitions are given. A free-field is "a sound field in a homogeneous, isotropic medium, free of boundaries." This means that any sound waves generated in a free-field will move away from the source and it is impossible for them to be reflected back to the source. This means that any measurements taken will not include any reflected sound waves. ISO 3745 [53] notes that a free-field in practice "is a field in which reflections at the boundaries are negligible over the frequency range of interest." An anechoic room is "a room in which a free-field is obtained." That is, an anechoic room is one which meets the environmental conditions for a free-field. A hemi-anechoic room is "a room in which a free-field over a reflecting plane is obtained." In other words, a hemi-anechoic room has the same properties as an anechoic room on all surfaces except for the floor, which is intended to be reflective.

The University of Windsor NVH-SQ Research Group has a hemi-anechoic room available for use. The room is a rectangular prism. The four walls and the ceiling are covered with acoustic foam wedges which absorb all of the acoustical emissions generated from within the room above the cut-off frequency of 200 Hz. This simulates a free-field environment. The floor of the anechoic room is concrete and is completely reflective of acoustical emissions generated from within the anechoic room. This is taken into consideration for the calculations performed.

3.5 Operating Conditions and Configurations Lists

The computer system being tested is a personal computer (PC) assembled by the author running the Microsoft Windows® XP Professional Operating System. The software applications utilised are designed for use in this operating system. Although there are several other operating systems available for use, such as Apple's Mac® OS X or Linux (freeware), Microsoft Windows® is the most widely used with over 91 percent market share as of February 2008 [55].

In order to correctly draw conclusions about the effectiveness of the three noise control techniques described earlier, some further explanation is required. The following is a list of the operating conditions under which the desktop computer system will be tested. The operating conditions are labelled (a) through (f).

(a) Idle
(b) CPU Benchmark
(c) GPU Benchmark
(d) Speedfan @ 50%
(e) Case fan 1 @ 5V and 7V
(f) Case fan 2 @ 5V and 7V

Operating condition (a) provides a baseline for the operation of the computer. Operating conditions (b), (c) and (d) involve software modification. Operating conditions (e) and (f) involve hardware modification. These six conditions are described in greater detail in Chapter 4 and can only be run while the computer system is in full operation. This means that all fans are running. Thus, only in operating configurations (iii) and (v) below are they directly applicable. In the other operating configurations, only one fan at a time is run while the computer system is off. This is done by powering the fans by a power source from outside of the hemi-anechoic room. The fans are run at different voltage levels.

There are five different operating configurations of the desktop computer system that are tested. The operating configurations are labelled (i) through (v). These configurations are described in greater detail in Chapter 4.

(i) Individual Fans – Stand-Alone

(ii) Individual Fans – In-System

(iii) Fully Assembled and Operating Desktop Computer System (FAODCS)

(iv) Individual Fans – In-System with Acoustic Insulation

(v) Fully Assembled and Operating Desktop Computer System with Acoustic Insulation

For configurations (i), (ii), and (iv) the operating conditions described above (a through f) must be simulated: the computer system was off and the fans were operated one at a time. This was done by externally powering the individual fans using the DC power source. In order to accurately simulate the operating conditions on a one-fan-at-time basis, it was necessary to perform the RPM testing that is described in Chapter 4. To summarise the experimental methodology, Figure 3-1 is provided to clarify the goals of this experimental work.

3.6 List of Specific Experimental Results to Compare

The following list outlines the sets of comparisons that are done in order for accurate conclusions to be made about of the effectiveness of the three noise control techniques described earlier. Comparisons 1 and 2 involve rpm measurement data. Comparisons 3 to 6 deal with the acoustical and psychoacoustical emissions of the computer fans being tested in various operating conditions and configurations.

1. Individual fan RPM data (with applied voltage) vs. individual fan RPM data (during all operating conditions)
2. Blade passing frequency vs. frequency spectrum of individual fans – stand-alone
3. Individual fans – stand-alone vs. individual fans – in-system
4. Individual fans – stand-alone vs. individual fans – in-system with acoustic insulation
5. Individual fans – in-system vs. individual fans – in-system with acoustic insulation
6. Fully assembled and operating desktop computer system vs. fully assembled and operating desktop computer system with acoustic insulation

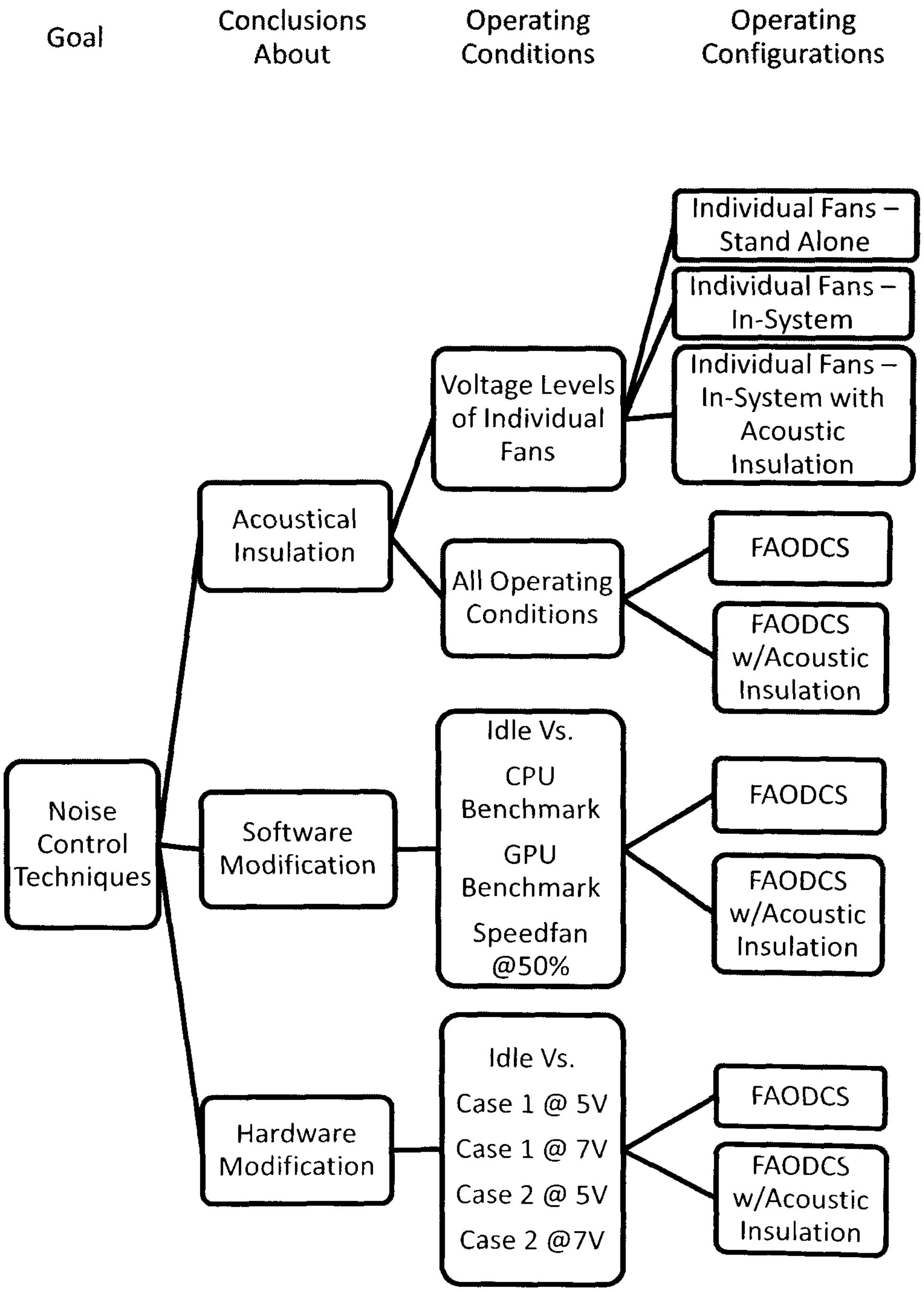

Figure 3-1: Design of Experiment Flowchart

CHAPTER IV

EXPERIMENTAL PROCEDURE

The experimental methodology and details chapter provided the motivation and presented general details for the experiments performed in this thesis work It gave descriptions of applicable acoustical measurement standards, measurement components, acoustical environment utilised, and the sets of results to be compared In order to make the comparisons, experimental work was needed This chapter provides details about the experimental procedure followed and illustrates how all measurements were performed

4.1 Explanation of Operating Conditions

Before detailing the experimental procedure it is necessary to describe the operating conditions mentioned in the previous chapter

4.1.1 Idle

This operating condition refers to the desktop computer running the Windows® XP operating system and included background processes only No other applications are active It is achieved by powering on a computer and allowing it to boot and load Windows® XP This operating condition is used as a standard for the computer system The results achieved from testing during this operating condition provided baseline results that were compared to the other results obtained

4.1.2 CPU Benchmark

This operating condition involves using a software utility installed on the test computer to alter the rotational velocity of the CPU fan The software is a CPU benchmarking program that operates in the background during the Windows® idle operating condition It is designed to fully utilise the CPU to perform floating point calculations Doing so increases the heat generation of the CPU and thus internal temperature of the processor leading to increased CPU fan speed. This test was done to determine how the acoustical emissions of the desktop computer system were changed compared to the system idle operating condition.

4.1.3 GPU Benchmark

This operating condition involves using a software utility installed on the test computer to alter the rotational velocity of the GPU fan. The software is a GPU benchmarking program that performs tests on the GPU of a computer system. This increases the heat generation of the GPU and thus internal temperature of the GPU processor leading to increased GPU fan speed. This test was done to determine how the acoustical emissions of the desktop computer system were changed compared to the system® idle operating condition.

4.1.4 Speedfan @ 50%

This operating condition involves three tests using software installed on the test computer to alter the rotational velocity of the CPU fan. This software utility is designed to reduce the rotational velocity of the CPU fan. The utility reduces the velocity by a certain percentage not by an actual numerical value. This program was run at each of the specified levels during the Windows® idle operating condition. This test was done to determine how the acoustical emissions of the desktop computer system were changed compared to the system idle operating condition.

4.1.5 Case fans 1 and 2 @ 5V and 7V

These operating conditions involved two tests using hardware modification on the test computer to alter the rotational velocity of each case fan. By modifying an existing Molex power cable, the input voltage level to the Case fan was changed from the standard 12V to either 7V or 5V. Acoustical testing was done on the computer system during the idle operating condition. This test was done to determine how the acoustical emissions of the desktop computer system were changed compared to the system idle operating condition. For a summary of all operating conditions, refer to Figure 4-1.

Idle
CPU Benchmark
GPU Benchmark
Speedfan @ 50%
Case fan 1 @ 5V
Case fan 1 @ 7V
Case fan 2 @ 5V
Case fan 2 @ 7V

Figure 4-1: Summary of Operating Conditions

4.2 RPM Measurements Performed

RPM measurements were taken of the computer fans using a photo tachometer. The objective of these measurements was to determine the applied voltage level necessary for individual fan operation to simulate behaviour during each of the operating conditions described above. In other words, when tested individually, the necessary applied voltage level to duplicate the behaviour of the fans during operation in the FAODCS is desired. This objective was achieved by performing two sets of RPM tests.

The first set of RPM tests were performed on each of the fans outside of the computer system. These were the stand-alone RPM tests. The CPU, GPU, and Case fans were powered by the DC power supply. The PSU fans were powered by simulating a power switch by shorting the appropriate pair of connectors. This was possible after referring to the ATX Specification [7]. RPM versus voltage level data was collected for each of the fans.

The second set of RPM tests were performed on each of the fans installed in the computer system. These were the in-system RPM tests. The fans were reinstalled into the computer system as was the PSU. The power cables were reconnected and the computer was powered on. The computer entered the system idle operating condition. RPM measurements were taken of all five fans at each of the operating conditions listed in section 4.1.

By comparing these two sets of results it was determined at what applied voltage levels the fans operate at during each of the operating conditions. The fans could now be operated individually to simulate their performance during the operating conditions listed in section 4.1. This allowed for the acoustical measurements described in the following sections to be completed. For a summary of all RPM tests completed, refer to Figure 4-2.

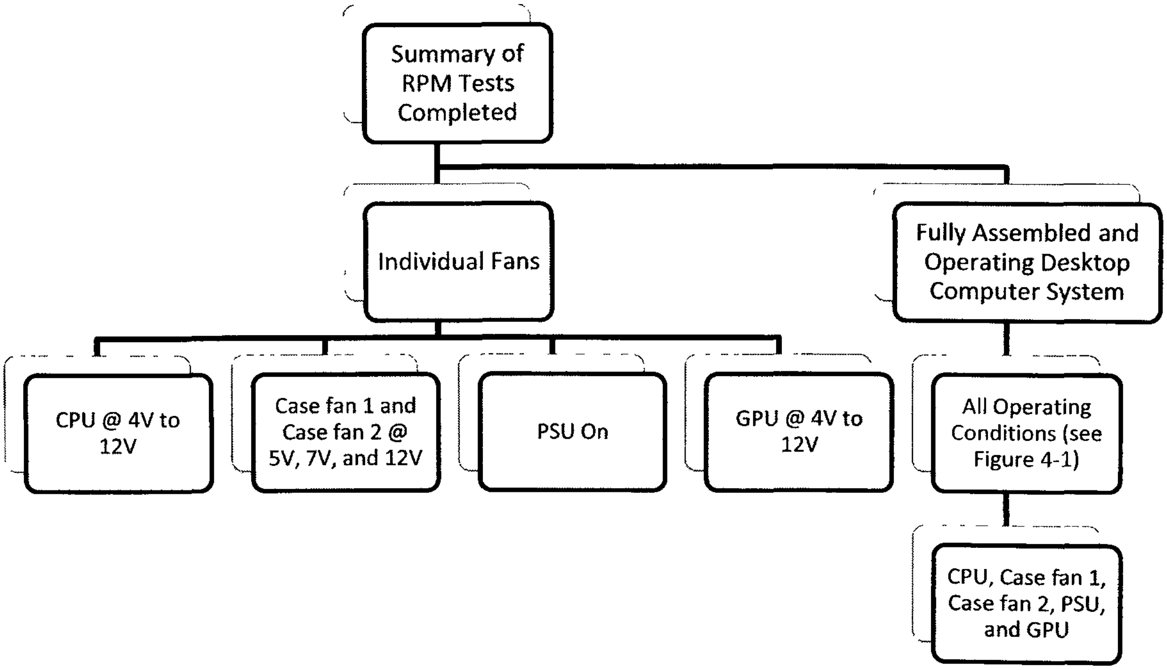

Figure 4-2: Summary of RPM Tests Completed

4.3 Acoustical Measurements Setup

Measurements were conducted using a 10-point hemispherical microphone array in accordance with ISO 3745 [53]. See Figure 4-3.

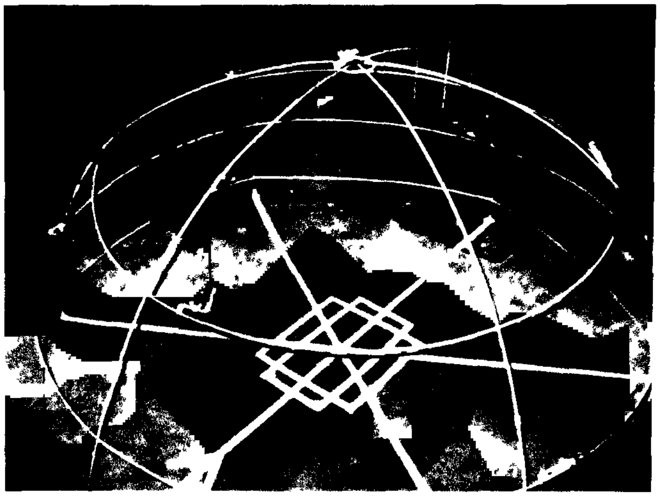

Figure 4-3: Testing Hemisphere

A laptop computer was setup outside of the hemi-anechoic room and was connected to the data acquisition hardware (Symphony) which was connected to the microphones. The laptop was used to control the data acquisition software (dB-RTA). A DC power supply was setup outside of the hemi-anechoic room and powered the fans during individual testing.

4.3.1 Stand-Alone Measurement Setup

The fans were tested independently of the desktop computer system. They were tested in a fixture as shown in Figure 4-4.

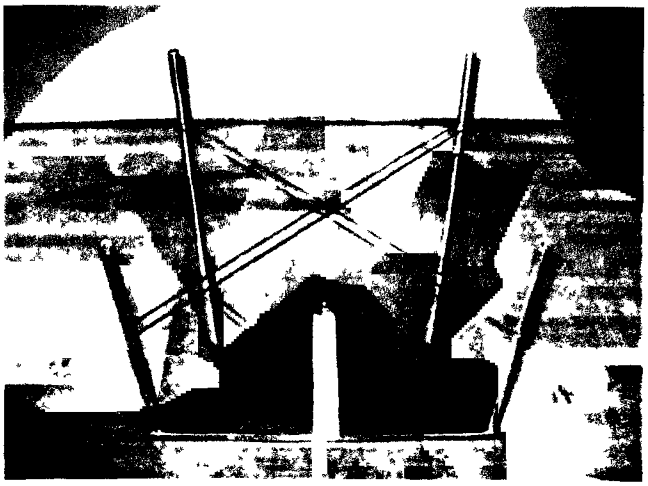

Figure 4-4: Individual Fan – Stand-Alone Testing Apparatus

4.3.2 In-System Measurement Setup

The fans and the PSU were installed in the desktop computer case. The case was placed on the floor of the hemi-anechoic room in the centre of the hemispherical measuring surface. An LCD monitor, keyboard, and mouse were connected to the computer case. These allowed for operation of the computer during the applicable testing but were not necessary for the individual fan tests. The computer system and LCD monitor were powered by a UPS within the hemi-anechoic room. This setup is shown in Figure 4-5.

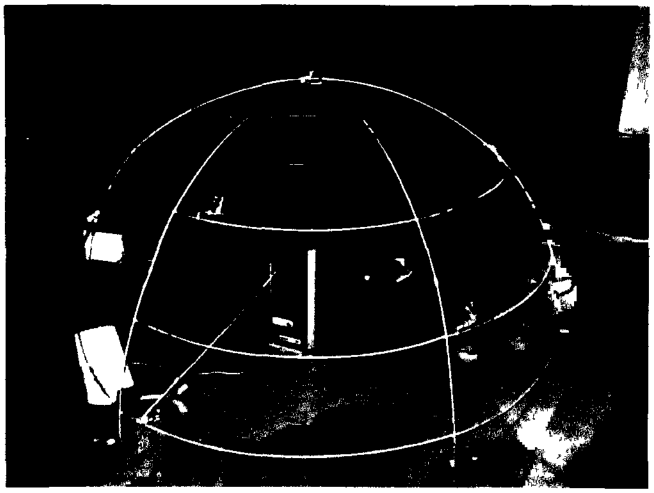

Figure 4-5: Anechoic Room Experimental Setup

Two microphones were used to conduct all of the acoustical measurements. The noise sources being tested were considered steady-state. Thus, data acquisition was taken from each of the ten microphone locations by moving two microphones around the hemispherical surface. The microphones were first located in location (1, 2) and then moved sequentially to locations (3, 4), (5, 6), (7, 8), and (9, 10). The locations of the microphones on the hemispherical surface as shown from above are given in are shown in Figure 4-6, as is the orientation of the computer case relative to the microphone location. Note that the figure is not to scale.

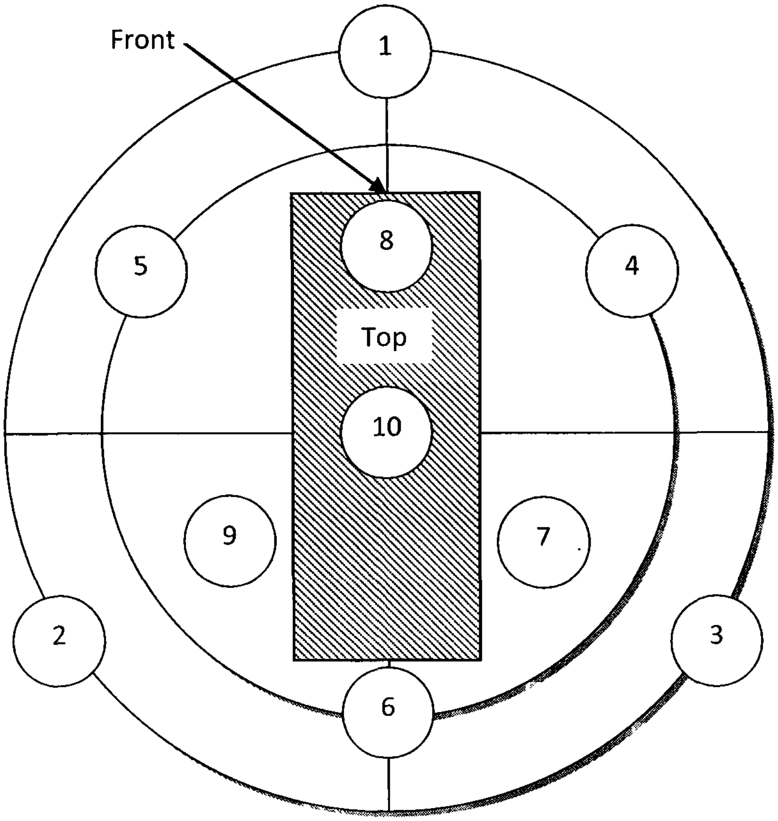

Figure 4-6: Top View of Microphone Locations on Hemispherical Surface

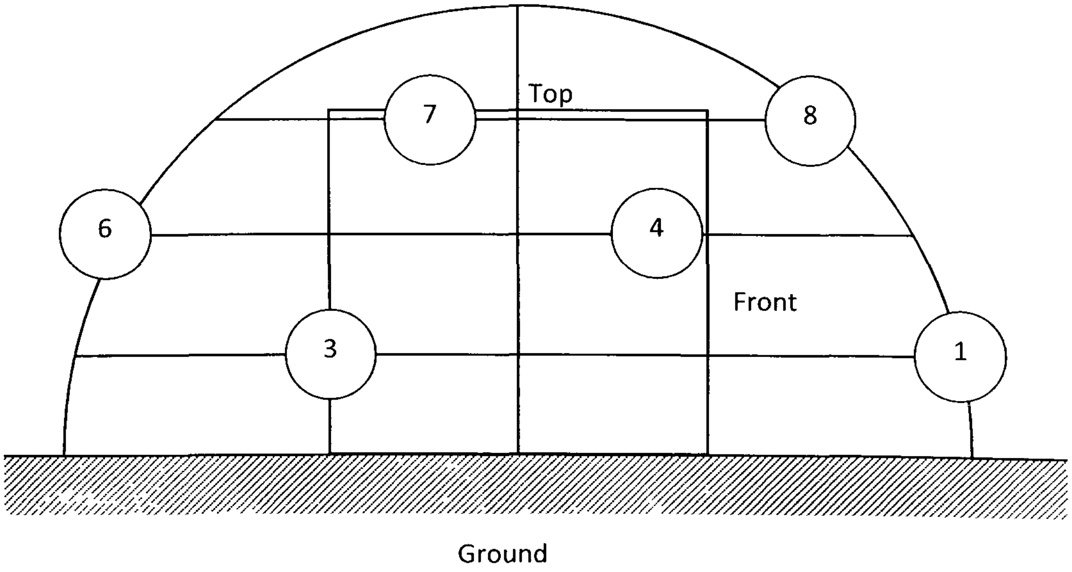

Figure 4-7: Side View of Microphone Locations on Hemispherical Surface

4.4 Acoustical Measurements Procedure

For all acoustical testing performed, ten second measurements were taken of sources with relatively constant acoustical emissions. Ten seconds was deemed an appropriate length of time to acquire data since the noise sources were steady state. For every test performed, three measurement samples were taken. This was done for redundancy.

4.4.1 Ambient Room Measurement

Ambient room measurements were taken. These were needed to determine the background noise and acoustical characteristics within the room itself. ISO 3745 [53] defines background noise as “noise from all sources other than the source under test.” To do this, two microphones were set up in the hemi-anechoic room. The microphones were properly calibrated and auto-ranged for accuracy. Data was acquired with no acoustical sources present.

4.4.2 General Measurement Procedure

Measurements began with the microphones in location (1, 2). The microphones were again properly calibrated and auto-ranged for accuracy. Measurements were then performed and data acquired for the two microphones for ten seconds. This was done using the laptop computer and data acquisition software (dB-RTA). The microphones were then moved to location (3, 4). The measurement process was repeated. The two microphones were then moved to locations (5, 6), (7, 8), and (9, 10), and measurements were repeated after every location change. This procedure was performed for every operating condition. Figure 4-8 gives a summary of the acoustical measurements performed.

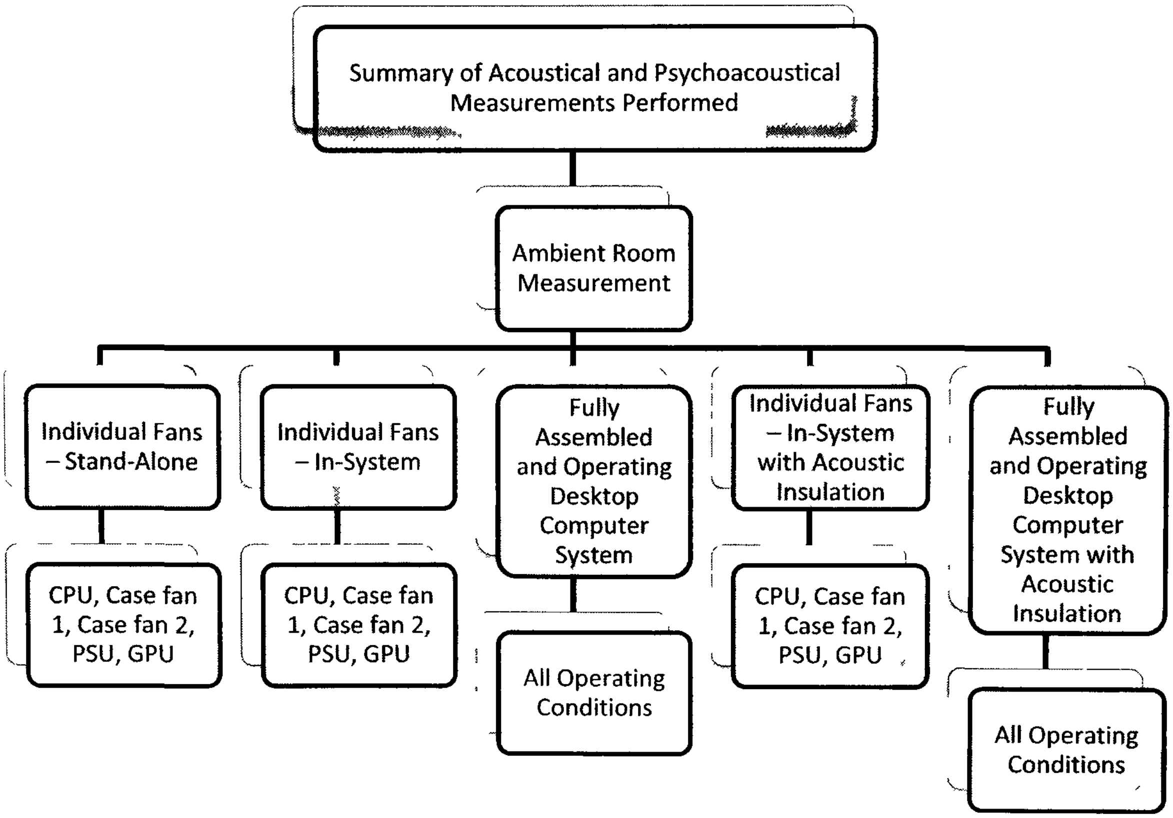

Figure 4-8: Summary of Acoustical and Psychoacoustical Measurements Performed

4.5 Acoustical Measurements Performed

The following sections detail the measurement procedure for each of the five operating configurations tested.

4.5.1 Individual Fans – Stand-Alone

Each fan was tested one at a time. Each of the fans was tested outside of the computer system in the stand-alone configuration. The fans were powered by the external DC power supply located outside of the hemi-anechoic room. The DC power supply was used to adjust the applied voltage level to the fan being tested. Measurements were conducted according to the general measurement procedure given above. First, the CPU fan was tested, and then the case fans, the GPU fan, and the PSU fan. See Figure 4-9 for the individual fan testing list.

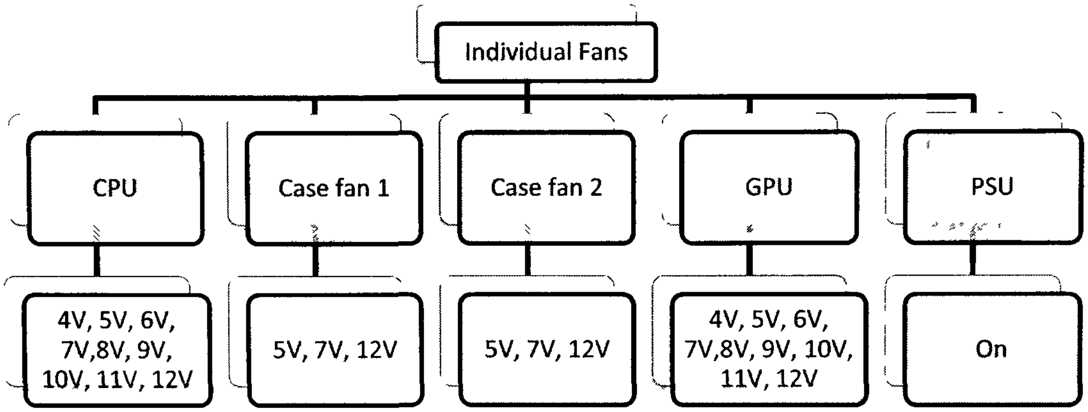

Figure 4-9: Testing List for Individual Fans

4.5.2 Individual Fans – In-System

The fans and the PSU were installed in the desktop computer case. Each fan was tested individually. Each of the fans was tested separately inside of the computer system.

4.5.3 Fully Assembled and Operating Desktop Computer System

After completing the first two operating configuration tests, the fans were disconnected from the DC power supply and connected to their individual power connections within the computer case. The computer was then turned on and the Windows® XP operating system was allowed to boot up. The system was allowed to run for at least five minutes in order to ensure it had reached thermal equilibrium. It was determined using temperature monitoring software that five minutes was an appropriate length of time for the computer to reach this state. After which, each of the operating conditions described in section 4.1 were run.

4.5.4 Individual Fans – In-System with Acoustic Insulation

In the fourth operating configuration, acoustical insulation was installed in the computer case on all interior surfaces. It was used to attenuate the acoustical emissions caused by the internal components. The fans were disconnected from their individual power connections. The fans were again powered individually by the external DC power supply. Each fan was tested in turn. Each of the fans was tested inside of the computer system in the in-system configuration. This set of tests was done in an identical manner to those of section 4.5.2.

4.5.5 Fully Assembled and Operating Desktop Computer System with Acoustic Insulation

In the fifth operating configuration, acoustical insulation was installed in the computer case on all interior surfaces, identical to the previous section. The fans were reconnected to their individual power connections within the computer case. The computer was then turned on and the Windows® XP operating system was allowed to boot up. The system was allowed to run for at least five minutes in order to ensure it had reached thermal equilibrium. Then, each of the operating conditions described in section 4.1 were run.

CHAPTER V

ANALYSIS OF RESULTS

The results of the experimentation performed are presented and analysed in this chapter. The results of each configuration tested are presented and the findings within each configuration are discussed. This will facilitate the experimental comparisons that were described in Chapter 3. By performing these comparisons, useful results are obtained about the effectiveness of the various noise control techniques tested: the installation of acoustic insulation within the desktop computer case, the implementation of software modification, and the addition of hardware modification.

5.1 Reasonable Assumptions

Based on the experimental setup it is appropriate to make reasonable assumptions regarding the results achieved. The relationships between the locations and orientations of the fans and the 10 microphone locations on the hemispherical surface are of importance. The overall SWL of the noise source is calculated and the direction from which the noise source is dominant is also determined since data acquired provides directionality information of the noise source. This information can be used by end users of the computer system. Table 5-1 lists the fans tested, their locations, and the direction of airflow that each fan causes.

Table 5-1: Fan Locations within Computer Case

Fan	Location	Direction of Airflow
CPU	Middle of the case	Perpendicular to motherboard
Case 1	Mid-Rear of the case	Parallel to the length of the case
Case 2	Front of the case	Parallel to the length of the case
PSU	Upper Rear of the case	Intake – Perpendicular to the height of the case Exhaust – Parallel to the length of the case
GPU	Lower Rear of the case	Parallel to the length of the case

There are several factors which may cause an attenuation of a constant noise source. The first factor is the distance between the noise source and the receiver. The greater the distance there is between a noise source and a microphone, the lesser the measured SPL. The second factor is obstacles in between the noise source and the receiver. In the case of a desktop computer system, the computer case is the greatest obstacle and thus should provide some attenuation of the noise sources. The third factor is the orientation of the noise source. Ideally, a perfect noise source radiates sound in spheres where an equal SPL can be measured at all locations on the spherical surface at all times. However, as was discussed in the Literature Review chapter, fans do not radiate sound in such a manner. Greater noise levels will be generated in the direction of the downstream and upstream caused by the fan under consideration.

5.2 Data Analysis

For each condition tested, pressure signal data was collected at each of the ten microphone locations. The pressure signal data was post-processed in the 01-dB software dB-FA. The first post-processing necessary was to high-pass filter the data at a frequency of 200 Hz. This is a necessary step for all acoustical data recorded in The University of Windsor NVH-SQ Research Group's hemi-anechoic room which is certified for noise sources above 200 Hz. After all of the pressure signal data was high-pass filtered at 200 Hz, the next step was to obtain values for overall SPL, both linear and A-weighted, loudness, and tonality. These values were all computed by dB-FA based on the 200 Hz high-pass filtered pressure signal. After values were obtained, they were inserted into data tables as shown in Table 5-2. This was done for the data obtained for each of the three trials performed.

Table 5-2: Example of Data Collection Table

CPU @ 4V	1	2	3	4	5	6	7	8	9	10	
Loudness	0.15	0.38	0.24	0.23	0.27	0.23	0.17	0.14	0.18	0.16	
Tonality	0.67	0.69	0.64	0.67	1.14	0.00	0.33	0.00	1.01	0.28	Avg.
SPL - Linear	21.0	26.5	24.4	23.8	25.0	23.3	21.8	20.4	22.1	20.9	23.4
SPL - A-Weighted	17.1	21.0	19.0	18.8	19.5	18.9	17.6	17.3	17.4	17.6	18.6
SWL - Linear	31.3										
SWL - A-Weighted	26.6										

The average linear and A-weighted SPLs were calculated based on the logarithmic average of the ten individual microphone measurements. These values were then used to determine the linear and A-weighted SWLs of the source being measured. The equations used as well as the A-weighting table and applicable functions are given in Appendix A. Following the calculations of the psychoacoustic criteria, further computation was completed by dB-FA to determine the 1/3 octave band and 1/12 octave band spectra of the noise sources. These spectra were based on the 200 Hz high-pass filtered pressure signal.

5.3 Repeatability of Measurements Taken

As stated before, three measurement samples were taken for every measurement performed. This was to ensure that there was sufficient backup data available in the event that one of the samples contained problematic data, usually due to an additional noise source present in the area of the hemi-anechoic measuring environment. Problematic samples were removed from consideration. For the purposes of this work, all noise sources were considered steady-state. Thus, three measurement samples should yield similar results. This is now shown with four specific examples: results of the CPU @ 12V during the individual fan – in-system testing; results of the GPU fan @ 8V during the individual fan stand-alone testing; system idle results during the FAODCS test; and GPU benchmarking results during the FAODCS with acoustic insulation testing. It should be noted that the maximum resolution of the measurement system used to determine SPL is to the nearest tenth of a dB, well within what is considered an unperceivable difference to human hearing.

5.3.1 CPU @ 12V Individual Fans – In-System

Figure 5-1 illustrates the repeatability of the test done on the CPU fan @ 12V during the individual fan – in-system testing. Linear and A-weighted SPLs are shown for every microphone location as well as the average of all locations. Between the three trials there is very little difference in the result measured. The greatest differences between the three trials were measured at microphone location 1, where there was both a 0.5 dB and a 0.5 dBA difference between trials 1 and 3. Since the practical use of SPLs requires rounding to the nearest dB or dBA, the difference of 0.5 dB/dBA or less is acceptable. This difference is also well within what would be considered an unperceivable difference to human hearing. This difference shows that the assumption that the noise source is steady-state is reasonable. The other examples shown have even less of a difference between their respective trials than 0.5 dB or 0.5 dBA.

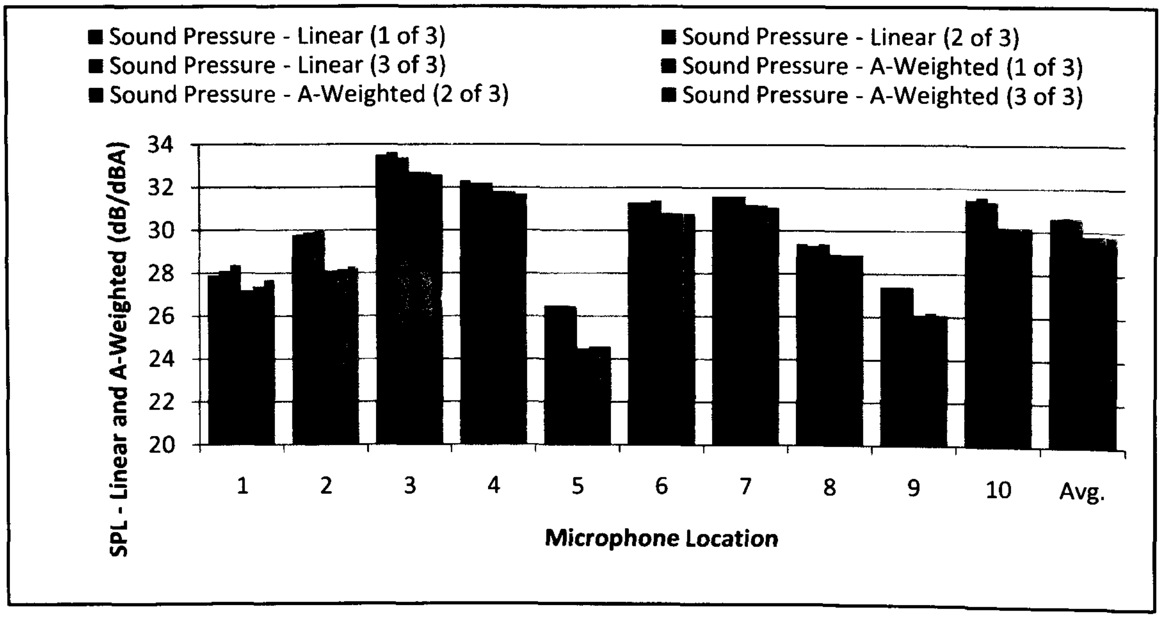

Figure 5-1: Repeatability – Individual Fans – In-System, CPU @ 12V

5.3.2 GPU @ 8V Individual Fans – Stand-Alone

Figure 5-2 illustrates the repeatability of the test done on the GPU fan @ 8V during the individual fan – stand alone testing. Again, there is very little difference in the result measured between the three trials. The greatest differences between the three trials were measured at microphone location 6, where there was a 0.4 dB and a 0.2 dBA difference between trials 1 and 2. Note that for all three trials at microphone locations 1, and 4 through 10, there is less than a 1 dB difference between the measured linear SPLs and the calculated A-weighted SPLs. The reason for this will be discussed in a later section.

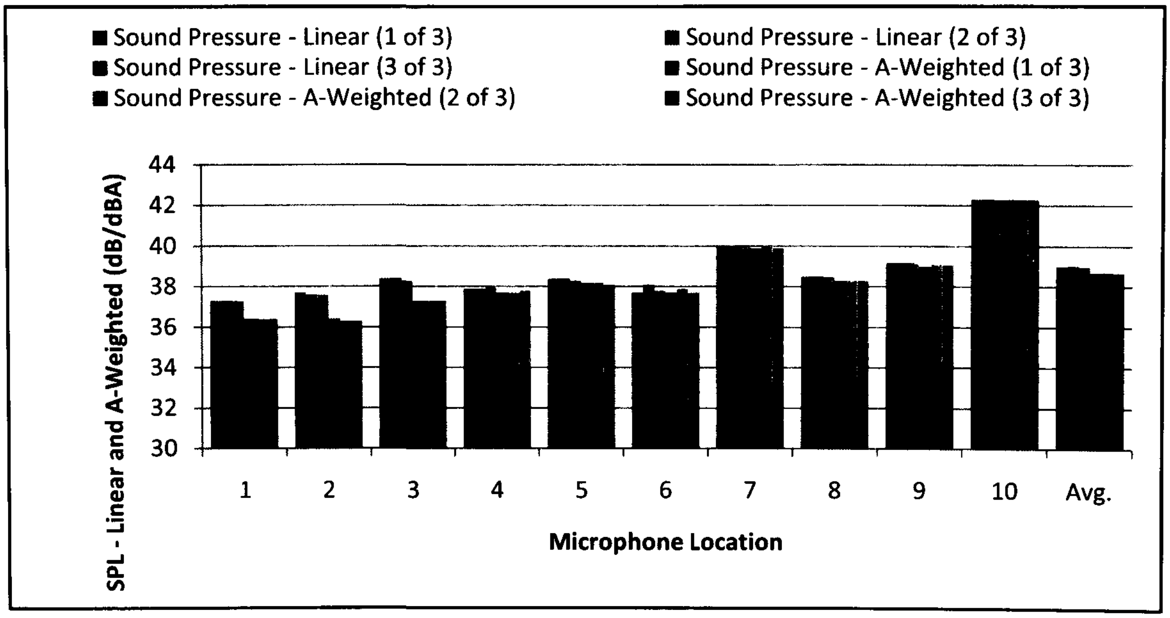

Figure 5-2: Repeatability – Individual Fans – Stand-Alone, GPU @8V

5.3.3 FAODCS – System Idle

Figure 5-3 illustrates the repeatability of the test done on the FAODCS while running system idle. Keeping in mind that there are multiple noise sources operating simultaneously, it is expected that the differences between the trials may be greater than those presented thus far. However, it may be seen that there is very little difference between the results measured for each trial. The greatest differences between the three trials were measured at microphone location 5, where there was a 0.3 dB and a 0.2 dBA difference between trials 1 and 2.

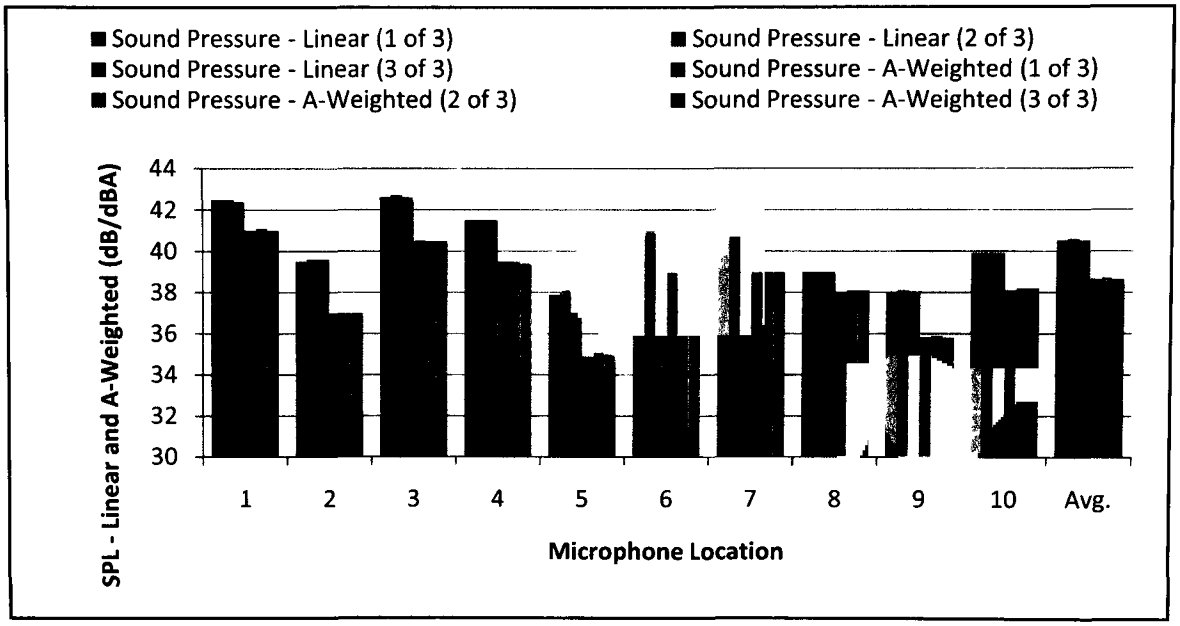

Figure 5-3: Repeatability – FAODCS – System Idle

5.3.4 FAODCS with Acoustic Insulation – GPU Benchmark

Figure 5-4 illustrates the repeatability of the test done on the FAODCS with acoustic insulation while running the GPU benchmark. Again, there are multiple noise sources operating simultaneously and it is expected that the differences between the trials may be greater than those where only once source is operating. However, again there is very little difference between the results measured for each trial, although there is more of a difference in the results than there was for the system idle configuration. This may be due to the additional complexity of the GPU benchmarking software. The greatest differences between the three trials were measured at microphone location 9, where there was a 0.4 dB and a 0.5 dBA difference between trials 1 and 3.

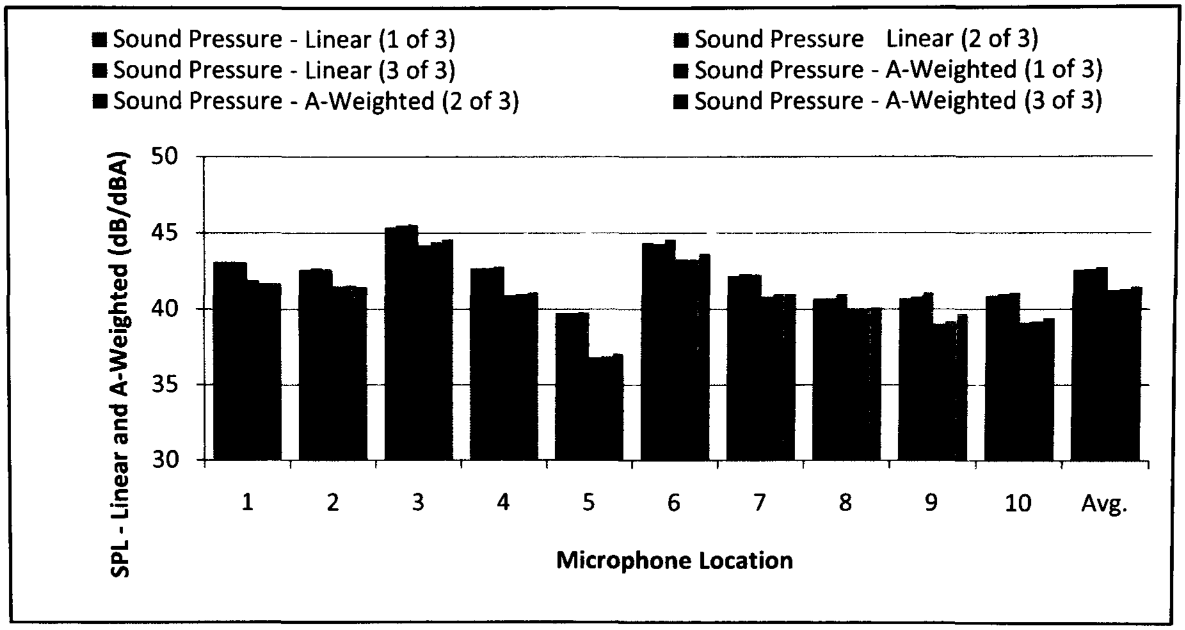

Figure 5-4: Repeatability – FAODCS with Acoustic Insulation – GPU Benchmark

5.3.5 Loudness

Figure 5-5 and Figure 5-6 illustrate the repeatability of the loudness measurements taken for the same examples shown above. Since loudness is a much more complicated value to calculate (see work done by Defoe [2]) it is expected that there may be some variation between the results of the three trials for each of the examples. However, the results are very similar. For the first three cases (CPU @ 12V, GPU @8V, system idle) the greatest difference between the trials observed is 0.05 sones. It should be noted that the maximum resolution of the measurement system used to determine loudness is to the nearest hundredth of a sone. For the fourth case, the GPU benchmark, there are higher discrepancies, the greatest being 0.15 sones, at microphone location 7 between trials 2 and 3. See Figure 5-6. This is not unexpected since the acoustical content is far more complicated during this test. Even very small changes in the noise source can alter loudness calculations. However, a difference of 0.15 sones is equal to about 4% to 4.15 % of the actual measured quantities.

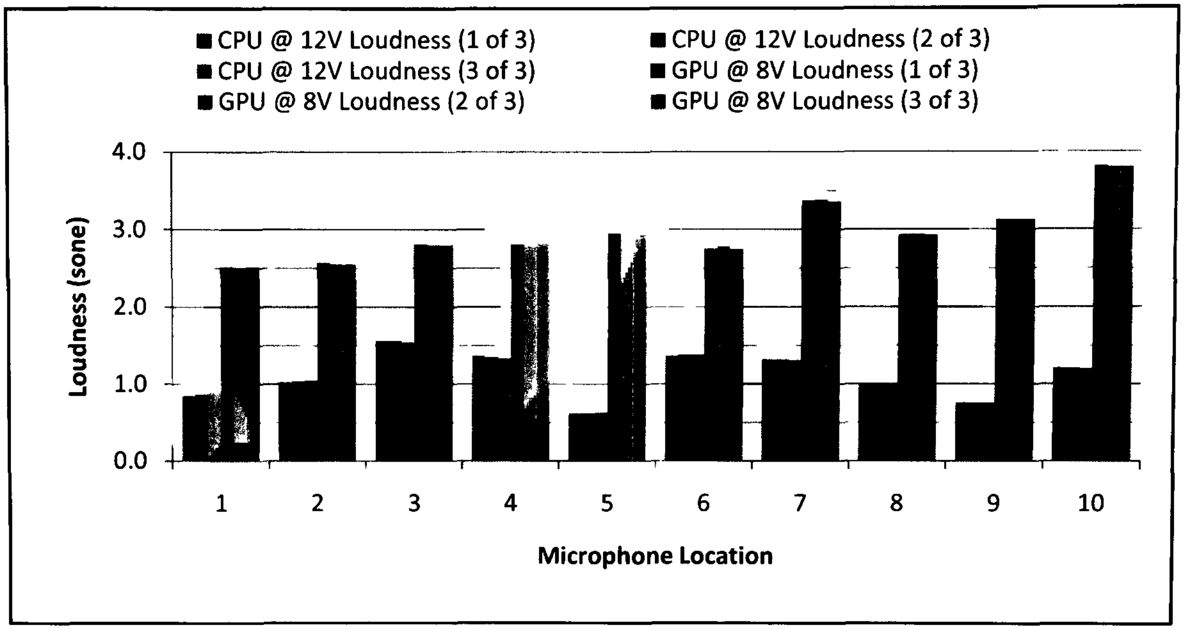

Figure 5-5: Repeatability – Loudness, CPU @ 12V and GPU @ 8V

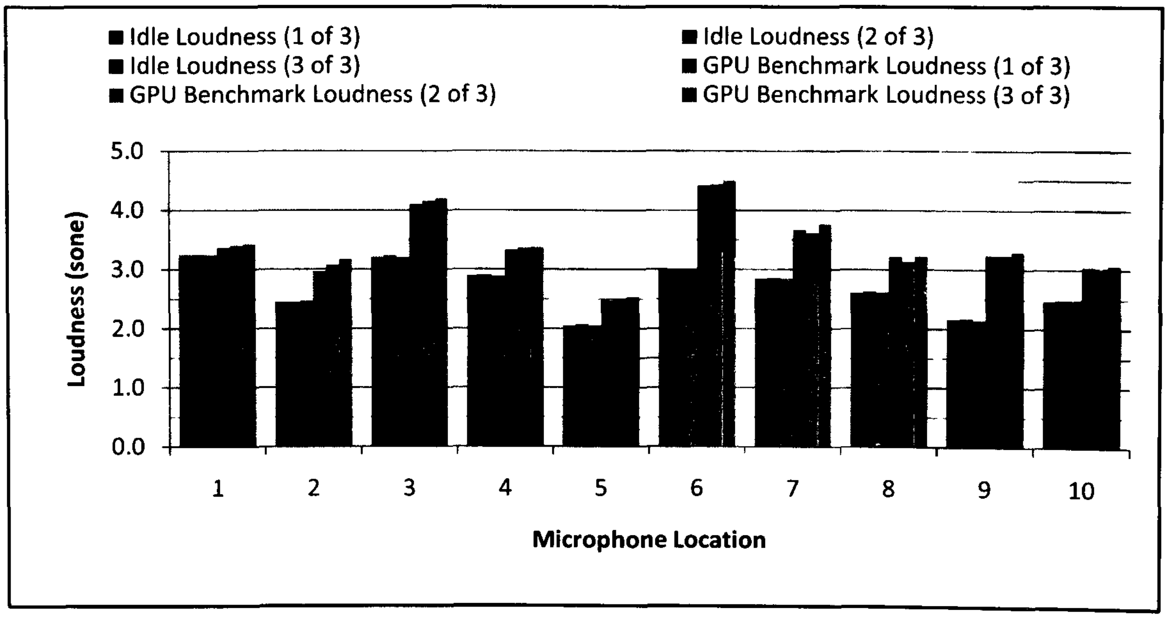

Figure 5-6: Repeatability – Loudness, System Idle and GPU Benchmark

It was assumed for this thesis work that all noise sources were steady-state. This is assumption is valid based on the results just presented. At worst there was a 0.5 dB and a 0.5 dBA variation between the three trials. There are nearly two orders of magnitudes between the actual values measured and these variations. Three samples are enough because there is such little variation between the measured values. Thus, the assumption of steady-state is valid.

5.4 Analysis of Fully Assembled and Operating Desktop Computer System – Worst Case

An attempt is now made to determine the worst (or most complex) experimental case. The results from the FAODCS acoustical measurements are now analysed. Based on findings from the all of the testing performed, it is relevant to point out the worst case of acoustical performance. By examining the following figures, it is clear that the worst case is that of the GPU benchmark condition. The highest SPLs (linear and A-weighted) achieved during the measurements performed occurred during this operating condition. In comparison with the idle operating configuration, there is a significant difference between the levels as well as differences between microphone locations. Figure 5-7 shows that the sound levels during the GPU benchmarking test are greater than any of the other tests.

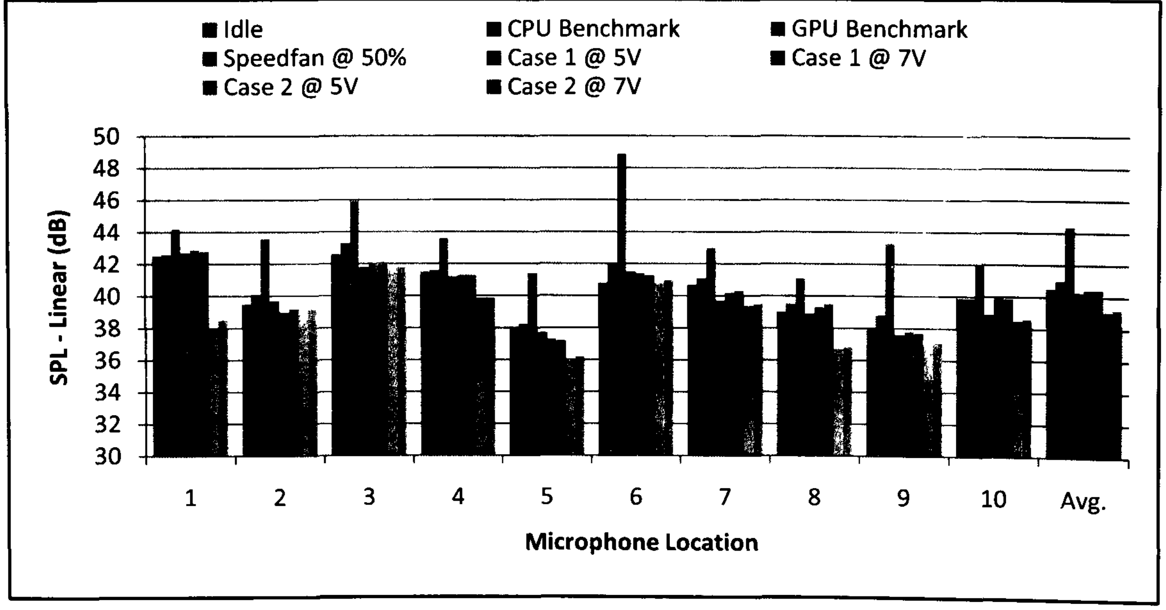

Figure 5-7: FAODCS SPL – Linear

As expected, the greatest level is recorded at microphone location 6, very near the exhaust of the GPU fan. There is variation between the levels during the other operating conditions. Modifying the Case fans does appear to reduce levels at microphone locations 1 and 8. Unfortunately, modifying case fan 1 does not appear to make a very noticeable difference at location 6, where it is nearest. Clearly the dominant noise source is the GPU fan, even when it is not running the benchmarking program. Figure 5-8 illustrates the A-weighted sound levels. Similar results are observed except that the levels during the GPU benchmarking test are not reduced. The differences between the levels during the GPU benchmarking and the other tests are more prominent. The level at location 6 is greater than before A-Weighting. This gives insight into the frequency content of the signal. Between frequencies of 1000 Hz and 6000 Hz, A-Weighting causes an increase in perceived SPL (see Appendix A). This is because humans are more sensitive to levels in this frequency range.

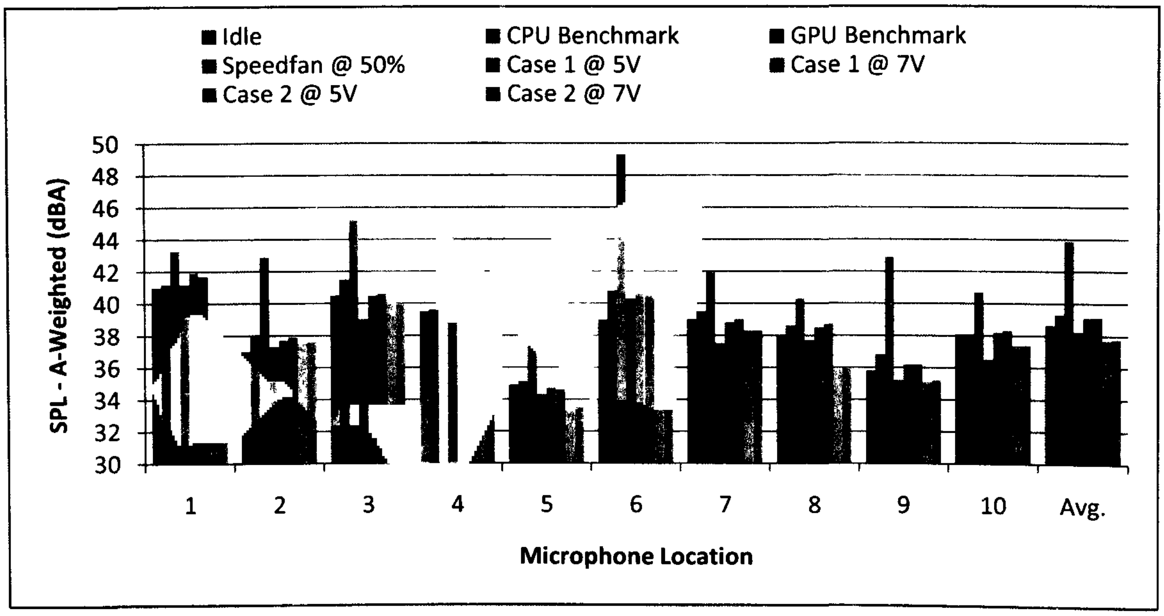

Figure 5-8: FAODCS SPL – A-Weighted

Figure 5-9 illustrates the loudness results of the FAODCS testing. The greatest values at each microphone location are again observed during the GPU benchmarking test. This is followed by the values during the CPU benchmarking test, although the other values measured follow closely after. There is a significant difference at location 1 when case fan 2 is modified. This hardware modification appears to improve the acoustic emissions versus idle conditions. However, it is unknown if this is significant if the computer is running the GPU benchmark.

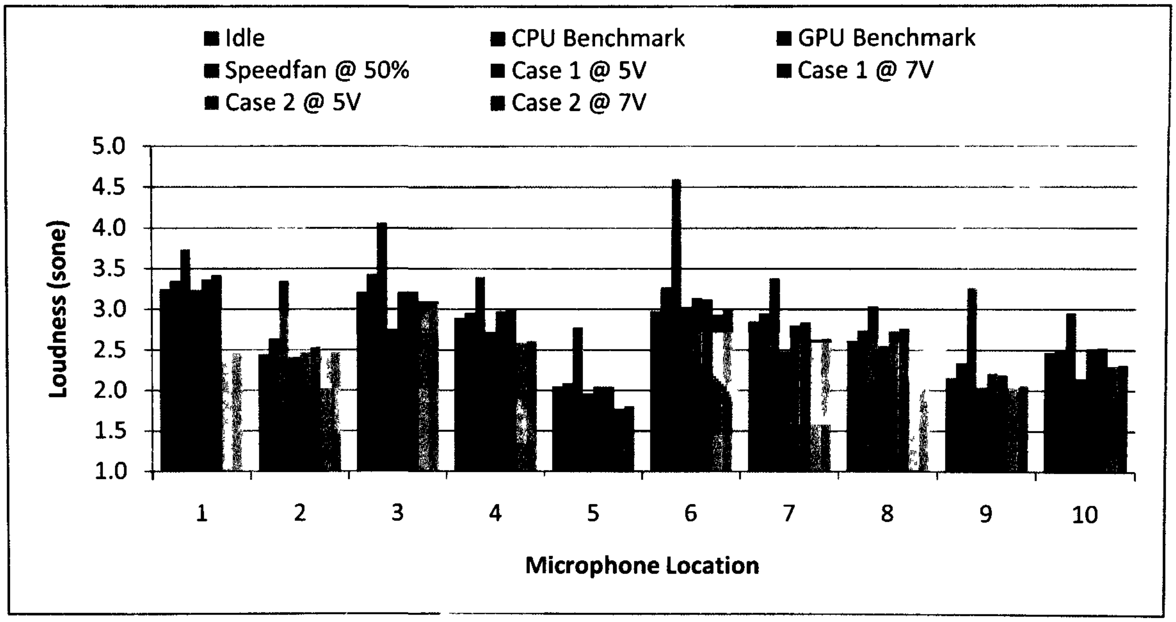

Figure 5-9: FAODCS Loudness

The same conditions are examined again, but now acoustic insulation is installed within the computer case. The linear SPLs are examined in Figure 5-10. There are similarities and differences between this configuration and without acoustic insulation. One similarity is that peak SPLs occur while the GPU benchmark test is running. However, the greatest level measured was at microphone location 3, not 6. Overall, the levels are less than they were without acoustic insulation, ranging from a difference of 0.1 dB to 4.5 dB at microphone location 6 during the GPU benchmark test. Any difference greater than 3 dB is of importance because it indicates a noticeable level change with respect to human perception. This indicates that some attenuation taking place.

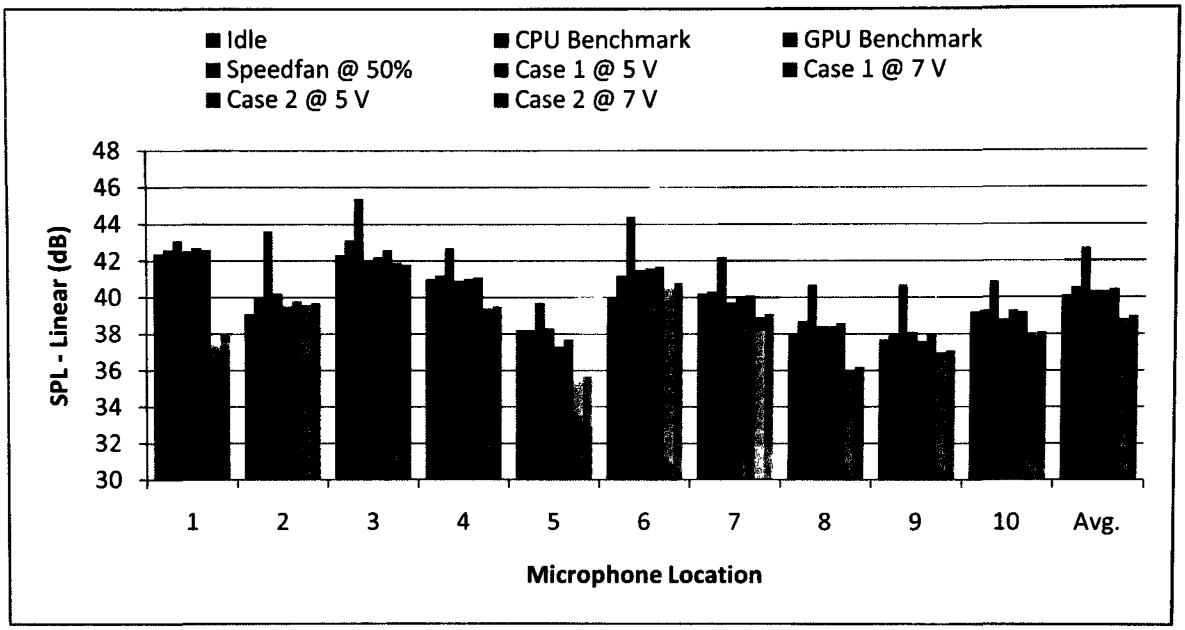

Figure 5-10: FAODCS w/AI SPL – Linear

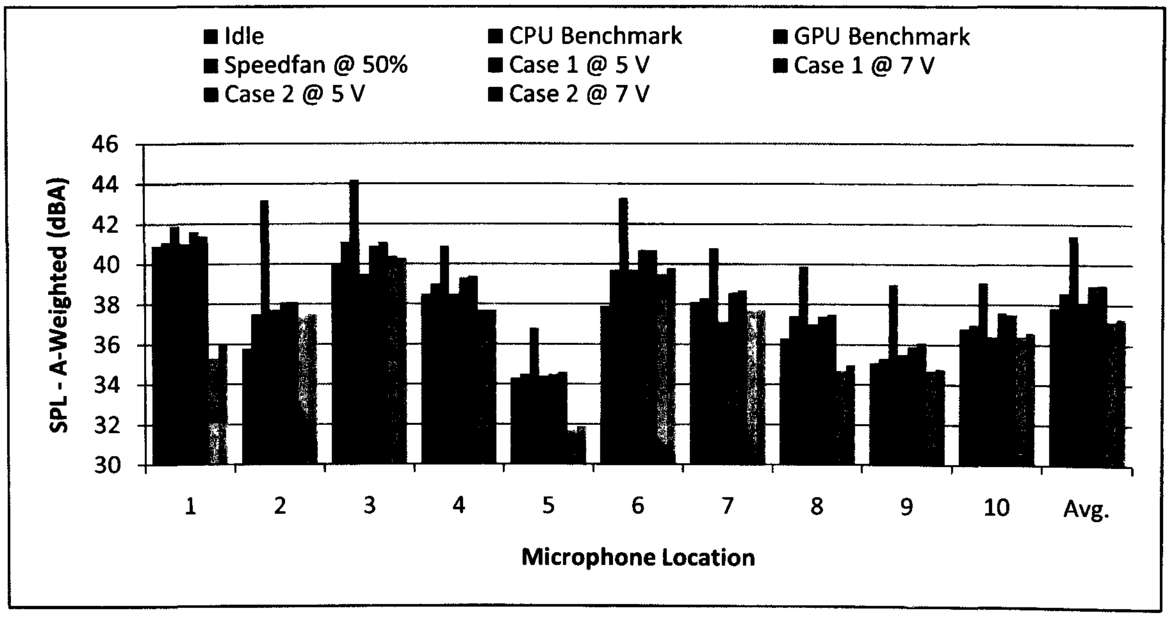

Figure 5-11: FAODCS w/AI SPL – A-Weighted

Figure 5-11 shows the A-weighted SPLs exhibits similar phenomena to that which was observed earlier. The levels are less than the linear values, although it is clear that the GPU benchmarking levels stand out from the rest as the dominant source. Having a difference of more than 3 dB from the idle levels at all microphone locations (with the exception of 1) indicates a perceivable difference when this test was run. However, the levels are less than those observed without the acoustic insulation. This means that the insulation is providing some attenuation.

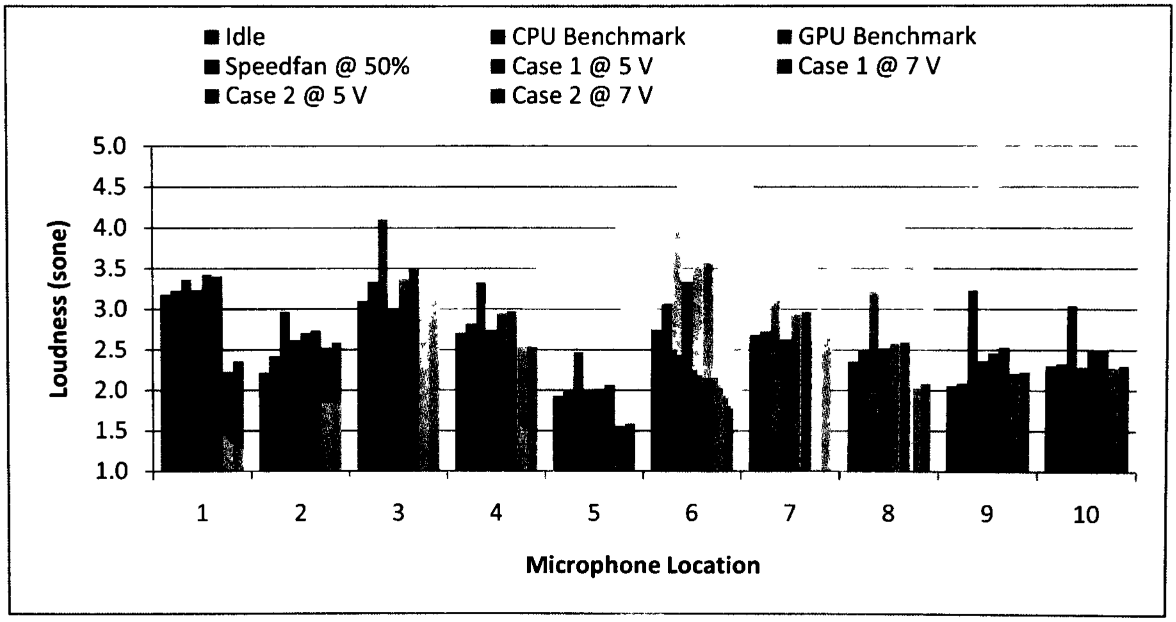

Figure 5-12: FAODCS w/AI Loudness

Figure 5-12 illustrates the loudness results of the FAODCS with acoustic insulation. The greatest values at each microphone location are again observed during the GPU benchmarking test. Again, there is a significant difference at location 1 when case fan 2 is modified, and appears to improve the acoustic emissions. At location 6 the loudness value of the GPU benchmark testing is only slightly less than it was without acoustic insulation. This indicates that although the acoustic insulation may reduce overall SPL, it does little to reduce loudness. There may be some characteristics of the noise produced by the GPU fan or cooling solution that increase the loudness value of the entire computer system. It is clear that this is the most problematic area for the acoustical performance of the computer system.

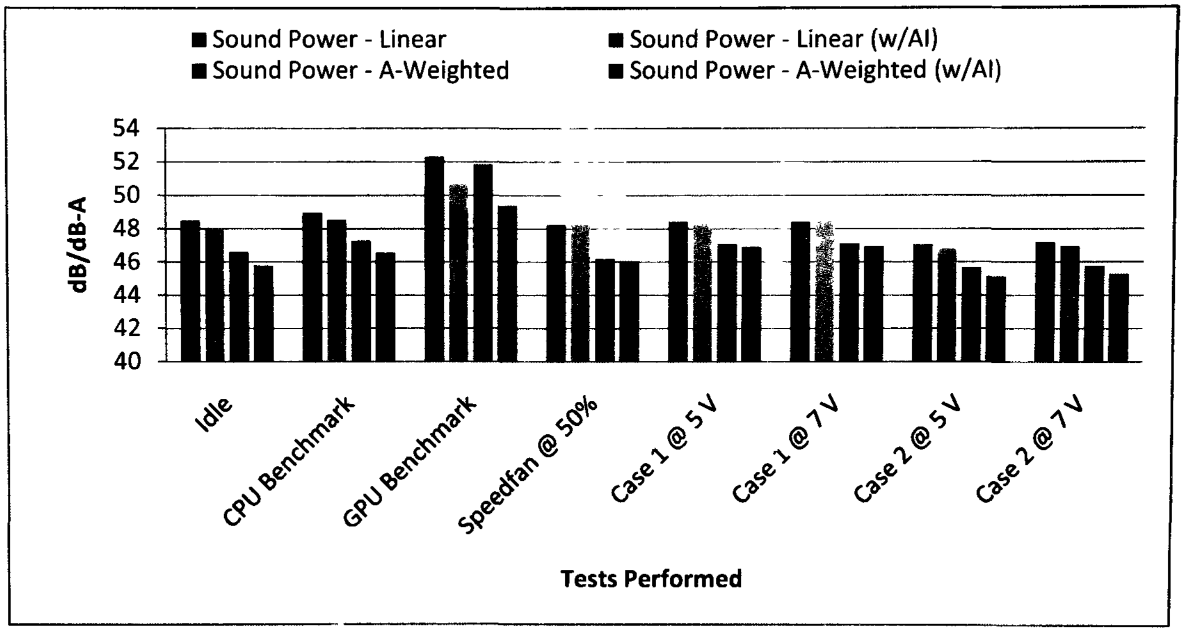

Figure 5-13: FAODCS SWLs – Linear and A-Weighted

Figure 5-13 summarises the sound power calculations for the eight FAODCS conditions with and without acoustic insulation. It is clear that the GPU benchmark is the source of the greatest levels measured and needs to be the focus of further study.

5.5 Analysis of RPM and BPF Data

It is important to now discuss each of the individual fans in detail. By doing so, some of the acoustical phenomena observed in the previous section can be understood.

5.5.1 RPM and BPF for Fully Assembled and Operating Desktop Computer System

The following tables provide fan RPM and blade passing frequency (BPF) information.

Table 5-3 lists the average fan RPM and corresponding BPF values for all fans and conditions tested during the FAODCS operating configurations. Important RPM and BPF values are highlighted. Recall that a fan's BPF is calculated using the following equation.

$$BPF = (\#\ of\ blades) \times \frac{RPM}{60} \tag{7}$$

Table 5-3 RPM and BPF for All Fans during FAODCS Operating Configurations

Fan	Condition	RPM	BPF (Hz)
CPU	Idle	3260	489
Case 1		1242	145
Case 2		1895	221
PSU		1095	128
GPU		1842	890
CPU	CPU Benchmark	3230	485
Case 1		1225	143
Case 2		1862	217
PSU		1110	130
GPU		2115	1022
CPU	GPU Benchmark	3215	482
Case 1		1238	144
Case 2		1875	219
PSU		1147	134
GPU		2948	1425
CPU	Speedfan @ 50%	1770	266
Case 1		1245	145
Case 2		1892	221
PSU		1100	128
GPU		1853	896

Fan	Condition	RPM	BPF (Hz)
CPU	Case 1 @ 5V	3265	490
Case 1		523	61
Case 2		1852	216
PSU		1073	125
GPU		1837	888
CPU	Case 1 @ 7V	3263	490
Case 1		743	87
Case 2		1868	218
PSU		1070	125
GPU		1832	885
CPU	Case 2 @ 5V	3275	491
Case 1		1230	144
Case 2		798	93
PSU		1055	123
GPU		1830	885
CPU	Case 2 @ 7V	3268	490
Case 1		1243	145
Case 2		1033	121
PSU		1095	128
GPU		1842	890

Based on the RPM data provided in the tables, it is possible to determine at approximately what voltage levels each of the computer fans operate at during the FAODCS operating configurations The BPF data is used in the next section

5.5.2 RPM and BPF for Individual Fans

In order to better understand the characteristics of the computer system as a whole, it is now appropriate to examine each of the individual fans independently This should give clues as to their behaviour while installed and operating within the desktop computer system Table 5 4 lists the average fan RPM values and the corresponding average BPF for all fans and conditions tested during the individual fan operating configurations (Stand-Alone, In-System, and In System with Acoustic Insulation) Again, important RPM and BPF values are highlighted They correspond to the values highlighted previously in Table 5 3

Table 5-4 RPM and BPF for All Fans during Individual Fan Operating Conditions

Fan	Condition	RPM	BPF (Hz)
CPU	4V	750	112
	5V	1068	160
	6V	1383	207
	7V	1696	254
	8V	2010	302
	9V	2321	348
	10V	2621	393
	11V	2890	434
	12V	3144	472
Case 1	5V	503	59
	7V	715	83
	12V	1180	138
Case 2	5V	738	86
	7V	1032	120
	12V	1695	198

Fans	Condition	RPM	BPF (Hz)
PSU	On	890	104
GPU	4V	1512	731
	5V	1904	920
	6V	2266	1095
	7V	2593	1253
	8V	2898	1401
	9V	3177	1536
	10V	3424	1655
	11V	3665	1771
	12V	3868	1869

Figure 5-14 illustrates the BPFs of the fans tested as a function of the applied voltage level The PSU fan is omitted because it was not tested at various voltage levels, only the default level that it operates at as determined by the PSU itself

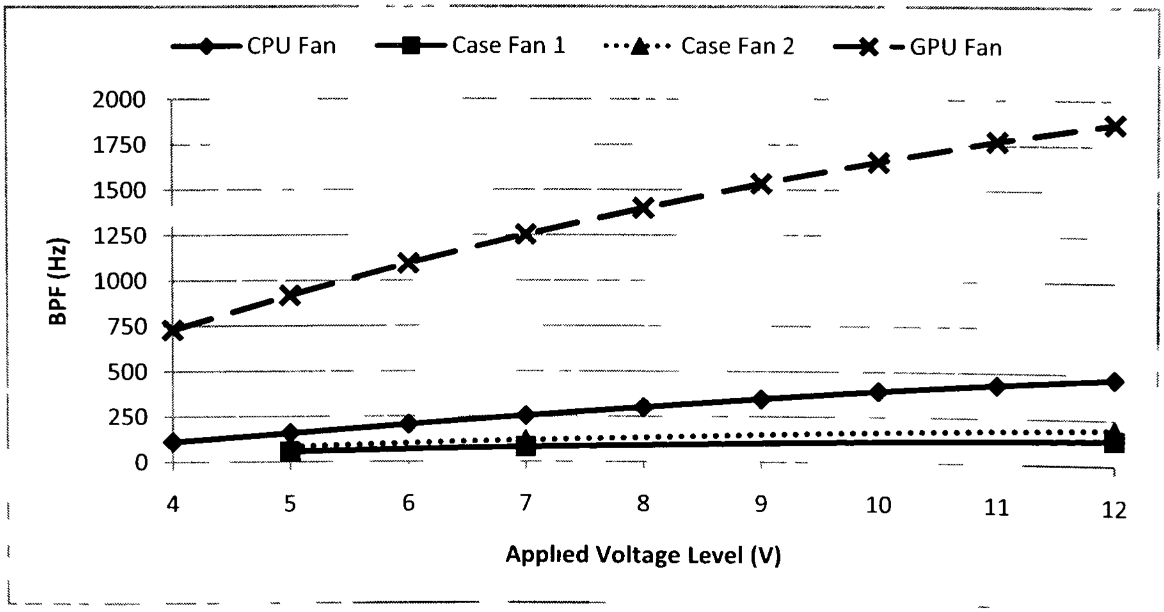

Figure 5-14 Blade Passing Frequency as a Function of Applied Voltage Level

Clearly the GPU fan has the highest BPFs. Even at its lowest operational voltage level it surpasses the BPF of the next closest fan, the CPU fan. The case fans have the lowest BPFs, staying below 200 Hz, the high-pass cut-off frequency of the hemi-anechoic room. This means that a portion of the acoustical content from these fans is lost due to the 200 Hz high pass filter. It is not clear if the remaining acoustical content will be significant compared to the other fans.

5.6 Analysis of Individual Fan Operating Configurations

In this section, the individual fans are analysed. In Section 5.4, it was discovered at what blade passing frequencies the fans perform at during their operation within the FAODCS during various conditions. These are cases of interest. The individual fans were tested independently and the results from the experimentation performed are now given and analysed. The emphases are on the cases of interest, which are based on the results of the FAODCS testing, as well as any information regarding the attenuation techniques employed. The cases of interest that will be examined are given in Figure 5-15.

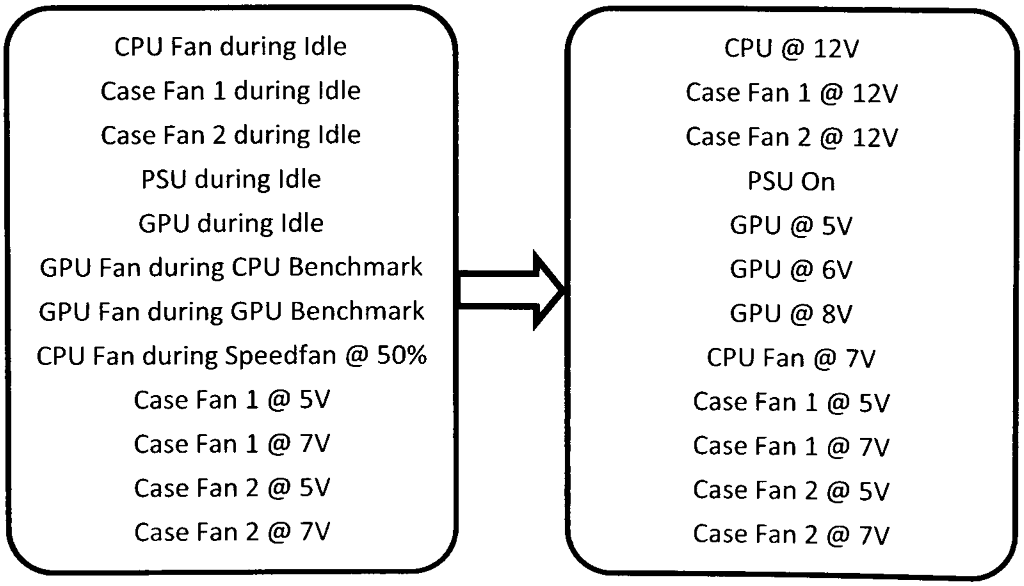

Figure 5-15: Cases of Interest

5.6.1 Frequency Analysis

In addition to the SPLs and loudness values for the tests performed, it is also of importance to analyse the frequency content of the pressure signals studied. It is expected that the signals that yielded a lower sound level after A-weighting will contain prominent frequencies less than 1000 Hz. It is expected that signals that yielded a higher sound level after A-Weighting (GPU fan) will contain prominent frequencies greater than 1000 Hz. First, the ambient pressure signal is analysed. Recall that all pressure signals were high-pass filtered at 200 Hz. At this point it is relevant to illustrate the importance of the 200 Hz high-pass filtering. Figure 5-16 illustrates the 1/12 octave band SPLs during an ambient level test, that is, when are there are no sources of sound present within the hemi-anechoic testing environment. In blue are the levels before the 200 Hz high-pass filtering, and in red are the levels after. Vertical lines indicate the boundaries of two full octave bands.

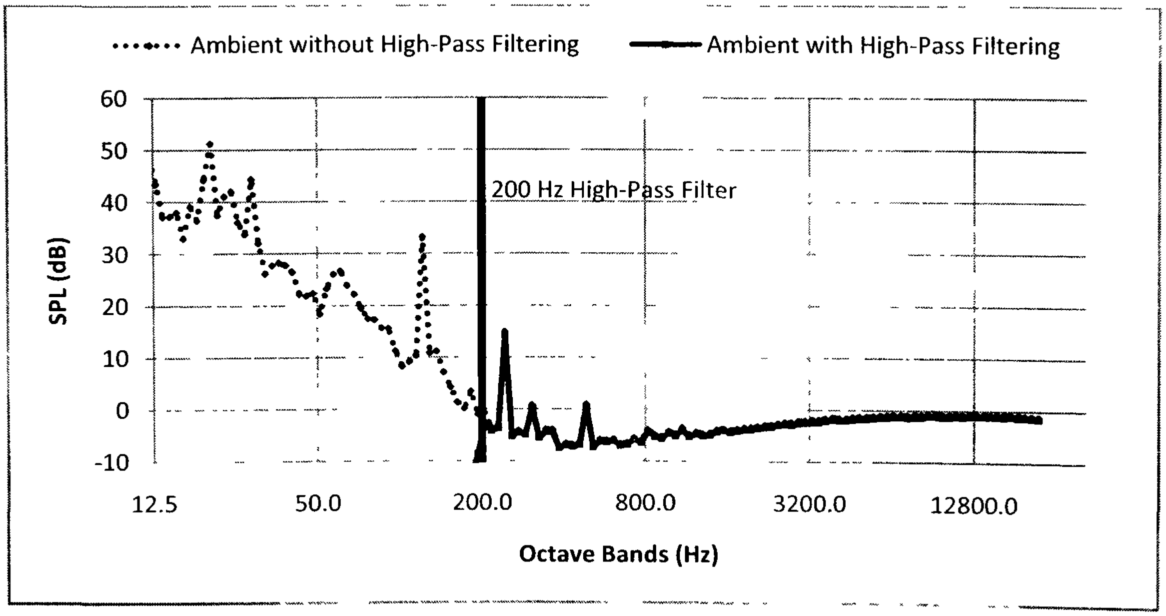

Figure 5-16: 1/12 Octave Band Ambient SPLs – Microphone 1

As can be seen, there is significant frequency content below 200 Hz. These levels come from sources that are outside of the hemi-anechoic testing environment and are beyond the control of this experimentation. After the high-pass filtering takes place, all of this content has been removed. Unfortunately, there are still positive level peaks present at 243 Hz, 306 Hz, and 486 Hz. The 306 Hz and 486 Hz peaks are negligible since they are less than 1 dB. However, the 243 Hz peak is a problem because of its high SPL of 15 dB (14.4 dB after high-pass filter). This peak is a harmonic of a greater peak of 33.3 dB at 121.5 Hz which is itself a harmonic of electrical line noise of 60 Hz from a transformer room near the hemi-anechoic testing environment. The reason that there is not a peak at 60 Hz is unknown. This peak will likely be present in all of the frequency spectrums analysed. Note that this level is difficult to hear as the A-weighting attenuation at this frequency is about -9 dB. It should also be noted that by implementing the high-pass filter at 200 Hz for the ambient pressure signal, the total logarithmic SPL is reduced from 56.8 dB to 18.4 dB.

5.6.2 Analysis of CPU Fan

Results from the CPU fan measurements at 7V and 12V (BPF of 254 Hz and 472 Hz respectively) are analysed. The linear SPLs are examined first and are shown in Figure 5-17 As expected, the levels measured at 12V are greater than those at 7V for each test at each microphone location. The differences in SPLs range from 4 dB to over 10 dB and thus is enough to be perceivable (>3dB) and thus utilising the Speedfan software (or other CPU fan speed reduction software) does appear to affect measured SPL. Surprisingly, the levels measured during the In-System tests are greater than during the Stand-Alone test. The levels measured at microphone location 3 are the greatest overall, most likely because it is located very near the vents at the back of the case as well as the side of the case. One possible explanation for this is as follows. Although the computer case may provide direct line attenuation of the noise source of the fan itself, it is possible that it provides additional noise sources. These additional noise sources may include the grating in the vents of the case. This is clearly an aeroacoustics phenomenon. In addition to the fan moving air, the case is causing the air to move through a series of jets. Lighthill [56] and [57] discussed aeroacoustics involving both fan noise and jet noise. This phenomenon will be explored further during the analysis of the other fans.

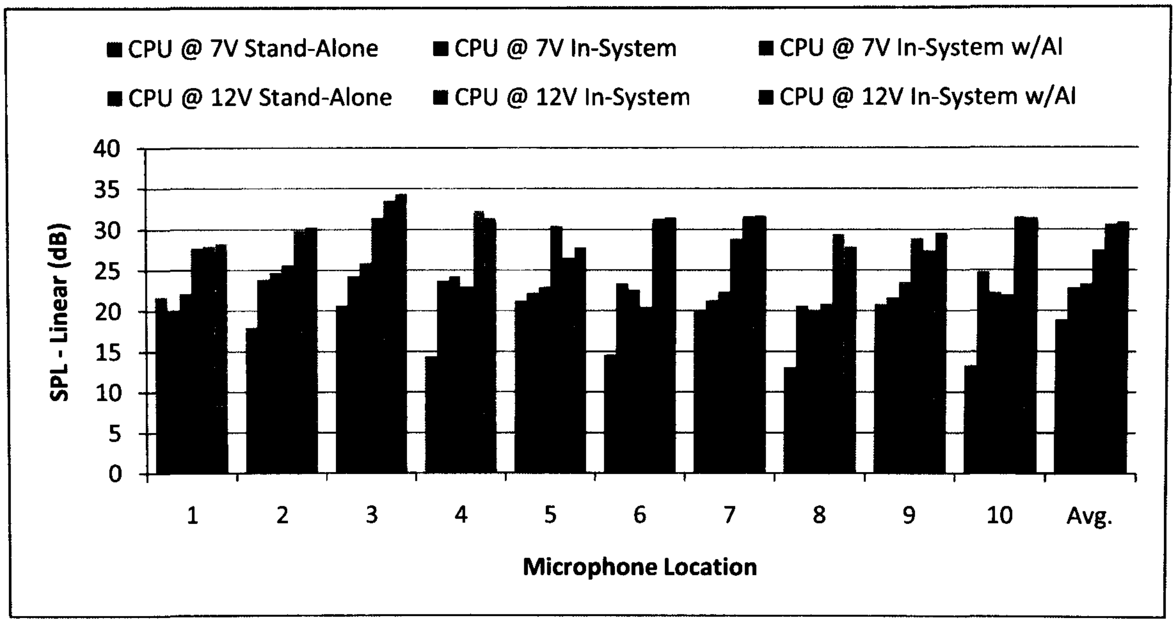

Figure 5-17: CPU Fan SPL – Linear Results

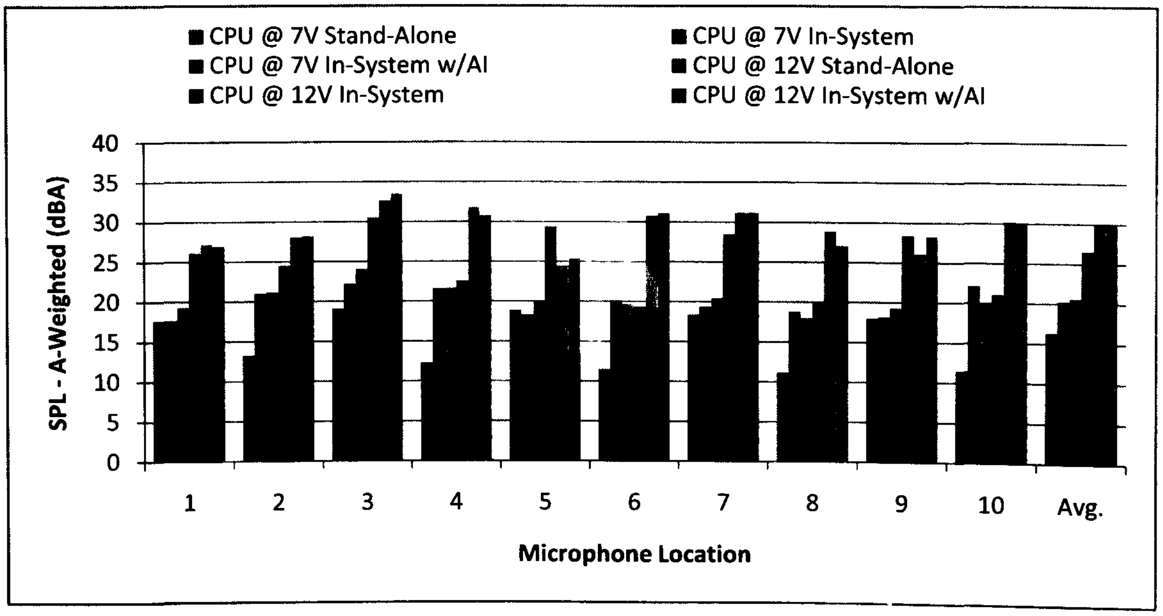

Figure 5-18: CPU Fan SPL – A-Weighted Results

The A-weighted SPLs are shown in Figure 5-18 and they reveal much of the same characteristics as the linear levels. The values are less than those of the linear levels. This reveals important information about the frequency content of the noise source. It is clear that the attenuation that takes place is in the frequency range between 100 Hz and 1000 Hz (-19dB to 0 dB attenuation), which is the range of the BPFs of the CPU fans at the speeds under consideration. Examining the measurement frequency spectrums reveals what prominent frequencies are present.

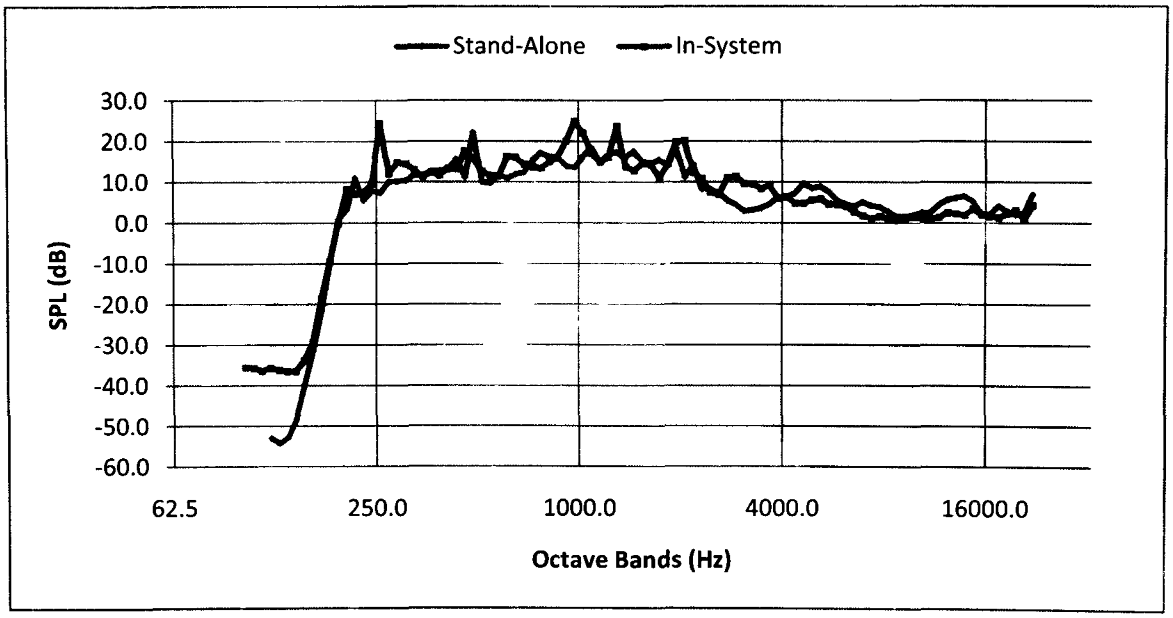

Figure 5-19: CPU Fan @ 12V – Microphone Location 3

Figure 5-19 illustrates the frequency content of the pressure signal from microphone location 3 during the CPU tests at 12V. Stand-alone (blue) and in-system (red) results are shown. The overall levels for these signals are 31.4 dB and 33.5 dB respectively, and the BPF during these tests is 472 Hz. For the stand-alone test, there is a peak at 486 Hz, which is close to the BPF For the in-system test, there are several peaks at frequencies including 257 Hz, 971 Hz, 1297 Hz, and 1943 Hz. Clearly there are more interactions going on while the fan is installed in the computer case. This results in a higher overall level. Note that there is negative SPL content shown on the figure. These levels correspond to pressure content that is below the reference pressure of 20 micro Pascals. Although negative sound levels are unperceivable to human hearing, they are nevertheless important because summing them up is necessary to find the total overall SPL.

The loudness values are shown in Figure 5-20. Here, the distinction between the two operating speeds is clear. The loudness values are much greater during the 12V testing, especially during the In-System tests. This indicates that although the case is contributing in a negative way to the overall acoustical acceptability of the computer system, for this particular fan, the operation at a higher speed is the primary contributor to loudness.

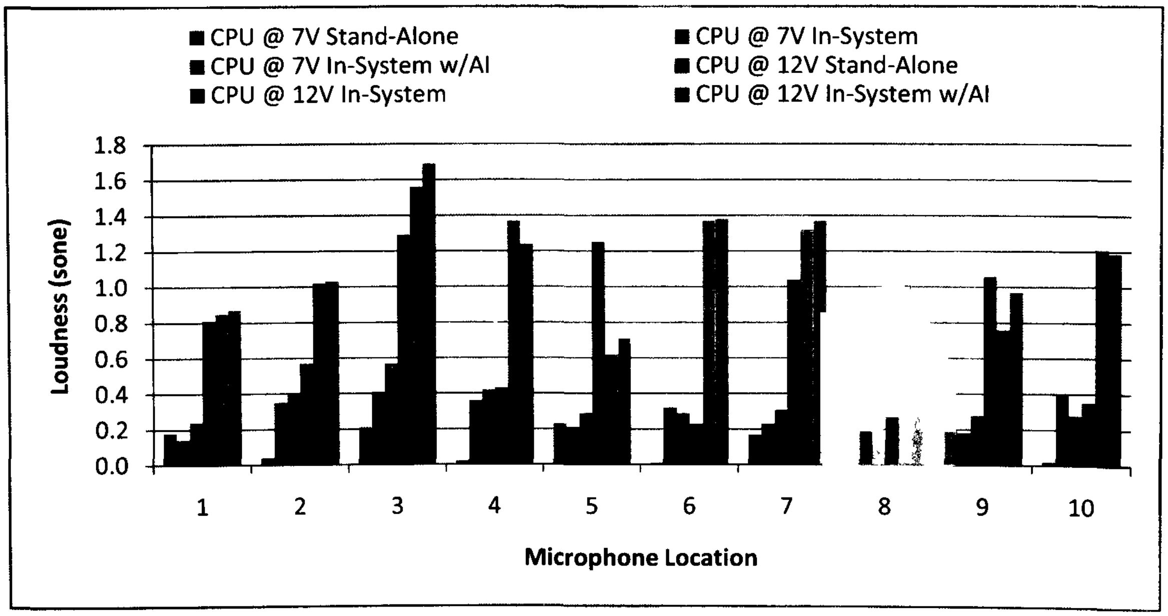

Figure 5-20: CPU Fan Loudness Results

The final comparison of results for the CPU fan is shown in Figure 5-21. Shown are the results for the calculated SWL, both linear and A-weighted. As expected, the levels are higher with increased applied voltage. This corresponds with the increase in BPF from 254 Hz to 472 Hz. Although the A-weighted levels are less than the linear levels in each case, the difference is less during the 12V tests. This indicates that the prominent frequencies present are closer to (but still less than) 1000 Hz. Recall that between 1000 Hz and 6000 Hz A-weighted attenuation is actually an increase in level rather than a reduction. Again, unexpectedly the levels calculated while acoustic insulation was installed in case are slightly higher than those without. This adds evidence to theory that the computer case contributes significantly to the measured SPL and thus to the calculated SWL. The acoustic insulation may not provide any attenuation, since none was installed in such a way as to block any vents or air passages in the case. If this was done, it is likely that significant reduction in SPL would be measured. However, this is not an appropriate solution, since it would be impossible for cool ambient air to enter the case.

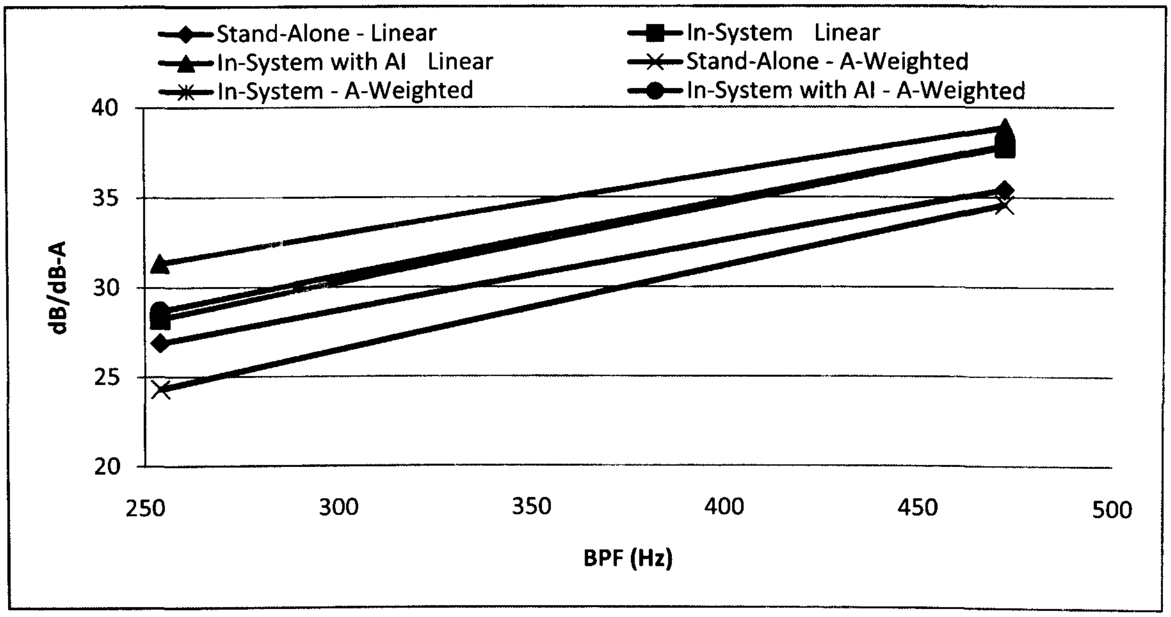

Figure 5-21: CPU Fan SWL Results

5.6.3 Analysis of Case Fan 1

The analysis now focuses on case fan 1, which is the larger of the case fans and is located at the rear of the computer case, exhausting out toward microphone location 6. The Individual – Fan measurement results for case fan 1 are now shown in Figure 5-22. Results are shown for testing done at 5V, 7V, and 12V (BPFs of 59 Hz, 83 Hz, and 138 Hz respectively). There is an obvious increase in the SPL as the voltage level increases. However, this is only true for tests at the same operating configuration. As was the case for the CPU fan, it appears that the computer case contributes to the measured SPLs. Also, the acoustic insulation does not appear to help attenuate the levels measured, but rather increase the SPLs. However, the difference between the SPLs during the In-System tests is minor compared to the difference between the In-System tests and the Stand-Alone test. In any case, reducing the fan speed does appear to significantly reduce the SPL. This is intuitive although somewhat unexpected since the BPFs of case fan 1 are well below the 200 Hz cut-off frequency for the anechoic room. Further inspection of the applicable frequency spectrums may reveal if higher multiple harmonics of the BPFs are significant.

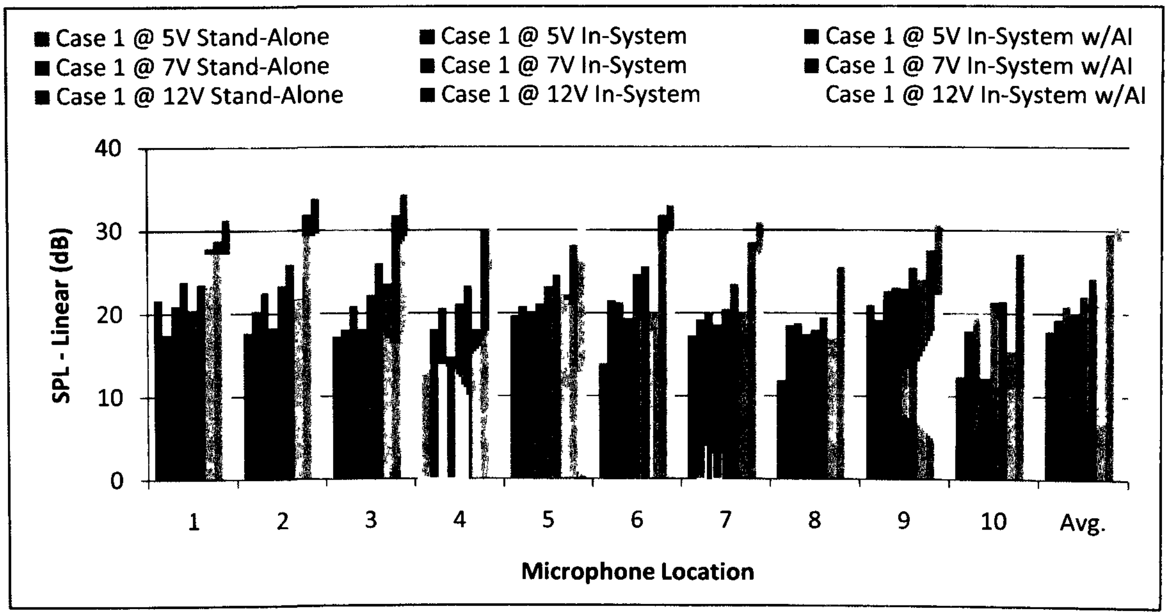

Figure 5-22: Case Fan 1 SPL – Linear Results

The A-weighted SPLs are shown in Figure 5-23. They show similar trends to those of the linear levels. Overall there is a reduction versus the linear levels, which again indicates prominent frequency content between 100 Hz and 1000 Hz

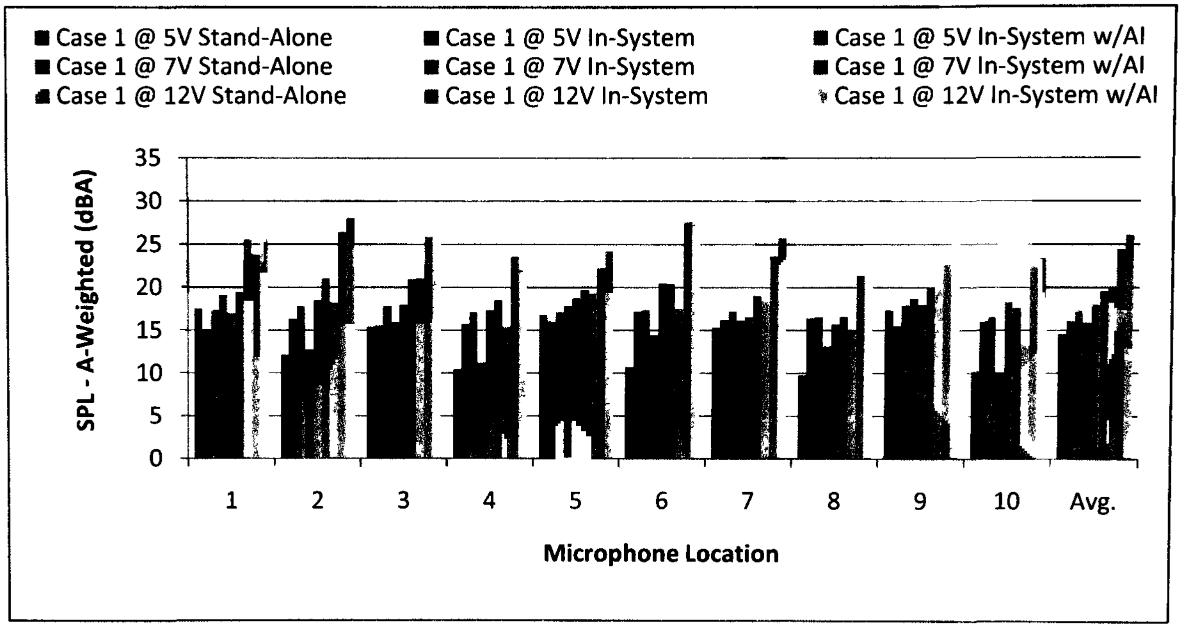

Figure 5-23: Case Fan 1 SPL – A-Weighted Results

Figure 5-24 shows the corresponding loudness results for case fan 1. Similarly to the CPU fan, the loudness values obtained when case fan 1 was operated at 12V are significantly higher than the loudness values obtained at the other fan speeds. This indicates that operating the fan at the lower speeds does improve acoustic acceptability. However, this is only one of the fans under consideration. Although improving its acoustical acceptability is important, it may be overshadowed by the results for one of the other noise sources. Recall that both the PSU and the GPU exhaust to the same approximate location as case fan 1, that being, the rear of the computer case, near microphone location 6.

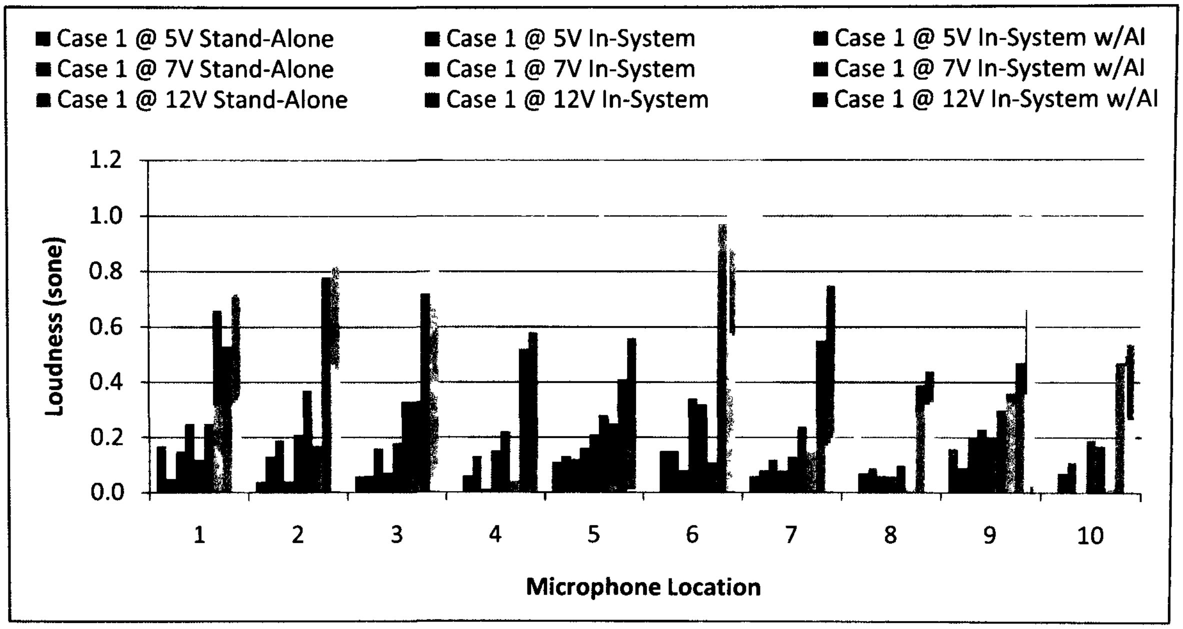

Figure 5-24: Case Fan 1 Loudness Results

Figure 5-25 shows the calculated SWL values for case fan 1. The SWL does increase with increasing fan speed. However, it also increases when tested in the system and then with the addition of acoustical insulation. Thus, not only does the case not necessarily provide any overall attenuation of the acoustical emissions, but the addition of the vent actually increases the SWL of the case fan. Since this cannot be avoided when operating the FAODCS, it is recommended that case fan 1 should be operated at the lowest fan speed possible. In each case shown, the A-weighted levels are lower than the linear levels. This is expected and desired.

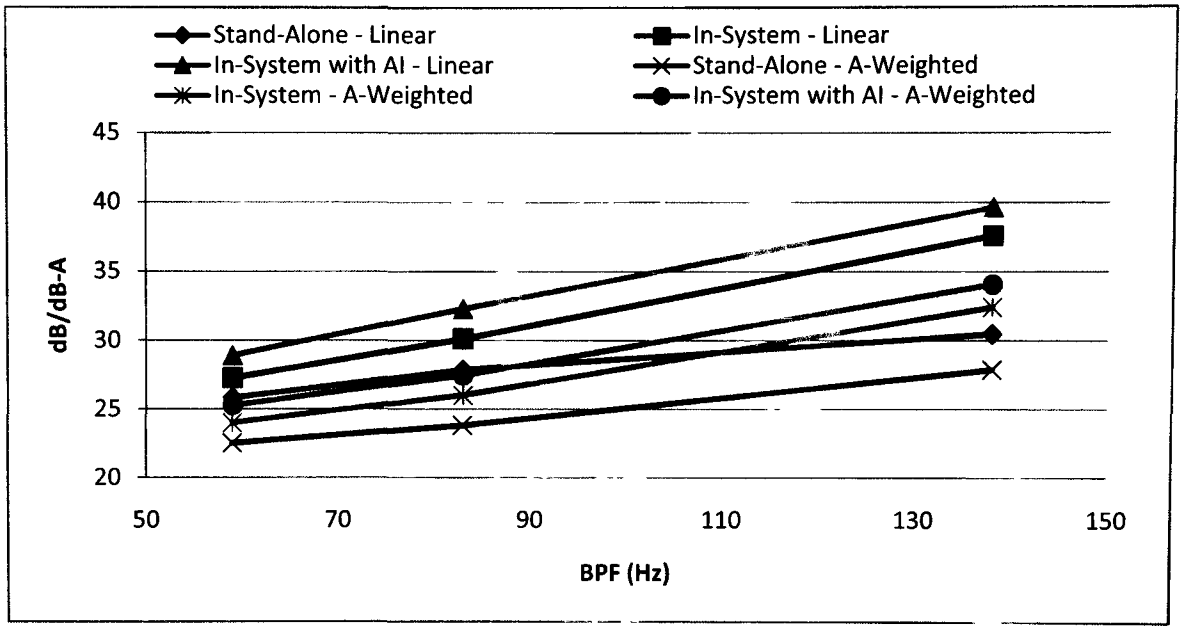

Figure 5-25: Case Fan 1 SWL Results

5.6.4 Analysis of Case Fan 2

Now the focuses moves to case fan 2, which is the smaller and faster-spinning of the case fans and is located at the front of the computer case, exhausting into the case. The Individual – Fan measurement results for case fan 2 are now shown in Figure 5-26. Results are shown for testing done at 5V, 7V, and 12V (BPFs of 86 Hz, 120 Hz, and 198 Hz respectively). There is an obvious increase in the SPL as the voltage level increases. However, this is only true for tests at the same operating configuration. Again it appears that the computer case contributes significantly to the measured SPLs. Also, the acoustic insulation does not appear to help attenuate the levels measured, but rather increase the SPLs. However, the difference between the SPLs during the In-System tests is minor compared to the difference between the In-System tests and the Stand-Alone test. The highest levels measured are at microphone location 1, which is intuitive since it is located upstream of the case fan 2 inlet. The average SPLs measured for case fan 2 are higher than those of case fan 1. One reason for this is because less of the acoustical content has been omitted due to high-pass filtering at 200 Hz. Once again, reducing the fan speed does appear to significantly reduce the SPL. However, the BPFs of case fan 2 are below the 200 Hz cut-off frequency for the anechoic room. It is expected that higher multiple harmonics of the BPF are present in the applicable frequency spectrums.

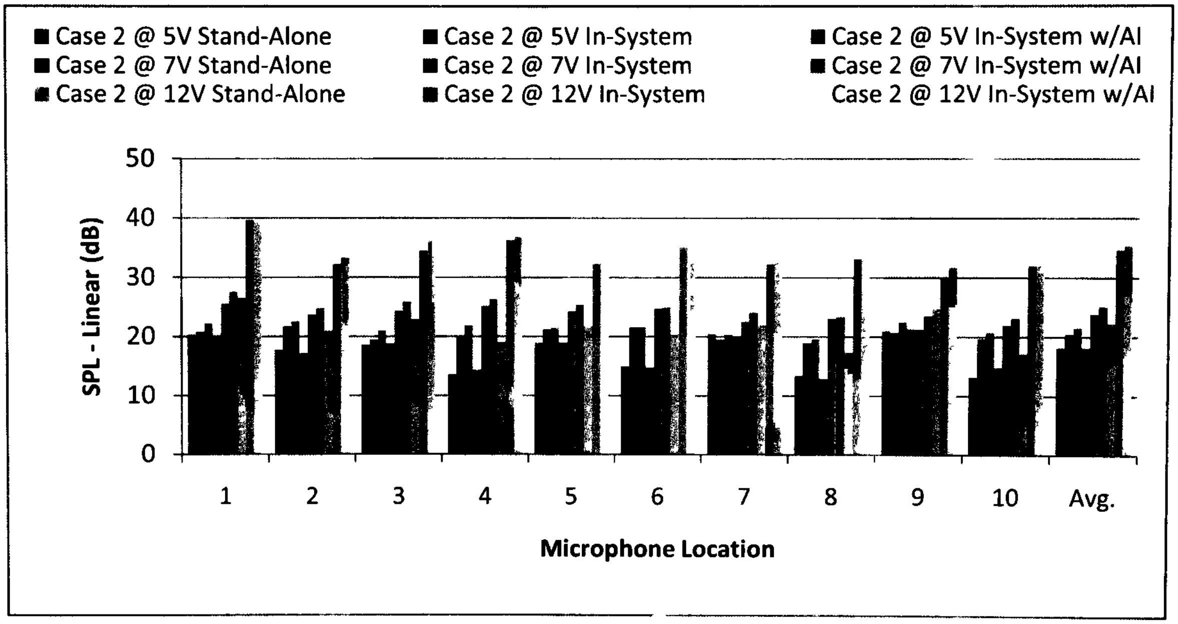

Figure 5-26: Case Fan 2 SPL – Linear Results

The A-weighted SPLs for case fan 2 are shown in Figure 5-27 They show similar trends to those of the linear levels. Overall there is a reduction versus the linear levels, which again indicates prominent frequency content between 100 Hz and 1000 Hz. This will be confirmed by investigating the frequency spectrums.

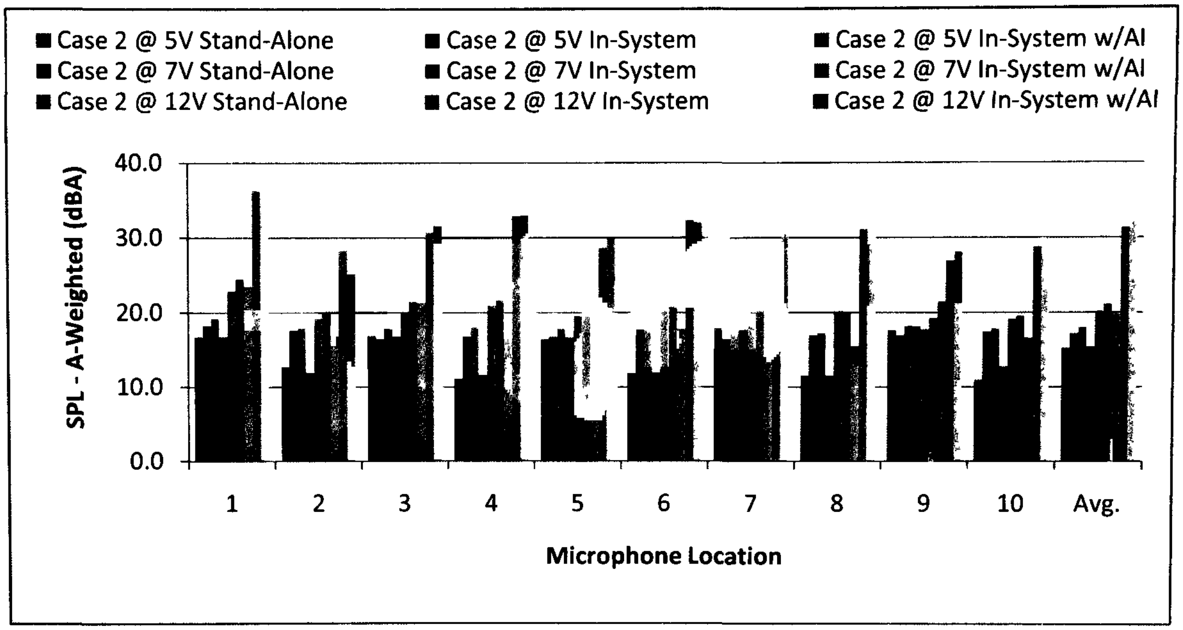

Figure 5-27: Case Fan 2 SPL – A-Weighted Results

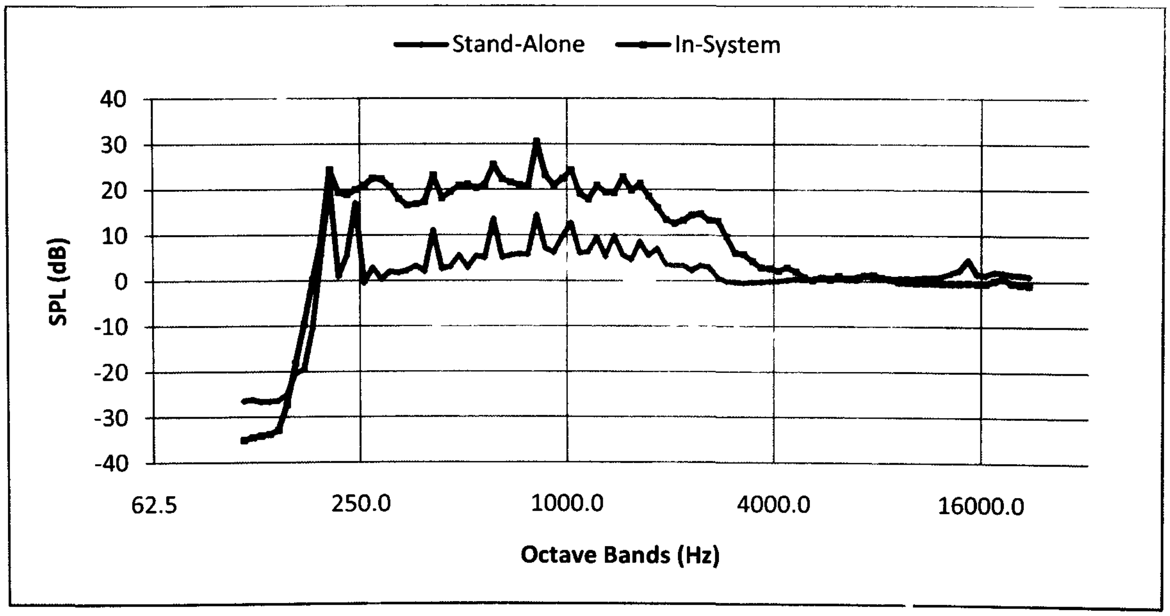

Figure 5-28: Case Fan 2 @12V – Microphone Location 1

Figure 5-28 illustrates the frequency content of the pressure signal from microphone location 1 during the case fan 2 tests at 12V. Stand-alone (blue) and in-system (red) results are shown. The overall levels for these signals are 26.6 dB and 37.9 dB respectively, and the BPF during these tests is 198 Hz. For the stand-alone test, there is a peak of 21.4 dB at 204 Hz, which is very close to the BPF, as well as lesser peaks at 242 Hz (related to ambient), 408 Hz (harmonic of BPF), 612 Hz, and 816 Hz (harmonic of BPF). For the in-system test, there are peaks at identical frequencies with the greatest being 30.5 dB at 816 Hz. The majority of the in-system signal is greater than the stand-alone signal, even though the peaks are at similar frequencies. It appears as though the case amplifies the peaks and this is especially noticeable at microphone location 1. As can be seen, the majority of the content is between 200 Hz and 1000 Hz, and then levels are reduced between 1000 Hz and 2000 Hz, and finally levelling off to 0 dB after 2000 Hz.

Figure 5-29 shows the corresponding loudness results for case fan 2. Similarly to case fan 1, the loudness values obtained when case fan 1 was operated at 12V are significantly higher than the loudness values obtained at the other fan speeds. This indicates that operating the fan at the lower speeds does improve acoustic acceptability. The values shown when case fan 2 operates at 12V are significantly higher than those observed for case fan 1, especially at microphone location 1. So, even though there are minor difference in actual SPL, case fan 2 is clearly has a greater negative impact on acoustic acceptability than case fan 1. However, reducing the applied voltage makes a significant change to the loudness measurements. Thus, this fan is candidate for hardware modification. This may be even more important since the greatest loudness results are at the front of the computer case, where it is likely the closest to an observer, in this case a computer end-user. Hardware modification of case fan 2 seems to provide the greatest difference in measured loudness level, and could easily be implemented.

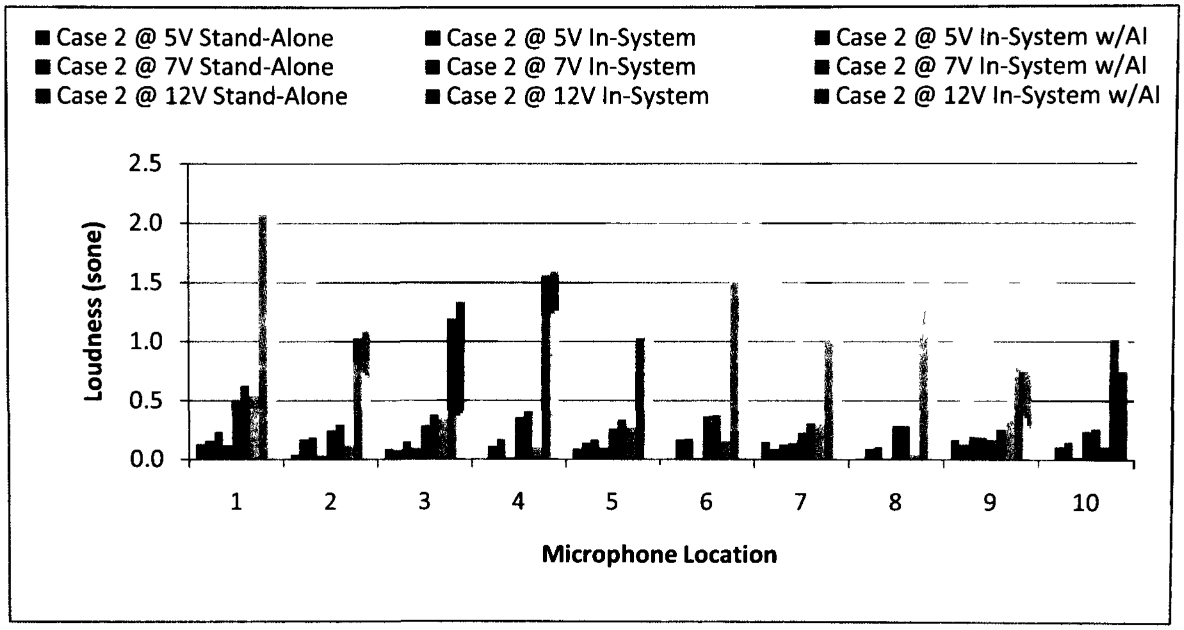

Figure 5-29: Case Fan 2 Loudness Results

Figure 5-30 shows the calculated SWL values for case fan 2. The SWL does increase with increasing fan speed. However, it also increases when tested in-system and then with the addition of acoustical insulation. These are similar results with case fan 1. Again, since this cannot be avoided when operating the FAODCS, it is recommended that case fan 2 should be modified to operate at the lowest fan speed possible. In each case shown, the A-weighted levels are lower than the linear levels. This is an expected and desired result. Overall, these SWLs are greater than those of case fan 1.

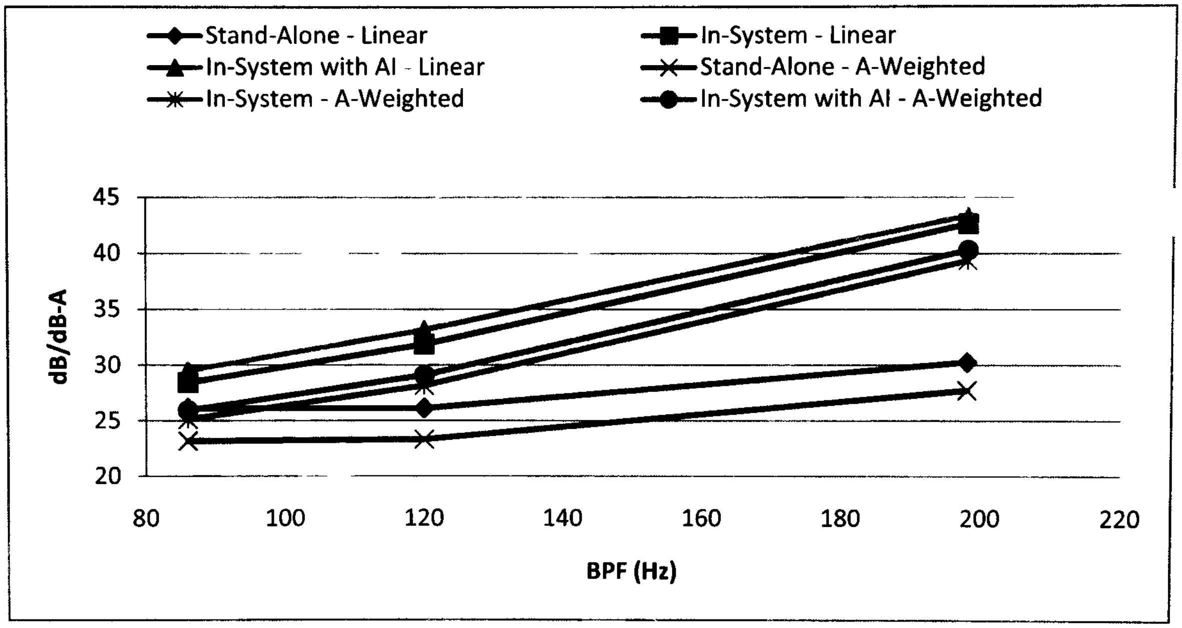

Figure 5-30: Case Fan 2 SWL Results

5.6.5 Analysis of PSU Fan

There is only one speed at which the PSU fan can be tested. The SPLs measured from the PSU testing are shown in Figure 5-31. As can be seen, there is an attenuation of the sound level at every microphone location with the exception of location 6 when the PSU fan is installed within the computer case. This would seem to contradict the results obtained from the measurements of the previous fans. However, the PSU fan is somewhat different. The fan itself has similar characteristics, but it is contained within the PSU housing. Thus, even during the Stand-Alone configuration, the vent grating of the PSU is present. This differs from the previous fans because vent grating is not present when the fan is tested alone. In the case of the PSU fan, it appears the computer case does provide attenuation for some microphone locations. Additionally, the acoustic insulation does provide additional attenuation at some microphone locations. It is clear that the levels are the greatest at microphone location 6, which is expected since the PSU exhaust is nearest to this location. The lowest levels observed are at location 10, which is above the case, and the greatest measured attenuations due to the acoustic insulation are at locations 1 and 8, which are located at the front of the computer case.

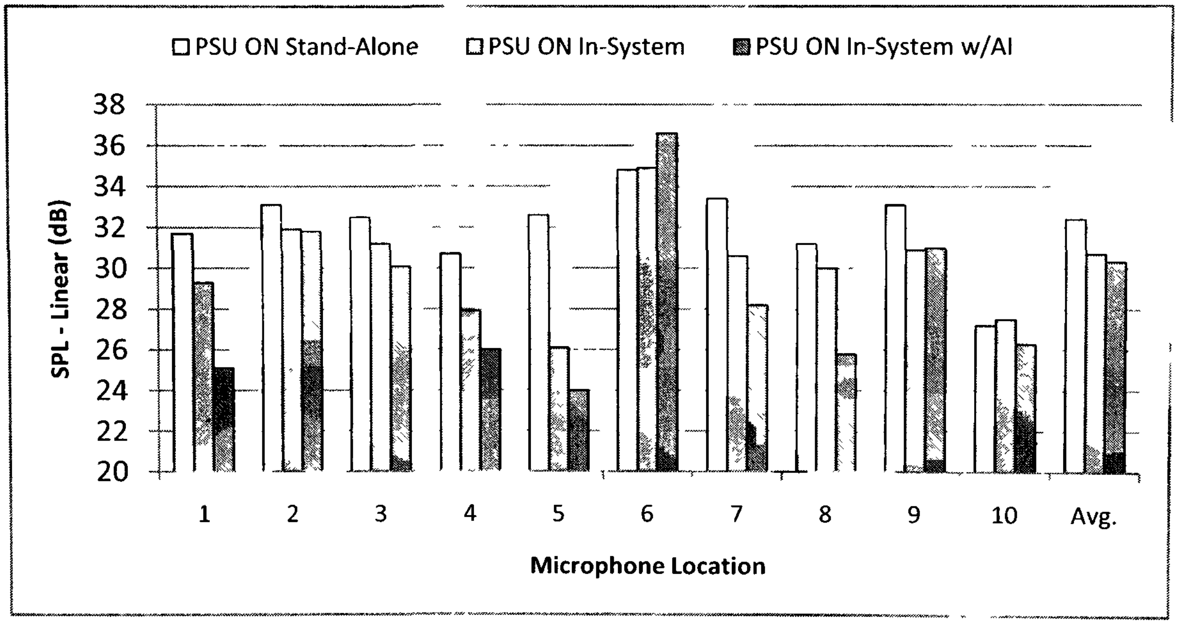

Figure 5-31: PSU Fan SPL – Linear Results

The A-weighted SPLs are shown in Figure 5-32. Observed patterns are very similar to that of the linear levels, although the levels themselves are less. Again, this is likely due to the frequency content below 1000 Hz. This is reasonable since the blade passing frequency of the PSU during these tests is only 104 Hz. Again, there may be important characteristics omitted from the frequency spectrum since the measurement data is high-pass filtered at 200 Hz.

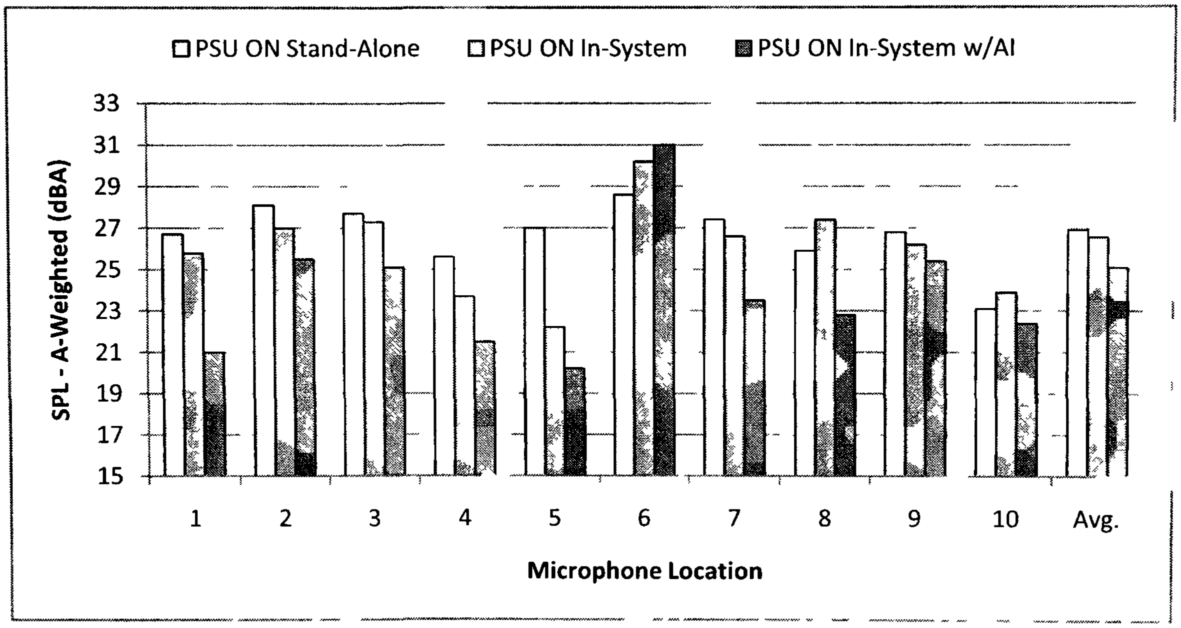

Figure 5-32: PSU Fan SPL – A-Weighted Results

The loudness results for the PSU fan are shown in Figure 5-33. Some interesting results are visible especially when the PSU fan was tested in-system without acoustic insulation. These levels are higher at nearly every microphone location. These results are then reduced once the acoustic insulation is installed in the computer case. Perhaps there is some phenomenon occurring while the PSU is installed that does not contribute to SPL, but does indeed impact the loudness, and thus the sound quality of the PSU fan. In any case, it may not be of significance as the PSU fan is one that cannot be modified by hardware or software, at least not within the scope of this thesis work. All of the loudness values are less than 0.9 sones, which is less than the values measured from the CPU fan or Case fan 2 at certain microphone locations.

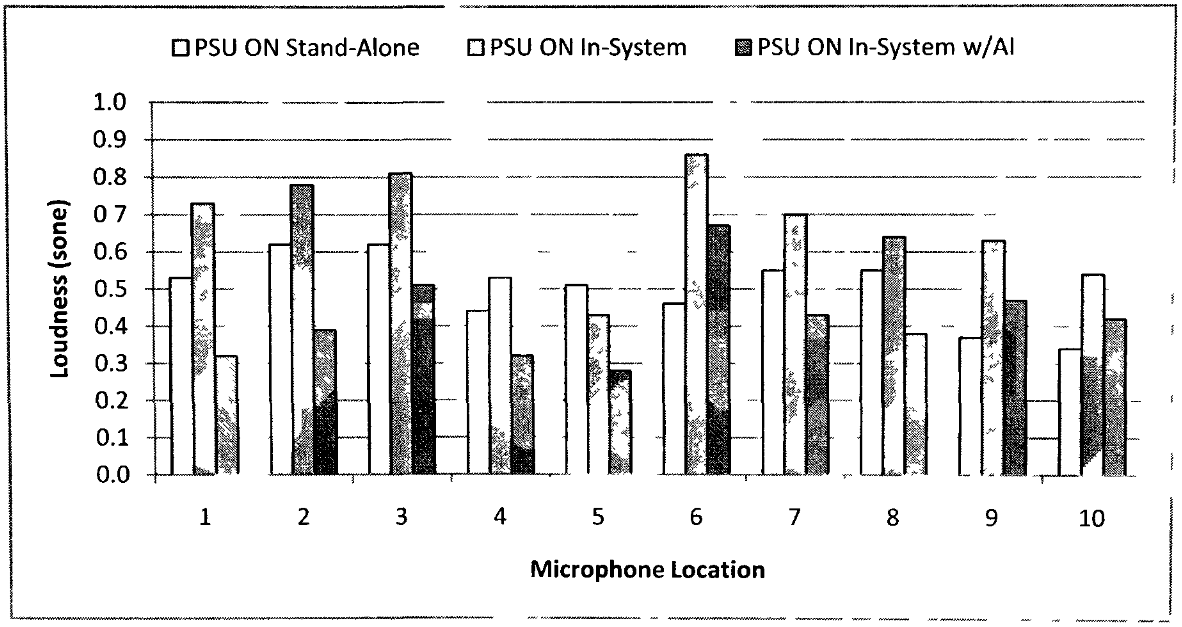

Figure 5-33: PSU Fan Loudness Results

Figure 5-34 illustrates the calculated SWLs for the PSU fan As can be seen, there is a significant difference between the overall linear and A-weighted SWLs. Also, there is some attenuation present when the PSU is installed within the computer case and then again when acoustic insulation is installed. This is consistent with the SPL measurements shown earlier, and again illustrates that the behaviour of the PSU fan differs from that of the other fans. Unfortunately, the overall difference made by the addition of acoustic insulation does will not make a noticeable difference, since it is less than 3 dB attenuation Thus, for this particular system under consideration, it does not appear as though the PSU fan contributes a great deal to the overall sound quality of the computer system

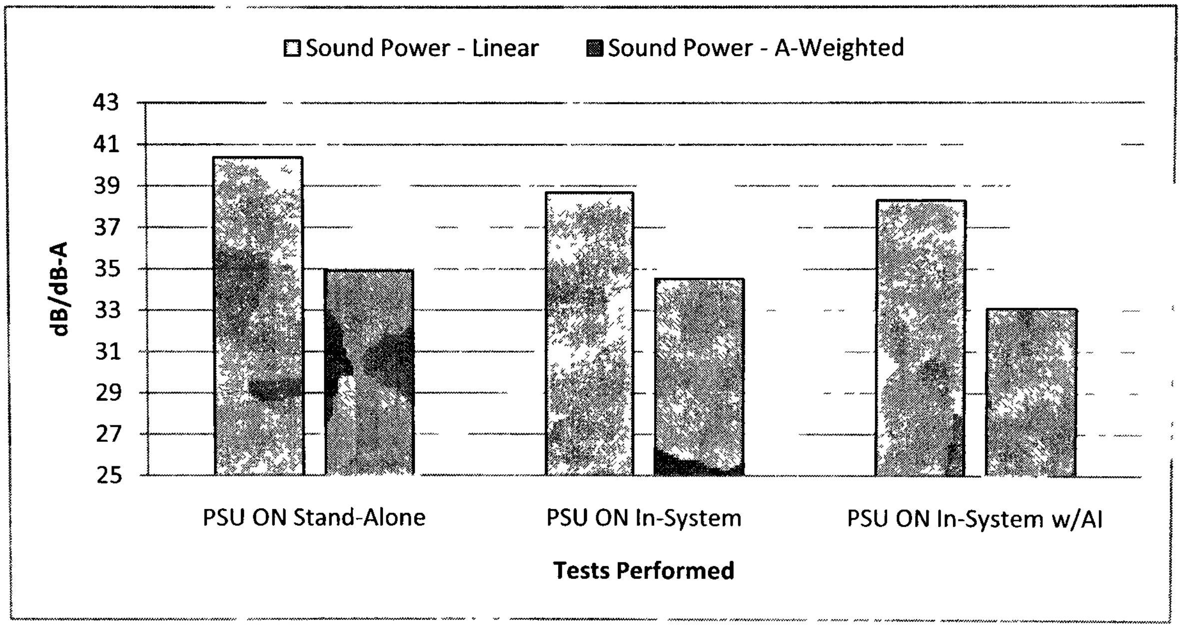

Figure 5-34: PSU Fan SWL Results

5.6.6 Analysis of GPU Fan

The GPU fan is the last to be analysed. Figure 5-35 illustrates the linear SPLs measured during the GPU fan testing. As expected, the levels increase with increasing voltage. Also, the levels measured at microphone location 6 are for the most part the highest of any location. This is expected since the GPU exhausts closer to microphone location 6 than any other location. It appears that the computer case does not provide acoustical attenuation of the noise source, as these levels are higher than the stand-alone levels. This could again be attributed to the fact that the GPU fan was tested outside of its mounting within GPU cooling solution. Interestingly, it appears that the acoustic insulation does provide some attenuation at certain microphone locations. However, this is not significant enough to be easily perceived by human hearing. During this testing the highest SPLs measured for any of the individual fan testing were recorded. This is attributed to the fact that the GPU has the highest BPFs of any of the fans (920 Hz, 1095 Hz, and 1401 Hz). Prominent acoustical content at these frequencies will not be omitted by the high-pass filtering at 200 Hz.

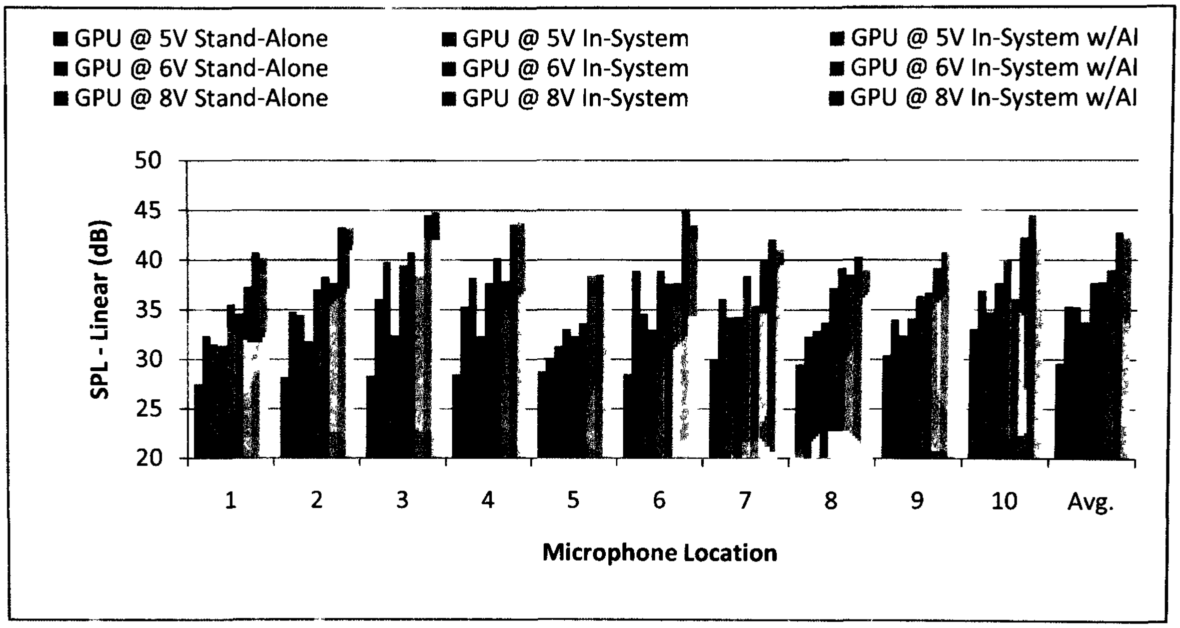

Figure 5-35: GPU Fan SPL – Linear Results

Figure 5-36 illustrates the A-weighted SPLs of the GPU fan. Not surprisingly, these levels are not that different from those of the linear levels. The simple reason for this is due to the frequency content of the pressure signal. For individual tones between approximately 1000 Hz and 6000 Hz (see A-Weighting table in Appendix A), A-weighting adds negative attenuation, or amplification to the SPL. This is a range of frequencies that must be avoided because human hearing is the most susceptible to them. The BPFs of the GPU fan and their harmonics are located within this range. Similar trends are observed in the A-weighted data as were found in the linear data.

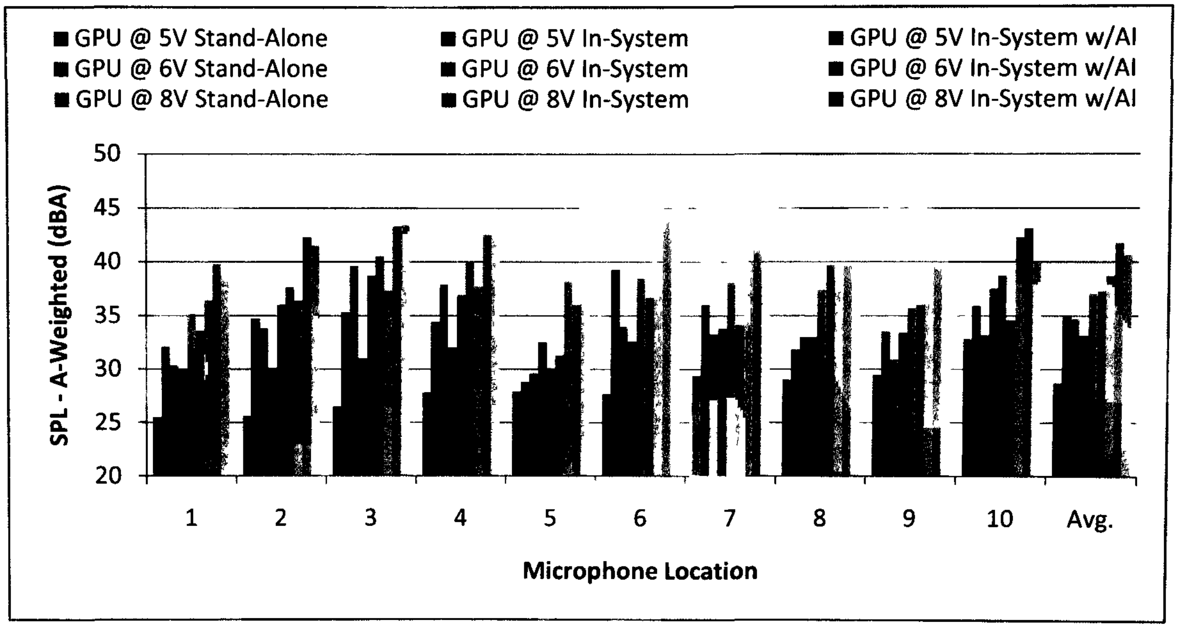

Figure 5-36: GPU Fan SPL – A-Weighted Results

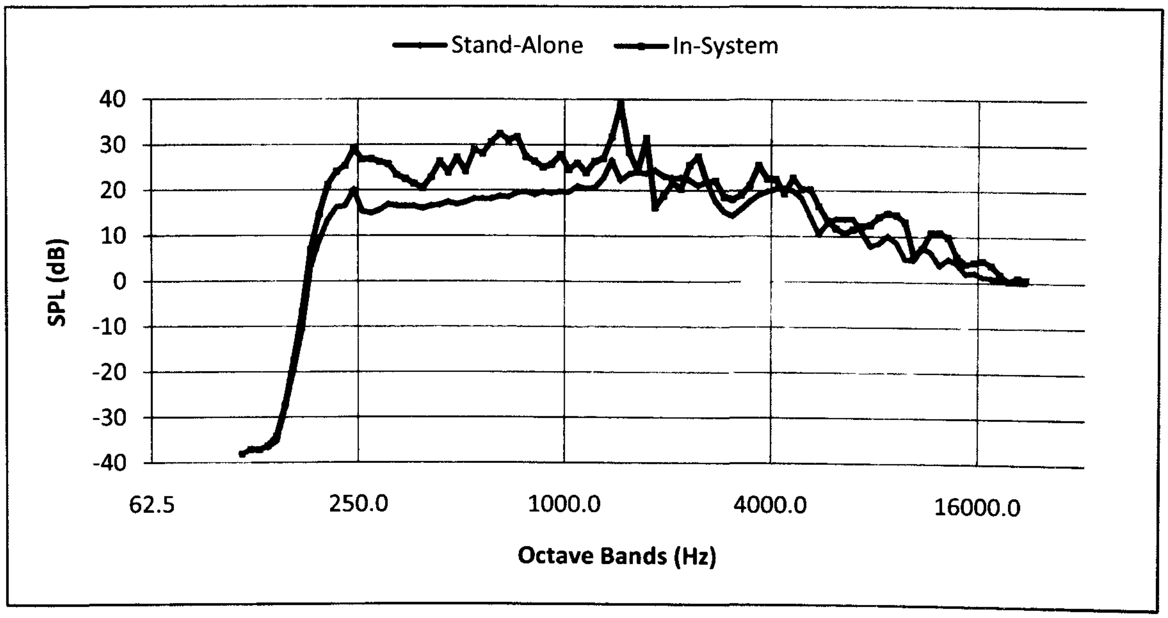

Figure 5-37: GPU Fan @ 8V – Microphone Location 6

Figure 5-37 illustrates the frequency content of the pressure signal from microphone location 6 during the GPU fan test at 8V. Stand-alone (blue) and in-system (red) results are shown. The overall levels for these signals are 37.7 dB and 45.1 dB respectively, and the expected BPF during these tests is about 1401 Hz. For the stand-alone test, there is a peak of 26.6 dB at 1374 Hz which is close to the BPF, and also a peak at 242 Hz which is related to the ambient levels. The levels are generally greater in the case of the GPU fan, and there is still a great deal of content between 1000 Hz and 8000 Hz. The levels do not begin to approach 0 dB until after 16000 Hz. For the in-system test, there are peaks at 242 Hz and 1455 Hz, which is also very close to the BPF Similarly to the stand-alone configuration, there is significant content at frequencies between 1000 Hz and 8000 Hz. This explains why the A-weighted levels are very close to the linear levels, 37.7 dBA and 44.5 dBA respectively. This shows the importance of the frequency content of a pressure signal. Even if the linear levels remained the same, but corresponded to lower frequency bands (or much higher frequency bands, greater than 6000 Hz), the A-weighted results would be far less overall than they are presently.

Figure 5-38 illustrates the loudness results obtained from the GPU fan. These results clearly show the importance of performing a sound quality analysis. At microphone location 6, there is a clear spike in loudness when the GPU fan is tested in the computer system. This spike of 4.58 sones is the highest measured thus far for the individual fans. This clearly shows that installing the fan within the case adds significantly to the acoustical content of the fan. This information is simply not present when examining the SPLs alone. In fact, the SPLs show very little difference between values at the various microphone locations. The loudness data clearly shows visible differences between the microphone locations. It is fortunate that the problem area is located at the back of the computer case. In most home or office configurations, microphone location 6 would be the furthest from the user. However, there are clearly spikes at the other microphone locations as well, especially when the GPU fan is operated at 8V, or when it is running the GPU benchmarking test.

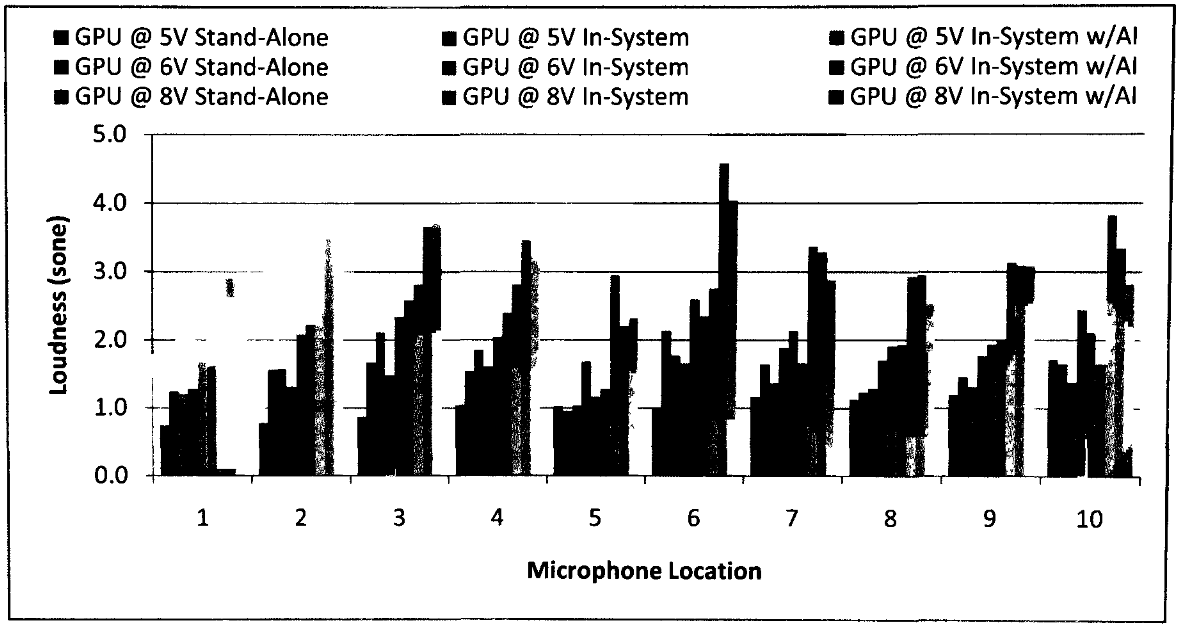

Figure 5-38: GPU Fan Loudness Results

Figure 5-39 illustrates the calculated SWLs of the GPU fan. As can be seen, there is an increase in SWL as the voltage to the fan is increased. The sound power increases again when the GPU fan is installed in the computer case, although, acoustic insulation does attenuate this slightly. Also, the A-weighted levels are very close to linear levels. This is not unexpected based on the SPLs shown earlier. These power levels are the greatest so far for an individual fan. Even at the lowest operating speed, (920 Hz BPF) the sound power of the GPU fan when operated within the computer system are greater than any of the other sources. This means that when added logarithmically, the GPU fan will have the greatest influence on the overall acoustic acceptability of the computer system. Even though the acoustic insulation does provide some attenuation, it is clear that the overall SWL is far more dependent on fan speed.

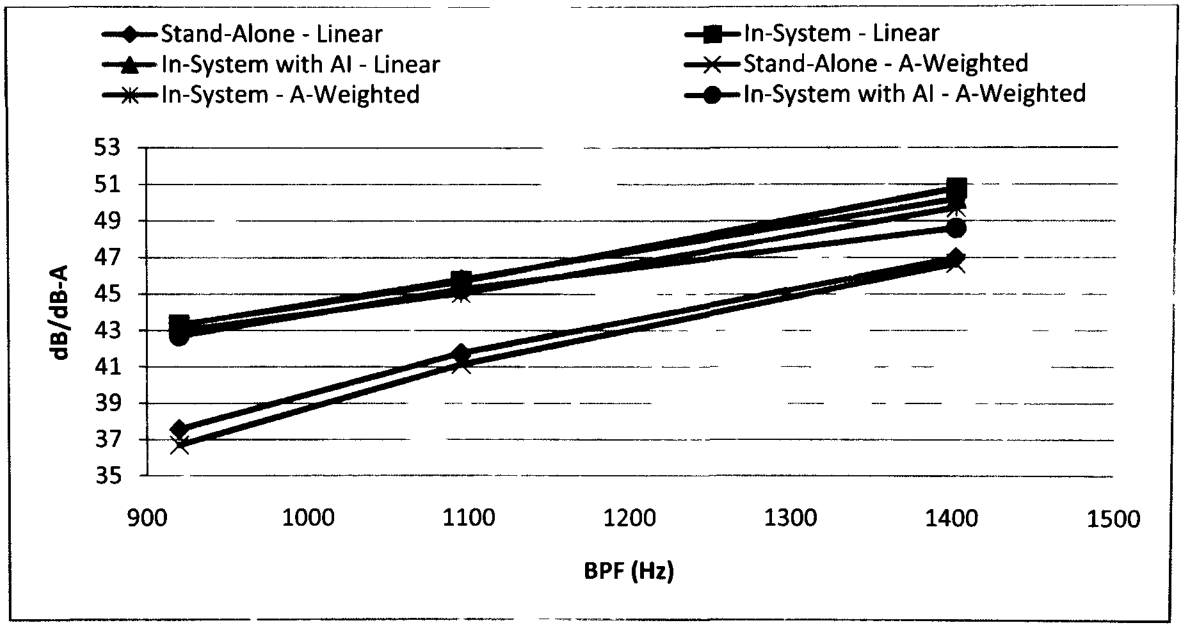

Figure 5-39: GPU Fan SWL Results

5.7 Comparison Analysis of Fully Assembled and Operating Desktop Computer System vs. Individual Fans

It is of interest to know if summing the acoustical emissions of individual computer fans is representative of the total emissions of the FAODCS. This analysis is done in order to determine how closely the results of two configurations tested (individual fans – in-system and the FAODCS) compare. The analysis treats each of the five fans being considered as a distinct noise source and that the logarithmic summation of the individual noise sources will yield the result measured when all fans were in operation in the FAODCS. It is expected that the levels measured of the FAODCS will be slightly greater than those of the individual fans, due to the presence of an additional noise source, the HDD, as well as the slightly greater BPFs of the fans during the configuration. Table 5-5 summarises BPF information that was presented earlier in Table 5-3 and Table 5-4.

Table 5-5: Summary of Fan BPFs at Conditions Tested

FAODCS					Individual Fans		
Fan	Condition	RPM	BPF		BPF	Fan	Condition
CPU	Idle	3260	489	---->	472	CPU	12V
Case 1		1242	145		138	Case 1	12V
Case 2		1895	221		198	Case 2	12V
PSU		1095	128		104	PSU	On
GPU		1842	890		920	GPU	5V
CPU	CPU Benchmark	3230	485	---->	472	CPU	12V
Case 1		1225	143		138	Case 1	12V
Case 2		1862	217		198	Case 2	12V
PSU		1110	130		104	PSU	On
GPU		2115	1022		1095	GPU	6V
CPU	GPU Benchmark	3215	482	---->	472	CPU	12V
Case 1		1238	144		138	Case 1	12V
Case 2		1875	219		198	Case 2	12V
PSU		1147	134		104	PSU	On
GPU		2948	1425		1401	GPU	8V
CPU	Speedfan @ 50%	1770	266	---->	254	CPU	7V
Case 1		1245	145		138	Case 1	12V
Case 2		1892	221		198	Case 2	12V
PSU		1100	128		104	PSU	On
GPU		1853	896		920	GPU	5V
CPU	Case 1 @ 5V	3265	490	---->	472	CPU	12V
Case 1		523	61		59	Case 1	5V
Case 2		1852	216		198	Case 2	12V
PSU		1073	125		104	PSU	On
GPU		1837	888		920	GPU	5V
CPU	Case 1 @ 7V	3263	490	---->	472	CPU	12V
Case 1		743	87		83	Case 1	7V
Case 2		1868	218		198	Case 2	12V
PSU		1070	125		104	PSU	On
GPU		1832	885		920	GPU	5V
CPU	Case 2 @ 5V	3275	491	---->	472	CPU	12V
Case 1		1230	144		138	Case 1	12V
Case 2		798	93		86	Case 2	5V
PSU		1055	123		104	PSU	On
GPU		1830	885		920	GPU	5V
CPU	Case 2 @ 7V	3268	490	---->	472	CPU	12V
Case 1		1243	145		138	Case 1	12V
Case 2		1033	121		120	Case 2	7V
PSU		1095	128		104	PSU	On
GPU		1842	890		920	GPU	5V

By presenting the corresponding BPFs for each of the fans during both the individual fan tests and the FAODCS tests, it is clear what sound level data is needed for analysis. By logarithmically summing the SPLs for each fan at ever microphone location (see Appendix A), the total theoretical SPL for that microphone location is found. This logarithmic total level is then subtracted from level measured when the FAODCS was being tested. These results are shown in Figure 5-40 (linear) and Figure 5-41 (A-weighted).

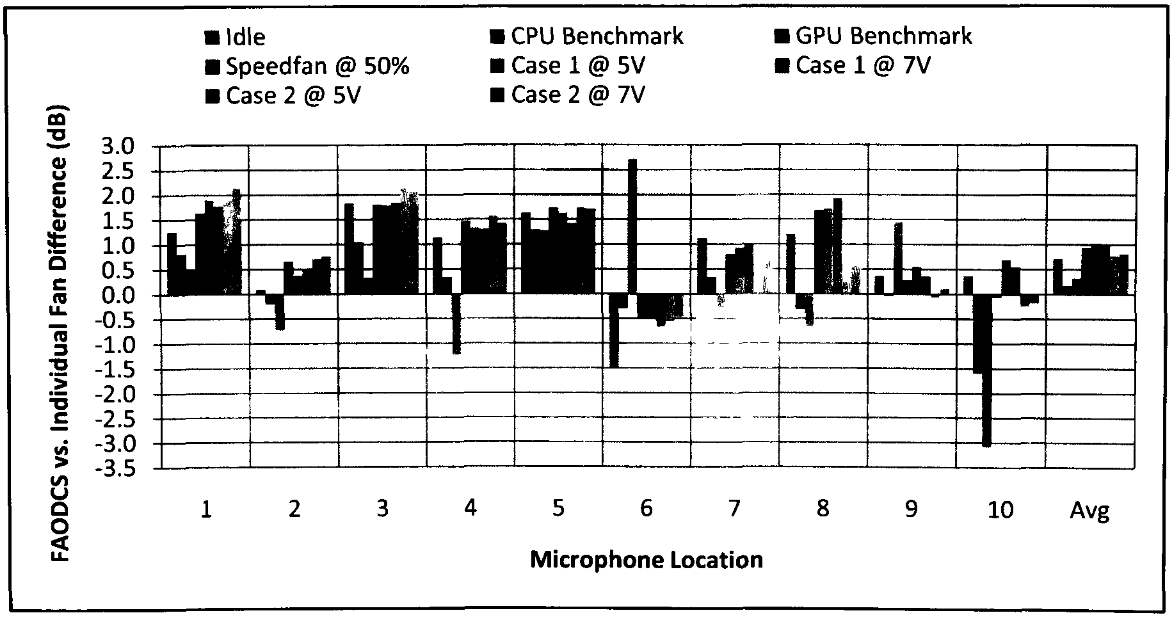

Figure 5-40: Difference between Linear SPLs of FAODCS and Individual Fans

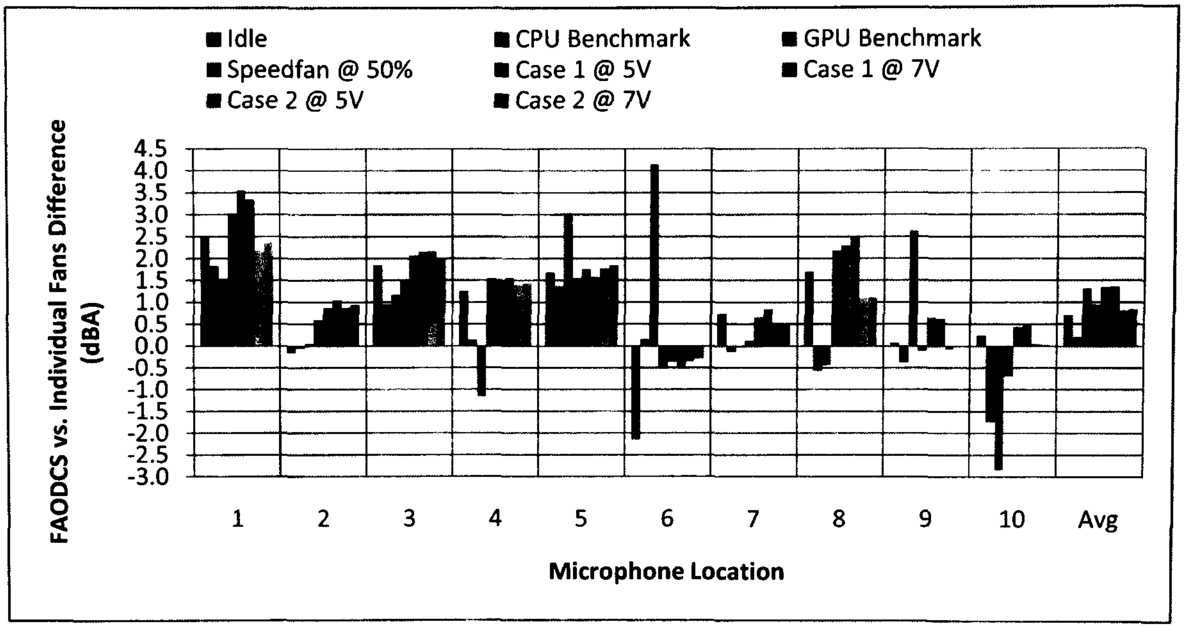

Figure 5-41: Difference between A-Weighted SPLs of FAODCS and Individual Fans

Figure 5-40 and Figure 5-41 provide insight as to how the individual fan measurements may be correlated with the FAODCS measurements. With very few exceptions, the levels measured during the FAODCS configurations were higher than the individual fan SPLs. This is expected. In terms of the overall average linear SPLs, the differences were approximately 1 dB or less. There are a few anomalies. At microphone location 6, during the GPU benchmarking test, the level was 2.7 dB greater than for the individual fans. In contrast, during all other FAODCS tests, the levels measured at location 6 are less than for the individual fans. Also during the GPU benchmarking test, the level at microphone location 10 was significantly (>3dB) less than for the individual fans. This appears to contradict the results at location 6. Further investigation is needed to explain this phenomenon. In terms of the A-weighted SPLs, the differences seem to be more pronounced. The peaks observed in the linear results are even greater. The overall average A-weighted SPLs were less than 1.5 dBA or less different between the FAODCS and the individual fans. This is acceptable since it is less than 3 dBA. However, some of the peaks observed at locations 1, 5, and 6 are greater than 3 dBA, and thus result in perceivable differences at those locations. Thus, it cannot be said for certain that substituting individual fans for the entire working computer system is entirely accurate. Greater analysis between the two configurations in terms of fan speeds and additional noise sources would have to be done in order to improve the accuracy.

5.8 Comparison Analysis of Individual Fans – In-System vs. Individual Fans – Stand-Alone

It is important to clearly illustrate the contribution to the overall noise emissions by the computer case. Obviously the computer case cannot be tested for noise directly since it does not produce any emissions without a source operating within. So, the computer case was tested indirectly. This was done by completing two sets of measurements. First, the individual fans were measured in the stand-alone (without the case) operating configuration. Then, the individual fans were measured in the in-system (with the case) operating configuration. The difference between these results is the contribution to the noise emissions by the addition of the computer case. These results are now shown.

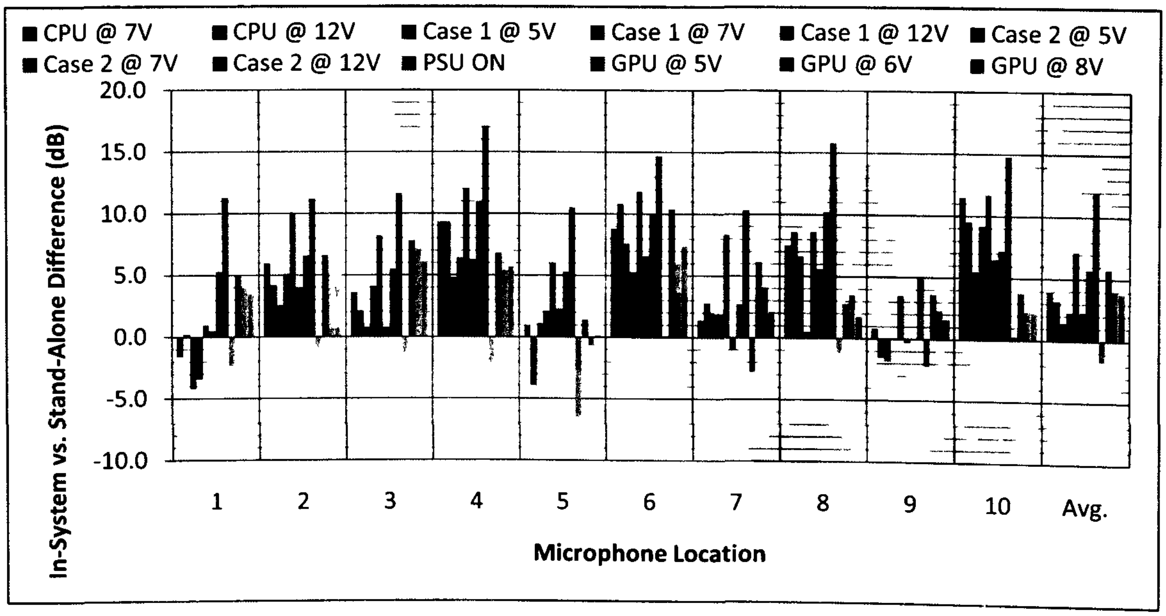

Figure 5-42: Difference between Linear SPLs of In-System and Stand-Alone

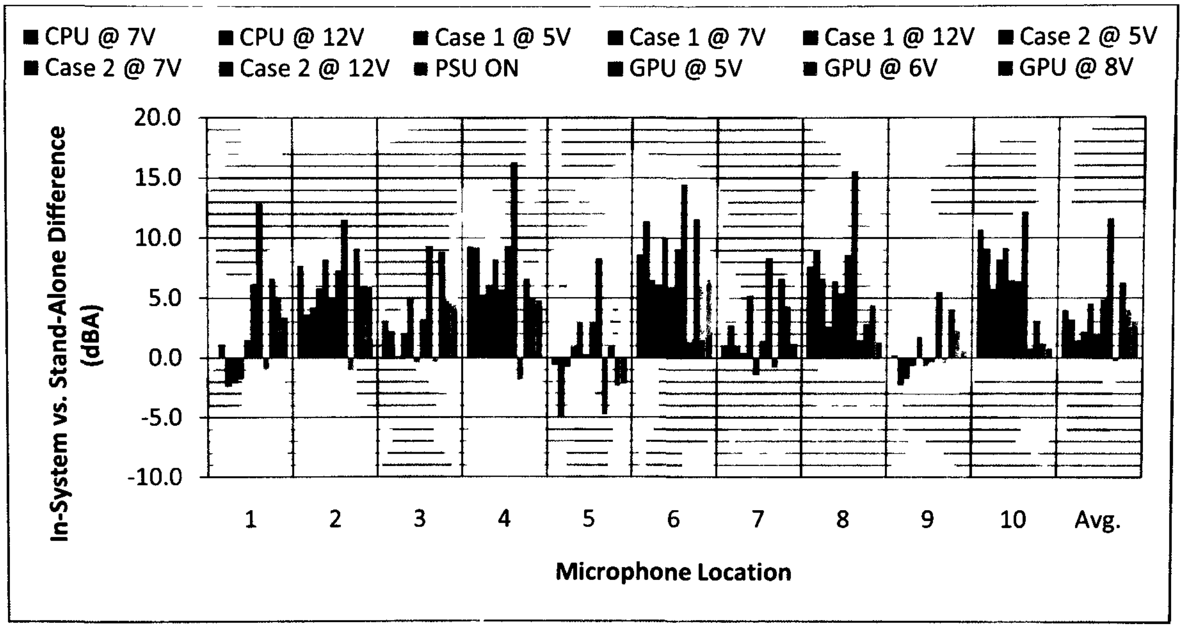

Figure 5-43: Difference between A-Weighted SPLs of In-System and Stand-Alone

As can be seen from Figure 5-42 and Figure 5-43, there are clearly some prominent differences between the two configurations. The positive values indicate that the results measured while the fans were operating within the computer system are higher than the results measured while the fans were operating independently of the computer case. This means that the case contributes significantly to the noise emissions of the overall computer system. If in the future other cases were to be tested, results could be compared using similar fans tested in the same operating configurations.

5.9 Summary

A brief summary is now presented, reiterating the important points touched on in this analysis chapter. High-pass filtering at 200 Hz was done on every pressure signal measured because there is significant ambient low frequency content present in the hemi-anechoic measurement environment. This high-pass filtering may omit some important content from the noise measurements, but it is unavoidable.

For the FAODCS, the highest levels measured were at microphone location 6 during the GPU benchmarking test. The greatest loudness values are obtained at location 6. Modifying case fan 2 does reduce the levels observed at microphone location 1 compared to the idle operating condition, but this does not translate into a significant reduction overall. Using acoustic insulation does attenuate the overall SWLs observed, however, for some configurations there is less than 1 dB difference, which is insignificant, and for all configurations, there is less than a 3 dB, thus, unperceivable to human hearing. Additional, A-weighted SWLs are less than the linear levels, however, again there is less than a 3 dB difference for all configurations. Recall that overall sound power is based on the average SPL of the 10 microphone locations.

The most important individual fan operating conditions are: CPU Fan at 7V and 12V, Case Fan 1 at 5V, 7V, and 12V, Case Fan 2 at 5V, 7V, and 12V, the PSU On, and the GPU fan at 5V, 6V, and 8V. These conditions correspond to the conditions tested during FAODCS testing.

For the individual fans, testing at a higher voltage level led to greater blade passing frequencies and higher measured sound levels. Testing the fans within the computer case (in-system) yields higher levels than testing them without the computer system (stand-alone). This is an unintuitive result but may be explained because the case itself is a source of noise generation. Also, the acoustic insulation does not provide any attenuation, as the levels measured with insulation installed are greater than without, except in the case of the GPU fan, where there is a slight reduction. The frequency content of the pressure signals were of importance. Octave bands whose frequencies are below 1000 Hz and above 6000 Hz see an attenuation due to A-weighing, whereas frequencies between see an amplification. This is a problem for the GPU fan, whose blade passing frequencies of importance are between approximately 900 Hz and 1400 Hz.

Additionally, measuring the acoustical emissions of individual fans installed within the computer system and summing them up logarithmically yields results that are (for the most part) less than those of the FAODCS. This is expected since there are other sources of noise when a computer is fully operational such as an HDD.

5.10 Uncertainty Analysis

An important aspect of any scientific work is an analysis of the uncertainty present in the results measured. In this thesis work, uncertainty is associated with any of the measured quantities. Thus, the uncertainty propagates through the equations used to calculate SWL. Recall these equations from ISO 3745 [53].

$$L_W = L_{p,ave} + 10 \times \log(2\pi r^2) + C_1 + C_2$$

$$C_1 = -10 \times \log\left[\frac{B}{B_0} \times \sqrt{\frac{313.15}{273.15 + \theta}}\right] \tag{7}$$

$$C_2 = -15 \times \log\left[\frac{B}{B_0} \times \left(\frac{296.15}{273.15 + \theta}\right)\right]$$

In general, the uncertainty of a function is as follows.

$$\Delta f(x, y, z) = \left|\frac{\partial f}{\partial x}\right| \times \Delta x + \left|\frac{\partial f}{\partial y}\right| \times \Delta y + \left|\frac{\partial f}{\partial z}\right| \times \Delta z \tag{8}$$

Where Δx, Δy, and Δz are the uncertainties of the individual variables. SWL is calculated by the summation of four terms. These terms are now examined individually. First, the SPL term is examined. It contains 10 variables, each one representing a measured SPL at a certain microphone location. Deriving the uncertainty of $L_{p,ave}$ is somewhat complicated, so steps will be described in detail in the following derivation.

$$L_{p,ave} = 10 \times \log\left[\frac{1}{n}\sum_{i=1}^{n}\left(10^{\frac{L_{pi}}{10}}\right)\right] \tag{9}$$

$$= 10 \times \log\left[\frac{1}{n}(10^{0\ 1L_{p1}} + 10^{0\ 1L_{p2}} + 10^{0\ 1L_{p3}} + 10^{0\ 1L_{p4}} + 10^{0\ 1L_{p5}}\right.$$

$$\left. + 10^{0\ 1L_{p6}} + 10^{0\ 1L_{p7}} + 10^{0\ 1L_{p8}} + 10^{0\ 1L_{p9}} + 10^{0\ 1L_{p10}})\right]$$

$$= 10 \times \log\left[f(L_{p1}, L_{p2}, \dots L_{p10})\right]$$

Breaking this collection of terms up into partial derivatives (one for each variable) is complex. The following equation illustrates symbolically what is needed.

$$\Delta L_{p,ave} = 10 \times \sum_{i=10}^{n} \left(\left| \frac{\partial L_{p,ave}}{\partial L_{pi}} \right| \times \Delta L_{pi} \right) \tag{10}$$

The most troubling part of this expansion is dealing with the $\left|\frac{\partial L_{p,ave}}{\partial L_{pi}}\right|$ terms. Not only are there 10 partial derivatives to consider, but each has two parts due to the chain rule:

$$\left| \frac{\partial L_{p,ave}}{\partial L_{pi}} \right| = \frac{\partial \log\left[f(L_{p1}, L_{p2}, \dots L_{p10})\right]}{\partial f(L_{p1}, L_{p2}, \dots L_{p10})} \times \frac{\partial f(L_{p1}, L_{p2}, \dots L_{p10})}{\partial L_{pi}} \tag{11}$$

The first factor in Equation 11 is due to the logarithm present in the $L_{p,ave}$ summation. This term is identical for each of the 10 partial derivatives, and is given as follows.

$$\frac{\partial \log\left[f(L_{p1}, L_{p2}, \dots L_{p10})\right]}{\partial f(L_{p1}, L_{p2}, \dots L_{p10})}$$

$$= \left[\left(\frac{1}{10}\right) \times (10^{0\ 1L_{p1}} + 10^{0\ 1L_{p2}} + 10^{0\ 1L_{p3}} + 10^{0\ 1L_{p4}} + 10^{0\ 1L_{p5}} + 10^{0\ 1L_{p6}}\right.$$

$$\left. + 10^{0\ 1L_{p7}} + 10^{0\ 1L_{p8}} + 10^{0\ 1L_{p9}} + 10^{0\ 1L_{p10}}) \times (\ln 10)\right]^{-1} \tag{12}$$

$$= \left[\frac{1}{10} \times M \times \ln 10\right]^{-1}$$

Where,

$$M = \sum_{i=10}^{n} 10^{0\ 1L_{pi}} \tag{13}$$

The second factor in Equation 11 is the partial derivative of the argument of the logarithm with respect to each SPL. It is similar for each of the 10 partial derivatives, the only difference being the SPL for each. The partial derivative is given in a general form as follows.

$$\frac{\partial f\left(L_{p1}, L_{p2}, \dots L_{p10}\right)}{\partial L_{pi}} = 10^{0.1L_{pi}} \times 0.1 \times \ln 10$$

$$= 10^{0.1L_{pi}} \times \frac{\ln 10}{10} \tag{14}$$

The results from Equations 13 and 14 can be substituted back into Equation 11.

$$\Delta L_{p,ave} = 10 \times \sum_{i=10}^{n} \left(\left| \left[\frac{1}{10} \times M \times \ln 10 \right]^{-1} \times 10^{0.1L_{pi}} \times \frac{\ln 10}{10} \right| \times \Delta L_{pi} \right)$$

$$= 10 \times \left[\frac{1}{10} \times M \times \ln 10 \right]^{-1} \times \frac{\ln 10}{10} \times \sum_{i=10}^{n} 10^{0.1L_{pi}} \times \Delta L_{pi} \tag{15}$$

This simplification is done in order to clarify $\Delta L_{p,ave}$. The substitutions of M and N were made to simplify the summation Additionally, if all ΔL_{pi} values are the same (which we assume that that they are) then that term may move to the left of the summation and become simply ΔL_p It was defined in Equation 13 that $M = \sum_{i=10}^{n} 10^{0.1L_{pi}}$. The result is as follows.

$$\Delta L_{p,ave} = 10 \times \left[\frac{1}{10} \times M \times \ln 10 \right]^{-1} \times \frac{\ln 10}{10} \times \Delta L_p \times M$$

$$\Delta L_{p,ave} = 10 \times \Delta L_p \tag{16}$$

The second term of the SWL calculation is now examined It can be expanded as follows Note that the radius of the hemispherical surface,r, is the only variable in this term of the of SWL calculation

$$Let\ f(r) = 10 \times \log\left(\frac{S_2}{S_0}\right)$$

$$= 10 \times (\log(2) + \log(\pi) + \log(\mathrm{r}^2) - \log(1))$$

$$= 10 \times \log(2) + 10 \times \log(\pi) + 20 \times \log(\mathrm{r}) \tag{17}$$

$$\Delta f = \left|\frac{\partial f}{\partial r}\right| \times \Delta r = \left|0 + 0 + 20 \times \frac{1}{r \times \ln 10}\right| \times \Delta r$$

$$= \left|\frac{20}{r \times \ln 10}\right| \times \Delta r$$

The C_1 term is now examined. It can be expanded as follows. Note that the only variables in this term of the SWL calculation are B and θ.

$$C_1 = -10 \times \log\left[\frac{B}{B_0} \times \sqrt{\frac{313.15}{273.15 + \theta}}\right]$$

$$= -10 \times \left(\log(B) - \log(B_0) + \frac{1}{2} \times \log(313.15) - \frac{1}{2} \times \log\,(273.15 + \theta)\right)$$

$$= -10 \times \log(B) + 10 \times \log(B_0) - 5 \times \log(313.15) + 5 \times \log\,(273.15 + \theta) \tag{18}$$

$$\Delta C_1 = \left|\frac{\partial C_1}{\partial B}\right| \times \Delta B + \left|\frac{\partial C_1}{\partial \theta}\right| \times \Delta\theta$$

$$= \left|\frac{-10}{B \times \ln 10}\right| \times \Delta B + \left|\frac{5}{(273.15 + \theta) \times \ln 10}\right| \times \Delta\theta$$

The C_2 term is now examined. It can be expanded as follows. Again, the only variables in this term are B and θ.

$$C_2 = -15 \times \log\left[\frac{B}{B_0} \times \left(\frac{296.15}{273.15 + \theta}\right)\right]$$

$$= -15 \times (\log(B) - \log(B_0) + \log(296.15) - \log(273.15 + \theta))$$

$$= -15 \times \log(B) + 15 \times \log(B_0) - 15 \times \log(296.15) + 15 \times \log(273.15 + \theta) \tag{19}$$

$$\Delta C_2 = \left|\frac{\partial C_2}{\partial B}\right| \times \Delta B + \left|\frac{\partial C_2}{\partial \theta}\right| \times \Delta \theta$$

$$= \left|\frac{-15}{B \times \ln 10}\right| \times \Delta B + \left|\frac{15}{(273.15 + \theta) \times \ln 10}\right| \times \Delta \theta$$

Each of the four terms of the SWL calculation has now been examined separately. They are now combined in order to determine the uncertainty of the calculated SWL.

$$\Delta L_W = \left|\frac{\partial L_W}{\partial L_{p,ave}}\right| \Delta L_{p,ave} + \left|\frac{\partial L_W}{\partial r}\right| \Delta r + \left|\frac{\partial L_W}{\partial B}\right| \Delta B + \left|\frac{\partial L_W}{\partial \theta}\right| \Delta \theta$$

$$= 10 \times \Delta L_p + \left|\frac{20}{r \times \ln 10}\right| \times \Delta r + \left|\frac{-25}{B \times \ln 10}\right| \times \Delta B \tag{20}$$

$$+ \left|\frac{20}{(273.15 + \theta) \times \ln 10}\right| \times \Delta \theta$$

It is not difficult to solve Equation 20 using mathematics software or Microsoft Excel® The measurement inputs required are values for r, B, and θ. The measurements of r, B, and θ are constants. The uncertainty inputs required are values for ΔL_p, Δr, ΔB, and $\Delta \theta$. These uncertainties are constants. Surprisingly, the measurements of $L_{p1}, L_{p2}, \ldots L_{p10}$ do not appear in this uncertainty function. This is because the terms containing them were cancelled in Equation 16. This simplifies the calculation. In addition to the linear uncertainty of the calculation of ΔL_W, it is relevant to show the RMS uncertainty as well. This is done as shown.

$$RMS\Delta L_W$$

$$= \sqrt{\left(\left|\frac{\partial L_W}{\partial L_{p,ave}}\right| \Delta L_{p,ave}\right)^2 + \left(\left|\frac{\partial L_W}{\partial r}\right| \Delta r\right)^2 + \left(\left|\frac{\partial L_W}{\partial B}\right| \Delta B\right)^2 + \left(\left|\frac{\partial L_W}{\partial \theta}\right| \Delta \theta\right)^2} \tag{21}$$

Table 5-6 lists the values used to determine ΔL_W and RMSΔL_W.

Table 5-6: Variables Used in the Determination of Experimental Uncertainty

Variable	Measurement	Units
r	1	m
B	101325	Pa
θ	23	°C
Uncertainties		
ΔLP	0.05	dB
Δr	0.05	cm
ΔB	100	Pa
Δθ	0.5	°C
Overall Uncertainty		
ΔLW	0.96	dB
RMS ΔLW	0.66	dB

It is important to make note of the influence of the each of the uncertainties. The influence of an individual variable's uncertainty is the partial derivative of the function with respect to that variable.

$$\left|\frac{\partial L_W}{\partial L_{p,ave}}\right|, \left|\frac{\partial L_W}{\partial r}\right|, \left|\frac{\partial L_W}{\partial B}\right|, \left|\frac{\partial L_W}{\partial \theta}\right| \tag{22}$$

The partial derivates have the following values.

Table 5-7: Influences of Variable Uncertainties

Influence	
LP	10
r	8.686
B	0.0001
θ	0.029

Thus, it is most important to keep the uncertainties of the individual SPL measurements and of the measurement distance between the microphone and the source to a minimum. They each have an influence over the uncertainty of SWL of more than two orders of magnitude greater than θ, and more than four orders of magnitude greater than B.

CHAPTER VI

CONCLUSIONS & RECOMMENDATIONS

As stated in Chapter 1, the motivation of this thesis is to understand, measure, and attenuate computer noise. In order to accomplish this, several goals were achieved. First, a review of available literature regarding computer systems, axial-flow fans, noise attenuation techniques, and other applicable subject matter was completed and was presented in Chapter 2. Second, applicable acoustical measurement standards were reviewed and an experimental methodology was developed to test and compare different attenuation techniques and both were presented in Chapter 3. Third, an experimental procedure was presented in Chapter 4. The results of the experimentation performed were presented in Chapter 5. Now, conclusions regarding the effectiveness of the various attenuations techniques and recommendations for future investigations are presented here.

6.1 Conclusions about the Effectiveness of Acoustic Insulation

Similar tests were completed both with and without acoustic insulation installed in the desktop computer case. For the individual fan testing it is difficult to say for certain that it does or does not attenuate the acoustical emissions from the individual fans. In some tests and at certain microphone locations it does provide some attenuation, but it also produces the opposite effect during other tests at certain microphone locations. However, for the overwhelming majority of the time, the difference achieved is insignificant and unperceivable. Not in one test done was the average overall SPL from all ten microphones altered by more than 3 dB. Since some microphones actually detected an amplification of the measured SPL, it is clear that the acoustic insulation does not improve the acoustic performance of the computer system, at least from the perspective of individual fans.

For the FAODCS testing, there was only one test completed in which the acoustic insulation provided a perceivable difference in the acoustic emissions measured. This was the GPU benchmarking test. Significant attenuations were observed in the A-weighted results at locations 5, 6, and 9. Unfortunately, these were not enough to reduce the average overall SPL by more than 3 dB.

Although providing some attenuation in some circumstances, acoustic insulation does not appear to be a viable noise reduction technique. This may not be due to its acoustic properties, but to the design of the computer case as a whole. The vents cannot be blocked as doing so would hinder or prevent airflow, thus increasing the internal temperature of the computer case. The vents act as a source of noise that cannot be attenuated by acoustic insulation. Other means must be employed to reduce this noise source, such as reducing the speed of the airflow through the vents.

6.2 Conclusions about the Effectiveness of Software Modification

By using a simple software modification it was possible to modify the speed of the CPU fan. There are several software applications available to perform such a task. The CPU fan is the only computer fan which was tested using such a modification. This is because the other fans are controlled in other ways. The Case fans are powered using a MOLEX connection, the PSU fan is controlled from within the power supply, and the GPU fan is controlled by the video card. It was determined that by using the Speedfan software that the CPU fan was reduced from its operating speed at 12V to its operating speed at 7V This corresponds to a BPF reduction from 472 Hz to 254 Hz for the CPU fan individually, and a reduction from 489 Hz to 266 Hz for the CPU fan operating within the computer system.

For all three individual-fan operating configuration, the voltage reduction led to an observable reduction in SPL (both linear and A-weighted) for every microphone location. There were also reductions in the loudness results for every microphone location. Thus, implementing software to reduce the CPU fan speed does make a significant difference to the acoustical emissions of the CPU fan.

Unfortunately, these differences were not present when the FAODCS was tested. At some microphone locations there was a reduction in SPL and at others there was an increase. Overall, there was no perceivable difference between the idle operating configuration and running the Speedfan software. Thus, operating the software for the purpose of noise reduction is not effective. It is unlikely that any harm would come to the system if the software is running, and in fact it may reduce the electrical energy used by a computer system. But this should only be for situations where the greater cooling capacity is not needed, such as when the computer is in idle. There is also software available that monitors the CPU temperature and then adjusts the CPU fan speed accordingly. Since there is no noticeable change in acoustic performance, modifying the fan speed only serves the use of reducing electricity use and possibly extending the life of the CPU fan.

6.3 Conclusions about the Effectiveness of Hardware Modification

Simple hardware modification was done to the case fans tested. The standard operating voltage level of each of the case fans using the Molex power connectors is 12V. These are the only two computer fans powered in such a way. By using a modified Molex connector, the voltage level supplied to either of the fans could be changed to either 5V or 7V. This is the most basic hardware modification that could be performed.

First, case 1 is discussed. During the stand-alone configuration, reducing the applied voltage level to 7V resulted in a perceivable difference at half of the microphone locations compared to operating the fan at 12V. This was increased to all but 1 microphone location when the voltage was reduced to 5V. When installed within the computer case, there was even greater reduction in SPL, as every microphone measured a perceivable difference. The average reduction was greater when the voltage was at 5V. The results were similar when acoustic insulation was installed in the computer case. Thus, the reduction of fan voltage does lead to a reduction in SPL. Unfortunately, as was the case with the CPU fan modification, once the FAODCS is operating, these differences to not lead to a perceivable difference in the overall SPL of the system. This means that the emissions of case fan 1 are overpowered by the emissions of other fans and sources of noise when the computer is operating.

For case fan 2, the stand-alone test reveals that at most microphone locations there is a reduction in measured SPLs when the voltage is reduced to 5V and 7V, although there is a negligible difference between these two voltage levels. The greatest reduction is at microphone location 1. When installed within the computer system, there is a much greater reduction observed for both voltage levels, and there is even more reduction for 5V than 7V. Unfortunately, when the fan is operating within the FAODCS, the differences observed are not repeated. The only perceivable difference is at microphone location 1, where a reduction of 4 dB was observed when the fan was at 7V, and 4.5 dB when at 5V. Thus, reducing the applied voltage to case fan 2 does make a perceivable difference at the front of the case, which may be desirable since it is likely that this location will be closest to an observer. Thus, hardware modification is recommended for case fan 2, assuming that there is still sufficient airflow within the computer case to remove the heat generated. This should not be of concern because case fans are usually added to a computer system after they are purchased by an end-user. This was the case for the computer tested in this thesis work. The computer should have no difficulty operating within normal specifications without either of the case fans. However, if additional cooling is needed because of the demand of the computer system, it is advisable to install case fans, just as a relatively cheap preventative measure. Case fan 2 could be modified to reduce its voltage only when additional cooling is not needed by the computer system, such as in idle.

6.4 Contributions

There were several contributions to Engineering knowledge and practice given by this thesis work. A literature review was performed which compiled previously determined information about the noise sources of axial-flow fans and possible attenuation techniques. An experimental methodology was shown that illustrates how computer fan testing may be performed in the future. The methodology was applied to develop an experimental procedure which involved using existing acoustical measurement standards and available measurement equipment. The experimental procedure allowed for results to be gathered which led to conclusions regarding the effectiveness of three attenuation techniques. Reasons were given for the potential benefits of the three methods as well as their overall ineffectiveness in this particular thesis work. There is clearly room to improve, expand, modify, and continue with further studies investigating computer noise and other attenuation techniques.

6.5 Recommendations for Future Work

There are further tests and experimentation that may be performed in the future to supplement this thesis work. The following is a list of possible avenues for future research investigations related to computer noise.

- Testing a variety of replacement after-market cooling fans that could be used as substitutes.
- Replace the CPU fan with a larger diameter but slower rotating fan.
- Implement other cooling solutions such as heat pipes.
- More accurate RPM analysis to determine the exact operating range of fans.
- Investigate active noise control options.

- Examine other sources of noise within a computer such as the HDD and ODD.
- Perform jury testing to determine if measured results are comparable.
- Improve results by completing measurements using ten microphones (one for each location) at once. Even if a noise source is steady-state in nature, there is no guarantee that taking measurements at multiple times will yield similar results.
- Perform a computational fluid dynamics (CFD) analysis of the fans and the computer case. This would illustrate the flow of air through the case and also determine how heat is transferred between the hot surfaces of the components and the air.
- Implement vibration absorption mechanisms to prevent vibration from being transferred from mechanical components like the computer fans, HDD, and ODD to the case.

APPENDICES

APPENDIX A

Important Additional Acoustics Information

There are many important concepts used throughout this thesis work that are involved in the study of acoustics. This appendix lists some of the concepts mentioned in this thesis work and provides important additional information pertaining to their definitions and functions.

A1 Sound

Sound is an oscillation of mechanical energy that moves through matter as a longitudinal wave with alternating regions of compression and rarefaction.

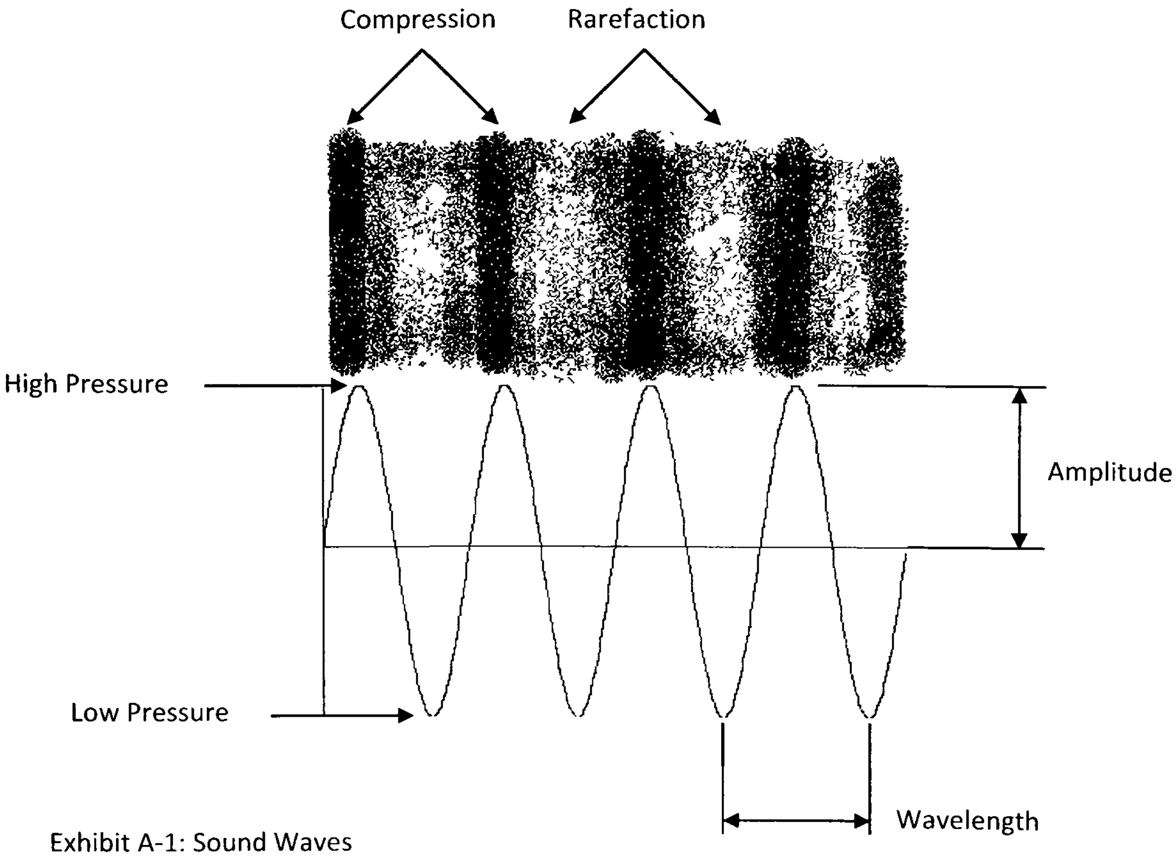

Exhibit A-1: Sound Waves

An overview of sound and sound propagation is presented in Chapter 1 of [1]. Exhibit A-1 illustrates how the properties of sound may be represented by a sinusoid. Sounds are vibrations that travel through air and are perceived by human hearing. High and low frequencies that cannot be heard by humans as well as structural vibrations are considered sound.

A2 Noise

Noise is considered unwanted or undesirable sound. In mechanical systems, noise is usually a characteristic that is reduced or eliminated if possible. In some situations, certain types of noise may have useful applications (Chapter 4 of [1]). Examples include white noise or pink noise. White noise is a random acoustic signal with equal power at every frequency. Pink noise is a random acoustic signal with equal power in every octave band.

A3 Acoustics

Acoustics is the branch of science dealing with the physical characteristics of the generation, propagation, reception, control, and effects of sound. The use of acoustics in technology is referred to as acoustical engineering.

A4 Psychoacoustics

Psychoacoustics is the branch of science dealing with the interaction between acoustics and the human auditory system (Chapter 3 of [1]). In other words, psychoacoustics deals with the human perception of sound. It relates the physical characteristics of sound to the human perception of sound. It involves the physical structure of the ear and the path that sound signals must travel to the brain.

A5 Sound Pressure

Sound pressure (p) is the pressure deviation from the ambient atmospheric pressure, in Pascals, caused by a sound wave. It can be measured using a microphone, which is a pressure transducer. Sound pressure is dependent on both the source of sound as well as the environment in which the sound is generated, propagated, and received.

A6 Sound Pressure Level

Sound pressure level is a logarithmic equivalent of sound pressure. Sound pressure level is a relative measurement scale, and it has a reference sound pressure of 20E-6 Pascals. Equation A1 is used to calculate the SPL based on measured sound pressure.

$$L_p = 10 \times \log\left(\frac{p^2}{p_{ref}{}^2}\right) = 20 \times \log\left(\frac{p}{p_{ref}}\right) \quad dB \qquad \text{A1}$$

A7 Adding Sound Pressure Levels

It may be desirable to find the total SPL at a location by summing the contributions of different sources. This is done using logarithmic addition.

$$L_p total = 10 \times \log\left(\sum_{i=1}^{n}\left(10^{\frac{L_{pi}}{10}}\right)\right) \quad dB \qquad \text{A2}$$

A8 Averaging Sound Pressure Levels

It may be desirable to find the average SPL at a location by averaging contributions of different sources. This must be done using logarithmic averaging.

$$L_p average = 10 \times \log\left(\frac{1}{n}\sum_{i=1}^{n}\left(10^{\frac{L_{pi}}{10}}\right)\right) \quad dB \qquad \text{A3}$$

A9 Sound Power

Sound power (W) is a measure of the acoustical power, in Watts, emitted by a source. Or, the acoustical energy emitted by a source over a period of time. Sound power is dependent on the source of sound only. The sound power of a source of sound cannot be directly measured. It must be calculated based on a measured sound pressure at a specified distance away from a source of sound.

A10 Sound Power Level

Sound power level (L_w) is a logarithmic equivalent of sound power. SWL is a relative measurement scale, and it has reference sound power of E-12 Watts. Equation A4 is used to calculate the SWL of a source based on calculated sound power.

$$L_W = 10 \times \log\left(\frac{W}{W_{ref}}\right) \quad dB \qquad \text{A4}$$

A11 Sound Intensity

Sound intensity (I) is a measure of the acoustical energy emitted by a source on a specific area over a period of time. It is measured in Watts/m2. There are techniques available that can directly measure the sound intensity at a specified location.

$$I = \frac{W}{A} \quad \frac{Watts}{m^2} \qquad \text{A5}$$

A12 Sound Intensity Level

Sound intensity level (L_I) is a logarithmic equivalent of sound intensity. Sound intensity level is a relative measurement scale, and it has a reference sound intensity of E-12 Watts/m2.

$$L_I = 10 \times log\left(\frac{I}{I_{ref}}\right) \quad dB \qquad \text{A6}$$

A13 Relationship between Sound Pressure, Sound Power, and Sound Intensity

As mentioned above, sound power is not a quantity that can be directly measured. However, sound pressure is. It is possible to take a measurement of sound pressure at a certain distance (r, in metres) and convert it to a sound power value at a source. The following equation is used to calculate the SWL of a source based on measured SPL. In using this equation it is assumed that the acoustical energy is propagating in the shape of a sphere [58].

$$L_W = L_p + 20 \times \log(r) + 11 \quad dB \tag{A7}$$

This relationship is derived on the following assumption [58].

$$I = \frac{p^2}{\rho_o \times c_o} \quad \frac{Watts}{m^2} \tag{A8}$$

Here, ρ_o is the density of air (kg/m3) and c_o is the speed of sound in air (m/s).

A14 A-Weighted Sound Pressure Level

The human perception of sound encompasses the frequency range from 20 Hz to 20 kHz. However, human sensitivity is highly nonlinear. In other words, perception of sound varies at different frequencies. In order to more accurately determine the human perception of a sound, this nonlinearity must be accounted for. The most common method is by employing the A-weighting curve. This curve is used by applying a value of attenuation from the curve to the SPL of a measurement at every applicable frequency. After doing so, the A-weighted SPL is given the unit dBA. The A-weighing curve is a basic sound quality metric. The weightings can be determined at every frequency as a function of frequency using Equation A9.

$$R_A(f) = \frac{12200^2 \times f^4}{(f^2 + 20.6^2) \times (f^2 + 12200^2) \times \sqrt{(f^2 + 107.7^2) \times (f^2 + 737.9^2)}}$$

$$A = 2.0 + 20 \times \log_{10}\big(R_A(f)\big) \tag{A9}$$

Exhibit A-2 illustrates the required SPLs for human perception of sound in the frequency range from 20 Hz to 20 kHz.

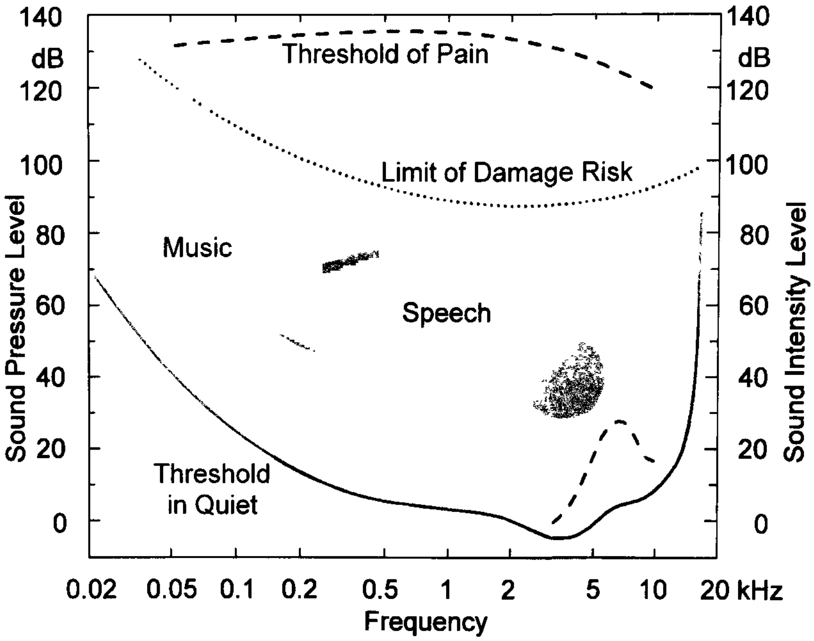

Exhibit A-2: Required SPLs at Frequencies for Human Hearing (image courtesy of Brüel & Kjaer)

Exhibit A-3: 1/3 Octave Band A-Weighting Table

Octave Band Centre Frequency (Hz)	A-Weighting Attenuation (dB)
10.0	-70.4
12.6	-63.4
15.9	-56.6
20.0	-50.4
25.2	-44.6
31.7	-39.4
40.0	-34.5
50.4	-30.1
63.5	-26.1
80.0	-22.4
100.8	-19.0
127.0	-16.0
160.0	-13.2
201.6	-10.8
254.0	-8.5
320.0	-6.5
403.2	-4.7
508.0	-3.1
640.0	-1.8
806.3	-0.8
1015.9	0.0
1280.0	0.6
1612.7	1.0
2031.9	1.2
2560.0	1.3
3225.4	1.2
4063.7	0.9
5120.0	0.5
6450.8	-0.2
8127.5	-1.2
10240.0	-2.7
12901.6	-4.5
16255.0	-6.9
20480.0	-9.6
25803.2	-12.8
32510.0	-16.2
40960.0	-19.8

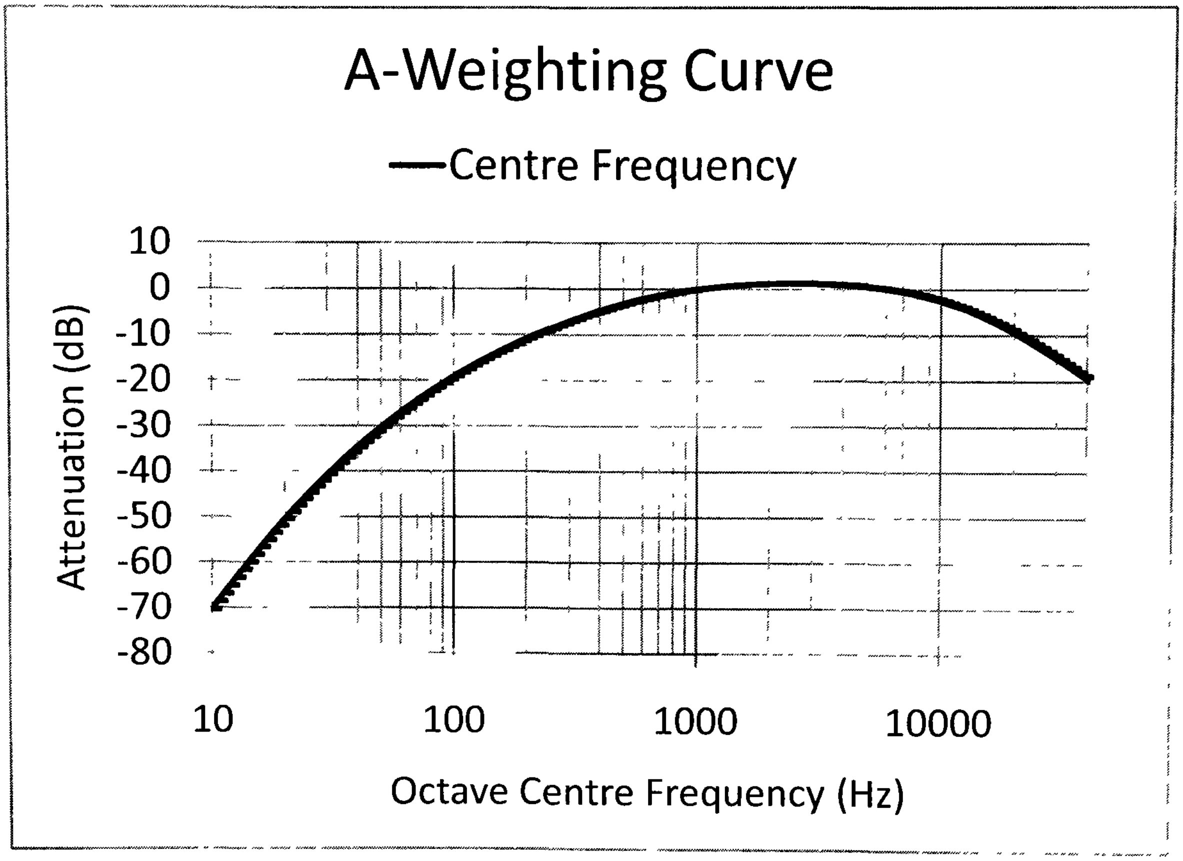

Exhibit A-4: A-Weighting Curve from 10 Hz to 40 kHz

A15 Loudness

Loudness, measured in sone, is a subjective measurement of the human perception of the intensity of a sound. It is the most fundamental psychoacoustic metric.

A16 Prominent Discrete Tone

A prominent tone is the centre frequency of a band that has the greatest SPL of a recorded sound's frequency spectrum.

A17 Octave Band Information

Because the human perception of sound encompasses the frequency range from 20 Hz to 20 kHz, it is convenient to examine measured data in terms of frequency bands, as opposed to every individual frequency. The frequency range of human perception of sound includes 10 frequency bands, or octaves. It is possible to break up octaves into various sizes including 1/3 octave bands and 1/12 octave bands. Octaves and octave bands are referred to by their centre frequency. Exhibit A-5, Exhibit A-6, and Exhibit A-7 list the centre frequencies (CF), lower band limits (LBL), and upper band limits (UBL) of all 10 octaves, 30 – 1/3 octave bands, and 120 – 1/12 octave bands.

Exhibit A-5: Octave Band Upper and Lower Band Limits and Centre Frequencies

Band Number	LBL (Hz)	CF (Hz)	UBL (Hz)
0	22.3	31.5	44.5
1	44.5	63	89.1
2	89.1	126	178.2
3	178.2	252	356.4
4	356.4	504	712.8
5	712.8	1008	1425.5
6	1425.5	2016	2851.1
7	2851.1	4032	5702.1
8	5702.1	8064	11404.2
9	11404.2	16128	22808.4

Exhibit A-6: 1/3 Octave Band Upper and Lower Band Limits and Centre Frequencies

LBL (Hz)	CF (Hz)	UBL (Hz)
22.3	25.0	28.1
28.1	31.5	35.4
35.4	39.7	44.5
44.5	50.0	56.1
56.1	63.0	70.7
70.7	79.4	89.1
89.1	100.0	112.3
112.3	126.0	141.4
141.4	158.8	178.2
178.2	200.0	224.5
224.5	252.0	282.9
282.9	317.5	356.4
356.4	400.0	449.0
449.0	504.0	565.7
565.7	635.0	712.8
712.8	800.1	898.0
898.0	1008.0	1131.4
1131.4	1270.0	1425.5
1425.5	1600.1	1796.1
1796.1	2016.0	2262.9
2262.9	2540.0	2851.1
2851.1	3200.2	3592.1
3592.1	4032.0	4525.8
4525.8	5080.0	5702.1
5702.1	6400.4	7184.2
7184.2	8064.0	9051.5
9051.5	10160.0	11404.2
11404.2	12800.8	14368.4
14368.4	16128.0	18103.1
18103.1	20320.0	22808.4

Exhibit A-7: 1/12 Octave Band Upper and Lower Band Limits and Centre Frequencies

LBL (Hz)	CF (Hz)	UBL (Hz)
22.3	22.9	23.6
23.6	24.3	25.0
25.0	25.7	26.5
26.5	27.3	28.1
28.1	28.9	29.7
29.7	30.6	31.5
31.5	32.4	33.4
33.4	34.4	35.4
35.4	36.4	37.5
37.5	38.6	39.7
39.7	40.9	42.0
42.0	43.3	44.5
44.5	45.9	47.2
47.2	48.6	50.0
50.0	51.5	53.0
53.0	54.5	56.1
56.1	57.8	59.5
59.5	61.2	63.0
63.0	64.8	66.7
66.7	68.7	70.7
70.7	72.8	74.9
74.9	77.1	79.4
79.4	81.7	84.1
84.1	86.6	89.1
89.1	91.7	94.4
94.4	97.2	100.0
100.0	102.9	106.0
106.0	109.1	112.3
112.3	115.5	118.9
118.9	122.4	126.0
126.0	129.7	133.5
133.5	137.4	141.4
141.4	145.6	149.8
149.8	154.2	158.8
158.8	163.4	168.2
168.2	173.1	178.2
178.2	183.4	188.8
188.8	194.3	200.0
200.0	205.9	211.9
211.9	218.1	224.5

LBL (Hz)	CF (Hz)	UBL (Hz)
224.5	231.1	237.9
237.9	244.8	252.0
252.0	259.4	267.0
267.0	274.8	282.9
282.9	291.1	299.7
299.7	308.5	317.5
317.5	326.8	336.4
336.4	346.2	356.4
356.4	366.8	377.6
377.6	388.6	400.0
400.0	411.7	423.8
423.8	436.2	449.0
449.0	462.2	475.7
475.7	489.7	504.0
504.0	518.8	534.0
534.0	549.6	565.7
565.7	582.3	599.4
599.4	616.9	635.0
635.0	653.6	672.8
672.8	692.5	712.8
712.8	733.6	755.1
755.1	777.3	800.1
800.1	823.5	847.6
847.6	872.5	898.0
898.0	924.3	951.4
951.4	979.3	1008.0
1008.0	1037.5	1067.9
1067.9	1099.2	1131.4
1131.4	1164.6	1198.7
1198.7	1233.8	1270.0
1270.0	1307.2	1345.5
1345.5	1384.9	1425.5
1425.5	1467.3	1510.3
1510.3	1554.5	1600.1
1600.1	1647.0	1695.2
1695.2	1744.9	1796.1
1796.1	1848.7	1902.9
1902.9	1958.6	2016.0
2016.0	2075.1	2135.9
2135.9	2198.5	2262.9

LBL (Hz)	CF (Hz)	UBL (Hz)
2262.9	2329.2	2397.4
2397.4	2467.7	2540.0
2540.0	2614.4	2691.0
2691.0	2769.9	2851.1
2851.1	2934.6	3020.6
3020.6	3109.1	3200.2
3200.2	3294.0	3390.5
3390.5	3489.8	3592.1
3592.1	3697.4	3805.7
3805.7	3917.2	4032.0
4032.0	4150.1	4271.8
4271.8	4396.9	4525.8
4525.8	4658.4	4794.9
4794.9	4935.4	5080.0
5080.0	5228.9	5382.1
5382.1	5539.8	5702.1
5702.1	5869.2	6041.2
6041.2	6218.2	6400.4
6400.4	6587.9	6781.0
6781.0	6979.7	7184.2
7184.2	7394.7	7611.4
7611.4	7834.4	8064.0
8064.0	8300.3	8543.5
8543.5	8793.9	9051.5
9051.5	9316.8	9589.8
9589.8	9870.8	10160.0
10160.0	10457.7	10764.1
10764.1	11079.6	11404.2
11404.2	11738.4	12082.3
12082.3	12436.4	12800.8
12800.8	13175.9	13562.0
13562.0	13959.4	14368.4
14368.4	14789.4	15222.8
15222.8	15668.9	16128.0
16128.0	16600.6	17087.0
17087.0	17587.7	18103.1
18103.1	18633.5	19179.5
19179.5	19741.5	20320.0
20320.0	20915.4	21528.3
21528.3	22159.1	22808.4

A18 Aeroacoustics

Lighthill [56, 57] provides a description of aeroacoustics Aeroacoustics is the science dealing with the study aerodynamically generated sound It is the science of sound produced as a result of airflow

A19 Monopole, Dipole, and Quadrupole

Russell et al [59] provide a description of a monopole, dipole, and quadrupole In terms of acoustics, a monopole, dipole, or quadrupole refers to a characteristic of a sound source An acoustic monopole is a source that radiates sound equally in all directions An acoustic dipole is a source composed of two monopoles of equal strength, opposite phase, and separated by a small distance An acoustic quadrupole is a source composed of two dipoles of equal strength, opposite phase, and separated by a small distance There are two types of quadrupoles, lateral and longitudinal A lateral quadrupole is a source where the two dipole axes do not lie along the same line A longitudinal quadrupole is a source where the two dipole axes do lie along the same line [59]

A20 Active Noise Control

Active noise control (ANC) is a technique used for reducing noise emissions from sound sources In systems were ANC is used, a speaker emits a sound wave with the same amplitude but opposite phase to the noise from the sound source The two sound waves combine and cancel each other out

A21 Heat Pipe

Mochizuki et al [42] provide a description of a heat pipe A heat pipe is an evacuated and sealed container which contains a small quantity of working fluid Most heat pipes are made of copper, a metal with high thermal conductivity Due to low internal pressure, when one end of the heat pipe is heated (evaporator), the working fluid vaporizes almost instantly. The vapour travels down to the lower pressured cold end (condenser) and condenses, giving off its latent heat. The condensed liquid is pumped back to the hot end by capillary force. The internal design of the heat pipe, the wicking structure and the liquid properties are the three driving factors. Since the latent heat of vaporization is large, considerable heat can be transported with a very small temperature difference from the hot end to the cold end. Heat pipes have many advantages compared to other cooling devices. They have a simple structure, are light weight, have no moving parts, and do not consume electrical power. They are also maintenance free. The implementation of heat pipes in personal computer systems is likely to be the next major step forward for manufacturers in an effort to meet future form factor requirements.

APPENDIX B

Visual Basic Code

B1 Individual Fan Measurement Data Code

The following code was used to generate the data entry tables for each of the Individual Fan operating configurations tested as well as to create the figures of SPL (linear and A-weighted), SWL (linear and A-weighted), and loudness, based on the data entered.

```
Sub Tables()
'This Macro is used to generate the tables in which the measured data will be entered.
n = Range("R16").Value   1 'This determines the number of tables to be created.
'These arrays define the labelling for each of the tables.
Dim Chart_Title(25) As String
Worksheets("Individual Fans").Range("O20").Select
For A   0 To n
    Chart_Title(A) = ActiveCell
    ActiveCell.Offset(1, 0).Range("A1").Select
Next A
Label = Array("Loudness", "Tonality", "Sound Pressure   Linear", _
                "Sound Pressure   A-Weighted", "Sound Power   Linear" _
                "Sound Power   A-Weighted")
Range("A3").Select
Selection.ColumnWidth = 30

For A = 0 To n
    ActiveCell.FormulaR1C1   Chart_Title(A)
    ActiveCell.Offset(0, 1).Range("A1").Select
    ActiveCell.FormulaR1C1   "=1"
    Selection.NumberFormat   "0"

    For B = 0 To 8
        ActiveCell.Offset(0, 1).Range("A1").Select
        ActiveCell.FormulaR1C1   "=1+RC[-1]"
        Selection.NumberFormat = "0"
    Next B

    ActiveCell.Offset(2, 1).Range("A1").Select
    ActiveCell.FormulaR1C1 = "Avg."
    ActiveCell.Offset(-1, -11).Range("A1").Select

    For C = 0 To 5
        ActiveCell.FormulaR1C1 = Label(C)
        ActiveCell.Offset(1, 0).Range("A1").Select
    Next C

    ActiveCell.Offset(-7, 0).Range("A1").Select
    ActiveCell.Range("A1.L7").Select

    With Selection
        .HorizontalAlignment   xlCenter
        .VerticalAlignment   xlBottom
        .WrapText   False
        .Orientation   0
        .AddIndent = False
        .IndentLevel   0
        .ShrinkToFit   False
        .ReadingOrder = xlContext
        .MergeCells = False
    End With

    ActiveCell.Range("A1:K5,L3:L5,A6:B7").Select
    With Selection
        .Borders(xlDiagonalDown).LineStyle = xlNone
        .Borders(xlDiagonalUp).LineStyle = xlNone
        .Borders.LineStyle   xlContinuous
        .Borders.ColorIndex   0
         Borders.TintAndShade   0
        .Borders.Weight   xlThin
    End With

    ActiveCell.Range("A1:K1,L3").Select
    With Selection.Interior
        .Pattern   xlSolid
         PatternColorIndex   xlAutomatic
        .Color - 5296274
        .TintAndShade   0
        .PatternTintAndShade   0
    End With
```

```
    ActiveCell.Offset(3, 11).Range("A1").Select
    ActiveCell.FormulaR1C1 = "=10*LOG(0.1*SUM(10^(0.1*RC[-10])+10^(0.1*RC[-9])+10^(0.1*RC[-8])+10^(0.1*RC[-
7])+10^(0.1*RC[-6])+10^(0.1*RC[-5])+10^(0.1*RC[-4])+10^(0.1*RC[-3])+10^(0.1*RC[-2])+ 10^(0.1*RC[-1])))"
    Selection.NumberFormat = "0.0"
    Selection.Copy
    ActiveCell.Offset(1, 0).Range("A1").Select
    ActiveSheet.Paste
    ActiveCell.Offset(1, -10).Range("A1").Select
    ActiveCell.FormulaR1C1 = "=R[-2]C[10]+10*LOG(2*PI())"
    Selection.NumberFormat = "0.0"
    Selection.Copy
    ActiveCell.Offset(1, 0).Range("A1").Select
    ActiveSheet.Paste
    ActiveCell.Offset(2, -1).Range("A1").Select
Next A

Sheets("Individual Fans").Range("A1").Select

End Sub
Sub Undo_Tables()

'This Macro is used to delete the data tables.

Sheets("Individual Fans").Range("A3:L241").Select
Selection.UnMerge
Selection.ClearContents
Selection.Borders.LineStyle = xlNone
    With Selection.Interior
        .Pattern = xlNone
        .TintAndShade = 0
        .PatternTintAndShade = 0
    End With

Sheets("Individual Fans").Range("A1").Select
End Sub
Sub Random_Values()

'This Macro is used to fill out the data tables with random values.
'This is only needed until actual measured data is inserted into the data tables.

n   Range("R16").Value   1 'This determines the number of tables to insert random values into.
Range("B4").Select

For A = 0 To n
ActiveCell.FormulaR1C1 = "=10*RAND(/
ActiveCell.Range("A1:J1").Select
Selection.FillRight
ActiveCell.Range("A1:J4").Select
Selection.FillDown
Selection.Copy
Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
        :=False, Transpose:=False
ActiveCell.Offset(8, 0).Range("A1").Select
Next A

Sheets("Individual Fans").Range("A1").Select

End Sub
Sub Random_Values_Undo()

'This Macro is used to fill out the data tables with random values.

n - Range("R16").Value   1 'This determines the number of tables to delete random values from.
Range("B4").Select

For A = 0 To n
    ActiveCell.Range("A1:J4").Select
    Selection.ClearContents
    ActiveCell.Offset(8, 0).Range("A1") Select
Next A
Sheets("Individual Fans").Range("A1").Select

End Sub
Sub Create_All_Figures()

'This Macro is used to create figures of Sound Pressure Level (Linear and A-Weighted),
'Loudness, and Tonality.  There are 25 Sets of figures to create.

n   Range("R16").Value   1 'This determines the number of sets of figures to be created.

'These arrays define the names of each of the figures that will be created.

Dim Chart_Title(25) As String
Worksheets("Individual Fans").Range("O20") Select
For Z = 0 To n
    Chart_Title(Z)   ActiveCell
    ActiveCell.Offset(1, 0).Range("A1") Select
Next Z

Dim Loudness_Title(25) As String
Worksheets("Individual Fans").Range("[illegible]20").Select
For Z   0 To n
    Loudness_Title(Z)   ActiveCell
```

```
    ActiveCell.Offset(1, 0).Range("A1").Select
Next Z

Dim Tonality_Title(25) As String
Worksheets("Individual Fans").Range("U20").Select
For Z = 0 To n
    Tonality_Title(Z) = ActiveCell
    ActiveCell.Offset(1, 0).Range("A1").Select
Next Z

Worksheets("Individual Fans").Range("R20").Select 'Check
For Z = 0 To n
    ActiveCell.FormulaR1C1 = Chart_Title(Z)
    ActiveCell.Offset(1, 0).Range("A1").Select
Next Z

'These arrays define the ranges in the Excel Spreadsheet that contain the data needed.

Data_Range_Pressure   Array("B6:L7", "B14:L15", "B22:L23". "B30:L31", "B38:L39", _
                    "B46:L47". "B54:L55", "B62.L63", "B70:L71", "B78:L79", "B86:L87". _
                    "B94:L95", "B102:L103", "B110:L111", "B118:L119", "B126:L127", _
                    "B134:L135", "B142:L143". "B150:L151". "B158:L159". "B166:l167" _
                    "B174:L175", "B182:L183". "B190:L191". "B198:L199", "B206:L207". _
                    "B214:L215", "B222:L223", "B230:L231". "B238:L239")

Data_Range_Loudness = Array("B4:K4", "B12:K12", "B20:K20". "B28:K28". "B36:K36", _
                    "B44:K44", "B52:K52", "B60:K60", "B68:K68"  "B76:K76", "B84:K84", _
                    "B92:K92", "B100:K100", "B108:K108", "B116:K116", "B124:K124", _
                    "B132:K132"  "B140:K140", "B148:K148"  "B156:K156"  "B164:K164" _
                    "B172:K172". "B180:K180", "B188:K188". "B196:K196", "B204:K204" _
                    "B212.K212". "B220.K220", "B228:K228". "B236:K236")

Data_Range_Tonality   Array("B5.K5",-"B13:K13"  "B21:K21", "B29.K29". "B37.K37". _
                    "B45.K45", "B53.K53", "B61:K61", "B69:K69"  "B77·K77", "B85:K85", _
                    "B93:K93", "B101:K101", "B109:K109", "B117:K117", "B125.K125", _
                    "B133:K133". "B141:K141", "B149.K149"  "B157:K157", "B165:K165", _
                    "B173 K173". "B181:K181", "B189.K189"  "B197 K197", "B205 K205", _
                    "B213.K213"  "B221:K221", "B229.K229". "B237.K237")

Title   Range("B1").Value 'This reads the configuration title from the spreadsheet.

For i   0 To n 'This For loop is used to create each set of figures.

'The following is used to create figures of Sound Pressure Level(Linear and A-Weighted).

    Range(Data_Range_Pressure(i)).Select
    ActiveSheet.Shapes.AddChart.Select
    ActiveChart.SetSourceData Source:=Range(Data_Range_Pressure(i))
    ActiveChart.ApplyLayout (2)
    ActiveChart.SeriesCollection(1).Name = "Sound Pressure   Linear"
    ActiveChart.SeriesCollection(2).Name   "Sound Pressure   A-Weighted"
    ActiveChart.SeriesCollection(1).XValues   _
        "='Individual Fans''$N$2.$X$2"
    ActiveChart.SeriesCollection(2).XValues   _
        "='Individual Fans''$N$2:$X$2"
    ActiveChart.SetElement (msoElementPrimaryValueAxisShow)
    ActiveChart.Axes(xlValue).Select
    Selection.TickLabels.NumberFormat   "0.0"
    ActiveChart.ChartWizard _
    Title =Title + Chr(10) + Chart_Title(i), _
        CategoryTitle:="Microphone Position"  ValueTitle:="dB/dB-A"
    ActiveChart.ChartArea Font.Size = 12
    ActiveChart.SeriesCollection(1).DataLabels.Font.Size = 11
    ActiveChart.SeriesCollection(2).DataLabels.Font.Size - 11
    ActiveChart.ChartTitle.Font.Size = 20
    ActiveChart.Location Where =xlLocationAsNewSheet, Name:=Chart_Title(i)
    Sheets("Individual Fans") Select

'The following is used to create figures of Loudness.

    'Range(Data_Range_Loudness(i)).Select
    'ActiveSheet.Shapes.AddChart.Select
    'ActiveChart.SetSourceData Source.=Range(Data_Range_Loudness(i))
    'ActiveChart.ApplyLayout (2)
    'ActiveChart.SeriesCollection(1).Name   "Loudness"
    'ActiveChart.SeriesCollection(1).XValues   _
    '    "-'Individual Fans''$N$2:$W$2"
    'ActiveChart.SetElement (msoElementPrimaryValueAxisShow)
    'ActiveChart.Axes(xlValue).Select
    'Selection.TickLabels.NumberFormat   "0.0C"
    'ActiveChart.ChartWizard _
    'Title.=Title + Chr(10) + Chart_Title(i), _
    '    CategoryTitle:="Microphone Position"  ValueTitle:="Sone"
    'ActiveChart.ChartArea.Font.Size = 12
    'ActiveChart SeriesCollection(1).DataLabels.Font.Size - 11
    'ActiveChart.ChartTitle Font.Size = 20
    'ActiveChart.Location Where.=xlLocationAsNewSheet, Name:=Loudness_Title(i)
    'Sheets("Individual Fans").Select

'The following is used to create figures of Tonality.

    'Range(Data_Range_Tonality(i)) Select
    'ActiveSheet Shapes.AddChart.Select
    'ActiveChart.SetSourceData Source =Range(Data_Range_Tonality(i))
```

```
    'ActiveChart.ApplyLayout (2)
    'ActiveChart.SeriesCollection(1).Name = "Tonality"
    'ActiveChart.SeriesCollection(1).XValues = _
    '    "='Individual Fans'!$N$2:$W$2"
    'ActiveChart.SetElement (msoElementPrimaryValueAxisShow)
    'ActiveChart.Axes(xlValue).Select
    'Selection.TickLabels.NumberFormat = "0.00"
    'ActiveChart.ChartWizard _
    'Title:=Title + Chr(10) + Chart_Title(i), _
    '    CategoryTitle:="Microphone Position", ValueTitle:="Tu"
    'ActiveChart.ChartArea.Font.Size = 12
    'ActiveChart.SeriesCollection(1).DataLabels.Font.Size = 11
    'ActiveChart.ChartTitle.Font.Size = 20
    'ActiveChart.Location Where:=xlLocationAsNewSheet, Name:=Tonality_Title(i)
    'Sheets("Individual Fans").Select

Next i

Sheets("Individual Fans").Move Before:=Sheets(1)
Sheets("Individual Fans").Range("A1").Select

End Sub
Sub Delete_All_Figures()

'This Macro is used to delete figures of Sound Pressure Level (Linear and A-Weighted),
'Loudness, and Tonality.

n = Range("R16").Value - 1 'This determines the number of sets of figures to be deleted.

'These arrays define the names of each of the figures that will be deleted.

Dim Chart_Title(25) As String
Worksheets("Individual Fans").Range("O20").Select
For Z = 0 To n
    Chart_Title(Z) = ActiveCell
    ActiveCell.Offset(1, 0).Range("A1").Select
Next Z

Dim Loudness_Title(25) As String
Worksheets("Individual Fans").Range("T20").Select
For Z = 0 To n
    Loudness_Title(Z) = ActiveCell
    ActiveCell.Offset(1, 0).Range("A1").Select
Next Z

Dim Tonality_Title(25) As String
Worksheets("Individual Fans").Range("U20").Select
For Z = 0 To n
    Tonality_Title(Z) = ActiveCell
    ActiveCell.Offset(1, 0).Range("A1").Select
Next Z

For i = 0 To n

    Sheets(Chart_Title(i)).Select
    ActiveWindow.SelectedSheets.Delete
    'Sheets(Loudness_Title(i)).Select
    'ActiveWindow.SelectedSheets.Delete
    'Sheets(Tonality_Title(i)).Select
    'ActiveWindow.SelectedSheets.Delete

Next i

Worksheets("Individual Fans").Range("A1").Select

End Sub
Sub Create_Power_Figures()

'The following is used to create Figures of Sound Power Level(Linear and A-Weighted)
'There are 2 Figures to Create.

Data_Range_Sound_Power = Array("AA2:AB10", "AA11:AB17", "AA18:AB26")

Horizontal_Labels = Array("='Individual Fans'!Z2:Z10", _
                        "='Individual Fans'!Z11:Z17", _
                        "='Individual Fans'!Z18:Z26")

Title = Range("B1").Value

Power_Title = Array("Pow1", "Pow2", "Pow3")

For j = 0 To 2

    Range(Data_Range_Sound_Power(j)).Select
    ActiveSheet.Shapes.AddChart.Select
    ActiveChart.SetSourceData Source:=Range(Data_Range_Sound_Power(j))
    ActiveChart.ApplyLayout (2)
    ActiveChart.SeriesCollection(1).Name = "Sound Power - Linear"
    ActiveChart.SeriesCollection(2).Name = "Sound Power - A-Weighted"
    ActiveChart.SeriesCollection(1).XValues = Horizontal_Labels(j)
    ActiveChart.SeriesCollection(2).XValues = Horizontal_Labels(j)
    ActiveChart.SetElement (msoElementPrimaryValueAxisShow)
    ActiveChart.Axes(xlValue).Select
    Selection.TickLabels.NumberFormat = "0.00"
```

```
    ActiveChart.ChartWizard _
    Title:=Title, CategoryTitle.="Tests Performed". ValueTitle:="dB/dB-A"
    ActiveChart.ChartArea.Font.Size = 12
    ActiveChart.SeriesCollection(1).DataLabels.Font.Size = 11
    ActiveChart.SeriesCollection(2).DataLabels.Font.Size = 11
    ActiveChart.ChartTitle.Font.Size = 20
    ActiveChart.Location Where:=xlLocationAsNewSheet, Name.=Power_Title(j)
    Sheets("Individual Fans").Select

Next j

Sheets("Individual Fans").Move Before:=Sheets(1)
Sheets("Individual Fans").Range("A1").Select

End Sub
Sub Delete_Power_Charts()

'This Macro is used to delete figures of Sound Power Level (Linear and A-Weighted)

Power_Title   Array("Pow1"  "Pow2", "Pow3")

For j = 0 To 2
    Sheets(Power_Title(j)).Select
    ActiveWindow.SelectedSheets.Delete
Next j
Worksheets("Individual Fans").Range("A1").Select
End Sub
Sub Test()

Table_Start   Array("Z1", "AD1", "AQ1", "AD33", "AQ33")
Label = Array("Sound Power", "Sound Pressure   Linear"  "Sound Pressure   A-Weighted". "Loudness",
"Tonality")
Label_2   Array("Linear"  "A-Weighted")

Dim Test_name(25) As Variant
Dim Sound_Power(25, 2) As Variant
Dim Pressure_Linear(25, 11) As Variant
Dim Pressure_A_Weighted(25, 11) As Variant
Dim Loudness(25, 10) As Variant
Dim Tonality(25, 10) As Variant

n = Range("R16") Value   1

Worksheets("Individual Fans").Range("O20").Select 'Test name
For i   0 To n
    Test_name(i)   ActiveCell
    ActiveCell.Offset(1, 0) Range("A1").Select
Next i

Worksheets("Individual Fans").Range("B8").Select 'Sound Power
For i = 0 To n
    For j = 0 To 1
        Sound_Power(i, j)   ActiveCell
        ActiveCell Offset(1, 0).Range("A1").Select
    Next j
ActiveCell.Offset(6, 0).Range("A1").Select
Next i

Worksheets("Individual Fans").Range("B6").Select 'Pressure_Linear
For i - 0 To n
    For j = 0 To 10
        Pressure_Linear(i, j)   ActiveCell
        ActiveCell.Offset(0, 1).Range("A1").Select
    Next j
ActiveCell.Offset(8, -11).Range("A1").Select
Next i

Worksheets("Individual Fans").Range("B7").Select 'Pressure_A_Weighted
For i = 0 To n
    For j   0 To 10
        Pressure_A_Weighted(i, j)   ActiveCell
        ActiveCell Offset(0, 1).Range("A1").Select
    Next j
ActiveCell.Offset(8, -11).Range("A1") Select
Next i

Worksheets("Individual Fans").Range("B4").Select 'Loudness
For i = 0 To n
    For j = 0 To 9
        Loudness(i, j)   ActiveCell
        ActiveCell.Offset(0, 1) Range("A1") Select
    Next j
ActiveCell.Offset(8, -10) Range("A1").Select
Next i

Worksheets("Individual Fans").Range("B5") Select 'Tonality
For i   0 To n
    For j   0 To 9
        Tonality(i, j)   ActiveCell
        ActiveCell.Offset(0, 1) Range("A1") Select
    Next j
ActiveCell  Offset(8, -10) Range("A1").Select
Next i
```

```
'The following creates the large data tables

For K = 0 To 4
Range(Table_Start(K)).Select
ActiveCell.FormulaR1C1 = Label(K)
    With Selection.Interior
        .Pattern = xlSolid
        .PatternColorIndex = xlAutomatic
        .Color = 5296274
    End With
    With Selection
        .Borders.LineStyle = xlContinuous
        .Borders.Weight = xlThin
        .HorizontalAlignment = xlCenter
    End With
    ActiveCell.Offset(1, 0).Range("A1").Select

    For i = 0 To n
        ActiveCell.FormulaR1C1 = Test_name(i)
    With Selection.Interior
        .Pattern = xlSolid
        .PatternColorIndex = xlAutomatic
        .Color = 5296274
    End With
    With Selection
        .Borders.LineStyle = xlContinuous
        .Borders.Weight = xlThin
        .HorizontalAlignment = xlCenter
    End With
        ActiveCell.Offset(1, 0).Range("A1").Select
    Next i

    If K = 0 Then
        Range("AA1").Select
        For i = 0 To 1
        Selection.ColumnWidth = 20
        ActiveCell.FormulaR1C1 = Label_2(i)
        With Selection.Interior
        .Pattern = xlSolid
        .PatternColorIndex = xlAutomatic
        .Color = 5296274
        End With
        With Selection
        .Borders.LineStyle = xlContinuous
        .Borders.Weight = xlThin
        .HorizontalAlignment = xlCenter
        End With
        ActiveCell.Offset(0, 1).Range("A1").Select
        Next i

    ElseIf K = 1 Or K = 2 Then
        Range("N2:X2").Select
        Selection.Copy
        Range(Table_Start(K)).Select
        ActiveCell.Offset(0, 1).Range("A1").Select
        ActiveSheet.Paste

    ElseIf K = 3 Or K = 4 Then
        Range("N2:W2").Select
        Selection.Copy
        Range(Table_Start(K)).Select
        ActiveCell.Offset(0, 1).Range("A1").Select
        ActiveSheet.Paste
    End If

Next K

Worksheets("Individual Fans").Range("AA2").Select
For i = 0 To n
    For j = 0 To 1
        ActiveCell.FormulaR1C1 = Sound_Power(i, j)
        Selection.Borders.LineStyle = xlContinuous
        Selection.Borders.Weight = xlThin
        Selection.NumberFormat = "0.0"
        Selection.HorizontalAlignment = xlCenter
        ActiveCell.Offset(0, 1).Range("A1").Select
    Next j
ActiveCell.Offset(1, -2).Range("A1").Select
Next i

Worksheets("Individual Fans").Range("AE2").Select
For i = 0 To n
    For j = 0 To 10
        ActiveCell.FormulaR1C1 = Pressure_Linear(i, j)
        Selection.Borders.LineStyle = xlContinuous
        Selection.Borders.Weight = xlThin
        Selection.NumberFormat = "0.0"
        Selection.HorizontalAlignment = xlCenter
        ActiveCell.Offset(0, 1).Range("A1").Select
    Next j
ActiveCell.Offset(1, -11).Range("A1").Select
Next i

Worksheets("Individual Fans").Range("AR2").Select
```

```
For i = 0 To n
    For j = 0 To 10
        ActiveCell.FormulaR1C1 = Pressure_A_Weighted(i, j)
        Selection.Borders.LineStyle = xlContinuous
        Selection.Borders.Weight = xlThin
        Selection.NumberFormat = "0.0"
        Selection.HorizontalAlignment = xlCenter
        ActiveCell.Offset(0, 1).Range("A1").Select
    Next j
ActiveCell.Offset(1, -11).Range("A1").Select
Next i

Worksheets("Individual Fans").Range("AE34").Select
For i = 0 To n
    For j = 0 To 9
        ActiveCell.FormulaR1C1 = Loudness(i, j)
        Selection.Borders.LineStyle = xlContinuous
        Selection.Borders.Weight = xlThin
        Selection.NumberFormat = "0.00"
        Selection.HorizontalAlignment = xlCenter
        ActiveCell.Offset(0, 1).Range("A1").Select
    Next j
ActiveCell.Offset(1, -10).Range("A1").Select
Next i

Worksheets("Individual Fans").Range("AR34").Select
For i = 0 To n
    For j = 0 To 9
        ActiveCell.FormulaR1C1 = Tonality(i, j)
        Selection.Borders.LineStyle = xlContinuous
        Selection.Borders.Weight = xlThin
        Selection.NumberFormat = "0.00"
        Selection.HorizontalAlignment = xlCenter
        ActiveCell.Offset(0, 1).Range("A1").Select
    Next j
ActiveCell.Offset(1, -10).Range("A1").Select
Next i

Worksheets("Individual Fans").Range("AD1").Select

End Sub
Sub Delete_Tables()

Range("Z1:BB63").Select 'This clears the large data tables
Selection.ClearContents
Selection.Borders.LineStyle = xlNone
    With Selection.Interior
        .Pattern = xlNone
        .TintAndShade = 0
        .PatternTintAndShade = 0
    End With
End Sub
Sub Create_Large_Figures()
Title = Range("B1").Value
Chart_Title = Array("Sound Pressure - Linear", "Sound Pressure - A-Weighted", _
                    "Loudness", "Tonality")
Data_Range = Array("AD2:AO10", "AD11:AO17", "AD18:AO26", _
                   "AQ2:BB10", "AQ11:BB17", "AQ18:BB26", _
                   "AD34:AN42", "AD43:AN49", "AD50:AN58", _
                   "AQ34:BA42", "AQ43:BA49", "AQ50:BA58")
For i = 0 To 2
Worksheets("Individual Fans").Range(Data_Range(i)).Select
ActiveSheet.Shapes.AddChart.Select
ActiveChart.SetSourceData Source:=Range(Data_Range(i))
'ActiveChart.ChartType = xlLineMarkers
ActiveChart.ChartType = xlColumnClustered
ActiveChart.SetElement (msoElementChartTitleAboveChart)
ActiveChart.SetElement (msoElementPrimaryCategoryAxisTitleAdjacentToAxis)
ActiveChart.SetElement (msoElementPrimaryValueAxisTitleRotated)
ActiveChart.SetElement (msoElementLegendTop)
ActiveChart.Axes(xlValue).Select
Selection.TickLabels.NumberFormat = "0.0"
ActiveChart.ChartWizard _
Title:=Title + Chr(10) + Chart_Title(0), _
    CategoryTitle:="Microphone Position", ValueTitle:="SPL - Linear (dB)"
If i = 0 Then
For j = 1 To 9
ActiveChart.SeriesCollection(j).XValues = "='Individual Fans'!$AE$1:$AO$1"
Next j
ElseIf i = 1 Then
For j = 1 To 7
ActiveChart.SeriesCollection(j).XValues = "='Individual Fans'!$AE$1:$AO$1"
Next j
ElseIf i = 2 Then
For j = 1 To 9
ActiveChart.SeriesCollection(j).XValues = "='Individual Fans'!$AE$1:$AO$1"
Next j
End If
ActiveChart.ChartArea.Font.Size = 12
ActiveChart.ChartTitle.Font.Size = 20
ActiveChart.Location Where:=xlLocationAsNewSheet, 'an
Sheets("Individual Fans").Select
Sheets("Individual Fans").Move Before:=Sheets(1)
Next i
```

```
For i = 3 To 5
Worksheets("Individual Fans").Range(Data_Range(i)).Select
ActiveSheet.Shapes.AddChart.Select
ActiveChart.SetSourceData Source:=Range(Data_Range(i))
'ActiveChart.ChartType = xlLineMarkers
ActiveChart.ChartType = xlColumnClustered
ActiveChart.SetElement (msoElementChartTitleAboveChart)
ActiveChart.SetElement (msoElementPrimaryCategoryAxisTitleAdjacentToAxis)
ActiveChart.SetElement (msoElementPrimaryValueAxisTitleRotated)
ActiveChart.SetElement (msoElementLegendTop)
ActiveChart.Axes(xlValue).Select
Selection.TickLabels.NumberFormat = "0.0"
ActiveChart.ChartWizard _
Title:=Title + Chr(10) + Chart_Title(1), _
    CategoryTitle:="Microphone Position", ValueTitle:="SPL   A-Weighted (dBA)"
If i = 3 Then
For j = 1 To 9
ActiveChart.SeriesCollection(j).XValues = "='Individual Fans'!$AE$1:$AO$1"
Next j
ElseIf i = 4 Then
For j = 1 To 7
ActiveChart.SeriesCollection(j).XValues = "='Individual Fans'!$AE$1:$AO$1"
Next j
ElseIf i = 5 Then
For j = 1 To 9
ActiveChart.SeriesCollection(j).XValues = "='Individual Fans'!$AE$1:$AO$1"
Next j
End If
ActiveChart.ChartArea.Font.Size = 12
ActiveChart.ChartTitle.Font.Size = 20
ActiveChart.Location Where:=xlLocationAsNewSheet, Name:=i
Sheets("Individual Fans").Select
Sheets("Individual Fans").Move Before:=Sheets(1)
Next i

For i = 6 To 8
Worksheets("Individual Fans").Range(Data_Range(i)).Select
ActiveSheet.Shapes.AddChart.Select
ActiveChart.SetSourceData Source:=Range(Data_Range(i))
'ActiveChart.ChartType = xlLineMarkers
ActiveChart.ChartType = xlColumnClustered
ActiveChart.SetElement (msoElementChartTitleAboveChart)
ActiveChart.SetElement (msoElementPrimaryCategoryAxisTitleAdjacentToAxis)
ActiveChart.SetElement (msoElementPrimaryValueAxisTitleRotated)
ActiveChart.SetElement (msoElementLegendTop)
ActiveChart.Axes(xlValue).Select
Selection.TickLabels.NumberFormat = "0.00"
ActiveChart.ChartWizard _
Title:=Title + Chr(10) + Chart_Title(2), _
    CategoryTitle:="Microphone Position", ValueTitle:="Sone"
ActiveChart.SeriesCollection(1).XValues = "='Individual Fans'!$AE$1:$AN$1"
ActiveChart.ChartArea.Font.Size = 12
ActiveChart.ChartTitle.Font.Size = 20
ActiveChart.Location Where:=xlLocationAsNewSheet, Name:=i
Sheets("Individual Fans").Select
Sheets("Individual Fans").Move Before:=Sheets(1)
Next i

For i = 9 To 11
Worksheets("Individual Fans").Range(Data_Range(i)).Select
ActiveSheet.Shapes.AddChart.Select
ActiveChart.SetSourceData Source:=Range(Data_Range(i))
'ActiveChart.ChartType = xlLineMarkers
ActiveChart.ChartType = xlColumnClustered
ActiveChart.SetElement (msoElementChartTitleAboveChart)
ActiveChart.SetElement (msoElementPrimaryCategoryAxisTitleAdjacentToAxis)
ActiveChart.SetElement (msoElementPrimaryValueAxisTitleRotated)
ActiveChart.SetElement (msoElementLegendTop)
ActiveChart.Axes(xlValue).Select
Selection.TickLabels.NumberFormat = "0.00"
ActiveChart.ChartWizard _
Title:=Title + Chr(10) + Chart_Title(3), _
    CategoryTitle:="Microphone Position", ValueTitle:="Tu"
ActiveChart.SeriesCollection(1).XValues = "='Individual Fans'!$AE$1:$AN$1"
ActiveChart.ChartArea.Font.Size = 12
ActiveChart.ChartTitle.Font.Size = 20
ActiveChart.Location Where:=xlLocationAsNewSheet, Name:=i
Sheets("Individual Fans").Select
Sheets("Individual Fans").Move Before:=Sheets(1)
Next i
End Sub

Sub Delete_Large_Figures()
'This Macro is used to delete the large figures of Sound Pressure Level (Linear and A-weighted),
'Loudness, and Tonality
Sheet_Name = Array("0", "1", "2", "3", "4", "5", "6", "7",
                    "8", "9", "10", "11")
For i = 0 To 11
    Sheets(Sheet_Name(i)).Select
    ActiveWindow.SelectedSheets.Delete
Next i
Sheets("Individual Fans").Range("[illegible]").Select
End Sub
```

B2 FAODCS Measurement Data Code

The following code was used to generate the data entry tables for each of the FAODCS operating configurations tested as well as to create the figures of SPL (linear and A-weighted), Sound Power Level (linear and A-weighted), and Loudness, based on the data entered.

```
Sub Tables()

'This Macro is used to generate the tables in which the measured data will be entered.

n = Range("R16").Value - 1 'This determines the number of tables to be created.

'These arrays define the labelling for each of the tables.

Dim Chart_Title(8) As String
Worksheets("Individual Fans").Range("O20").Select

For A = 0 To n
    Chart_Title(A) = ActiveCell
    ActiveCell.Offset(1, 0).Range("A1").Select
Next A

Label = Array("Loudness", "Tonality", "Sound Pressure   Linear", _
                "Sound Pressure   A-Weighted", "Sound Power   Linear", _
                "Sound Power   A-Weighted")

Range("A3").Select
Selection.ColumnWidth = 30

For A = 0 To n
    ActiveCell.FormulaR1C1 = Chart_Title(A)
    ActiveCell.Offset(0, 1).Range("A1").Select
    ActiveCell.FormulaR1C1 = "=1"
    Selection.NumberFormat = "0"

    For B = 0 To 8
        ActiveCell.Offset(0, 1).Range("A1").Select
        ActiveCell.FormulaR1C1 = "=1+RC[-1]"
        Selection.NumberFormat = "0"
    Next B

    ActiveCell.Offset(2, 1).Range("A1").Select
    ActiveCell.FormulaR1C1 = "Avg."
    ActiveCell.Offset(-1, -11).Range("A1").Select

    For C = 0 To 5
        ActiveCell.FormulaR1C1 = Label(C)
        ActiveCell.Offset(1, 0).Range("A1").Select
    Next C

    ActiveCell.Offset(-7, 0).Range("A1").Select
    ActiveCell.Range("A1:L7").Select

    With Selection
        .HorizontalAlignment = xlCenter
        .VerticalAlignment = xlBottom
        .WrapText = False
        .Orientation = 0
        .AddIndent = False
        .IndentLevel = 0
        .ShrinkToFit = False
        .ReadingOrder = xlContext
        .MergeCells = False
    End With

    ActiveCell.Range("A1:K5,L3:L5,A6:B7").Select
    With Selection
        .Borders(xlDiagonalDown).LineStyle = xlNone
        .Borders(xlDiagonalUp).LineStyle = xlNone
        .Borders.LineStyle = xlContinuous
        .Borders.ColorIndex = 0
        .Borders.TintAndShade = 0
        .Borders.Weight = xlThin
    End With

    ActiveCell.Range("A1:K1,L3").Select
    With Selection.Interior
        .Pattern = xlSolid
        .PatternColorIndex = xlAutomatic
        .Color = 5296274
        .TintAndShade = 0
        .PatternTintAndShade = 0
    End With
```

```
    ActiveCell.Offset(3, 11).Range("A1").Select
    ActiveCell.FormulaR1C1 = "=10*LOG(0.1*SUM(10^(0.1*RC[-10])+10^(0 1*RC[-9])+10^(0.1*RC[-8])+10^(0.1*RC[-
7])+10^(0.1*RC[-6])+10^(0.1*RC[-5])+10^(0.1*RC[-4])+10^(0.1*RC[-3])+10^(0.1*RC[-2])+ 10^(0.1*RC[-1])))"
    Selection.NumberFormat = "0.0"
    Selection.Copy
    ActiveCell.Offset(1, 0).Range("A1").Select
    ActiveSheet.Paste
    ActiveCell.Offset(1, -10).Range("A1").Select
    ActiveCell.FormulaR1C1 = "=R[-2]C[10]+10*LOG(2*PI())"
    Selection.NumberFormat = "0.0"
    Selection.Copy
    ActiveCell.Offset(1, 0).Range("A1").Select
    ActiveSheet.Paste
    ActiveCell.Offset(2, -1).Range("A1").Select
Next A

Sheets("Individual Fans").Range("A1").Select

End Sub
Sub Undo_Tables()

'This Macro is used to delete the data tables.

Sheets("Individual Fans").Range("A3.L241") Select
Selection.UnMerge
Selection.ClearContents
Selection.Borders.LineStyle   xlNone
    With Selection.Interior
        .Pattern = xlNone
        .TintAndShade = 0
        .PatternTintAndShade = 0
    End With

Sheets("Individual Fans").Range("A1").Select
End Sub
Sub Random_Values()

'This Macro is used to fill out the data tables with random values.
'This is only needed until actual measured data is inserted into the data tables.

n   Range("R16").Value   1 'This determines the number of tables to insert random values into
Range("B4") Select

For A = 0 To n
ActiveCell.FormulaR1C1   "=10*RAND()"
ActiveCell.Range("A1.J1").Select
Selection.FillRight
ActiveCell.Range("A1.J4").Select
Selection.FillDown
Selection.Copy
Selection PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
        :=False, Transpose =False
ActiveCell.Offset(8, 0) Range("A1").Select
Next A

Sheets("Individual Fans") Range("A1") Select

End Sub
Sub Random_Values_Undo()

'This Macro is used to fill out the data tables with random values

n = Range("R16").Value   1 'This determines the number of tables to delete random values from.
Range("B4").Select

For A = 0 To n
    ActiveCell.Range("A1.J4").Select
    Selection.ClearContents
    ActiveCell.Offset(8, 0) Range("A1").Select
Next A
Sheets("Individual Fans") Range("A1") Select

End Sub
Sub Create_All_Figures()

'This Macro is used to create figures of Sound Pressure Level (Linear and A-Weighted),
'Loudness, and Tonality.  There are 25 Sets of figures to create

n   Range("R16") Value   1 'This determines the number of sets of figures to be created.

'These arrays define the names of each of the figures that will be created

Dim Chart_Title(8) As String
Worksheets("Individual Fans").Range("O20").Select
For Z   0 To n
    Chart_Title(Z) = ActiveCell
    ActiveCell.Offset(1, 0).Range("A1").Select
Next Z

Dim Loudness_Title(8) As String
Worksheets("Individual Fans") Range("O20") Select
For Z   0 To n
    Loudness_Title(Z) = ActiveCell
    ActiveCell.Offset(1, 0).Range("A1").Select
```

```
Next Z

Dim Tonality_Title(8) As String
Worksheets("Individual Fans").Range("U20").Select
For Z = 0 To n
    Tonality_Title(Z) = ActiveCell
    ActiveCell.Offset(1, 0).Range("A1").Select
Next Z

Worksheets("Individual Fans").Range("R20").Select 'Check
For Z = 0 To n
    ActiveCell.FormulaR1C1 = Chart_Title(Z)
    ActiveCell.Offset(1, 0).Range("A1").Select
Next Z

'These arrays define the ranges in the Excel Spreadsheet that contain the data needed.

Data_Range_Pressure = Array("B6:L7". "B14:L15", "B22:L23", "B30:L31", "B38:L39", _
                      "B46:L47"  "B54:L55", "B62:L63", "B70:L71", "B78:L79", "B86:L87", _
                      "B94:L95", "B102:L103", "B110:L111", "B118:L119", "B126:L127", _
                      "B134:L135", "B142:L143", "B150:L151". "B158:L159". "B166:1167". _
                      "B174:L175", "B182:L183", "B190:L191". "B198:L199", "B206:L207", _
                      "B214:L215", "B222:L223", "B230:L231". "B238:L239")

Data_Range_Loudness = Array("B4:K4", "B12:K12". "B20:K20"  "B28:K28", "B36:K36", _
                      "B44.K44". "B52:K52", "B60:K60", "B68:K68", "B76:K76", "B84:K84", _
                      "B92:K92", "B100:K100", "B108:K108", "B116:K116", "B124:K124", _
                      "B132:K132"  "B140:K140", "B148:K148"  "B156:K156"  "B164:K164", _
                      "B172:K172", "B180:K180", "B188:K188". "B196:K196", "B204:K204", _
                      "B212:K212"  "B220:K220", "B228:K228". "B236:K236")

Data_Range_Tonality   Array("B5:K5", "B13:K13", "B21:K21", "B29:K29", "B37:K37", _
                      "B45:K45", "B53:K53", "B61:K61", "B69:K69", "B77:K77", "B85:K85". _
                      "B93:K93", "B101:K101", "B109:K109", "B117:K117", "B125:K125", _
                      "B133:K133"  "B141:K141"  "B149:K149". "B157:K157"  "B165:K165", _
                      "B173:K173"  "B181.K181"  "B189:K189". "B197:K197", "B205:K205", _
                      "B213.K213"  "B221:K221", "B229:K229". "B237:K237")

Title = Range("B1").Value 'This reads the configuration title from the spreadsheet.

For i = 0 To n 'This For loop is used to create each set of figures.

'The following is used to create figures of Sound Pressure Level(Linear and A-Weighted).

    Range(Data_Range_Pressure(i)).Select
    ActiveSheet.Shapes.AddChart.Select
    ActiveChart.SetSourceData Source:=Range(Data_Range_Pressure(i))
    ActiveChart.ApplyLayout (2)
    ActiveChart.SeriesCollection(1).Name   "Sound Pressure   Linear"
    ActiveChart.SeriesCollection(2).Name   "Sound Pressure   A-Weighted"
    ActiveChart.SeriesCollection(1).XValues   _
        "='Individual Fans''$N$2:$X$2"
    ActiveChart.SetElement (msoElementPrimaryValueAxisShow)
    ActiveChart.Axes(xlValue).Select
    Selection.TickLabels.NumberFormat   "0"
    ActiveChart.ChartWizard _
    Title:=Title + Chr(10) + Chart_Title(i), _
        CategoryTitle:="Microphone Position". ValueTitle:="dB/dB-A"
    ActiveChart.ChartArea.Font.Size = 12
    ActiveChart.Axes(xlValue).HasMajorGridlines   True
    ActiveChart.SeriesCollection(1).DataLabels.Select
    Selection.Delete
    ActiveChart.SeriesCollection(2).DataLabels.Select
    Selection.Delete
    'ActiveChart SeriesCollection(1).DataLabels.Font.Size = 11
    'ActiveChart.SeriesCollection(2).DataLabels.Font.Size   11
    ActiveChart.ChartTitle.Font.Size = 20
    ActiveChart.Location Where:=xlLocationAsNewSheet, Name:=Chart_Title(i)
    Sheets("Individual Fans").Select

'The following is used to create figures of Loudness.

    'Range(Data_Range_Loudness(i)).Select
    'ActiveSheet.Shapes.AddChart.Select
    'ActiveChart.SetSourceData Source:=Range(Data_Range_Loudness(i))
    'ActiveChart.ApplyLayout (2)
    'ActiveChart.SeriesCollection(1).Name   "Loudness"
    'ActiveChart.SeriesCollection(1).XValues   _
    '    "='Individual Fans''$N$2:$W$2"
    'ActiveChart.SetElement (msoElementPrimaryValueAxisShow)
    'ActiveChart.Axes(xlValue).Select
    'Selection.TickLabels.NumberFormat   "0"
    'ActiveChart.ChartWizard _
    'Title.=Title + Chr(10) + Chart_Title(i), _
    '    CategoryTitle:="Microphone Position"  ValueTitle  "Sone"
    'ActiveChart.ChartArea.Font.Size = 12
    'ActiveChart.SeriesCollection(1).DataLabels.Font.Size - 11
    'ActiveChart.ChartTitle Font.Size   20
    'ActiveChart.Location Where:=xlLocationAsNewSheet, Name =Loudness_Title(i)
    'Sheets("Individual Fans").Select

'The following is used to create figures of Tonality.

    'Range(Data_Range Tonality(i)).Sele
```

```
    'ActiveSheet.Shapes.AddChart.Select
    'ActiveChart.SetSourceData Source:=Range(Data_Range_Tonality(i))
    'ActiveChart.ApplyLayout (2)
    'ActiveChart.SeriesCollection(1).Name = "Tonality"
    'ActiveChart.SeriesCollection(1).XValues _
    '    "='Individual Fans''$N$2:$W$2"
    'ActiveChart.SetElement (msoElementPrimaryValueAxisShow)
    'ActiveChart.Axes(xlValue).Select
    'Selection.TickLabels.NumberFormat = "0"
    'ActiveChart.ChartWizard _
    'Title:=Title + Chr(10) + Chart_Title(i), _
    '    CategoryTitle:="Microphone Position". ValueTitle.="Tu"
    'ActiveChart.ChartArea.Font.Size = 12
    'ActiveChart.SeriesCollection(1).DataLabels.Font.Size   11
    'ActiveChart.ChartTitle.Font.Size = 20
    'ActiveChart.Location Where:=xlLocationAsNewSheet, Name:=Tonality_Title(i)
    'Sheets("Individual Fans").Select

Next i

Sheets("Individual Fans").Move Before:=Sheets(1)
Sheets("Individual Fans").Range("A1").Select

End Sub
Sub Delete_All_Figures()

'This Macro is used to delete figures of Sound Pressure Level (Linear and A-Weighted),
'Loudness, and Tonality.

n = Range("R16").Value   1 'This determines the number of sets of figures to be deleted.

'These arrays define the names of each of the figures that will be deleted.

Dim Chart_Title(25) As String
Worksheets("Individual Fans").Range("O20").Select
For Z = 0 To n
    Chart_Title(Z) = ActiveCell
    ActiveCell.Offset(1, 0).Range("A1").Select
Next Z

Dim Loudness_Title(25) As String
Worksheets("Individual Fans").Range("T20").Select
For Z   0 To n
    Loudness_Title(Z) = ActiveCell
    ActiveCell.Offset(1, 0).Range("A1").Select
Next Z

Dim Tonality_Title(25) As String
Worksheets("Individual Fans").Range("U20").Select
For Z = 0 To n
    Tonality_Title(Z) = ActiveCell
    ActiveCell.Offset(1, 0).Range("A1").Select
Next Z

For i   0 To n

    Sheets(Chart_Title(i)).Select
    ActiveWindow.SelectedSheets.Delete
    'Sheets(Loudness_Title(i)).Select
    'ActiveWindow.SelectedSheets.Delete
    'Sheets(Tonality_Title(i)).Select
    'ActiveWindow.SelectedSheets.Delete

Next i

Sheets("Individual Fans").Range("A1").Select

End Sub
Sub Create_Power_Figures()

'The following is used to create Figures of Sound Power Level(Linear and A-Weighted).
'There is 1 Figures to Create.

Data_Range_Sound_Power = Array("AA2:AB9")

Horizontal_Labels   Array("='Individual Fans''Z2.Z9")

Title   Range("B1").Value

Power_Title = Array("Pow1")

For j   0 To 0

    Range(Data_Range_Sound_Power(j)).Select
    ActiveSheet Shapes.AddChart.Select
    ActiveChart.SetSourceData Source.=Range(Data_Range_Sound_Power(j))
    ActiveChart.ApplyLayout (2)
    ActiveChart.SeriesCollection(1) Name   "Sound Power   Linear"
    ActiveChart.SeriesCollection(2) Name   "Sound Power   A-Weighted"
    ActiveChart.SeriesCollection( ).XValues = Horizontal_Labels(j)
    ActiveChart.SetElement (msoElementPrimaryValueAxisShow)
    ActiveChart.Axes(xlValue) Select
    Selection.TickLabels.NumberFormat = "0"
    ActiveChart.ChartWizard
```

```
    Title:=Title, CategoryTitle:="Tests Performed", ValueTitle:="dB/dB-A"
    ActiveChart.ChartArea.Font.Size = 12
    ActiveChart.Axes(xlValue).HasMajorGridlines = True
    ActiveChart.SeriesCollection(1).DataLabels.Select
    Selection.Delete
    ActiveChart.SeriesCollection(2).DataLabels.Select
    Selection.Delete
    'ActiveChart.SeriesCollection(1).DataLabels.Font.Size = 11
    'ActiveChart.SeriesCollection(2).DataLabels.Font.Size = 11
    ActiveChart.ChartTitle.Font.Size = 20
    ActiveChart.Location Where:=xlLocationAsNewSheet, Name:=Power_Title(j)
    Sheets("Individual Fans").Select

Next j

Sheets("Individual Fans").Move Before:=Sheets(1)
Sheets("Individual Fans").Range("A1").Select

End Sub
Sub Delete_Power_Charts()

'This Macro is used to delete the figure of Sound Power Level (Linear and A-Weighted)
    Sheets("Pow1").Select
    ActiveWindow.SelectedSheets.Delete

Sheets("Individual Fans").Range("A1").Select

End Sub
Sub Test()

Table_Start = Array("Z1", "AD1", "AQ1", "AD33", "AQ33")
Label = Array("Sound Power", "Sound Pressure   Linear", "Sound Pressure   A-Weighted", "Loudness",
"Tonality")
Label_2 = Array("Linear", "A-Weighted")

Dim Test_name(25) As Variant
Dim Sound_Power(25, 2) As Variant
Dim Pressure_Linear(25, 11) As Variant
Dim Pressure_A_Weighted(25, 11) As Variant
Dim Loudness(25, 10) As Variant
Dim Tonality(25, 10) As Variant

n = Range("R16").Value - 1

Worksheets("Individual Fans").Range("O20").Select 'Test name
For i = 0 To n
    Test_name(i) = ActiveCell
    ActiveCell.Offset(1, 0).Range("A1").Select
Next i

Worksheets("Individual Fans").Range("B8").Select 'Sound Power
For i = 0 To n
    For j = 0 To 1
        Sound_Power(i, j) = ActiveCell
        ActiveCell.Offset(1, 0).Range("A1").Select
    Next j
ActiveCell.Offset(6, 0).Range("A1").Select
Next i

Worksheets("Individual Fans").Range("B6").Select 'Pressure_Linear
For i = 0 To n
    For j = 0 To 10
        Pressure_Linear(i, j) = ActiveCell
        ActiveCell.Offset(0, 1).Range("A1").Select
    Next j
ActiveCell.Offset(8, -11).Range("A1").Select
Next i

Worksheets("Individual Fans").Range("B7").Select 'Pressure_A_Weighted
For i = 0 To n
    For j = 0 To 10
        Pressure_A_Weighted(i, j) = ActiveCell
        ActiveCell.Offset(0, 1).Range("A1").Select
    Next j
ActiveCell.Offset(8, -11).Range("A1").Select
Next i

Worksheets("Individual Fans").Range("B4").Select 'Loudness
For i = 0 To n
    For j = 0 To 9
        Loudness(i, j) = ActiveCell
        ActiveCell.Offset(0, 1).Range("A1").Select
    Next j
ActiveCell.Offset(8, -10).Range("A1").Select
Next i

Worksheets("Individual Fans").Range("B5").Select 'Tonality
For i = 0 To n
    For j = 0 To 9
        Tonality(i, j) = ActiveCell
        ActiveCell.Offset(0, 1).Range("A1").Select
    Next j
ActiveCell.Offset(8, -10).Range("A1").Select
Next i
```

```
'The following creates the large data tables

For K   0 To 4
Range(Table_Start(K)).Select
ActiveCell.FormulaR1C1 = Label(K)
    With Selection.Interior
        .Pattern   xlSolid
        .PatternColorIndex = xlAutomatic
        .Color = 5296274
    End With
    With Selection
        .Borders.LineStyle = xlContinuous
        .Borders.Weight = xlThin
        .HorizontalAlignment   xlCenter
    End With
    ActiveCell.Offset(1, 0).Range("A1").Select

    For i = 0 To n
        ActiveCell.FormulaR1C1 = Test_name(i)
    With Selection.Interior
        .Pattern = xlSolid
        .PatternColorIndex = xlAutomatic
        .Color   5296274
    End With
    With Selection
        .Borders.LineStyle   xlContinuous
        .Borders.Weight   xlThin
        .HorizontalAlignment = xlCenter
    End With
        ActiveCell.Offset(1, 0).Range("A1").Select
    Next i

    If K = 0 Then
        Range("AA1").Select
        For i = 0 To 1
        Selection.ColumnWidth = 20
        ActiveCell.FormulaR1C1 = Label_2(i)
        With Selection.Interior
        .Pattern = xlSolid
        .PatternColorIndex   xlAutomatic
        .Color   5296274
        End With
        With Selection
        .Borders.LineStyle   xlContinuous
        .Borders.Weight   xlThin
        .HorizontalAlignment   xlCenter
        End With
        ActiveCell.Offset(0, 1).Range("A1").Select
        Next i

    ElseIf K = 1 Or K = 2 Then
        Range("N2.X2").Select
        Selection.Copy
        Range(Table_Start(K)) Select
        ActiveCell.Offset(0, 1).Range("A1").Select
        ActiveSheet.Paste

    ElseIf K   3 Or K = 4 Then
        Range("N2:W2").Select
        Selection.Copy
        Range(Table_Start(K)).Select
        ActiveCell.Offset(0, 1).Range("A1").Select
        ActiveSheet.Paste
    End If

Next K

Worksheets("Individual Fans").Range("AA2").Select
For i = 0 To n
    For j = 0 To 1
        ActiveCell.FormulaR1C1 = Sound_Power(i, j)
        Selection.Borders.LineStyle   xlContinuous
        Selection.Borders.Weight   xlThin
        Selection.NumberFormat = "0.0"
        Selection.HorizontalAlignment   xlCenter
        ActiveCell.Offset(0, 1).Range("A1").Select
    Next j
ActiveCell.Offset(1, -2).Range("A1").Select
Next i

Worksheets("Individual Fans") Range("AE2").Select
For i = 0 To n
    For j - 0 To 10
        ActiveCell FormulaR1C1 = Pressure_Linear(i, j)
        Selection.Borders.LineStyle   xlContinuous
        Selection.Borders Weight   xlThin
        Selection.NumberFormat   "0.0"
        Selection.HorizontalAlignment   xlCenter
        ActiveCell.Offset(0, 1).Range("A1").Select
    Next j
ActiveCell.Offset(1, -11).Range("A1").Select
Next i
```

```
Worksheets("Individual Fans").Range("AR2").Select
For i = 0 To n
    For j = 0 To 10
        ActiveCell.FormulaR1C1 = Pressure_A_Weighted(i, j)
        Selection.Borders.LineStyle = xlContinuous
        Selection.Borders.Weight = xlThin
        Selection.NumberFormat = "0.0"
        Selection.HorizontalAlignment = xlCenter
        ActiveCell.Offset(0, 1).Range("A1").Select
    Next j
ActiveCell.Offset(1, -11).Range("A1").Select
Next i

Worksheets("Individual Fans").Range("AE34").Select
For i = 0 To n
    For j = 0 To 9
        ActiveCell.FormulaR1C1 = Loudness(i, j)
        Selection.Borders.LineStyle = xlContinuous
        Selection.Borders.Weight = xlThin
        Selection.NumberFormat = "0.00"
        Selection.HorizontalAlignment = xlCenter
        ActiveCell.Offset(0, 1).Range("A1").Select
    Next j
ActiveCell.Offset(1, -10).Range("A1").Select
Next i

Worksheets("Individual Fans").Range("AR34").Select
For i = 0 To n
    For j = 0 To 9
        ActiveCell.FormulaR1C1 = Tonality(i, j)
        Selection.Borders.LineStyle = xlContinuous
        Selection.Borders.Weight = xlThin
        Selection.NumberFormat = "0.00"
        Selection.HorizontalAlignment = xlCenter
        ActiveCell.Offset(0, 1).Range("A1").Select
    Next j
ActiveCell.Offset(1, -10).Range("A1").Select
Next i

Worksheets("Individual Fans").Range("AD1").Select

End Sub
Sub Delete_Tables()

Range("Z1:BB63").Select 'This clears the large data tables
Selection.ClearContents
Selection.Borders.LineStyle = xlNone
    With Selection.Interior
        .Pattern = xlNone
        .TintAndShade = 0
        .PatternTintAndShade = 0
    End With
End Sub
Sub Create_Large_Figures()

'This Macro is used to create the large figures of Sound Pressure Level (Linear and A-Weighted),
'Loudness, and Tonality.

Title = Range("B1").Value

Chart_Title = Array("Sound Pressure - Linear", "Sound Pressure - A-Weighted", _
                    "Loudness", "Tonality")

Data_Range = Array("AD2:AO9", "AQ2:BB9", _
                    "AD34:AN41", "AQ34:BA41")
For i = 0 To 0
Worksheets("Individual Fans").Range(Data_Range(i)).Select
ActiveSheet.Shapes.AddChart.Select
ActiveChart.SetSourceData Source:=Range(Data_Range(i))
'ActiveChart.ChartType = xlLineMarkers
ActiveChart.ChartType = xlColumnClustered
ActiveChart.SetElement (msoElementChartTitleAboveChart)
ActiveChart.SetElement (msoElementPrimaryCategoryAxisTitleAdjacentToAxis)
ActiveChart.SetElement (msoElementPrimaryValueAxisTitleRotated)
ActiveChart.SetElement (msoElementLegendTop)
ActiveChart.Axes(xlValue).Select
Selection.TickLabels.NumberFormat = "0.0"
ActiveChart.ChartWizard _
Title:=Title + Chr(10) + Chart_Title(0), _
    CategoryTitle:="Microphone Position", ValueTitle:="SPL - Linear (dB)"
ActiveChart.SeriesCollection(1).XValues = "='Individual Fans'!$AE$1:$AO$1"
ActiveChart.ChartArea.Font.Size = 12
ActiveChart.ChartTitle.Font.Size = 20
ActiveChart.Location Where:=xlLocationAsNewSheet, Name:=i
Sheets("Individual Fans").Select
Sheets("Individual Fans").Move Before:=Sheets(1)
Next i

For i = 1 To 1
Worksheets("Individual Fans").Range(Data_Range(i)).Select
ActiveSheet.Shapes.AddChart.Select
ActiveChart.SetSourceData Source:=Range(Data_Range(i))
'ActiveChart.ChartType = xlLineMarkers
ActiveChart.ChartType = xlColumnClustered
```

```
ActiveChart.SetElement (msoElementChartTitleAboveChart)
ActiveChart.SetElement (msoElementPrimaryCategoryAxisTitleAdjacentToAxis)
ActiveChart.SetElement (msoElementPrimaryValueAxisTitleRotated)
ActiveChart.SetElement (msoElementLegendTop)
ActiveChart.Axes(xlValue).Select
Selection.TickLabels.NumberFormat = "0.0"
ActiveChart.ChartWizard _
Title:=Title + Chr(10) + Chart_Title(1), _
    CategoryTitle:="Microphone Position", ValueTitle:="SPL   A-Weighted (dBA)"
ActiveChart.SeriesCollection(1).XValues = "='Individual Fans'!$AE$1:$AO$1"
ActiveChart.ChartArea.Font.Size = 12
ActiveChart.ChartTitle.Font.Size = 20
ActiveChart.Location Where:=xlLocationAsNewSheet, Name:=i
Sheets("Individual Fans").Select
Sheets("Individual Fans").Move Before:=Sheets(1)
Next i

For i = 2 To 2
Worksheets("Individual Fans").Range(Data_Range(i)).Select
ActiveSheet.Shapes.AddChart.Select
ActiveChart.SetSourceData Source:=Range(Data_Range(i))
'ActiveChart.ChartType = xlLineMarkers
ActiveChart.ChartType = xlColumnClustered
ActiveChart.SetElement (msoElementChartTitleAboveChart)
ActiveChart.SetElement (msoElementPrimaryCategoryAxisTitleAdjacentToAxis)
ActiveChart.SetElement (msoElementPrimaryValueAxisTitleRotated)
ActiveChart.SetElement (msoElementLegendTop)
ActiveChart.Axes(xlValue).Select
Selection.TickLabels.NumberFormat = "0.00"
ActiveChart.ChartWizard _
Title:=Title + Chr(10) + Chart_Title(2), _
    CategoryTitle:="Microphone Position", ValueTitle:="Sone"
ActiveChart.SeriesCollection(1).XValues = "='Individual Fans'!$AE$1:$AN$1"
ActiveChart.ChartArea.Font.Size = 12
ActiveChart.ChartTitle.Font.Size = 20
ActiveChart.Location Where:=xlLocationAsNewSheet, Name:=i
Sheets("Individual Fans").Select
Sheets("Individual Fans").Move Before:=Sheets(1)
Next i

For i = 3 To 3
Worksheets("Individual Fans").Range(Data_Range(i)).Select
ActiveSheet.Shapes.AddChart.Select
ActiveChart.SetSourceData Source:=Range(Data_Range(i))
'ActiveChart.ChartType = xlLineMarkers
ActiveChart.ChartType = xlColumnClustered
ActiveChart.SetElement (msoElementChartTitleAboveChart)
ActiveChart.SetElement (msoElementPrimaryCategoryAxisTitleAdjacentToAxis)
ActiveChart.SetElement (msoElementPrimaryValueAxisTitleRotated)
ActiveChart.SetElement (msoElementLegendTop)
ActiveChart.Axes(xlValue).Select
Selection.TickLabels.NumberFormat = "0.00"
ActiveChart.ChartWizard _
Title:=Title + Chr(10) + Chart_Title(3), _
    CategoryTitle:="Microphone Position", ValueTitle:="Tu"
ActiveChart.SeriesCollection(1).XValues = "='Individual Fans'!$AE$1:$AN$1"
ActiveChart.ChartArea.Font.Size = 12
ActiveChart.ChartTitle.Font.Size = 20
ActiveChart.Location Where:=xlLocationAsNewSheet, Name:=i
Sheets("Individual Fans").Select
Sheets("Individual Fans").Move Before:=Sheets(1)
Next i
End Sub

Sub Delete_Large_Figures()

'This Macro is used to delete the large figures of Sound Pressure Level (Linear and A-Weighted),
'Loudness, and Tonality.

Sheet_Name = Array("0", "1", "2", "3")
For i = 0 To 3
    Sheets(Sheet_Name(i)).Select
    ActiveWindow.SelectedSheets.Delete
Next i
Sheets("Individual Fans").Range("-1").Select

End Sub
```

APPENDIX C

Additional Data

C1 Individual Fans – Stand-Alone

CPU @ 4V	1	2	3	4	5	6	7	8	9	10	
Loudness	0 16	0 04	0 11	0 00	0 16	0 00	0 11	0 00	0 15	0 00	
Tonality	0 58	0 87	0 00	0 00	0 35	0 00	0 00	0 00	0 23	0 00	Avg
Sound Pressure - Linear	21 3	17 3	18 9	13 3	20 8	14 4	18 6	12 1	21 2	13 4	18 3
Sound Pressure - A Weighted	17 0	11 8	17 2	10 9	17 9	11 2	16 9	10 2	18 2	11 0	15 4
Sound Power - Linear	26 3										
Sound Power A-Weighted	23 3										

CPU @ 5V	1	2	3	4	5	6	7	8	9	10	
Loudness	0 17	0 04	0 11	0 01	0 16	0 00	0 13	0 00	0 16	0 01	
Tonality	0 57	0 87	0 00	0 00	0 31	0 00	0 00	0 00	0 21	0 00	Avg
Sound Pressure Linear	21 8	17 4	18 6	13 1	20 3	14 2	19 1	12 3	21 2	12 8	18 3
Sound Pressure - A Weighted	17 7	12 0	17 1	10 8	17 6	10 9	17 4	10 5	18 3	10 7	15 5
Sound Power - Linear	26 3										
Sound Power - A Weighted	23 5										

CPU @ 6V	1	2	3	4	5	6	7	8	9	10	
Loudness	0 17	0 04	0 15	0 01	0 25	0 02	0 14	0 01	0 16	0 01	
Tonality	0 55	0 87	0 00	0 00	0 37	0 00	0 07	0 00	0 21	0 00	Avg
Sound Pressure - Linear	21 4	17 5	19 8	13 9	21 9	16 3	19 4	12 5	21 2	12 6	18 8
Sound Pressure - A Weighted	17 3	12 2	18 1	11 6	19 2	13 0	17 8	10 7	18 3	10 8	16 1
Sound Power - Linear	26 8										
Sound Power - A-Weighted	24 0										

CPU @ 7V	1	2	3	4	5	6	7	8	9	10	
Loudness	0 18	0 04	0 21	0 02	0 23	0 01	0 17	0 01	0 19	0 02	
Tonality	0 55	0 86	0 20	0 00	0 36	0 00	0 12	0 00	0 40	0 00	Avg
Sound Pressure Linear	21 7	18 0	20 7	14 4	21 3	14 6	19 9	13 1	20 8	13 3	18 9
Sound Pressure - A Weighted	17 7	13 3	19 1	12 3	18 9	11 5	18 4	11 2	18 0	11 5	16 3
Sound Power Linear	26 9										
Sound Power - A Weighted	24 3										

CPU @ 8V	1	2	3	4	5	6	7	8	9	10	
Loudness	0.23	0.07	0.35	0.03	0.32	0.01	0.25	0.02	0.26	0.02	
Tonality	0.58	1.23	0.83	0.00	0.46	0.00	0.05	0.00	0.28	0.00	Avg
Sound Pressure - Linear	22.4	19.0	22.9	15.7	22.4	15.1	21.1	14.1	21.7	14.2	20.1
Sound Pressure - A Weighted	18.8	15.3	21.3	13.6	20.2	12.2	19.8	12.3	19.3	12.5	17.8
Sound Power - Linear	28.1										
Sound Power - A Weighted	25.8										

CPU @ 9V	1	2	3	4	5	6	7	8	9	10	
Loudness	0.29	0.15	0.60	0.07	0.47	0.02	0.37	0.02	0.40	0.04	
Tonality	0.38	1.25	0.28	0.29	0.28	0.00	0.14	0.00	0.38	0.00	Avg
Sound Pressure - Linear	23.1	20.8	26.1	17.6	24.0	15.9	22.5	15.1	23.5	16.3	21.9
Sound Pressure - A-Weighted	19.9	18.2	25.0	15.8	22.1	13.3	21.4	13.5	21.4	14.5	20.1
Sound Power - Linear	29.9										
Sound Power - A-Weighted	28.1										

CPU @ 10V	1	2	3	4	5	6	7	8	9	10	
Loudness	0.48	0.23	0.73	0.15	0.69	0.05	0.58	0.07	0.59	0.10	
Tonality	0.45	0.65	0.21	0.58	0.48	0.38	0.25	0.66	0.33	0.36	Avg
Sound Pressure - Linear	25.3	22.0	27.0	19.2	25.9	17.4	24.7	17.3	25.2	17.9	23.6
Sound Pressure - A-Weighted	22.3	19.8	25.9	17.7	24.4	15.4	24.0	16.1	23.9	16.6	22.1
Sound Power - Linear	31.5										
Sound Power - A-Weighted	30.0										

CPU @ 11V	1	2	3	4	5	6	7	8	9	10	
Loudness	0.60	0.41	1.00	0.27	0.91	0.09	0.76	0.13	0.77	0.20	
Tonality	0.39	0.83	0.33	0.22	0.35	0.23	0.17	0.46	0.29	0.30	Avg
Sound Pressure - Linear	26.0	24.2	29.5	21.1	28.0	18.4	26.4	18.8	26.6	19.8	25.4
Sound Pressure - A Weighted	23.8	22.7	28.5	20.1	26.6	16.7	25.8	17.6	25.7	18.7	24.2
Sound Power - Linear	33.4										
Sound Power - A Weighted	32.2										

CPU @ 12V	1	2	3	4	5	6	7	8	9	10	
Loudness	0.81	0.57	1.29	0.43	1.25	0.23	1.04	0.27	1.06	0.35	
Tonality	1.03	0.55	0.26	0.00	0.47	0.37	0.26	0.54	0.61	0.43	Avg
Sound Pressure - Linear	27.7	25.6	31.4	23.0	30.4	20.5	28.8	20.8	28.9	22.0	27.4
Sound Pressure - A Weighted	26.1	24.5	30.5	22.6	29.4	19.4	28.5	19.9	28.4	21.1	26.6
Sound Power - Linear	35.4										
Sound Power - A Weighted	34.6										

Case 1 @ 5V	1	2	3	4	5	6	7	8	9	10	
Loudness	0 17	0 04	0 06	0 00	0 11	0 00	0 06	0 00	0 16	0 00	
Tonality	0 62	0 87	0 00	0 00	0 34	0 00	0 00	0 00	0 49	0 00	Avg
Sound Pressure - Linear	21 7	17 7	17 2	13 2	19 7	13 9	17 3	11 9	21 0	12 4	17 9
Sound Pressure - A-Weighted	17 5	12 1	15 4	10 4	16 8	10 7	15 3	9 8	17 3	10 2	14 6
Sound Power - Linear	25 8										
Sound Power - A-Weighted	22 5										

Case 1 @ 7V	1	2	3	4	5	6	7	8	9	10	
Loudness	0 25	0 04	0 07	0 01	0 16	0 08	0 08	0 06	0 23	0 00	
Tonality	0 89	1 04	0 00	0 99	0 60	1 02	0 24	0 95	0 83	0 00	Avg
Sound Pressure - Linear	23 9	18 3	18 1	14 7	21 1	19 4	18 6	17 5	23 1	12 2	19 9
Sound Pressure - A-Weighted	19 1	12 7	15 9	11 2	17 8	14 4	16 1	13 1	18 7	10 1	15 9
Sound Power - Linear	27 9										
Sound Power - A Weighted	23 8										

Case 1 @ 12V	1	2	3	4	5	6	7	8	9	10	
Loudness	0 66	0 17	0 33	0 04	0 25	0 11	0 15	0 02	0 36	0 02	
Tonality	0 70	1 08	0 55	0 91	0 69	0 79	0 21	0 00	0 56	0 65	Avg
Sound Pressure - Linear	27 9	21 8	23 6	18 0	22 2	20 0	20 2	17 0	24 1	15 5	22 5
Sound Pressure - A Weighted	25 6	18 2	21 0	15 4	19 3	17 5	18 4	15 0	20 9	13 3	19 9
Sound Power - Linear	30 5										
Sound Power - A Weighted	27 9										

Case 2 @ 5V	1	2	3	4	5	6	7	8	9	10	
Loudness	0 13	0 04	0 09	0 00	0 09	0 01	0 15	0 01	0 17	0 00	
Tonality	0 45	0 87	0 00	0 00	0 15	0 00	0 22	0 00	0 45	0 00	Avg
Sound Pressure Linear	20 3	17 7	18 6	13 6	18 9	15 0	20 5	13 4	21 0	13 2	18 1
Sound Pressure - A Weighted	16 7	12 7	16 8	11 1	16 4	11 8	17 9	11 5	17 6	10 9	15 2
Sound Power - Linear	26 1										
Sound Power - A Weighted	23 2										

Case 2 @ 7V	1	2	3	4	5	6	7	8	9	10	
Loudness	0 12	0 03	0 09	0 01	0 10	0 01	0 14	0 01	0 19	0 02	
Tonality	0 44	0 87	0 00	0 00	0 12	0 00	0 20	0 00	0 44	0 00	Avg
Sound Pressure - Linear	20 2	17 1	18 8	14 3	19 0	14 8	19 9	12 9	21 3	14 8	18 1
Sound Pressure A-Weighted	16 7	11 9	16 8	11 6	16 6	11 9	17 7	11 5	18 1	12 7	15 3
Sound Power - Linear	26 1										
Sound Power A Weighted	23 3										

Case 2 @ 12V	1	2	3	4	5	6	7	8	9	10	
Loudness	0 54	0 12	0 35	0 10	0 27	0 16	0 30	0 04	0 42	0 11	
Tonality	0 48	0 27	0 18	0 00	0 14	0 10	0 14	0 00	0 00	0 00	Avg
Sound Pressure - Linear	26 6	21 0	22 9	19 1	21 8	20 4	22 0	17 4	24 8	17 2	22 3
Sound Pressure - A-Weighted	23 5	16 8	21 3	16 6	20 3	17 8	20 3	15 5	21 4	16 6	19 8
Sound Power - Linear	30 3										
Sound Power - A-Weighted	27 7										

PSU ON	1	2	3	4	5	6	7	8	9	10	
Loudness	0 53	0 62	0 62	0 44	0 51	0 46	0 55	0 55	0 37	0 34	
Tonality	0 57	0 48	0 00	0 07	0 14	0 23	0 07	0 37	0 30	0 09	Avg
Sound Pressure - Linear	31 7	33 1	32 5	30 7	32 6	34 8	33 4	31 2	33 1	27 2	32 4
Sound Pressure - A-Weighted	26 7	28 1	27 7	25 6	27 0	28 6	27 4	25 9	26 8	23 1	26 9
Sound Power - Linear	40 4										
Sound Power - A-Weighted	34 9										

GPU @ 4V	1	2	3	4	5	6	7	8	9	10	
Loudness	0 39	0 43	0 46	0 66	0 65	0 66	0 70	0 74	0 82	1 23	
Tonality	0 26	0 34	0 12	0 48	0 34	0 40	0 30	0 34	0 39	0 38	Avg
Sound Pressure - Linear	24 1	25 1	24 0	25 3	25 6	25 8	26 4	26 6	27 5	30 0	26 4
Sound Pressure A-Weighted	21 2	21 6	22 2	24 5	24 8	24 8	25 6	26 0	26 4	29 6	25 4
Sound Power - Linear	34 4										
Sound Power A-Weighted	33 3										

GPU @ 5V	1	2	3	4	5	6	7	8	9	10	
Loudness	0 74	0 78	0 87	1 04	1 02	0 99	1 16	1 12	1 19	1 71	
Tonality	0 16	0 20	0 00	0 24	0 13	0 24	0 20	0 21	0 28	0 19	Avg
Sound Pressure - Linear	27 5	28 2	28 3	28 5	28 7	28 5	30 0	29 5	30 4	33 1	29 6
Sound Pressure A-Weighted	25 5	25 6	26 5	27 8	27 9	27 7	29 4	29 0	29 5	32 8	28 7
Sound Power - Linear	37 6										
Sound Power - A-Weighted	36 7										

GPU @ 6V	1	2	3	4	5	6	7	8	9	10	
Loudness	1 28	1 31	1 48	1 60	1 68	1 65	1 88	1 70	1 76	2 44	
Tonality	0 12	0 11	0 00	0 27	0 66	0 40	0 19	0 22	0 33	0 36	Avg
Sound Pressure - Linear	31 4	31 8	32 4	32 3	33 0	33 0	34 3	33 7	34 1	37 7	33 8
Sound Pressure - A Weighted	30 0	30 1	31 0	32 0	32 5	32 6	33 8	33 0	33 4	37 5	33 2
Sound Power - Linear	41 8										
Sound Power - A-Weighted	41 1										

GPU @ 7V	1	2	3	4	5	6	7	8	9	10	
Loudness	1 88	1 90	2 12	2 17	2 24	2 07	2 55	2 25	2 38	2 98	
Tonality	0 00	0 14	0 00	0 00	0 09	0 11	0 00	0 00	0 13	0 00	Avg
Sound Pressure - Linear	34 6	34 9	35 6	35 2	35 5	34 8	37 0	35 7	36 4	39 4	36 2
Sound Pressure - A-Weighted	33 6	33 4	34 4	34 9	35 2	34 6	36 8	35 5	36 1	39 4	35 8
Sound Power - Linear	44 1										
Sound Power A-Weighted	43 7										

GPU @ 8V	1	2	3	4	5	6	7	8	9	10	
Loudness	2 52	2 57	2 81	2 81	2 95	2 75	3 37	2 93	3 13	3 82	
Tonality	0 09	0 11	0 00	0 00	0 08	0 10	0 00	0 00	0 10	0 00	Avg
Sound Pressure - Linear	37 3	37 7	38 4	37 9	38 4	37 7	40 0	38 5	39 2	42 3	39 0
Sound Pressure - A-Weighted	36 4	36 4	37 3	37 7	38 2	37 7	39 9	38 3	39 0	42 3	38 7
Sound Power Linear	47 0										
Sound Power - A Weighted	46 7										

GPU @ 9V	1	2	3	4	5	6	7	8	9	10	
Loudness	3 15	3 21	3 48	3 48	3 64	3 42	4 15	3 59	3 82	4 62	
Tonality	0 11	0 11	0 00	0 00	0 09	0 10	0 00	0 00	0 10	0 03	Avg
Sound Pressure Linear	39 6	40 0	40 7	40 4	40 9	40 3	42 4	40 7	41 4	44 7	41 4
Sound Pressure - A-Weighted	38 8	38 8	39 8	40 3	40 8	40 3	42 4	40 6	41 2	44 9	41 2
Sound Power Linear	49 4										
Sound Power - A Weighted	49 2										

GPU @ 10V	1	2	3	4	5	6	7	8	9	10	
Loudness	3 73	3 79	4 14	4 14	4 27	4 03	4 89	4 28	4 46	5 42	
Tonality	0 10	0 00	0 00	0 00	0 12	0 14	0 00	0 06	0 07	0 06	Avg
Sound Pressure - Linear	41 5	41 9	42 8	42 4	42 8	42 3	44 5	42 9	43 3	46 8	43 4
Sound Pressure - A Weighted	40 8	40 7	41 9	42 3	42 8	42 3	44 6	42 8	43 2	47 1	43 3
Sound Power - Linear	51 4										
Sound Power A Weighted	51 3										

GPU @ 11V	1	2	3	4	5	6	7	8	9	10	
Loudness	4 31	4 38	4 74	4 73	4 93	4 79	5 56	4 86	5 09	6 17	
Tonality	0 06	0 07	0 00	0 00	0 13	0 08	0 00	0 06	0 06	0 19	Avg
Sound Pressure - Linear	43 2	43 6	44 4	44 1	44 7	44 6	46 2	44 5	44 9	48 7	45 2
Sound Pressure A-Weighted	42 6	42 5	43 6	44 1	44 7	44 3	46 2	44 4	44 9	49 0	45 1
Sound Power - Linear	53 2										
Sound Power A Weighted	53 0										

GPU @ 12V	1	2	3	4	5	6	7	8	9	10	
Loudness	4 86	4 88	5 31	5 31	5 51	5 35	6 23	5 46	5 69	6 90	
Tonality	0 10	0 00	0 00	0 00	0 10	0 13	0 00	0 07	0 07	0 18	Avg
Sound Pressure - Linear	44 7	44 9	45 8	45 7	46 2	46 2	47 7	46 0	46 4	50 3	46 7
Sound Pressure - A-Weighted	44 1	43 9	45 1	45 7	46 2	45 7	47 8	45 9	46 4	50 6	46 6
Sound Power - Linear	54 7										
Sound Power - A-Weighted	54 6										

C2 Individual Fans – In-System

CPU @ 4V	1	2	3	4	5	6	7	8	9	10	
Loudness	0 15	0 38	0 24	0 23	0 27	0 23	0 17	0 14	0 18	0 16	
Tonality	0 67	0 69	0 64	0 67	1 14	0 00	0 33	0 00	1 01	0 28	Avg
Sound Pressure Linear	21 0	26 5	24 4	23 8	25 0	23 3	21 8	20 4	22 1	20 9	23 4
Sound Pressure - A Weighted	17 1	21 0	19 0	18 8	19 5	18 9	17 6	17 3	17 4	17 6	18 6
Sound Power - Linear	31 3										
Sound Power - A Weighted	26 6										

CPU @ 5V	1	2	3	4	5	6	7	8	9	10	
Loudness	0 10	0 36	0 33	0 31	0 34	0 23	0 18	0 16	0 23	0 17	
Tonality	0 97	1 12	1 36	1 01	0 93	0 54	0 85	0 54	0 89	0 47	Avg
Sound Pressure - Linear	19 7	26 8	24 8	24 5	26 5	23 0	21 1	20 7	23 6	20 7	23 8
Sound Pressure A Weighted	16 3	20 9	20 5	20 1	20 7	19 0	17 6	17 3	18 3	17 9	19 1
Sound Power - Linear	31 8										
Sound Power - A-Weighted	27 1										

CPU @ 6V	1	2	3	4	5	6	7	8	9	10	
Loudness	0 15	0 31	0 34	0 26	0 20	0 23	0 22	0 14	0 16	0 22	
Tonality	0 00	0 44	0 59	0 65	1 10	0 55	0 61	0 39	1 04	0 18	Avg
Sound Pressure - Linear	20 9	24 1	24 7	23 2	23 0	22 9	22 1	19 9	21 7	21 3	22 6
Sound Pressure A Weighted	18 0	20 1	20 6	19 8	18 0	18 9	18 6	17 8	17 4	18 9	18 9
Sound Power Linear	30 6										
Sound Power - A Weighted	26 9										

CPU @ 7V	1	2	3	4	5	6	7	8	9	10	
Loudness	0 14	0 35	0 41	0 36	0 21	0 32	0 23	0 19	0 18	0 40	
Tonality	0 53	0 71	0 87	0 00	0 42	0 74	0 38	0 17	0 51	0 00	Avg
Sound Pressure - Linear	20 1	23 9	24 3	23 7	22 2	23 4	21 3	20 6	21 6	24 8	22 9
Sound Pressure - A Weighted	17 7	21 0	22 2	21 6	18 3	20 1	19 4	18 8	18 2	22 2	20 3
Sound Power - Linear	30 8										
Sound Power A Weighted	28 2										

CPU @ 8V	1	2	3	4	5	6	7	8	9	10	
Loudness	0 18	0 44	0 63	0 48	0 26	0 50	0 50	0 33	0 28	0 47	
Tonality	0 27	0 26	0 67	0 10	0 59	0 45	0 33	0 21	0 75	0 67	Avg
Sound Pressure - Linear	20 5	24 6	26 5	24 7	23 1	24 9	25 0	22 6	22 8	24 8	24 2
Sound Pressure - A-Weighted	18 6	22 4	24 7	23 1	19 3	22 5	22 9	21 0	19 8	23 1	22 1
Sound Power - Linear	32 2										
Sound Power A Weighted	30 1										

CPU @ 9V	1	2	3	4	5	6	7	8	9	10	
Loudness	0 41	0 58	0 77	0 67	0 36	0 63	0 57	0 39	0 41	0 62	
Tonality	0 90	0 49	0 00	0 33	0 48	0 39	0 46	0 22	0 54	0 67	Avg
Sound Pressure Linear	23 7	26 1	27 6	26 7	24 5	26 0	25 2	23 0	24 3	26 6	25 6
Sound Pressure - A Weighted	22 0	24 1	26 2	25 5	20 9	24 1	24 3	22 1	21 8	25 1	23 9
Sound Power - Linear	33 6										
Sound Power - A Weighted	31 9										

CPU @ 10V	1	2	3	4	5	6	7	8	9	10	
Loudness	0 42	0 68	1 00	0 82	0 39	0 80	0 80	0 55	0 45	0 83	
Tonality	0 57	0 52	0 87	0 17	0 40	0 56	0 45	0 27	0 50	0 58	Avg
Sound Pressure - Linear	23 8	27 2	29 7	28 0	24 2	27 3	27 6	25 0	24 5	28 6	27 0
Sound Pressure - A Weighted	22 2	25 5	28 8	27 3	21 6	26 1	26 9	24 3	22 6	27 3	25 9
Sound Power - Linear	35 0										
Sound Power - A Weighted	33 8										

CPU @ 11V	1	2	3	4	5	6	7	8	9	10	
Loudness	0 61	0 81	1 22	1 02	0 52	1 10	0 99	0 77	0 64	0 99	
Tonality	0 47	0 61	0 37	0 58	1 07	0 74	0 31	0 70	0 59	0 28	Avg
Sound Pressure Linear	25 7	28 0	30 9	29 6	25 5	29 5	29 0	27 1	26 4	30 0	28 5
Sound Pressure A Weighted	24 5	26 5	29 8	28 8	23 4	28 7	28 2	26 3	25 0	28 6	27 4
Sound Power Linear	36 5										
Sound Power - A Weighted	35 4										

CPU @ 12V	1	2	3	4	5	6	7	8	9	10	
Loudness	0 85	1 02	1 56	1 37	0 62	1 37	1 32	1 01	0 76	1 21	
Tonality	0 59	0 11	0 93	1 02	0 57	0 37	1 13	0 78	0 40	1 35	Avg
Sound Pressure - Linear	27 9	29 8	33 5	32 3	26 5	31 3	31 6	29 4	27 4	31 5	30 6
Sound Pressure - A-Weighted	27 2	28 1	32 7	31 8	24 5	30 8	31 2	28 9	26 1	30 2	29 8
Sound Power Linear	38 6										
Sound Power A Weighted	37 8										

Case 1 @ 5V	1	2	3	4	5	6	7	8	9	10	
Loudness	0 05	0 13	0 06	0 06	0 13	0 15	0 08	0 07	0 09	0 07	
Tonality	0 00	0 56	0 00	0 00	0 69	0 58	0 16	0 00	0 51	0 00	Avg
Sound Pressure - Linear	17 5	20 3	18 0	18 0	20 8	21 5	19 2	18 5	19 2	17 9	19 3
Sound Pressure - A-Weighted	15 1	16 3	15 5	15 7	16 0	17 2	16 2	16 4	15 5	16 0	16 0
Sound Power - Linear	27 3										
Sound Power - A-Weighted	24 0										

Case 1 @ 7V	1	2	3	4	5	6	7	8	9	10	
Loudness	0 12	0 21	0 18	0 15	0 21	0 34	0 13	0 06	0 20	0 19	
Tonality	0 39	0 95	0 88	0 55	0 83	0 80	0 77	0 00	0 92	0 48	Avg
Sound Pressure - Linear	20 5	23 4	22 2	21 1	23 2	24 7	20 5	18 0	23 0	21 4	22 2
Sound Pressure - A-Weighted	17 0	18 5	17 9	17 3	18 7	20 5	16 5	15 7	18 0	18 3	18 0
Sound Power Linear	30 1										
Sound Power - A-Weighted	26 0										

Case 1 @ 12V	1	2	3	4	5	6	7	8	9	10	
Loudness	0 53	0 78	0 72	0 52	0 41	0 97	0 55	0 39	0 47	0 47	
Tonality	0 00	0 04	0 03	0 11	0 11	0 13	0 24	0 00	0 25	0 00	Avg
Sound Pressure Linear	28 8	31 9	31 8	30 0	28 2	31 8	28 5	25 6	27 6	27 2	29 6
Sound Pressure - A-Weighted	23 8	26 4	25 9	23 6	22 2	27 6	23 6	21 4	22 7	22 5	24 4
Sound Power Linear	37 6										
Sound Power A-Weighted	32 4										

Case 2 @ 5V	1	2	3	4	5	6	7	8	9	10	
Loudness	0 16	0 17	0 08	0 11	0 14	0 17	0 09	0 09	0 13	0 11	
Tonality	0 00	0 60	0 24	0 37	0 64	0 55	0 00	0 00	0 57	0 00	Avg
Sound Pressure - Linear	20 8	21 7	19 4	19 9	21 2	21 6	19 5	19 0	20 7	19 7	20 4
Sound Pressure - A Weighted	18 2	17 6	16 4	16 8	16 7	17 7	16 5	16 9	16 9	17 4	17 1
Sound Power - Linear	28 4										
Sound Power A-Weighted	25 1										

Case 2 @ 7V	1	2	3	4	5	6	7	8	9	10	
Loudness	0 49	0 25	0 29	0 36	0 26	0 37	0 23	0 29	0 17	0 24	
Tonality	0 57	0 00	0 28	0 18	0 13	0 43	0 00	0 04	0 56	0 18	Avg
Sound Pressure Linear	25 5	23 7	24 3	25 2	24 3	24 8	22 6	23 1	21 3	22 0	23 9
Sound Pressure - A Weighted	22 9	19 2	20 0	20 9	19 5	21 0	19 1	20 1	17 7	19 1	20 2
Sound Power - Linear	31 9										
Sound Power A Weighted	28 2										

Case 2 @ 12V	1	2	3	4	5	6	7	8	9	10	
Loudness	2 07	1 03	1 19	1 56	1 03	1 50	1 03	1 43	0 82	1 02	
Tonality	0 30	0 31	0 44	0 40	0 38	0 33	0 92	0 08	0 35	0 11	Avg
Sound Pressure - Linear	37 9	32 2	34 5	36 2	32 3	35 1	32 3	33 2	29 7	32 0	34 2
Sound Pressure - A Weighted	36 3	28 3	30 6	32 9	28 6	32 3	28 6	31 1	26 9	28 8	31 4
Sound Power - Linear	42 1										
Sound Power - A-Weighted	39 4										

PSU ON	1	2	3	4	5	6	7	8	9	10	
Loudness	0 73	0 78	0 81	0 53	0 43	0 86	0 70	0 64	0 63	0 54	
Tonality	0 17	0 11	0 43	0 10	0 13	0 43	1 09	1 08	0 46	0 21	Avg
Sound Pressure - Linear	29 3	31 9	31 2	27 9	26 1	34 9	30 6	30 0	30 9	27 5	30 7
Sound Pressure - A-Weighted	25 8	27 0	27 3	23 7	22 2	30 2	26 6	27 4	26 2	23 9	26 6
Sound Power - Linear	38 7										
Sound Power - A-Weighted	34 5										

GPU @ 4V	1	2	3	4	5	6	7	8	9	10	
Loudness	0 82	0 96	1 06	1 19	0 62	1 43	1 11	0 86	0 77	1 11	
Tonality	0 64	0 87	0 23	0 93	0 44	0 71	0 48	0 65	0 03	0 63	Avg
Sound Pressure - Linear	28 4	30 1	32 1	33 1	26 8	34 7	32 2	29 4	28 4	31 8	31 3
Sound Pressure - A Weighted	28 2	29 5	31 1	32 3	25 2	35 2	32 1	29 5	27 4	31 0	31 0
Sound Power - Linear	39 3										
Sound Power - A Weighted	39 0										

GPU @ 5V	1	2	3	4	5	6	7	8	9	10	
Loudness	1 24	1 56	1 67	1 54	0 95	2 13	1 64	1 23	1 45	1 65	
Tonality	0 55	0 00	0 62	0 50	0 54	0 64	0 96	0 55	0 63	1 20	Avg
Sound Pressure Linear	32 4	34 8	36 1	35 3	30 1	38 9	36 1	32 3	34 0	36 9	35 3
Sound Pressure - A Weighted	32 1	34 7	35 3	34 4	28 8	39 3	36 0	31 8	33 5	35 9	35 0
Sound Power Linear	43 3										
Sound Power - A Weighted	43 0										

GPU @ 6V	1	2	3	4	5	6	7	8	9	10	
Loudness	1 73	2 08	2 33	2 04	1 16	2 59	2 13	1 91	1 93	2 11	
Tonality	0 79	0 39	0 82	0 37	0 29	0 34	1 43	0 88	0 28	0 79	Avg
Sound Pressure - Linear	35 5	37 0	39 5	37 7	32 3	38 9	38 4	37 2	36 4	40 0	37 7
Sound Pressure - A Weighted	35 1	36 0	38 7	36 9	30 1	38 5	38 1	37 4	35 7	38 7	37 1
Sound Power Linear	45 7										
Sound Power - A Weighted	45 0										

GPU @ 7V	1	2	3	4	5	6	7	8	9	10	
Loudness	2 17	3 00	3 20	2 98	1 87	3 63	2 78	2 29	2 48	2 70	
Tonality	0 53	0 77	0 67	0 45	1 14	0 44	0 69	0 39	0 94	0 61	Avg
Sound Pressure - Linear	37 7	41 4	44 7	43 8	37 1	42 7	41 4	37 9	39 9	42 2	41 6
Sound Pressure - A-Weighted	36 8	40 3	44 1	42 8	35 0	42 1	40 5	37 1	38 8	41 0	40 7
Sound Power - Linear	49 5										
Sound Power - A-Weighted	48 6										

GPU @ 8V	1	2	3	4	5	6	7	8	9	10	
Loudness	2 90	3 72	3 66	3 46	2 20	4 58	3 29	2 95	3 09	3 34	
Tonality	0 94	0 31	0 48	0 38	0 37	0 69	0 60	0 87	0 57	0 54	Avg
Sound Pressure - Linear	40 8	43 3	44 5	43 6	38 5	45 1	42 1	40 3	40 8	44 5	42 8
Sound Pressure - A-Weighted	39 8	42 3	43 3	42 5	36 0	44 5	41 1	39 6	39 6	43 1	41 7
Sound Power - Linear	50 8										
Sound Power - A-Weighted	49 7										

GPU @ 9V	1	2	3	4	5	6	7	8	9	10	
Loudness	3 68	5 06	5 11	4 63	3 16	5 86	4 66	4 36	4 42	4 68	
Tonality	0 55	0 44	0 60	0 52	0 37	0 37	0 50	0 49	0 52	0 62	Avg
Sound Pressure - Linear	43 5	47 6	50 9	50 3	44 0	48 3	48 9	46 9	47 4	50 7	48 5
Sound Pressure A Weighted	43 1	46 9	50 3	49 4	42 3	47 7	48 2	46 5	46 6	49 8	47 7
Sound Power - Linear	56 4										
Sound Power - A Weighted	55 7										

GPU @ 10V	1	2	3	4	5	6	7	8	9	10	
Loudness	4 52	5 83	5 42	5 58	3 68	7 18	5 30	4 30	4 68	5 04	
Tonality	0 44	0 56	0 73	0 40	0 55	0 32	0 94	0 33	0 48	0 54	Avg
Sound Pressure Linear	46 0	48 9	49 7	50 7	44 1	51 4	48 5	44 6	45 9	49 0	48 5
Sound Pressure - A Weighted	45 6	48 0	48 6	49 9	42 4	51 2	48 0	43 8	44 8	48 0	47 8
Sound Power Linear	56 5										
Sound Power - A Weighted	55 8										

GPU @ 11V	1	2	3	4	5	6	7	8	9	10	
Loudness	5 23	6 69	6 42	5 67	4 53	8 29	5 80	6 00	5 96	5 90	
Tonality	0 45	0 43	0 46	0 32	0 48	0 43	0 45	0 48	0 48	0 37	Avg
Sound Pressure - Linear	47 5	50 6	51 0	49 8	46 4	52 8	48 6	49 9	48 9	50 1	49 9
Sound Pressure A-Weighted	47 3	49 9	49 9	48 2	44 7	52 4	47 8	50 1	48 4	49 2	49 2
Sound Power - Linear	57 9										
Sound Power A-Weighted	57 2										

GPU @ 12V	1	2	3	4	5	6	7	8	9	10	
Loudness	5 49	7 35	7 30	6 39	4 83	8 74	6 45	6 24	6 10	6 03	
Tonality	0 69	0 24	0 47	0 30	0 27	0 36	0 80	0 85	0 25	0 05	Avg
Sound Pressure - Linear	47 9	51 6	53 2	51 5	46 9	53 1	49 9	49 5	49 0	50 8	50 8
Sound Pressure - A-Weighted	47 0	50 5	52 2	50 1	44 8	52 5	49 1	49 4	47 9	49 3	49 8
Sound Power - Linear	58 8										
Sound Power - A-Weighted	57 8										

C3 Fully Assembled and Operating Desktop Computer System

Idle	1	2	3	4	5	6	7	8	9	10	
Loudness	3 25	2 45	3 21	2 90	2 05	2 98	2 85	2 61	2 16	2 47	
Tonality	0 45	0 42	0 32	0 43	0 30	0 28	0 23	0 39	0 13	0 34	Avg
Sound Pressure - Linear	42 5	39 5	42 6	41 5	37 9	40 8	40 7	39 0	38 0	39 9	40 5
Sound Pressure - A-Weighted	41 0	37 0	40 5	39 5	34 9	39 0	39 0	38 0	35 8	38 1	38 6
Sound Power - Linear	48 5										
Sound Power - A-Weighted	46 6										

CPU Benchmark	1	2	3	4	5	6	7	8	9	10	
Loudness	3 35	2 64	3 43	2 96	2 09	3 27	2 95	2 74	2 34	2 50	
Tonality	1 10	0 46	0 69	0 63	0 32	0 50	0 30	0 80	0 14	0 72	Avg
Sound Pressure Linear	42 6	40 1	43 3	41 6	38 2	42 0	41 1	39 5	38 8	39 9	41 0
Sound Pressure - A-Weighted	41 2	37 9	41 5	39 6	35 1	40 8	39 5	38 6	36 8	38 1	39 3
Sound Power Linear	49 0										
Sound Power - A-Weighted	47 3										

GPU Benchmark	1	2	3	4	5	6	7	8	9	10	
Loudness	3 74	3 35	4 06	3 40	2 78	4 60	3 38	3 04	3 27	2 96	
Tonality	0 58	0 73	0 54	0 72	0 65	0 49	0 76	0 60	0 57	0 69	Avg
Sound Pressure Linear	44 2	43 6	45 9	43 6	41 4	48 9	43 0	41 1	43 3	42 0	44 4
Sound Pressure A Weighted	43 3	42 9	45 2	42 2	40 3	49 3	41 9	40 3	42 9	40 7	43 9
Sound Power Linear	52 3										
Sound Power - A Weighted	51 9										

Speedfan @ 50%	1	2	3	4	5	6	7	8	9	10	
Loudness	3 24	2 41	2 75	2 72	1 96	3 03	2 48	2 55	2 04	2 15	
Tonality	0 70	0 57	0 14	0 25	0 21	0 32	0 84	0 65	0 23	0 20	Avg
Sound Pressure - Linear	42 7	39 7	41 8	41 2	37 7	41 5	39 7	38 9	37 6	38 9	40 3
Sound Pressure - A-Weighted	41 2	37 3	39 0	38 8	34 3	40 3	37 5	37 7	35 2	36 5	38 2
Sound Power Linear	48 3										
Sound Power A-Weighted	46 2										

Case 1 @ 5V	1	2	3	4	5	6	7	8	9	10	
Loudness	3 37	2 47	3 21	2 98	2 05	3 14	2 80	2 73	2 22	2 52	
Tonality	0 73	0 87	0 45	0 57	0 74	0 46	0 90	0 87	0 52	0 65	Avg
Sound Pressure - Linear	42 9	39 0	42 0	41 3	37 3	41 4	40 2	39 3	37 8	40 0	40 5
Sound Pressure - A-Weighted	41 9	37 7	40 5	39 6	34 7	40 6	38 8	38 5	36 2	38 2	39 1
Sound Power - Linear	48 4										
Sound Power - A-Weighted	47 1										

Case 1 @ 7V	1	2	3	4	5	6	7	8	9	10	
Loudness	3 42	2 54	3 22	2 99	2 05	3 13	2 84	2 77	2 20	2 53	
Tonality	0 87	0 86	0 67	0 39	0 46	0 98	1 08	0 93	0 41	0 64	Avg
Sound Pressure - Linear	42 8	39 2	42 1	41 3	37 2	41 3	40 3	39 5	37 7	39 9	40 5
Sound Pressure - A-Weighted	41 7	37 9	40 6	39 7	34 6	40 5	39 0	38 7	36 2	38 3	39 1
Sound Power - Linear	48 4										
Sound Power - A-Weighted	47 1										

Case 2 @ 5V	1	2	3	4	5	6	7	8	9	10	
Loudness	2 37	2 45	3 10	2 59	1 78	2 94	2 63	2 14	2 04	2 30	
Tonality	0 85	0 62	0 30	0 31	0 41	0 37	0 39	0 64	0 36	0 37	Avg
Sound Pressure - Linear	38 0	39 3	41 8	39 9	36 0	40 8	39 4	36 7	36 9	38 5	39 1
Sound Pressure - A Weighted	36 7	37 5	40 1	38 2	33 3	40 2	38 3	35 9	35 1	37 4	37 7
Sound Power - Linear	47 1										
Sound Power - A-Weighted	45 7										

Case 2 @ 7V	1	2	3	4	5	6	7	8	9	10	
Loudness	2 46	2 47	3 10	2 61	1 81	3 00	2 64	2 17	2 07	2 32	
Tonality	0 52	0 33	0 29	0 31	0 40	0 32	0 39	0 35	0 29	0 27	Avg
Sound Pressure - Linear	38 5	39 4	41 8	39 9	36 2	41 0	39 5	36 8	37 1	38 6	39 2
Sound Pressure - A Weighted	37 1	37 6	40 0	38 3	33 5	40 3	38 3	36 0	35 2	37 4	37 8
Sound Power - Linear	47 2										
Sound Power - A Weighted	45 8										

C4 Individual Fans – In-System with Acoustic Insulation

CPU @ 4V	1	2	3	4	5	6	7	8	9	10	
Loudness	0 13	0 23	0 23	0 17	0 21	0 17	0 18	0 10	0 20	0 13	
Tonality	0 42	0 30	0 35	0 00	0 08	0 53	0 01	0 00	0 60	0 00	Avg
Sound Pressure - Linear	20 5	23 5	22 6	21 2	23 3	21 1	21 2	19 1	23 1	20 3	21 8
Sound Pressure A Weighted	17 2	18 5	19 2	17 9	18 4	17 3	18 1	16 6	18 4	17 4	18 0
Sound Power Linear	29 8										
Sound Power A Weighted	25 9										

CPU @ 5V	1	2	3	4	5	6	7	8	9	10	
Loudness	0 16	0 25	0 46	0 34	0 30	0 22	0 28	0 10	0 23	0 22	
Tonality	0 61	0 73	1 06	0 89	0 85	0 47	0 78	0 10	0 76	1.12	Avg
Sound Pressure - Linear	21 1	23 1	25 3	24 0	23 4	22 4	23 1	18 9	23 2	21 6	22 9
Sound Pressure - A-Weighted	17 8	18 9	22 2	20 5	19 9	18 8	19 8	16 8	18 6	18 7	19 4
Sound Power - Linear	30 9										
Sound Power - A-Weighted	27 4										

CPU @ 6V	1	2	3	4	5	6	7	8	9	10	
Loudness	0 20	0 38	0 41	0 28	0 31	0 29	0 35	0 29	0 32	0 31	
Tonality	0 77	1 02	1 43	0 66	1 06	0 77	0 26	0 71	0 77	0 32	Avg
Sound Pressure - Linear	21 7	25 3	24 1	22 7	24 1	23 1	23 3	22 7	24 6	23 2	23 6
Sound Pressure - A Weighted	18 3	21 2	22 1	19 8	20 3	19 7	20 8	19 9	20 2	20 2	20 4
Sound Power - Linear	31 6										
Sound Power - A-Weighted	28 3										

CPU @ 7V	1	2	3	4	5	6	7	8	9	10	
Loudness	0 24	0 40	0 57	0 42	0 29	0 29	0 31	0 14	0 28	0 28	
Tonality	0 46	0 71	0 64	0 78	0 65	0 35	0 31	0 20	0 86	0 17	Avg
Sound Pressure - Linear	22 1	24 7	25 9	24 3	23 0	22 6	22 4	19 9	23 6	22 3	23 4
Sound Pressure A-Weighted	19 3	21 2	24 1	21 7	20 0	19 7	20 5	18 0	19 3	20 0	20 7
Sound Power - Linear	31 3										
Sound Power - A-Weighted	28 7										

CPU @ 8V	1	2	3	4	5	6	7	8	9	10	
Loudness	0 31	0 46	0 68	0 45	0 25	0 39	0 47	0 18	0 32	0 37	
Tonality	0 77	0 35	0 17	0 27	0 50	0 38	0 15	0 05	0 40	0 11	Avg
Sound Pressure - Linear	22 8	24 9	26 7	24 2	22 3	23 5	24 1	20 5	23 8	23 4	23 9
Sound Pressure - A-Weighted	20 4	22 2	26 0	22 9	19 4	21 2	23 0	18 8	20 2	21 9	22 1
Sound Power - Linear	31 9										
Sound Power - A-Weighted	30 1										

CPU @ 9V	1	2	3	4	5	6	7	8	9	10	
Loudness	0 38	0 55	0 95	0 60	0 39	0 58	0 69	0 32	0 49	0 60	
Tonality	0 34	0 63	0 35	0 46	0 55	0 35	0 18	0 24	0 67	0 25	Avg
Sound Pressure - Linear	23 4	26 0	29 3	25 8	24 0	25 5	26 3	22 3	25 3	26 2	25 8
Sound Pressure A-Weighted	21 6	23 8	28 8	24 7	21 5	23 6	25 7	21 0	22 7	24 8	24 5
Sound Power - Linear	33 8										
Sound Power A Weighted	32 4										

CPU @ 10V	1	2	3	4	5	6	7	8	9	10	
Loudness	0 54	0 78	1 18	0 79	0 43	0 81	0 89	0 50	0 66	0 80	
Tonality	0 15	0 47	0 19	0 30	0 24	0 47	0 09	0 49	0 93	0 12	Avg
Sound Pressure - Linear	25 2	28 2	31 1	27 8	24 3	27 5	28 1	24 6	27 1	28 1	27 6
Sound Pressure - A-Weighted	23 6	26 3	30 8	27 5	22 2	26 5	27 6	23 5	25 4	27 2	26 7
Sound Power - Linear	35 6										
Sound Power - A-Weighted	34 7										

CPU @ 11V	1	2	3	4	5	6	7	8	9	10	
Loudness	0 77	1 00	1 68	1 09	0 76	1 04	1 18	0 61	0 81	0 98	
Tonality	0 65	1 00	2 05	0 63	1 35	0 36	0 52	0 36	0 60	0 91	Avg
Sound Pressure - Linear	27 6	30 2	35 0	30 4	29 1	29 0	30 4	25 9	28 0	30 0	30 3
Sound Pressure A-Weighted	26 2	28 2	34 1	29 4	26 9	28 1	30 0	24 7	26 4	28 4	29 1
Sound Power Linear	38 2										
Sound Power - A Weighted	37 1										

CPU @ 12V	1	2	3	4	5	6	7	8	9	10	
Loudness	0 87	1 03	1 69	1 24	0 71	1 38	1 37	0 81	0 97	1 19	
Tonality	1 29	0 89	1 40	0 64	0 27	0 39	0 28	0 33	0 68	0 22	Avg
Sound Pressure - Linear	28 3	30 3	34 4	31 4	27 8	31 5	31 7	27 9	29 6	31 4	30 9
Sound Pressure - A Weighted	27 0	28 2	33 5	30 8	25 4	31 1	31 2	27 1	28 3	29 9	29 9
Sound Power - Linear	38 9										
Sound Power - A Weighted	37 9										

Case 1 @ 5V	1	2	3	4	5	6	7	8	9	10	
Loudness	0 15	0 19	0 16	0 13	0 12	0 15	0 12	0 09	0 20	0 11	
Tonality	0 54	0 77	0 56	0 52	0 34	0 52	0 23	0 00	0 70	0 30	Avg
Sound Pressure - Linear	21 0	22 6	20 9	20 6	20 2	21 3	20 1	18 8	22 7	19 5	20 9
Sound Pressure A-Weighted	17 4	17 8	17 8	17 1	17 1	17 4	17 2	16 5	17 9	16 6	17 3
Sound Power Linear	28 9										
Sound Power A-Weighted	25 3										

Case 1 @ 7V	1	2	3	4	5	6	7	8	9	10	
Loudness	0 25	0 37	0 33	0 22	0 28	0 32	0 24	0 10	0 30	0 17	
Tonality	0 81	0 94	0 91	0 88	0 87	0 98	0 74	0 25	0 94	0 74	Avg
Sound Pressure Linear	23 6	26 0	26 0	23 3	24 6	25 6	23 5	19 5	25 5	21 5	24 3
Sound Pressure A-Weighted	19 4	21 0	20 9	18 5	19 7	20 4	19 0	16 6	20 0	17 6	19 5
Sound Power Linear	32 3										
Sound Power A Weighted	27 5										

Case 1 @ 12V	1	2	3	4	5	6	7	8	9	10	
Loudness	0 72	0 94	0 94	0 58	0 56	1 10	0 75	0 44	0 70	0 54	
Tonality	0 00	0 00	0 09	0 00	0 00	0 22	0 27	0 00	0 23	0 20	Avg
Sound Pressure - Linear	31 4	33 8	34 3	31 2	30 7	33 0	30 9	27 1	30 7	28 8	31 7
Sound Pressure - A-Weighted	25 9	28 0	28 2	24 5	24 2	28 8	25 7	22 1	25 2	23 4	26 1
Sound Power Linear	39 6										
Sound Power - A-Weighted	34 1										

Case 2 @ 5V	1	2	3	4	5	6	7	8	9	10	
Loudness	0 24	0 19	0 15	0 17	0 17	0 18	0 13	0 11	0 20	0 15	
Tonality	0 19	0 70	0 22	0 00	0 00	1 08	0 14	0 00	0 69	0 00	Avg
Sound Pressure - Linear	22 2	22 6	21 0	21 9	21 5	21 7	20 4	19 7	22 5	20 8	21 5
Sound Pressure - A-Weighted	19 2	17 9	17 8	18 0	17 8	17 8	17 5	17 2	18 2	17 8	18 0
Sound Power - Linear	29 5										
Sound Power - A-Weighted	25 9										

Case 2 @ 7V	1	2	3	4	5	6	7	8	9	10	
Loudness	0 63	0 30	0 38	0 41	0 34	0 38	0 31	0 29	0 26	0 26	
Tonality	0 13	0 00	0 04	0 03	0 01	0 00	0 00	0 05	0 00	0 00	Avg
Sound Pressure - Linear	27 6	24 8	25 9	26 3	25 4	25 0	24 1	23 4	23 6	23 2	25 1
Sound Pressure - A Weighted	24 5	19 8	21 4	21 7	20 7	21 2	20 3	20 0	19 2	19 5	21 1
Sound Power - Linear	33 1										
Sound Power A Weighted	29 1										

Case 2 @ 12V	1	2	3	4	5	6	7	8	9	10	
Loudness	2 35	1 09	1 33	1 59	1 18	1 44	1 26	1 56	0 98	1 15	
Tonality	0 66	0 45	0 46	0 49	0 44	0 41	0 67	0 56	0 55	0 56	Avg
Sound Pressure - Linear	39 5	33 3	36 1	36 8	34 2	35 2	34 3	34 2	31 7	33 4	35 4
Sound Pressure - A-Weighted	37 8	29 0	31 6	33 1	29 9	32 0	30 5	31 9	28 1	30 0	32 4
Sound Power Linear	43 4										
Sound Power A Weighted	40 3										

PSU ON	1	2	3	4	5	6	7	8	9	10	
Loudness	0 32	0 39	0 51	0 32	0 28	0 67	0 43	0 38	0 47	0 42	
Tonality	0 00	0 07	0 00	0 05	0 00	0 25	0 14	0 16	0 45	0 21	Avg
Sound Pressure - Linear	25 1	31 8	30 1	26 0	24 0	36 6	28 2	25 8	31 0	26 3	30 3
Sound Pressure - A Weighted	21 0	25 5	25 1	21 5	20 2	31 0	23 5	22 8	25 4	22 4	25 1
Sound Power Linear	38 3										
Sound Power A-Weighted	33 1										

GPU @ 4V	1	2	3	4	5	6	7	8	9	10	
Loudness	0 82	0 96	1 49	1 32	0 78	1 00	1 09	0 89	1 05	1 21	
Tonality	1 21	0 33	0 33	0 39	0 23	0 29	0 19	0 47	0 09	0 30	Avg
Sound Pressure - Linear	29 6	30 3	37 1	36 0	29 7	29 6	34 1	29 9	32 1	35 3	33 3
Sound Pressure - A-Weighted	28 2	28 3	36 6	35 2	27 3	28 3	33 1	29 2	30 6	34 1	32 3
Sound Power - Linear	41 3										
Sound Power - A-Weighted	40 3										

GPU @ 5V	1	2	3	4	5	6	7	8	9	10	
Loudness	1 21	1 58	2 12	1 85	1 03	1 77	1 37	1 29	1 31	1 38	
Tonality	0 72	0 54	0 79	0 81	0 52	0 32	0 63	0 41	0 23	0 52	Avg
Sound Pressure - Linear	31 6	34 5	39 8	38 2	31 3	34 6	34 3	32 9	32 4	34 8	35 3
Sound Pressure - A Weighted	30 4	33 8	39 6	37 9	29 6	34 0	33 3	33 0	30 9	33 2	34 7
Sound Power - Linear	43 3										
Sound Power - A-Weighted	42 7										

GPU @ 6V	1	2	3	4	5	6	7	8	9	10	
Loudness	1 62	2 23	2 58	2 39	1 28	2 35	1 66	1 93	2 00	1 65	
Tonality	0 45	0 15	0 16	0 70	0 53	0 55	0 33	0 49	0 21	0 46	Avg
Sound Pressure - Linear	34 6	38 3	40 8	40 2	33 6	37 6	35 4	39 2	36 7	36 1	37 8
Sound Pressure - A Weighted	33 6	37 6	40 5	39 9	31 3	36 7	34 1	39 7	36 0	34 6	37 3
Sound Power - Linear	45 8										
Sound Power - A Weighted	45 3										

GPU @ 7V	1	2	3	4	5	6	7	8	9	10	
Loudness	2 25	3 01	3 24	2 84	2 05	3 27	2 57	2 02	2 39	2 21	
Tonality	1 09	0 41	0 41	0 52	0 42	0 44	0 40	0 65	0 45	0 32	Avg
Sound Pressure Linear	38 0	41 6	44 8	43 1	38 1	41 1	40 1	36 7	38 3	39 1	40 8
Sound Pressure - A Weighted	36 7	40 4	44 1	42 4	35 8	40 1	39 2	36 0	36 5	37 3	39 8
Sound Power - Linear	48 8										
Sound Power A-Weighted	47 8										

GPU @ 8V	1	2	3	4	5	6	7	8	9	10	
Loudness	2 76	3 62	3 70	3 22	2 32	4 04	2 88	2 53	3 08	2 82	
Tonality	0 28	0 18	0 22	0 32	0 09	0 05	0 20	0 94	0 22	0 13	Avg
Sound Pressure Linear	40 2	43 2	44 8	43 9	39 8	43 5	41 1	39 0	40 9	41 9	42 2
Sound Pressure - A Weighted	38 7	41 5	43 4	42 6	36 9	42 0	39 3	38 3	39 1	40 0	40 6
Sound Power Linear	50 2										
Sound Power - A-Weighted	48 6										

GPU @ 9V	1	2	3	4	5	6	7	8	9	10	
Loudness	3 57	4 59	4 80	4 03	3 13	5 17	3 84	3 19	4 15	3 81	
Tonality	0 49	0 31	0 33	0 51	0 39	0 26	0 23	1 09	0 32	0 58	Avg
Sound Pressure - Linear	43 4	46 1	48 5	47 4	43 5	46 4	45 7	41 9	45 0	47 2	45 9
Sound Pressure - A Weighted	41 9	44 4	47 2	46 2	40 5	45 1	44 3	40 7	43 4	45 8	44 5
Sound Power - Linear	53 9										
Sound Power - A-Weighted	52 4										

GPU @ 10V	1	2	3	4	5	6	7	8	9	10	
Loudness	4 15	5 43	5 31	4 56	3 49	6 17	4 38	3 55	4 70	4 23	
Tonality	0 35	0 09	0 20	0 16	0 15	0 05	0 07	0 06	0 16	0 29	Avg
Sound Pressure Linear	44 9	48 0	49 4	48 5	44 5	48 6	46 1	42 6	46 0	47 0	47 0
Sound Pressure - A Weighted	43 5	46 4	47 8	47 2	41 6	47 3	44 5	41 2	44 4	45 4	45 4
Sound Power Linear	55 0										
Sound Power A Weighted	53 4										

GPU @ 11V	1	2	3	4	5	6	7	8	9	10	
Loudness	5 08	6 62	6 53	5 53	4 28	7 41	5 28	4 29	5 77	5 01	
Tonality	0 33	0 24	0 62	0 50	0 35	0 28	0 39	0 34	0 39	0 47	Avg
Sound Pressure - Linear	47 2	50 7	51 9	50 7	46 5	51 0	48 0	44 8	48 2	48 3	49 2
Sound Pressure A-Weighted	46 2	49 6	50 6	49 4	43 8	49 9	46 4	43 7	47 0	46 7	47 9
Sound Power Linear	57 2										
Sound Power - A-Weighted	55 9										

GPU @ 12V	1	2	3	4	5	6	7	8	9	10	
Loudness	5 68	7 22	7 55	6 20	4 75	8 13	5 97	5 06	6 46	5 49	
Tonality	0 16	0 06	0 93	0 35	0 17	0 06	0 33	0 42	0 27	0 05	Avg
Sound Pressure - Linear	48 5	51 5	54 4	52 0	47 9	52 3	49 7	46 9	49 9	50 1	50 9
Sound Pressure A-Weighted	47 4	50 1	53 2	50 7	44 9	51 1	48 1	46 1	48 7	48 2	49 5
Sound Power Linear	58 8										
Sound Power - A Weighted	57 5										

C5 Fully Assembled and Operating Desktop Computer System with Acoustic Insulation

Idle	1	2	3	4	5	6	7	8	9	10	
Loudness	3 18	2 22	3 10	2 71	1 93	2 75	2 69	2 36	2 06	2 31	
Tonality	0 61	0 41	0 43	0 24	0 32	0 15	0 27	0 22	0 36	0 37	Avg
Sound Pressure Linear	42 4	39 1	42 3	41 0	38 2	40 0	40 2	37 9	37 7	39 2	40 1
Sound Pressure A Weighted	40 9	35 8	40 0	38 5	34 3	37 9	38 1	36 3	35 1	36 8	37 8
Sound Power Linear	48 1										
Sound Power A Weighted	45 8										

CPU Benchmark	1	2	3	4	5	6	7	8	9	10	
Loudness	3 23	2 42	3 34	2 82	1 98	3 07	2 73	2 50	2 09	2 33	
Tonality	0 81	0 33	0 40	0 37	0 23	0 82	0 57	0 39	0 59	0 50	Avg
Sound Pressure - Linear	42 6	40 0	43 1	41 2	38 2	41 2	40 3	38 7	37 9	39 3	40 6
Sound Pressure A-Weighted	41 1	37 5	41 1	39 0	34 5	39 7	38 3	37 4	35 3	37 0	38 6
Sound Power Linear	48 6										
Sound Power A Weighted	46 6										

GPU Benchmark	1	2	3	4	5	6	7	8	9	10	
Loudness	3 37	2 97	4 10	3 33	2 47	4 42	3 67	3 22	3 24	3 05	
Tonality	1 37	0 85	0 26	0 34	0 74	0 51	0 41	0 83	0 45	0 73	Avg
Sound Pressure - Linear	43 1	43 6	45 4	42 7	39 7	44 4	42 2	40 7	40 7	40 9	42 7
Sound Pressure - A-Weighted	41 9	43 2	44 2	40 9	36 8	43 3	40 8	39 9	39 0	39 1	41 4
Sound Power - Linear	50 7										
Sound Power - A Weighted	49 4										

Speedfan @ 50%	1	2	3	4	5	6	7	8	9	10	
Loudness	3 24	2 62	3 00	2 74	2 00	3 34	2 63	2 52	2 37	2 29	
Tonality	1 25	0 41	0 43	0 38	0 52	0 60	0 83	0 38	0 43	0 52	Avg
Sound Pressure Linear	42 5	40 2	42 0	40 9	38 3	41 5	39 7	38 4	38 1	38 8	40 3
Sound Pressure - A-Weighted	41 0	37 7	39 5	38 5	34 4	39 7	37 1	37 0	35 5	36 4	38 1
Sound Power Linear	48 3										
Sound Power - A Weighted	46 1										

Case 1 @ 5 V	1	2	3	4	5	6	7	8	9	10	
Loudness	3 43	2 71	3 37	2 95	2 02	3 56	2 94	2 58	2 46	2 51	
Tonality	0 71	0 49	0 42	0 69	0 70	0 58	0 62	0 86	0 77	0 51	Avg
Sound Pressure - Linear	42 7	39 5	42 2	41 0	37 3	41 6	40 0	38 4	37 6	39 3	40 3
Sound Pressure - A-Weighted	41 6	38 1	40 9	39 3	34 5	40 7	38 6	37 4	35 9	37 6	39 0
Sound Power - Linear	48 3										
Sound Power - A Weighted	46 9										

Case 1 @ 7 V	1	2	3	4	5	6	7	8	9	10	
Loudness	3 41	2 74	3 49	2 98	2 07	3 57	2 97	2 60	2 53	2 51	
Tonality	0 91	0 47	0 36	0 68	0 49	0 50	0 67	0 83	0 62	0 48	Avg
Sound Pressure Linear	42 6	39 8	42 6	41 1	37 7	41 7	40 1	38 6	38 0	39 2	40 5
Sound Pressure - A-Weighted	41 4	38 1	41 1	39 4	34 6	40 7	38 7	37 5	36 1	3 5	39 0
Sound Power - Linear	48 5										
Sound Power A Weighted	47 0										

Case 2 @ 5 V	1	2	3	4	5	6	7	8	9	10	
Loudness	2 23	2 53	3 24	2 53	1 56	3 18	2 64	2 03	2 21	2 28	
Tonality	0 23	0 30	0 34	0 33	0 17	0 25	0 48	0 40	0 29	0 27	Avg
Sound Pressure - Linear	37 4	39 6	41 9	39 4	35 4	40 5	38 9	36 0	37 0	37 9	38 8
Sound Pressure - A-Weighted	35 3	37 4	40 4	37 7	31 7	39 5	37 7	34 7	34 7	36 4	37 2
Sound Power - Linear	46 8										
Sound Power - A-Weighted	45 2										

Case 2 @ 7 V	1	2	3	4	5	6	7	8	9	10	
Loudness	2 36	2 59	3 21	2 54	1 59	3 26	2 69	2 09	2 23	2 31	
Tonality	0 26	0 33	0 40	0 46	0 60	0 25	0 30	0 48	0 30	0 25	Avg
Sound Pressure - Linear	38 0	39 7	41 8	39 5	35 7	40 8	39 1	36 2	37 1	38 1	39 0
Sound Pressure - A-Weighted	36 0	37 5	40 3	37 7	31 9	39 8	37 7	35 0	34 8	36 6	37 3
Sound Power - Linear	47 0										
Sound Power A-Weighted	45 3										

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