UNIVERSITY OF ALBERTA

DIFFUSION MEASUREMENT IN REVERBERATION CHAMBERS

BY

D. BRUCE LARSON ©

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled **Diffusion Measurement in Reverberation Chambers** submitted by **D. Bruce Larson** in partial fulfillment of the requirements for the degree of Master of Science.

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To my parents

ABSTRACT

It is well established that the sound field in a reverberation chamber must be highly diffuse to meet the assumptions inherent in standard acoustical tests. However, there is no established definition as to what constitutes a "highly diffuse" sound field and diffusion is not a quantity that can be measured directly.

In this thesis, a previously developed measure of diffusion levels is used to evaluate the level of diffusivity in the reverberation chambers at the Mechanical Engineering Acoustics and Noise Unit (MEANU). Additionally, different configurations of diffusing elements are studied to establish their effect on diffusion levels.

The measurement technique was found to be sensitive to small changes in diffusion levels and showed that diffusing elements can effectively increase diffusivity in reverberant rooms.

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Introduction

1.1 Diffusion and Diffusivity Measurement

The subject of diffusion in reverberant rooms has been the source of much misunderstanding in the past. There is no disagreement as to its necessity. In room acoustics we are not interested in the behaviour of specific sound waves but in the simultaneous reflection of a large number of waves impinging from very different directions onto the wall of interest [1]. Instead of studying each wave individually and summing the effects of a wall on every wave we can average the effect of the wall over many directions. Common acoustical testing uses statistical reverberation theory which assumes perfect diffusion to predict results so it is universally understood that acoustical testing in reverberation rooms requires that a "highly diffuse" sound field be present to produce correct results. The problems arise in deciding on an adequate definition of diffusion or in establishing what is meant by a "high" degree of diffusion. To add to the difficulties, diffusion is not a quantity that can be measured directly. The work on this subject to date is briefly discussed below.

Schultz discusses both definitions of diffusion and methods used to measure the quantity [2]. He mentions some very poor definitions used in the past, namely, that a perfectly diffuse sound field is guaranteed by a uniform sound pressure level [3,4]. Also included are some more accurate definitions. These are:

i) In a diffuse sound field there is a uniform total energy density at all points in the room and each volume element radiates equally in all directions [5].

ii) In a diffuse sound field there is equal probability of energy flow in all directions and random angle of incidence of energy upon the boundaries of the room [6].

iii) A diffuse sound field comprises a superposition of an infinite number of plane progressive waves, such that all directions of propagation are equally probable and the phase relations of the waves are random at any given point in space [7].

While these definitions help to conceptualize the idea of diffusion, they are of little practical help. From a practical sense, an adequate level of diffusion is one which would produce test results that do not vary significantly from the test results obtained in a perfectly diffuse field. They would, of course, vary significantly if the sound field were sufficiently "non-diffuse". Common acoustic test standards are based on the assumption that the reverberant sound field is perfectly diffuse [8,9]. If the assumption is not valid, the model will likely yield incorrect estimates. The question remains, however, as to what an adequate level of diffusion is and to answer this we must have a measure of diffusion.

Numerous techniques have been used in the attempt to find a meaningful measure of diffusivity. These methods have included directional microphones, acoustic wattmeters, cross-correlation measurements of sound pressure levels at neighboring positions in the field, absorption measurements, frequency irregularity, spatial uniformity of sound pressure, uniformity of decay rate, and linearity of decay curves [2]. All of these methods have proved to have limitations. Usually, the methods are not sensitive enough or are not directional enough at low frequencies where diffusion levels are typically the lowest. The method described below and used in the present work is one developed by Bodlund [10].

Bodlund used a cross-correlation technique in his measurement. A two microphone technique is logical since diffusion is defined in terms of energy flow. Earlier difficulties in using cross-correlation functions are overcome since technology has improved so that the technique is sensitive enough to detect small changes in diffusion levels.

With a useful measure of diffusion, some investigation into the effects of various room designs and treatments can be made. Common methods of achieving diffusion in reverberation chambers are also discussed by Schultz [2]. The most successful approaches include large room volumes and the addition of diffusing elements to reverberation chambers.

Room volume is probably the most important factor in achieving diffusion. As frequency increases, the number of room resonance modes increase and there are more potential paths along which sound energy may propagate. Therefore, the level of diffusion also increases. The number of room modes present at a given frequency f is calculated from the following expression [1].

$$N_f = \frac{4\pi}{3} V \left(\frac{f}{c}\right)^3 + \frac{4}{\pi} S \left(\frac{f}{c}\right)^2 + \frac{L}{8} \left(\frac{f}{c}\right)$$

where V is the room volume, S is the surface area, L is the sum of all end lengths, and c is the speed of sound. From the above equation, it is obvious that the modal density is related to room dimensions so that the number of modes present at low frequencies can be increased, and consequently the level of diffusion raised, by building large rooms. Eventually cost becomes prohibitive however, and air absorption can reduce reverberation times to values which are too low to be useful when room volumes are greater than approximately 300 m^3 [2]. As a result, supplementary methods must be used to increase diffusion.

The addition of diffusing elements is the next most frequently used method of increasing diffusion levels. Diffusing elements can take the form of large geometric shapes applied to walls, hanging panels, or moving vanes. The idea behind these systems is that they reflect sound energy in a more random manner than the surfaces of a rectangular room. They vary in effectiveness, with wall treatments being considered least effective and most intrusive due to the large volume they occupy, whereas moving vanes are considered more effective.

Diffusing elements can be troublesome. They must be large, with a minimum dimension of at least one-half the wavelength of the lowest frequency of interest, and heavy enough to reflect sound energy. However, it has been reported that moving vanes, which act to continuously change the effective shape of a room, can produce significant increases in diffusion levels [2].

1.2 Scope of Investigation

No investigations have previously been made into the levels of diffusion present in the reverberation rooms at the Mechanical Engineering Acoustics and Noise Unit (MEANU). The goal of this study was to use the diffusivity measurement technique developed by Bodlund to evaluate the MEANU reverberation chambers and diffusing elements and consider alternate designs if necessary.

The present study includes data collection to determine Bodlund's diffusivity measure. This involved experimental apparatus and development of processing programming.

Computer simulation also played a part in this study. To provide a low cost and flexible method of evaluating alternate diffuser designs in future work, numerical modelling was investigated. Initial room and diffuser models were formed to allow recommendations to be made as to how this may be more successfully accomplished when alternate designs for diffusers are seriously considered.

Chapter two introduces the acoustical theory used as a background to this investigation. Basic room acoustics theory is discussed to more clearly define diffusion. The cross-correlation function and the measurement technique used is also developed in detail. A discussion of the modelling of the reverberation chambers and the diffusing panels is also found here.

Chapter three considers the data collection aspects of the study. The qualifications of the test facilities are presented and the specific instrumentation is listed. The experimental method followed is also described along with calculations of the experimental error that might be expected.

Chapter four contains the results of the investigation and discusses their implications. The use of computer modelling in predicting room frequency response, the spatial variation of diffusion in a reverberant field, the effect of differing room treatments on diffusion levels, and the effect of changing diffusion levels on transmission loss results are presented and discussed.

Finally, chapter five presents the conclusion of this study and summarizes the logical extensions of this work.

Chapter
TWO

Room Acoustics and Diffusivity

The measurement of diffusivity is not directly available. Instead, a measure of the level of diffusion in a room is derived from more easily obtained acoustical data. These fundamental quantities are reviewed below and are followed by the development of the specific measure of diffusion used in this investigation.

2.1 Room Acoustics

One of the most basic quantities that is directly measurable with standard acoustical instrumentation is the mean square sound pressure level (P^2_{RMS}) of the sound pressure disturbance (p(t)).

$$P^2_{RMS}(x,y,z) = \frac{1}{T}\int_0^T p^2(x,y,z,t)\,dt \qquad (2.1.1)$$

where T is the integration time and x,y,z are the coordinates of the measurement point.

Due to the large pressure ranges encountered in common acoustic environments, the sound pressure level (SPL) is defined as

$$SPL = 10\log_{10}\left(\frac{p^2}{p_{ref}^2}\right) \ dB \qquad (2.2.2)$$

where p_{ref} = RMS sound pressure reference, $2*10^{-5}$ N/m^2

p = RMS sound pressure in N/m^2

If a sound pressure wave were allowed to propagate freely in all directions from a constant source then the sound pressure level would drop in an easily predictable manner as a function of the distance to the source. However, in a three-dimensional enclosure, the sound wave is no longer free to travel infinitely outwards. It reflects obliquely from all boundary surfaces and enclosed obstructions as it travels in all directions. If each path that the wave takes is traced there will be certain paths that repeat to form normal modes of vibration. When the frequency of the sound wave equals one of the normal frequencies, resonance occurs and the resulting standing wave produces specific SPL's throughout the enclosure.

The wave equation

$$\nabla^2\psi - \frac{1}{c^2}\frac{\partial^2\psi}{\partial t^2} = 0, \qquad (2.1.3)$$

where $\psi(x,t)$ represents the acoustic velocity potential, and with

$$p = \rho\frac{\partial\psi}{\partial t}$$

may be solved for the normal frequencies (f_{ijk}) and room modes $M_{ijk}(x,y,z)$ for simple geometries [11]. In a closed rectangular cavity these are

$$f_{ijk} = \frac{c}{2}\sqrt{\left(\frac{i}{L_x}\right)^2+\left(\frac{j}{L_y}\right)^2+\left(\frac{k}{L_z}\right)^2} \qquad (2.1.4)$$

$$M_{ijk}(x,y,z) = \cos\left(\frac{i\pi x}{L_x}\right)\cos\left(\frac{j\pi y}{L_y}\right)\cos\left(\frac{k\pi z}{L_z}\right) \qquad (2.1.5)$$

where c = speed of sound, L_x, L_y, L_z = room dimensions (m) and

$i = 0,1,2,\ldots, j = 0,1,2,\ldots, k = 0,1,2,\ldots$

For an undamped and rigid wall enclosure (similar to a reverberation chamber), the sound pressure p(x,y,z,t) is (again from [11])

$$p(x,y,z,t) = \rho c^2 Q \sum_{i=0}^{I}\sum_{j=0}^{J}\sum_{k=0}^{K} \frac{\omega M_{x,y,z} M_{x_0 y_0 z_0} \cos\left(\omega t+\phi-\frac{\pi}{2}\right)}{V_{ijk}(\omega^2-\omega_{ijk}^2)} \qquad (2.1.6)$$

where $f_{ijk} = \omega_{ijk}/2\pi$

$V_{ijk}/V = E_i E_j E_k$ $\qquad$ E_n = 1 for n=0

$V = L_x L_y L_z$ $\qquad$ = 1/2 for n≥1

x,y,z - location of observer

x_0, y_0, z_0 - location of source

Q - noise source magnitude

That is, the sound pressure is found by summing the contributions of individual room modes. The number of room modes occurring from 0 Hz to f Hz in a rectangular room is given by

$$N_f = \frac{4\pi}{3}V\left(\frac{f}{c}\right)^3 + \frac{4}{\pi}S\left(\frac{f}{c}\right)^2 + \frac{L}{8}\left(\frac{f}{c}\right) \qquad (2.1.7)$$

where V is the room volume, S is the surface area, and L is the sum of all end lengths. For the same room, the modal density (from [1]) is given by

$$\frac{\partial N_f}{\partial f} = \frac{4\pi V f^2}{c^3} + \frac{\pi S f}{2c^2} + \frac{L}{8c}. \qquad (2.1.8)$$

The above equation can be used to indicate how evenly the modes in a room are distributed along the frequency axis.

At low frequencies, where there are few room modes governing the pressure distribution in a room, the sound energy in the room propagates in distinct paths. However, as the number of modes increases, the sound energy propagates more uniformly in all directions, until eventually there are enough modes present so that there is nearly an equal probability of sound energy propagating in any direction - a perfectly diffuse sound field. For reverberation rooms, considerable attention is taken to generate as diffuse a field as possible. It is important that no strong room modes be present in a reverberation chamber as this would mean that energy was propagating in preferred directions and diffusion in the room would decrease. In fact, reverberation chamber dimensions are suggested by the American Society for Testing of Materials (ASTM) to avoid strong room modes.

From equation (2.1.6), it can be seen that it is no simple task to solve for the pressure distribution in a room even with a very simple geometry. As the frequency range increases and the number of room modes accumulate, the equations become far too cumbersome to deal with. Computer models can account for more complex geometries and boundary conditions (as will be discussed later), but these too are frequency limited due to the huge computational requirements for calculations involving high frequencies. Fortunately, if there are a large number of room modes present (the sound field is diffuse), as is the case at high frequencies, we can assume that the amplitudes of the incident waves are uniformly distributed over all directions of incidence in such a way that from each element of the solid angle, the same amount of energy arrives on a wall surface per second and per unit of area element perpendicular to the respective direction [1]. Furthermore, it is assumed that the phases of the elementary waves are distributed at random so that interference effects can be neglected and the energies or intensities of waves impinging can simply be added. For these reasons, standard acoustical tests assume a perfectly diffuse reverberant field.

With the above assumptions, tests such as those for the absorption properties of a material or system and the transmission loss (T.L.) of walls or wall components may be performed. An absorption test (ASTM C423) measures the fraction of randomly incident sound power absorbed by a specimen. The test is based on the Sabine Equation [9]

$$A = 0.9210\,Vd/c \qquad (2.1.9)$$

where d is the rate at which the diffuse reverberant field SPL decays (dB/second) once the source is shut off. It is assumed that the reverberant field remains diffuse during the decay.

The T.L. test is performed as part of this investigation to determine if a measured change in the level of diffusion has any effect on common laboratory tests. While the absorption test requires only one room, the T.L. test is attempting to measure the transmission coefficient τ

$$TL = 10\log_{10}\left[\frac{1}{\tau}\right] \qquad (2.1.10)$$

where $\tau = I_t/I_i$, I_t, I_i are the transmitted and incident reverberant intensities in two adjacent rooms. Again it is assumed that the fields are diffuse so that the intensities can be inferred from an energy balance which requires only an average SPL to be measured in each of the source and receiver rooms. With the diffuse field assumption, the T.L. can be calculated as in the ASTM E90 standard [8]

$$TL = L_1 - L_2 + 10\log_{10}\left(\frac{S}{A}\right) \qquad (2.1.11)$$

where L_1, L_2 - source and receiver room SPL's in dB

S - wall panel surface area

A - absorption in receiver room, Sabines

Diffusion is indicated by the direction of energy propagation and therefore it is impossible to use the SPL measured at only one position to establish the degree of diffusion present in a room. This is the reason that cross functions, which correlate information between two points, have been used in the past. Bodlund uses the cross-correlation function ($R_{xy}(x,y,\beta)$) of the sound pressure instead of the cross-power spectral density function ($G_{xy}(f)$) [10]. Because the cross-power function contains no more information than the cross-correlation function, (it is simply the Fourier transform of the cross-correlation function) he is justified, in order to simplify matters, in using real values from the cross-correlation function as opposed to complex values from the cross-power function. The cross-correlation function is described as

$$R_{xy}(x,y,\beta) = \frac{1}{T}\int_0^T p(x,t)\,p(y,t+\beta)\,dt \tag{2.1.12}$$

where x,y are vectors of the two positions and β is a time delay. The cross-correlation function measures the extent to which a displaced copy of a second signal (measured at y) resembles the first signal (measured at x).

2.2 Specifics of the Diffusivity Measure

The diffusivity measure used in this work is essentially that developed by Bodlund [10]. He, in turn, based his work on previous studies [12] which had established a theoretical relationship for the cross-correlation coefficient in a perfectly diffuse sound field energized with narrow band sound. From [1], the correlation coefficient

$$\rho_{xy}(x-y,\beta=0)=\frac{p_x p_y}{(p_x^2 p_y^2)^{\frac{1}{2}}} \tag{2.2.1}$$

where x-y indicates the direction of the transducer axis, is calculated by assuming that the room is excited by random noise with a very narrow bandwidth. The sound field can be considered to be composed of plane waves with randomly distributed amplitudes $A_{f,\phi,\theta}$ and phase angles $\eta_{f,\phi,\theta}$, and with angles of incidence θ, which are measured against the connecting line between both points. Figure 2.2.1 illustrates the definition of θ, ϕ is similarly defined for the vertical plane if θ is thought to lie in the horizontal plane.

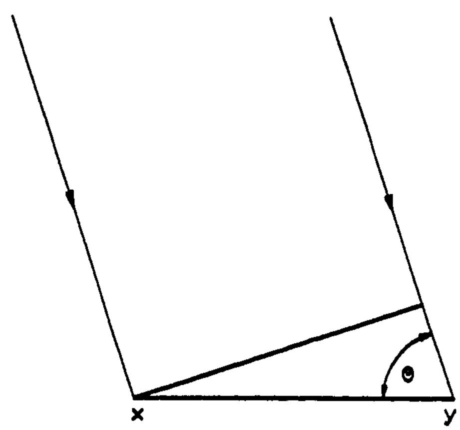


Figure 2.2.1 Angle of Incidence of a Plane Wave

With this assumption, the pressure is found from

$$p_x=\sum_{f}\sum_{\phi,\theta}A_{f,\phi,\theta}\cos(\omega t-\eta_{f,\phi,\theta})\,. \tag{2.2.2}$$

At point y, which is a distance r from point x, additional phase lags occur, and therefore

$$p_y = \sum_f \sum_{\phi,\theta} A_{f,\phi,\theta} \cos(\omega t - \eta_{f,\phi,\theta} - kr\cos\theta) \qquad (2.2.3)$$

where $k=2\pi f/c$. Time averaging of both sound pressure squares yields

$$p_x^2 = p_y^2 = \frac{1}{2}\sum_f \sum_{\phi,\theta} A_{f,\phi,\theta} \qquad (2.2.4)$$

Furthermore we obtain the time average of the product,

$$\begin{aligned} p_x p_y = & \sum_{f,\phi,\theta_x} \sum_{f,\phi,\theta_y} A_{f,\phi,\theta_x} A_{f,\phi,\theta_y} [\cos(\omega t - \eta_{f,\phi,\theta_x})\cos(\omega t - \eta_{f,\phi,\theta_y}) \\ & \times \cos(kr\cos\theta_{f,\phi,\theta_y}) + \sin(\omega t - \eta_{f,\phi,\theta_x})\cos(\omega t - \eta_{f,\phi,\theta_y}) \\ & \times \sin(kr\cos\theta_{f,\phi,\theta_y})] \\ = & \frac{1}{2}\sum_f \sum_{\phi,\theta} A^2_{f,\phi,\theta} \cos(kr\cos\theta) \end{aligned} \qquad (2.2.5)$$

If from each solid angle element $d\phi d\theta$, the same amount of sound energy arrives at both points, we obtain, by replacing the summation by integrations and simplifying the sound field so that all plane waves have equal amplitude A

$$p_x^2 = p_y^2 = \frac{1}{2} 4\pi A^2$$

and

$$\begin{aligned} p_x p_y &= \frac{1}{2} A^2 \iint \cos(kr\cos\theta)\, d\phi d\theta \\ &= 2\pi A^2 \frac{\sin(kr)}{kr} \end{aligned}$$

Inserting these expressions into equation (2.2.1) finally yields

$$\rho_{xy}(x-y,\beta=0)=\frac{\sin(kr)}{kr} \qquad (2.2.6)$$

It has been shown however, that sin(kr)/kr behaviour is strictly correct only for a perfectly diffuse field in an octant (that is, plane, travelling waves within the angle area $0\leq\theta\leq\pi/2$, $0\leq\phi\leq\pi/2$) [10]. Therefore, the direction of the microphone axis (x-y) is important, as is the distance between the two microphones (from (2.2.6)). The study concluded that satisfying sin(kr)/kr behavior in a number of x-y directions is a strong indication of perfect diffusion.

Recognizing that with modern instrumentation there is no need to limit investigation to β = 0 in the cross-correlation function (as was the case in earlier studies), Bodlund studied $R_{xy}(\beta)$ [10]. By regarding the sound field in the same manner as above, he has assumed p_x from equation (2.2.2) and p_y as

$$p_y(t+\beta)=\sum_f\sum_{\phi,\theta}A_{f,\phi,\theta}\cos(\omega t-\eta_{f,\phi,\theta}-\omega\beta-kr\cos\theta) \qquad (2.2.7)$$

Thus, from equations (2.1.1) and (2.1.12)

$$R_{xy}=\lim_{t\to\infty}\frac{1}{T}\int_0^T\sum_f\Big[\sum_{\phi,\theta}A_{f,\phi,\theta}\cos(\omega t+\eta_{f,\phi,\theta})\Big]$$

$$\Big[\sum_{\phi,\theta}\cos(\omega t+kr\cos\theta+\omega\beta+\eta_{f,\phi,\theta})\Big]dt \qquad (2.2.8)$$

$$p_x^2=p_y^2=\lim_{t\to\infty}\frac{1}{T}\int_0^T\sum_f\Big[\sum_{\phi,\theta}A_{f,\phi,\theta}\cos(\omega t+\eta_{f,\phi,\theta})\Big]^2dt.$$

By computing the time integrals and by neglecting those sums which consist of terms like $\cos\eta_i\eta_j$, equations (2.2.1) and (2.2.8) give

$$\rho_{xy}=\frac{\frac{1}{2n}\sum_{f}\sum_{\phi,\theta}A^2_{f,\phi,\theta}\left[\cos(kr\cos\theta)\cos\omega\beta-\sin(kr\cos\theta)\sin\omega\beta\right]}{\frac{1}{2n}\sum_{f}\sum_{\phi,\theta}A^2_{f,\phi,\theta}}. \quad (2.2.9)$$

The condition for this equation to be valid is that there must be a large number of wave components. Equation (2.2.9) is equivalent to (2.2.1) if $A_{f,\phi,\theta}$ is independent of f,ϕ, and θ, and when there are a large number of wave components evenly distributed over all solid angles. The expressions in the numerator and denominator may be regarded as mean value expressions with the result that for a narrow frequency band this reduces to

$$\rho_{xy}=\frac{\int_0^{2\pi}d\phi\int_0^{\pi}\left[\cos(kr\cos\theta)\cos\omega\beta-\sin(kr\cos\theta)\sin\omega\beta\right]\sin\theta\,d\theta}{\int_0^{2\pi}d\phi\int_0^{\pi}\sin\theta\,d\theta} \quad (2.2.10)$$

This indicates that a variation in ρ_{xy} with the measurement direction x-y is an indication of the level of diffusion since isotropy for ρ_{xy} is a necessary condition for perfect diffusion. If there is a variation in ρ_{xy} with direction, the field is not perfectly diffuse. For third octave band excitation then, the expression for the theoretical cross correlation function (ρ_T) is obtained from equations (2.2.9) and (2.2.10)

$$\rho_T(r,\beta) = \frac{\int_{f_0/\kappa}^{f_0\kappa} |H(f)|^2 \sin(kr)\cos(\omega\beta)/kr \; df}{\int_{f_0/\kappa}^{f_0\kappa} |H(f)|^2 \; df} \qquad (2.2.11)$$

where f_0 is the center frequency in Hz, κ, which indicates the bandwidth, is $2^{1/6}$ for 1/3 octave bands and H(f) is the frequency response of the 1/3 octave band filter used. This expression is integrated numerically. Figure 2.2.2 shows a sample of a theoretical cross-correlation function calculated in this manner. Also shown is the general close agreement between the theoretical results and an actual measurement of the cross-correlation function.

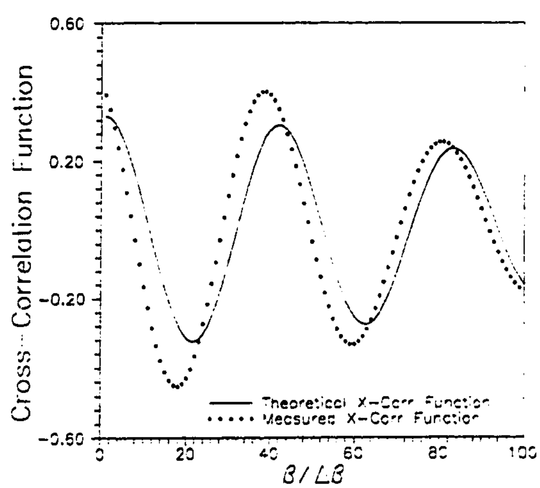


Figure 2.2.2 Theoretical and measured cross-correlation functions

As equation (2.2.11) must be satisfied as a necessary condition for perfect diffusion, deviations (for a constant r) detected by calculating the spatial variance between several cross-correlation functions measured around a fixed microphone at x in various x-y directions and the expected function are measures of the diffusivity.

By averaging along the θ axis ($\theta i = i\Delta\theta$, $i = 0,1,2,\ldots,99$), (arbitrarily choosing 100 samples to average), the quantity for measuring the level of diffusion becomes

$$\epsilon = \left[\frac{\sum_{i=0}^{99}\sum_{j=0}^{n}(\rho_j(\beta_i)-\rho_T(\beta_i))^2}{100n}\right]^{\frac{1}{2}} \qquad (2.2.12)$$

where n is the number of microphone positions used.

This quantity has been found to be a suitable measure of diffusivity. While it has been found to be sensitive to directional and frequency composition of the sound fields [10], there are some factors of secondary interest that should be noted. In short, Bodlund showed that the integration time T can give some time variance contribution to ε but the lower limit will be established [10]. The sample increment must be chosen so that $\Delta\theta$ is less than the Nyquist frequency ($1/2f_{max}$) to prevent aliasing where f_{max} is the maximum frequency expected in the data. Bodlund found that ε did not change significantly if $\Delta\theta$ was below this value [10]. He also found that microphone spacing r was not important as long as the wavelengths were large compared with the microphone dimensions [10]. It was found that sound pressure levels cause no significant variation in ε since the cross-correlation coefficient is normalized with respect to the sound pressure level. Finally, temperature differences of ±5°C were not observed to introduce errors in ε.

2.3 Computer Simulation

In part, this study was to measure the variation in diffusivity in reverberation rooms resulting from the addition or deletion of the current and new design diffuser systems. Due to the length of time involved in gathering data, and complexities involved in building and testing new diffuser systems, it was anticipated that computer modelling would assist in predicting which system would increase diffusivity. For this purpose the finite element method was used, as implemented by Numerical Integration Technologies' SYSNOISE. The relations that form the mathematical basis for the prediction of acoustic fields by SYSNOISE are derived from the wave equation (2.1.3). Both pressure (p) and velocity (v) can be derived from $\psi(x,t)$, the acoustic velocity potential. If harmonic behaviour with frequency ω is considered, then ψ may be written as $\psi(x,t)=\phi(x)\exp(i\omega t)$ and the equation becomes Helmholtz's equation

$$\nabla^2\phi + k^2\phi = 0 \tag{2.3.1}$$

and p and v may be expressed as

$$p(x,t)=p(x)\exp(i\omega t)$$
$$v(x,t)=v(x)\exp(i\omega t)\,. \qquad (2.3.2)$$

Furthermore, since p is related to ψ by $p=\rho\frac{\partial\psi}{\partial t}$, we have

$$p=\rho i\omega\phi. \qquad (2.3.3)$$

Now Helmholtz's equation can be rewritten as

$$\nabla^2 p+k^2 p=0 \qquad (2.3.4)$$

To complete the model, appropriate boundary conditions must be supplied along with noise source specifications and diffuser characteristics. For the case of a reverberation room, the walls can be considered as hard (rigid walls, perfectly reflecting) with a zero velocity condition. Current computer facilities limit the model to two dimensions so that the noise source is treated as a cylindrical wave source. SYSNOISE defines this type of source by the following equation

$$p=-iAH_0^{(2)}(kd) \qquad (2.3.5)$$

where A is the pressure on a cylinder of unit radius

$H_0^{(2)}$ is the Hankel function of the second kind of zero order

d is the distance from the source

To avoid the complexity of a coupled finite element model to account for room/diffuser interactions, the diffusers were considered as elements with a transfer admittance. That is, the diffusers were considered as permeable membranes. The transfer admittance of the diffusers was calculated taking only mass into account. No measure of panel stiffness or damping was included although this assumption is suspect at low frequencies. Thus, the transfer admittance of a limp mass

$$Y=\frac{-i}{m\omega} \tag{2.3.6}$$

was used.

With the above relationships, a basic model of the test rooms and test configurations could be established. The mesh used in modelling the small room with diffusers is shown in figure 2.3.1.

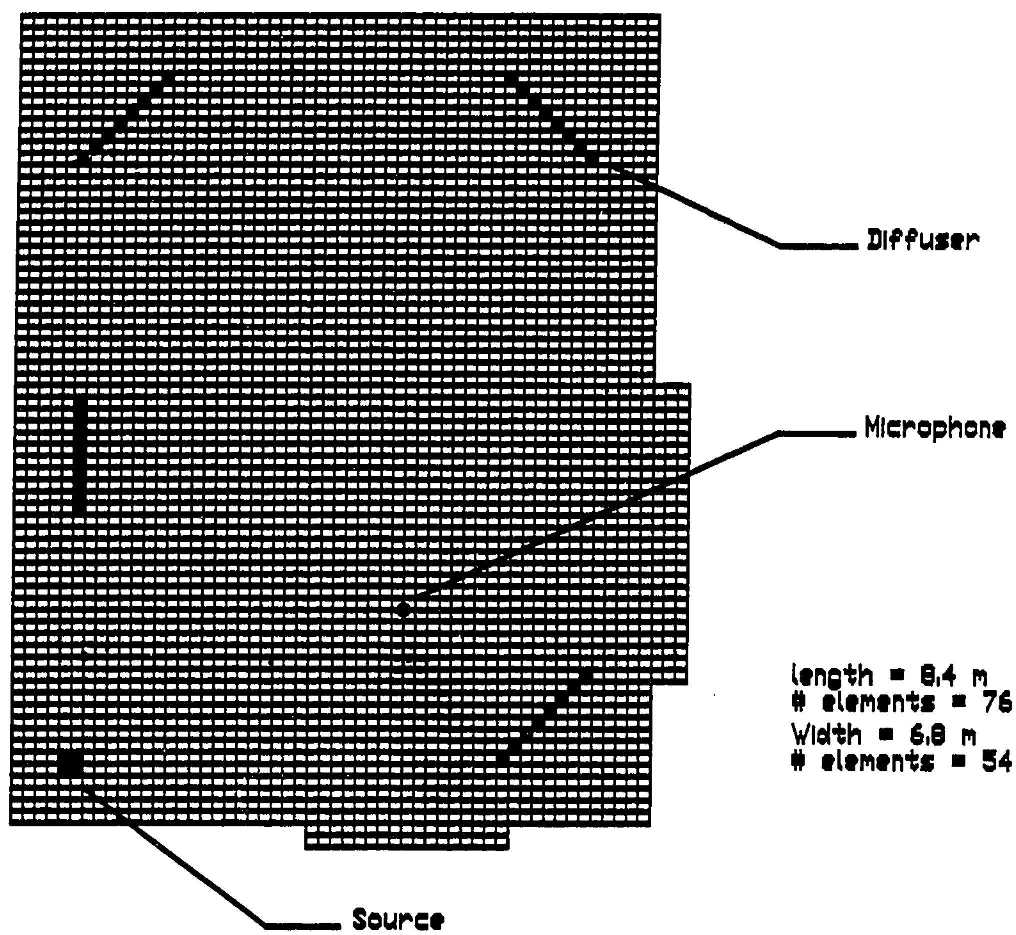


Figure 2.3.1: Finite Element Mesh for Small Reverberation Chamber with Diffusers

Chapter THREE

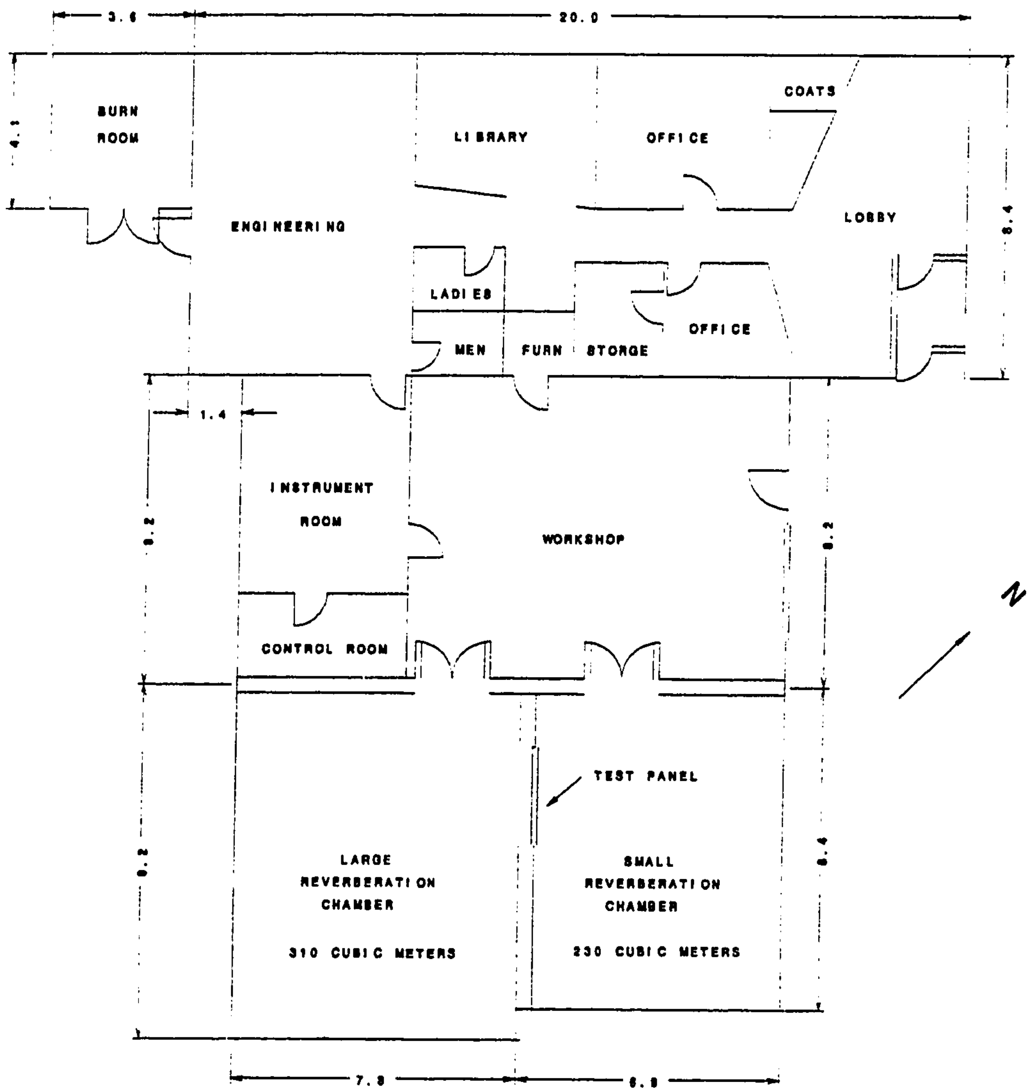
Experimental Details

There can be no confidence in any experimental results if key equipment is inadequate or if experimental practice is questionable. For this reason the qualifications of the facilities, the instrumentation used and a description of the experimental procedure is detailed below. Additionally, discussion of the potential errors in the procedure is included.

3.1 Facilities

Much of the work and all of the testing involved in this study was carried out at the University of Alberta's Mechanical Engineering Acoustics and Noise Unit (MEANU). A floor plan of the complex is shown in Figure 3.1.1. The facility includes two adjoining reverberation chambers which can be linked through a common opening to allow testing in either or both rooms.

The reverberation chamber dimensions are included in figure 3.1.1. The rooms are isolated from each other and from the rest of the facility by separate foundations. Walls are formed of 10" thick dense aggregate concrete blocks filled



MECHANICAL ENGINEERING ACOUSTICS AND NOISE UNIT

Figure 3.1.1 MEANU Floorplan

with sand. The roof consists of 12" thick precast concrete panels and the floor is 4" hardened reinforced concrete resting on compacted sand fill.

To meet ASTM requirements for absorption testing, reverberation chambers must meet several requirements. The test rooms at MEANU exceed the required empty room reverberation times at all frequencies. Both rooms exceed the 180 m^3 minimum room volume and meet room dimension specifications. Specifically, the smallest room dimension should be at least one wavelength and preferably two at the center frequency of the lowest 1/3 octave band for which measurements are to be taken. At approximately 20°C the smallest room dimension corresponds to one wavelength at 65 and 73.5 Hz for the large and small rooms respectively. For two wavelengths the corresponding frequencies are 130 and 147 Hz respectively. The length of the greatest straight line which can fit in the room, l_{max}, must be less than $1.9V^{1/3}$. This criterion is met in both rooms. ASTM specifies that the ratio of the largest to smallest dimension be less than 2:1. The actual room dimension ratios at MEANU are 1.63:1.29:1 for the large room and 1.67:1.32:1 for the small room and are within the specified range. Finally, the standard specifies that the rooms should yield an absorption coefficient to a satisfactory precision (±2%) with sufficiently high confidence limits (95%).

There are also requirements to be met to satisfy the ASTM transmission loss standard. The room volumes meet the required values and the room proportions quoted above are close to the recommended proportions of 2:1.3:1.6. The absorption coefficients of all exposed surfaces in the test rooms were measured to be 0.02 between 125 and 4000 Hz. This is below the specified value of 0.06. Precision requirements of ±1 dB (95% confidence) for all bands (except 125 Hz where the requirement is ±2 dB) are also met for the T.L. standard.

ASTM recommends the use of a number of sound reflecting panels, either stationary or moving, hung or distributed at random angles about a reverberation chamber to approximate a diffuse sound field. The facility at MEANU uses slightly curved 1.2 x 2.4 x .01m plywood panels for this purpose. The large room uses eight panels while the small room uses six panels. In both rooms, the panels are capable of oscillating rotational motion by means of a system of rope pulleys attached to a rotating arm. The arrangement may be seen in figure 3.1.2.

3.2 Instrumentation

The primary tool for data acquisition and analysis was a dual channel Larson-Davis Model 3200 real time analyzer equipped with digital 1/1, 1/3, 1/12 octave filters and Fast Fourier Transform (FFT) capabilities. The 1/3 octave digital filters were used in performing the T.L. and absorption tests used in

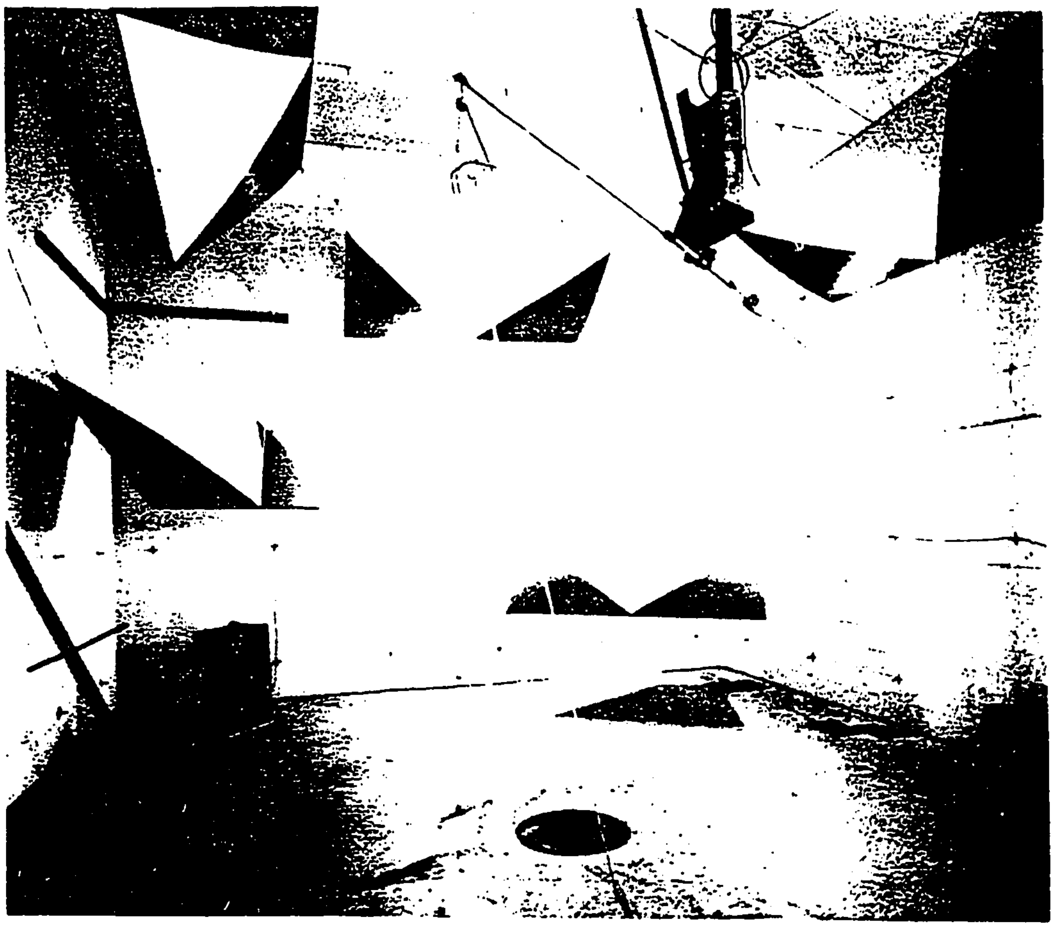


Figure 3.1.2: Diffuser Arrangement at MEANU

the study. A sample filter is shown in figure 3.2.1. All filters satisfy requirements for fractional octave filters according to ANSI S1.11-1986. An 800 line FFT was used in obtaining cross-correlation functions. Frequency accuracy is better than ±0.01% full scale. The unit was operated by remote control through an IEEE-488 interface to a PC. The Larson-Davis analyzer also contains a noise generator which was used to trigger a custom built white/pink noise generator used at MEANU.

As mentioned in Chapter 2, the frequency response of the 1/3 octave filters used to filter the white noise must be taken into account in calculating the theoretical cross-correlation coefficient. The filter set used was a Bruel and Kjaer (B&K) model 1614 with analog 1/1 and 1/3 octave band filters. The frequency response for the filters used (125, 250, 500, and 1000 Hz) can be seen in figure 3.2.2.

The filtered white noise was then sent to a single 15" JBL 2220H woofer. The speaker cabinet was located in a room corner to excite the maximum number of room modes.

Finally, B&K type 4165 microphones were used to measure the SPL's in the test rooms. These microphones have a flat (±2 dB) response from 1 Hz to 20 kHz. The microphones were a matched pair (phase and amplitude) in order to minimize any errors in the measured cross-correlation function due to the measurement microphones. The factory data for the phase mismatch between the two microphones from 20 to 1000 Hz is

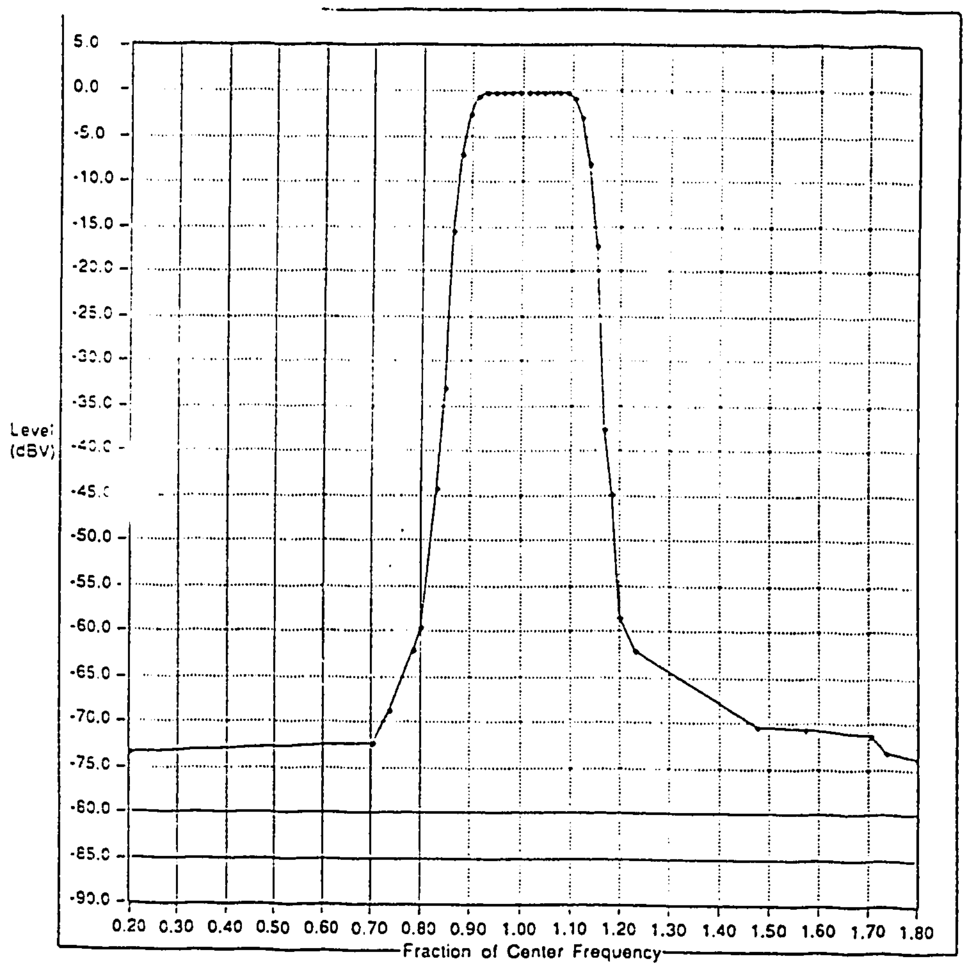


Figure 3.2.1 Frequency Response of Larson-Davis 1/3 octave Digital Filter

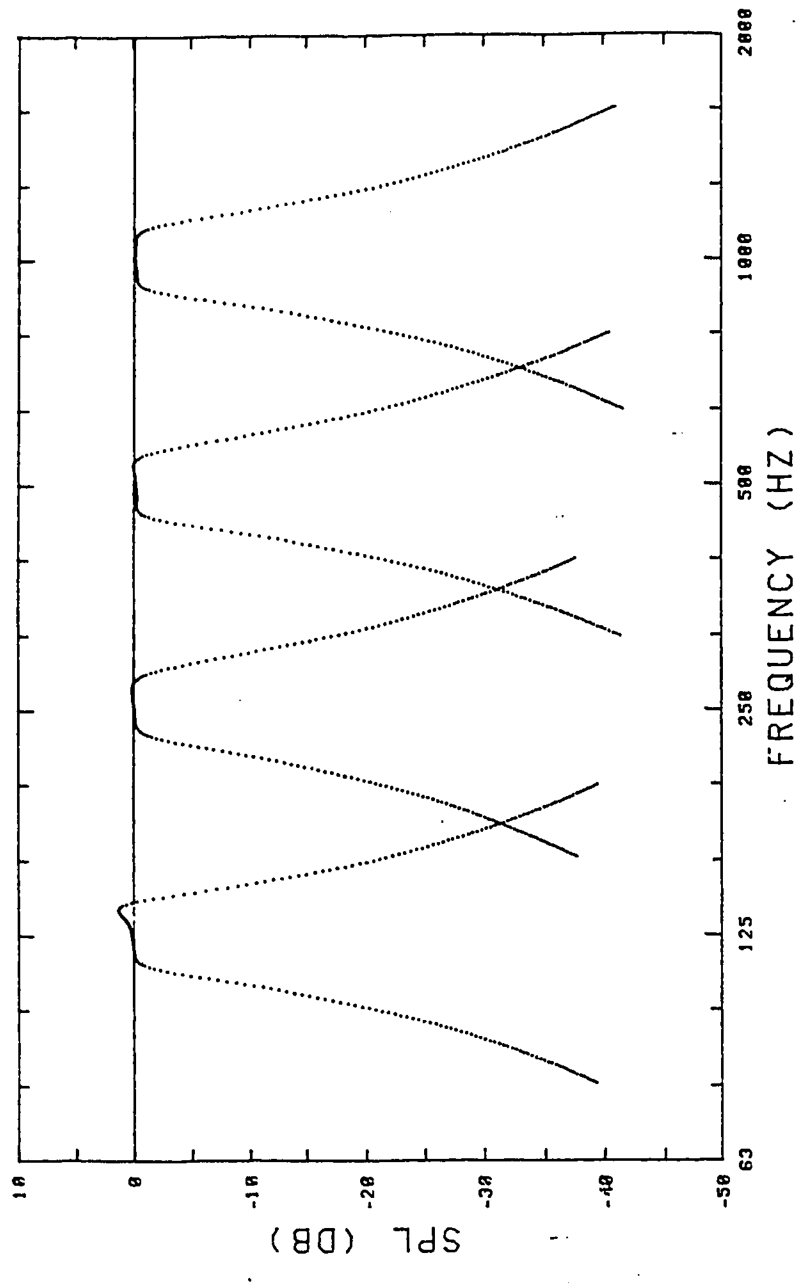


Figure 3.2.2 Frequency Response of B&K 1/3 octave Filters

shown in figure 3.2.3 while the frequency response curves for the two microphones are shown in figure 3.2.4. For each microphone the upper curve shows the response for the microphone cartridge with the protecting grid on in a diffuse sound field while the lower curve shows the open circuit pressure response recorded with an electrostatic actuator.

The complete measurement system is illustrated in figure 3.2.5.

3.3 Data Collection Method

Every attempt was made to follow experimental procedures that would produce accurate and repeatable results. Environmental conditions were monitored in all tests and microphones were calibrated daily to account for atmospheric variations. Microphone placement varied depending on the type of test to be performed and will be discussed below.

The diffusivity measurement used ten microphone positions placed an equal distance r from a stationary central microphone. That is, ten microphones locations on the surface of a sphere of radius r. Ideally, the ten positions would be determined randomly to provide a better indication of the level of diffusion (since more directions x-y would be studied), but due to the practical difficulties involved, a fixed set of microphone positions was studied. Figure 3.3.1 shows the microphone positions on the three concentric spheres

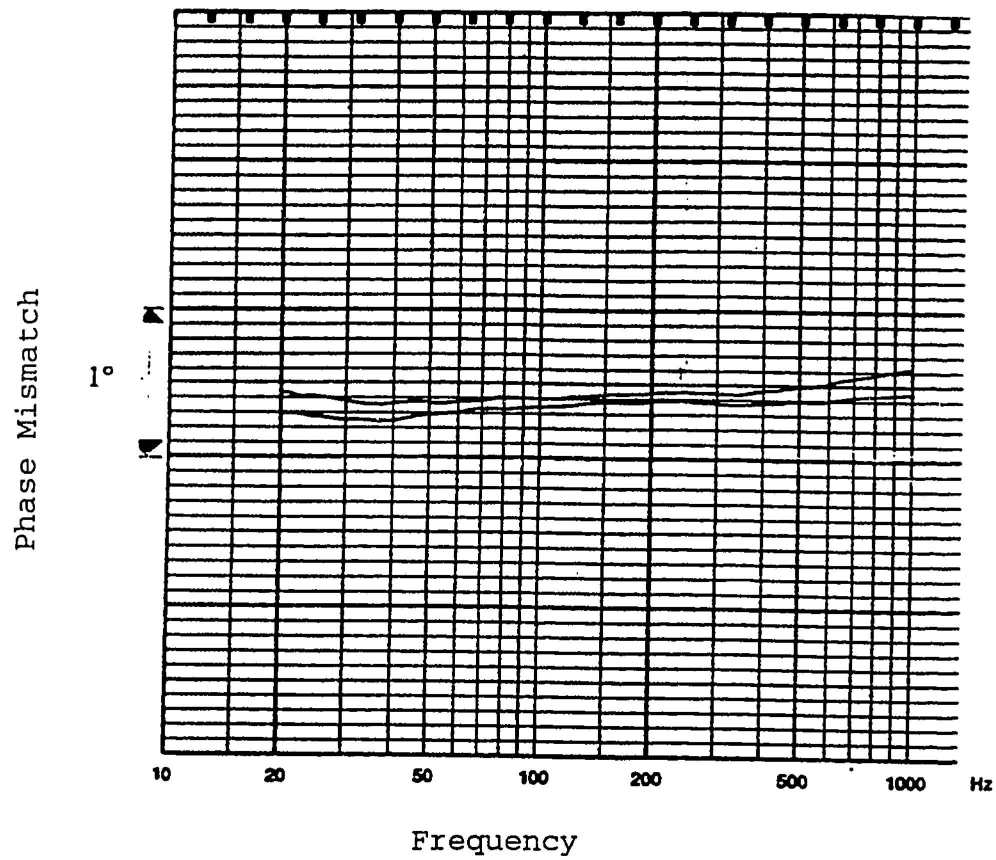


Figure 3.2.3 Phase Mismatch Between type 4165 Microphones

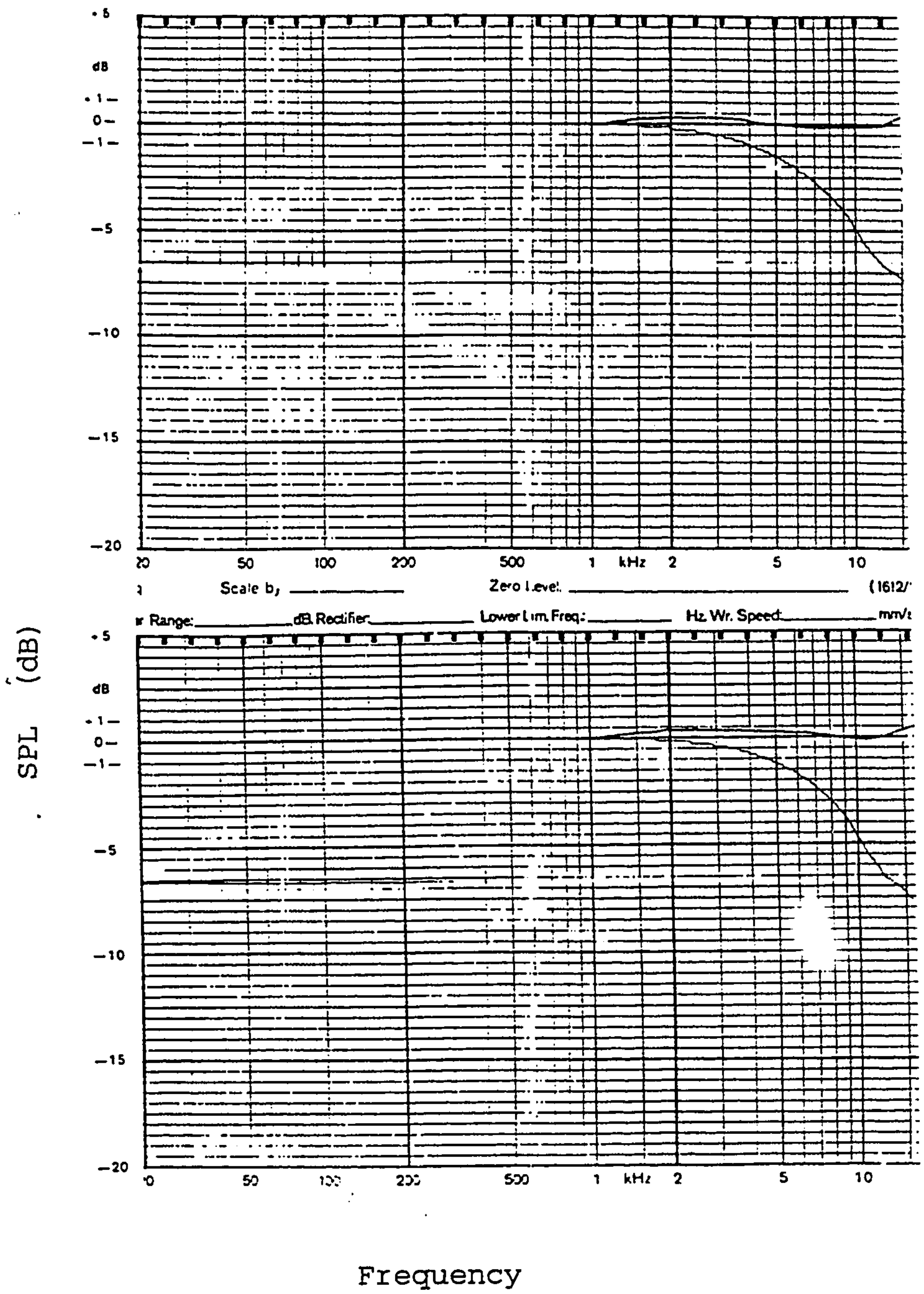


Figure 3.2.4 Frequency Response Curves for type 4165 Microphones

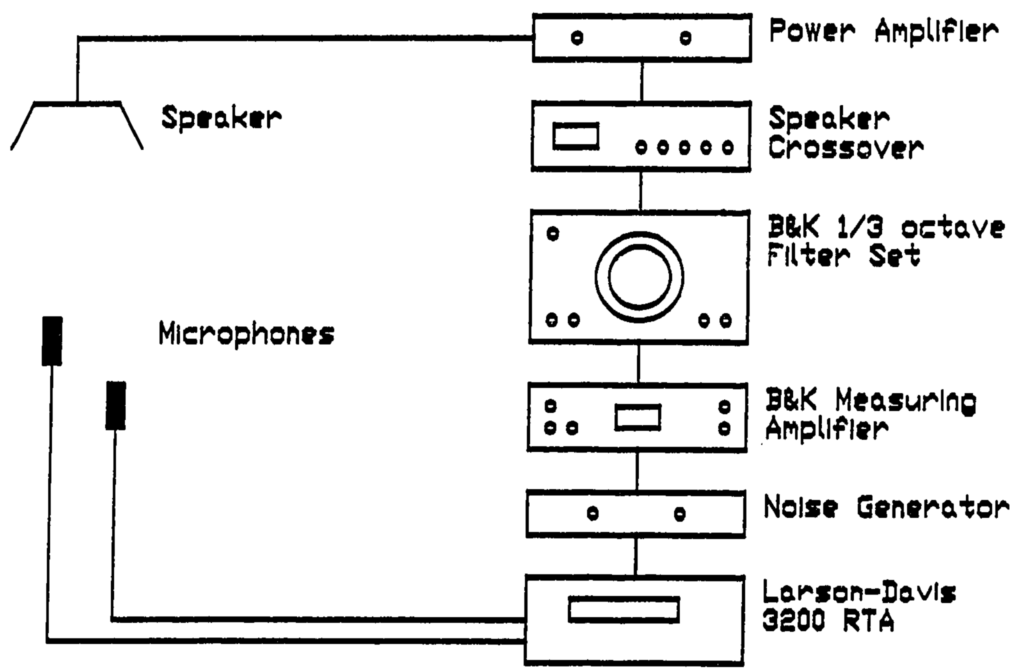


Figure 3.2.5 Instrumentation for Diffusivity Measurement

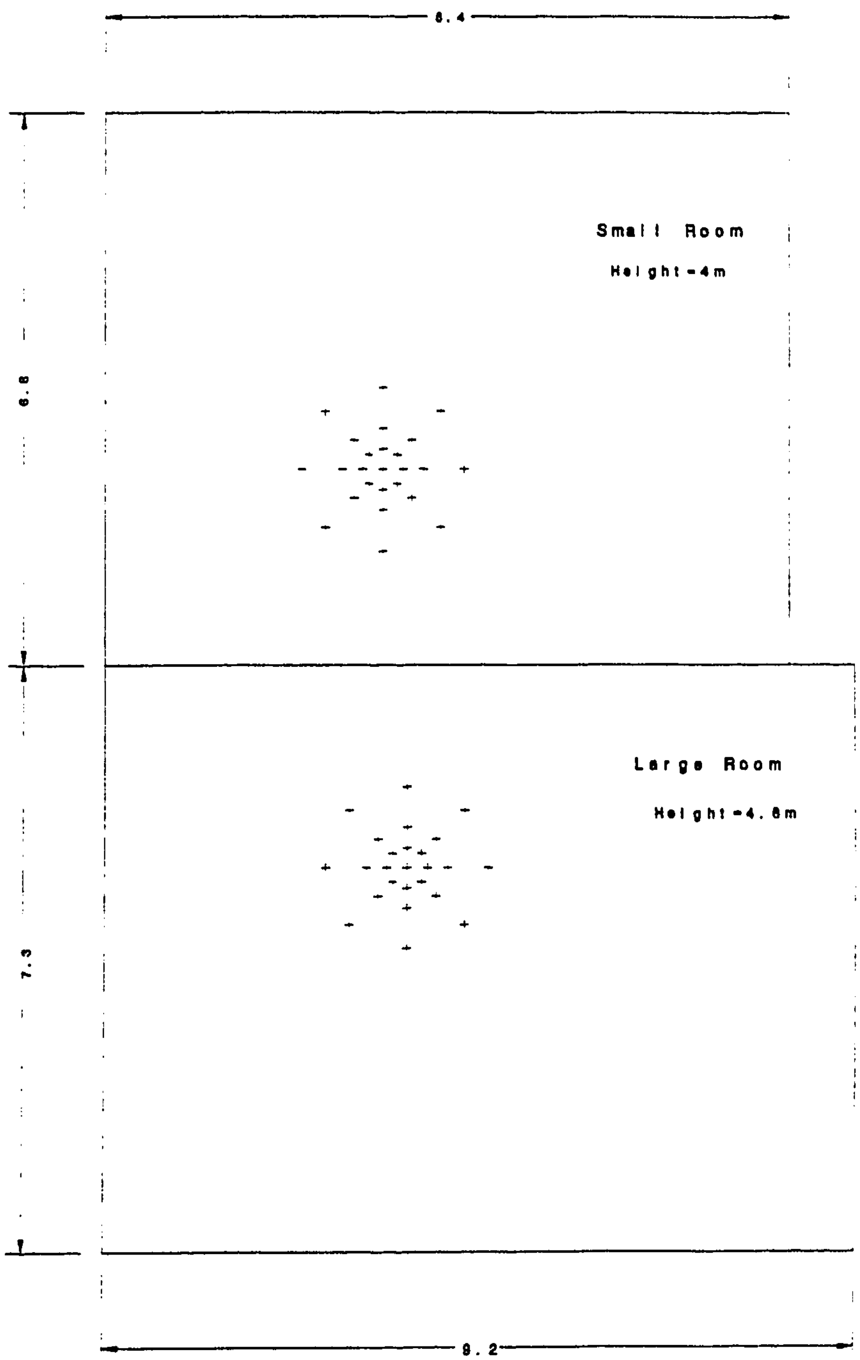


Figure 3.3.1 Plan View of Microphone Positions for Diffusivity Measurement ir Reverberation Suite

mapped onto the floors of the reverberation chambers while figure 3.3.2 shows a three dimensional representation of the microphone locations. The spacing r used was 0.25 m for 1000 Hz, 0.5 m for 500 and 250 Hz, and 1 m for 125 Hz. Near the boundaries of a room or near objects in a room the sound field is known to be partially made up of a direct field and accordingly, all positions are at least 1 m away from any wall surface or diffuser and out of the speaker's direct field.

For each test, the movable microphone was placed in the first position and a cross-correlation measurement was taken. Measurement times were taken from Bodlund's data [10] for 125 and 1250 Hz and the equation for finding averaging times to measure SPL to a specified uncertainty [11] is

$$T = \frac{306.2}{e^2 f} \qquad (3.3.1)$$

where e is the specified uncertainty for SPL in dB. The resulting averaging times are 262 s for 125 Hz, 260 s for 250 Hz, 130 s for 500 Hz and 64 s for 1000 Hz. After a measurement was completed, the microphone was moved to the next position and the process repeated until all ten positions were recorded.

As mentioned previously, T.L. tests were carried out to study the effects of changing levels of diffusion on T.L. measurements. To meet the requirements of the E90 ASTM TL test, six microphone positions in each of the reverberation rooms were used. These positions are shown in figure 3.3.3.

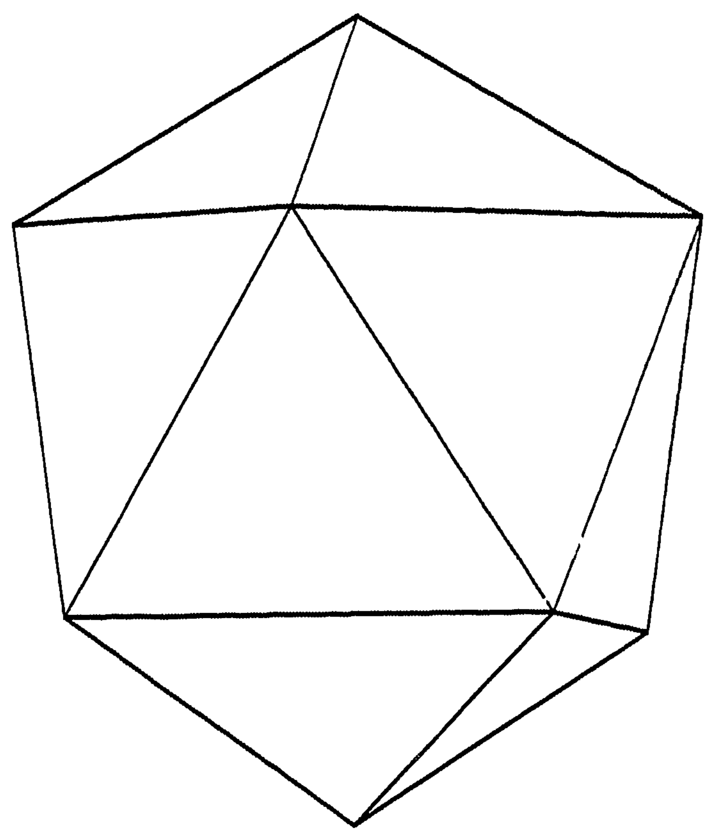


Figure 3.3.2: Three-dimensional View of Microphone Positions for Diffusion Measurement

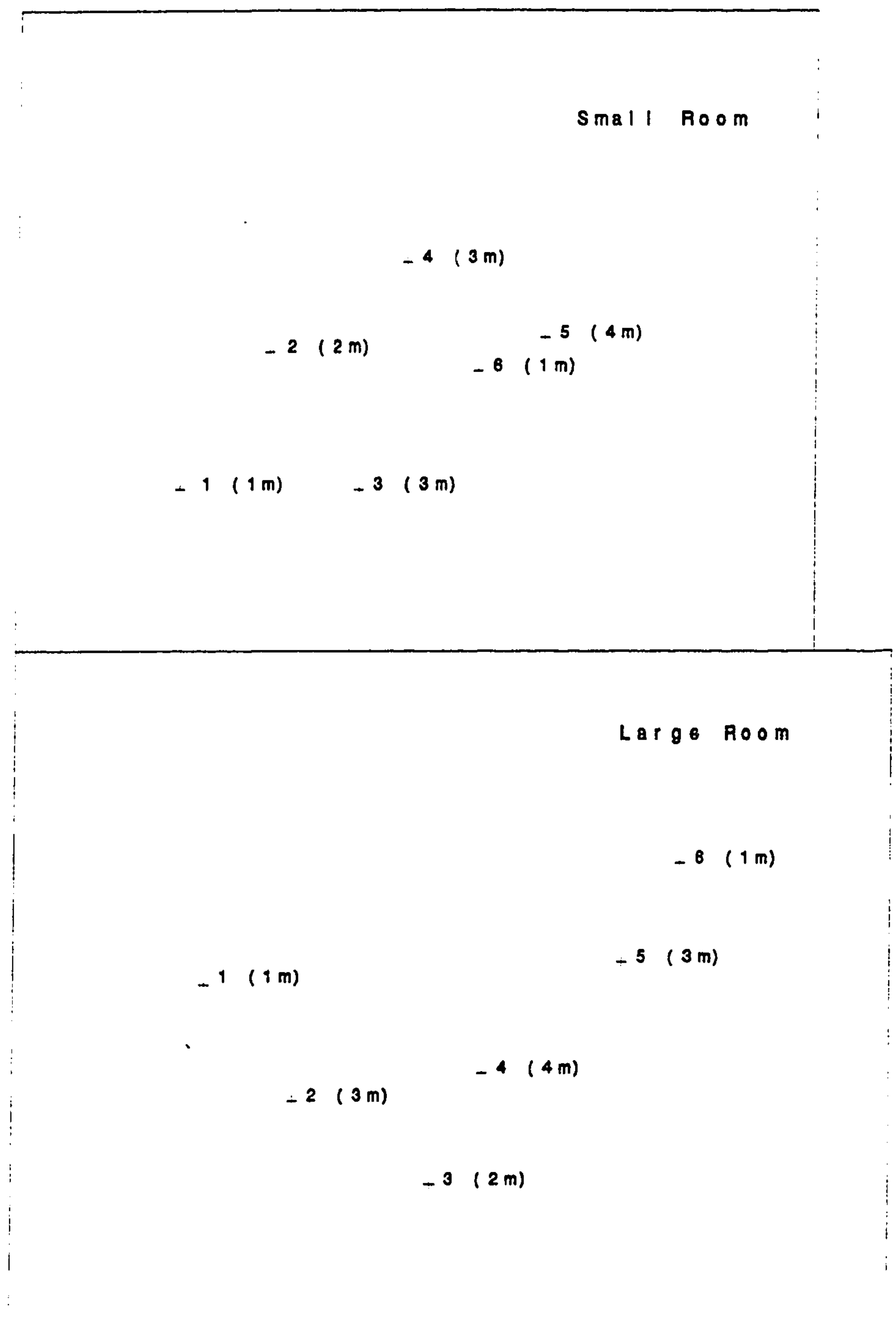


Figure 3.3.3 Plan View of Microphone Positions for Transmission Loss Tests in Reverberation Suite

Similar to the diffusivity test, the microphones were placed in the first position in each room and a SPL measurement was take: The measurement times were chosen to produce SPLs with a specified uncertainty. The microphones were then moved to the next position and the process repeated. After all positions were measured, the reverberation times (T_{60}'s) in the receiver room were found at each of the six positions. From this data the TL calculations can be performed.

To study the possible correlation between room diffusion levels and room frequency response, it was necessary to measure the frequency response of the reverberation suite. In measuring room frequency response at a point, only one microphone position in each room was used; that position being the same as the stationary microphone position in the diffusivity test. A speaker testing equipment package and a reference speaker were used to determine the response. A B&K slave filter was used to step through frequencies from 20 to 500 Hz. To allow for the long reverberation times, at each frequency the room was allowed to stabilize for approximately 5 s before recording a measurement .

3.4 Error Analysis

Some of the potential sources of error, measurement parameters and temperature variations have already been mentioned but changes in air absorption due to relative humidity and variation in ε due to microphone positioning error have not. The statistical variance in ε will also be established with the use of the Student t test.

It has been shown that air absorption does not change significantly if the relative humidity (RH) is 50% or greater and for this reason standards recommend RH levels be at least 50% during testing [8]. Dry winter air caused the RH of the air in the test chambers at MEANU to drop to values ranging from 10 to 30% during testing and so it was possible that the amount of air absorption changed from day to day with changing RH. Figure 3.4.1 shows the effects of corrections made to account for air absorption in a room [9] on sound absorption coefficients. It is clear that this correction is not necessary below 1000 Hz, the maximum frequency of interest in this study. At the frequencies examined, air absorption was not an important factor.

Errors arising from inaccurate microphone placement are potentially more significant. Manual microphone positioning is obviously inexact and prone to variation. It is easily imaginable for variations of 2-3 cm to occur. The impact of this Δr on ε was determined by differentiating

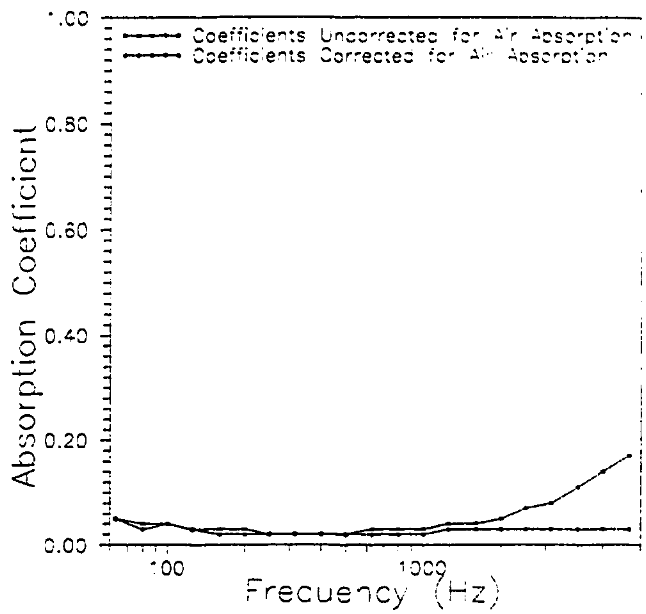


Figure 3.4.1 Variation of Air Absorption of Sound Energy with Frequency

equation(2.2.12) with respect to the measured and theoretical cross-correlation functions to get

$$\frac{\partial \epsilon}{\partial \rho_j} = \frac{\sum_{i=0}^{99} \sum_{j=1}^{n} (\rho_j - \rho_T)}{\epsilon}$$
$$\frac{\partial \epsilon}{\partial \rho_T} = \frac{\sum_{i=0}^{99} \sum_{j=1}^{n} (\rho_j - \rho_T)}{\epsilon} \tag{3.4.1}$$

and since we know that for random independent uncertainties

$$e_\varepsilon^2 = \left(\frac{\partial\varepsilon}{\partial\rho_j}\right)^2 e_{\rho_j}^2 + \left(\frac{\partial\varepsilon}{\partial\rho_T}\right)^2 e_{\rho_T}^2 \qquad (3.4.2)$$

then with equation (3.4.1), equation (3.4.2) becomes

$$e_\varepsilon^2 = \sum_{i=0}^{99} \sum_{j=1}^{n} \left[\frac{(\rho_j - \rho_T)^2}{\varepsilon^2} (e_{\rho_j}^2 + e_{\rho_T}^2) \right]. \qquad (3.4.3)$$

The error in ρ_T due to a small variation in r can easily be found. A sample of the resulting errors in ρ_T can be seen in figure 3.4.2. If we estimate the errors in ρ_j to be of the same order as those of ρ_T then the resulting error can be calculated to be as large as approximately 15% of ε depending on the frequency studied and the air temperature. This is not insignificant and it clearly shows that care must be taken in placing the microphones. Fortunately the error is not large enough that the uncertainty is as large as the values considered.

Five measurements were taken of ε for each frequency in each case examined. Because of the small sample population the Student t distribution was used to find the 95% confidence intervals on the mean value using

$$Confidence\ Limits = \pm\frac{t_{\nu,95}}{\sqrt{n}}\sigma. \qquad (3.4.4)$$

where $t_{v,95}$ = 2.132 for n=5, 95% confidence limits and σ is the sample standard deviation.

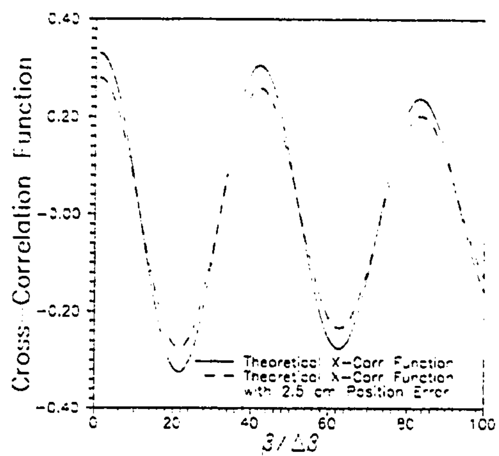


Figure 3.4.2 Effects of Microphone Positioning Error on Cross-Correlation Function

CHAPTER FOUR

Results and Discussion

Once data has been gathered, it remains to interpret the results. The modal response of the test rooms is discussed first, followed by spatial variation of the diffusivity measure, variation in diffusivity in response to different room treatments, and the effects of changing diffusion levels on the standard T.L. test.

4.1 Modal Response

At one time it was thought that the level of diffusion in a room could be simply inferred from the room's frequency response characteristics [13]. More recent experimental and theoretical studies [14,15,16] have shown that this technique is of questionable use, especially at high frequencies, where the room response is related to the reverberation time of the room. It is still possible that the frequency response technique may give useful insights into the diffusion levels at low frequencies. However, as mentioned previously, a strong room mode could adversely affect the level of diffusion in a room by causing sound energy to propagate along preferred paths. To look for correlations of diffusivity and room response the modal response of the reverberation rooms at MEANU are discussed below.

The numerical models of the reverberation chambers provided some interesting, if not necessarily believable results. Figure 4.1.1 shows the calculated frequency response of the small chamber in 1/3 octaves with and without diffusers. According to these results, the empty small room has strongly dominant modes at 60 and 125 Hz and has a more regular response at frequencies above 160 Hz. It also shows that the addition of diffusing elements has a very pronounced effect, even at low frequencies. The 125 Hz peak is almost entirely removed although the 60 Hz peak is mostly unaffected and a new peak at 400 Hz is introduced. This suggests that even stationary diffusing elements could be effective at removing unwanted room frequency irregularities. This idea must be viewed with caution as it is unrealistic that a diffusing panel with a minimum dimension of approximately 1.2 m and a surface density of roughly 4 kg/m^2 to have any pronounced effect at 125 H; the panel is too small and too light.

The frequency response of the large chamber with and without diffusers is shown in figure 4.1.2. It is immediately apparent that the dramatic effects of diffusers which were indicated for the small chamber are not repeated here. The addition of diffusers causes a 10 dB drop at 200 Hz but other differences between the two curves are less than 5 dB. Every

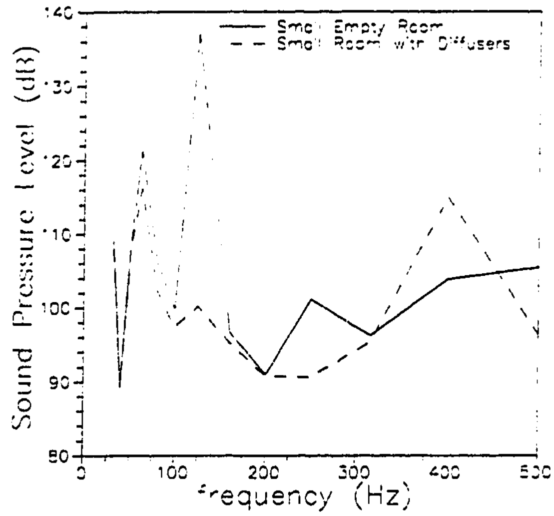


Figure 4.1.1: Response of Small Room with and without Diffusers Calculated by Model

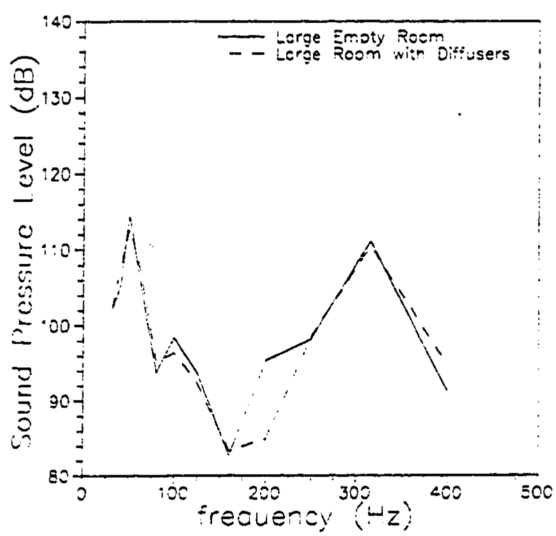


Figure 4.1.2: Response of Large Room with and without Diffusers Calculated by Model

attempt was made to make the models as equivalent as possible however, the diffusing elements were not placed in identical locations in the two models nor were the responses measured in geometrically identical spots due to the different room geometries. It is therefore more likely that limitations in the modelling account for the widely varying results when diffusers were added to the reverberation chambers.

Some confidence is gained in the models when looking at the comparison between the large and small empty rooms found in figure 4.1.3 which shows the large and small empty room calculated frequency responses. The dominant modes at 60 Hz and 125 Hz in the small room are shifted to 50 Hz and 100 Hz in the large room. This is not unexpected due to the increased room dimensions in the large room. There is also some consistency in the calculated levels other than the peak measuring 140 dB at 125 Hz which is not explained by an increase in modal density. A similar result is seen in figure 4.1.4 which is a comparison between large and small rooms with diffusers included. Again, peaks in the small room's frequency response are shifted to lower values along the frequency axis and the levels are more consistent between the two rooms. In fact, apart from the frequency shift, the two response curves show very similar trends.

As a companion to the numerical results, the actual room response was measured for the small room with diffusers and the large room with and without diffusers. Speaker and

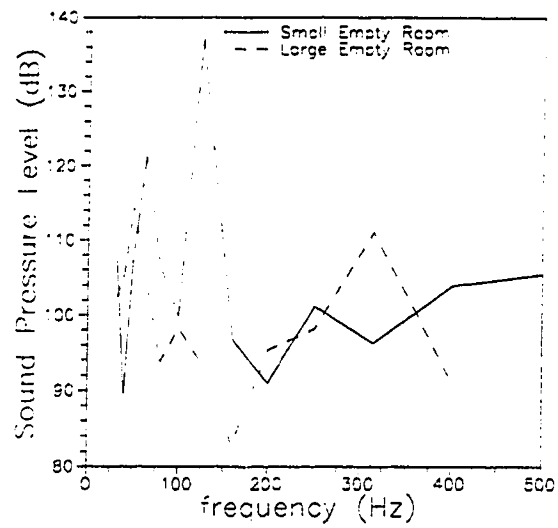


Figure 4.1.3: Response of Large & Small Empty Rooms Calculated by Model

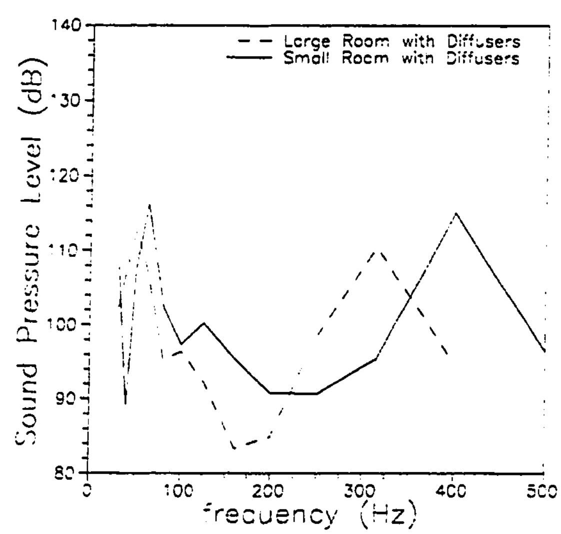


Figure 4.1.4: Response of Large & Small Rooms with Diffusers Calculated by Model

microphone positions were roughly the same as those in the models although the actual diffuser configuration was used as opposed to the simplified approximation used in the simulation.

The large room frequency response measured with and without diffusers is shown in figure 4.1.5. In general, these results repeat the information gained from the computer model. That is, the two curves generally agree within 5 dB although differences as great as 14 dB occur at 31.5 Hz. It is also apparent that no strong modes are present from 5-500 Hz. In comparing the large and small room response with diffusers in (figure 4.1.6), it is once again evident that the peaks in the small room response (at 100 Hz and 200 Hz) are shifted along the frequency axis (to 60 Hz and 125 Hz) although the small peak at 400 Hz remains.

However, while the experimental results are consistent and the general shapes of the curves have similarities to each other, the response curves calculated by the model are vastly different. Comparisons between the calculated and measured frequency responses are shown in figures 4.1.7 to 4.1.9. In figure 4.1.7 the differences between the calculated and measured responses in the small room with diffusers are shown. Aside from the fact that both results show peaks at approximately 60-80 Hz, 125 Hz and 400 Hz the results are not comparable. The differences in levels vary from 10 to 20 dB between 50 and 500 Hz.

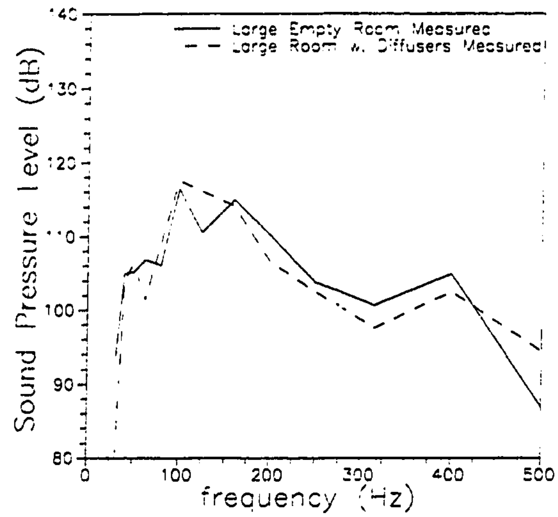


Figure 4.1.5: Measured Response of Large Room with and without Diffusers

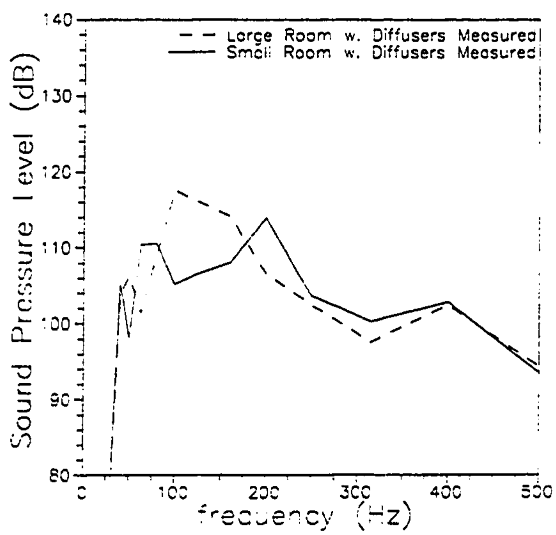


Figure 4.1.6: Measured Response of Large and Small Rooms with Diffusers

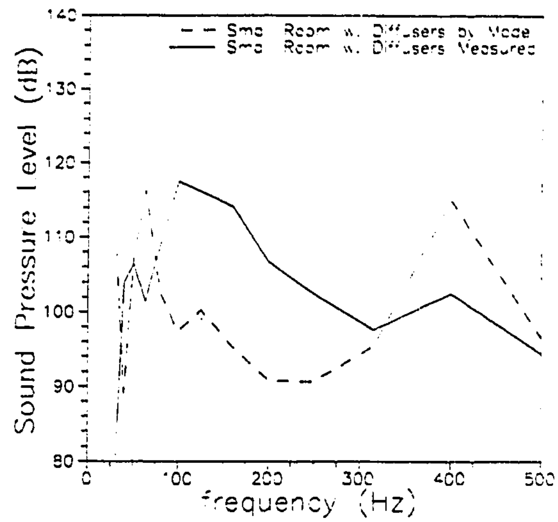


Figure 4.1.7: Measured and Modelled Response of Small Room with Diffusers

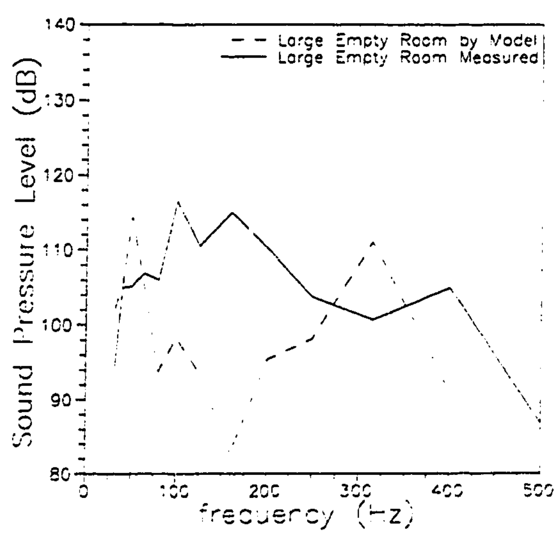


Figure 4.1.8: Measured and Modelled Response of Large Empty Room

The differences between modelled and measured responses in the large empty room are shown in figure 4.1.8. Again, it is difficult to see any agreement between these two curves although peaks at 50 Hz and 100 Hz in each curve might be said to coincide. The comparison between modelled and measured response in the large room with diffusers in is shown in figure 4.1.9. As in figure 4.1.8 it is difficult to see much agreement between the two curves although it is more evident that peaks at 50 Hz, 100 Hz, and 315-400 Hz likely coincide. The model once again predicts a much more irregular and mode dominated response than measurements indicate are actually the case. Once more the levels predicted by the two methods vary widely; as much as by 30 dB.

It is clearly evident that the numerical models do not provide a satisfactory representation of the true frequency response of the reverberation chambers. The most likely explanation for the large discrepancies is that the two-dimensional model is limited. With two dimensions, only half of the actual room modes are included. This would also explain the more irregular nature of the calculated frequency response curves, especially at low frequencies. Additionally, once a three dimensional model is available to accurately model the room, a three dimensional, or even a more realistic two-dimensional model of the diffuser panels which includes stiffness and damping would likely produce more believable results for the diffuser cases, especially at low frequencies

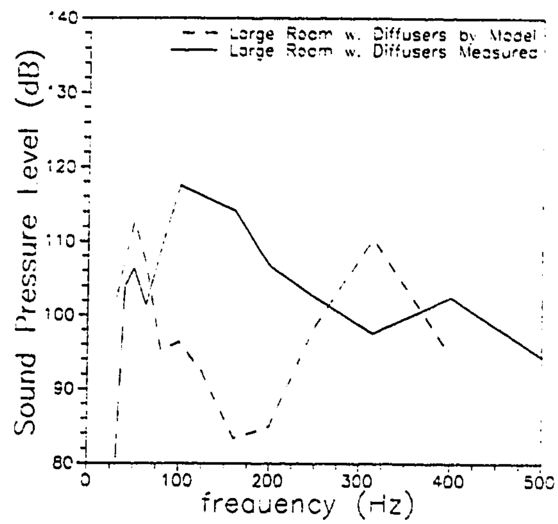


Figure 4.1.9: Measured and Modelled Response of Large Room with Diffusers

where panel characteristics are dominated by stiffness and damping. The result is that the numerical model is not useful to assist in predicting the influence of diffusers.

4.2 Spatial Variation of the Diffusivity Measure

In a perfectly diffuse reverberant field, with equal probability of energy flow in every direction at every point within the field, there is no spatial variation in the level of diffusion. Even if a nearly perfectly diffuse field exists within a reverberation chamber then it would still be expected that this diffuse field would not extend to the boundaries of the room. Near walls, room modes are potentially at maximum values and the sound energy density may not be uniform. Near diffusing panels and sound sources the sound field is partially made up of the direct field of the panel or source so that also in these regions the sound field is not perfectly diffuse and diffusivity levels could vary from point to point. It is still hoped that in some region of the room spatial variation of diffusivity would be minimal. If, however, the sound field is not perfectly diffuse, then larger spatial variation in diffusivity would occur.

To evaluate the spatial variation in the reverberation suite at MEANU, diffusivity measurements were made at 125, 250, 500 and 1000 Hz at each of two locations in the small reverberation chamber. The diffusers were installed but were stationary. The two locations were separated by greater than one half wavelength at 125 Hz and were placed so that at least one meter separated the microphones from any wall or diffuser. The results of the testing are shown in figure 4.2.1. It is evident that the 95% confidence limits overlap at every frequency except 500 Hz. It was suspected that the stationary diffusers might be responsible for the variation in diffusivity levels. At 125 and 250 Hz, the diffusers were thought to be ineffective and therefore, their orientation with respect to the measurement positions would be of no concern and have no effect on measured diffusivity. At 1000 Hz, the separation between diffusers and measurement position was thought to be large enough that the microphone was

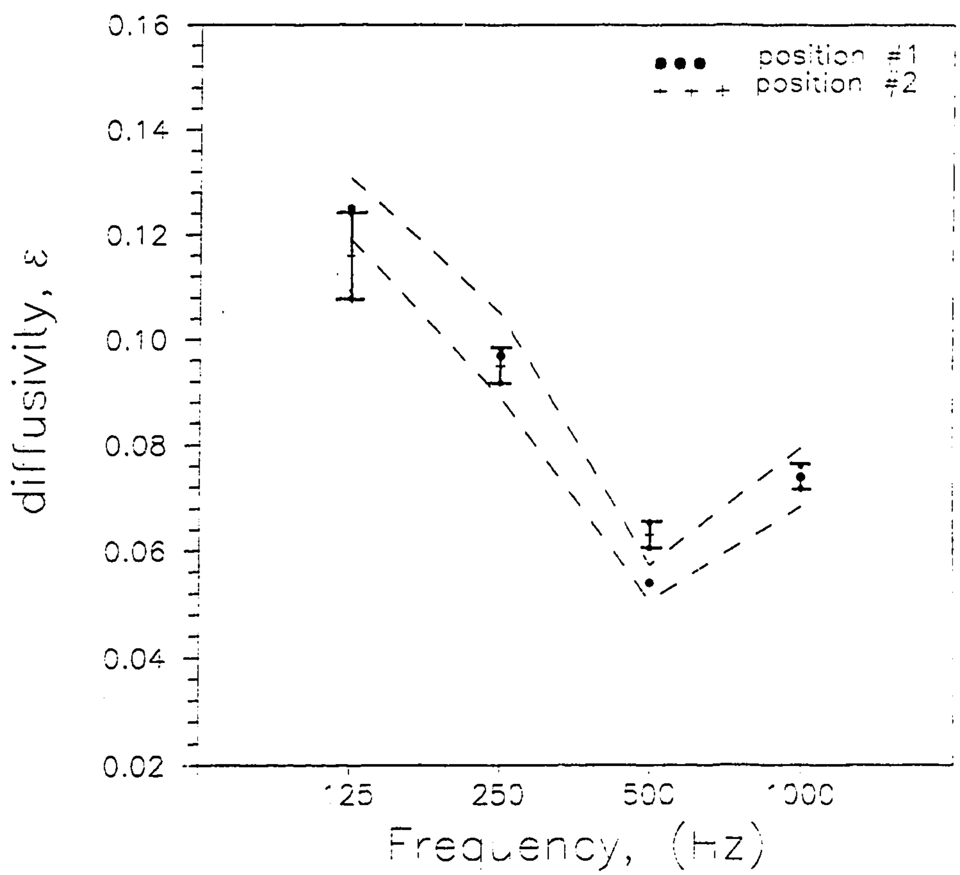


Figure 4.2.1: Spatial Variation of Diffusivity as a Function of Frequency

entirely in the more diffuse reverberant field and again the diffuser orientation would have no effect on measured diffusivity. At 500 Hz, however, the diffusers were thought to be large and dense enough to be effective and the separation between diffuser and microphone small enough so that diffuser orientation was a factor.

To test this idea, the diffusers were moved to a different orientation and the diffusivity measurement was repeated at 500 Hz. Figure 4.2 2 shows the results of this further testing compared with the original diffuser testing. At this second orientation, the 95% confidence limits increased so that the two positions were no longer statistically different but more importantly, it can be seen that the diffusion levels at both points decreased by almost the same amount. It was concluded that while there may be some statistically significant spatial variation of diffusion in the reverberation chambers at some frequencies, different room treatments effect all points equally so that one point is as useful as any other to compare the effects of room treatments on diffusion levels as long as the same point is used for comparison in each case.

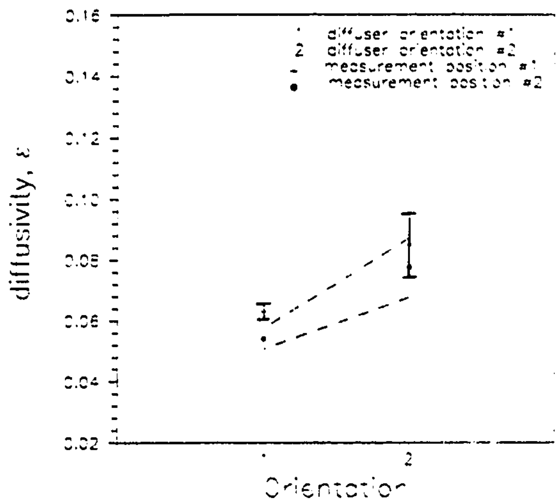


Figure 4.2.2: Effect of Diffuser Orientation on Diffusivity at 500 Hz

4.3 Diffusion Testing Results

The main purpose of this investigation was, of course, to study the effect of changes in reverberation room configurations on the state of diffusion present in the room. While many possible changes could be studied, the variables examined were limited to room volume, presence or absence of diffusers, both moving and stationary, and the amount of absorption in a room. Specifically, six different configurations were investigated. In the small reverberation chamber, tests were performed without diffusers, with diffusers stationary, with diffusers moving, and with diffusers moving plus an absorptive sample present. Tests were also performed in the large reverberation chamber without diffusers and with moving diffusers. Results were gathered in each configuration at 125, 200, 500, and 1000 Hz.

The results for the empty small room (called the reference configuration), are shown in figure 4.3.1. The means of the data are shown with 95% confidence limits in this and subsequent figures. These results confirm the basic idea of diffusion in reverberant sound fields. As frequency increases, more and more room modes are present so that it is increasingly more probable that sound energy will be propagating in any direction and as a result the diffusivity increases (ε decreases). Diffusivity values range from approximately 0.124 at 125 Hz to approximately 0.066 at 1000 Hz. Again, a diffusivity value of $\varepsilon=0$ would indicate a perfectly diffuse field.

Figure 4.3.2 shows the effect on diffusion levels of adding stationary diffusers to the room. There is no statistically significant difference in the results at 125 and 250 Hz between this case and the bare room (no diffusers). This is to be expected as the diffuser panel sizes are too small and too light to have any noticeable effect. The results do show a difference in diffusion at the higher frequencies tested. The diffusivity of the sound field increased at 500 Hz as is generally expected. However, unexpectedly, the addition of diffusers to the small room marginally decreased the diffusivity of the sound field at

1000 Hz. This may be due to the fact that not all diffuser orientations have identical effects as discussed in the previous section. In this case different stationary diffuser orientations produced different levels of diffusion. It is certainly possible that some orientations even have detrimental effects by introducing localized modes between diffusers and walls.

For the case of a continuously moving diffuser system, the results shown in figure 4.3.3 were obtained, while figure 4.3.4 shows a comparison of the results for the first three cases. As in the stationary diffuser case at 125 and 250 Hz, no statistically significant difference appears between the results with no diffusers and with moving diffusers. The diffusers are simply not effective at these frequencies. At the higher frequencies there is a significant increase in diffusion levels at 500 and 1000 Hz. Unlike the stationary case, the effect is also positive at 1000 Hz. With the diffusers changing orientation continuously, there is no opportunity for sound energy to be redirected along fixed paths, as may have been the case with fixed diffusers. Instead, the paths sound energy travels along are constantly changing. This creates, in effect, a room with a continuously changing shape. Sound energy is more likely to be directed along different paths and the diffusivity of the sound field increases. It is surprising how effective the moving diffusers seem to be at 500 Hz. It was noted in the previous

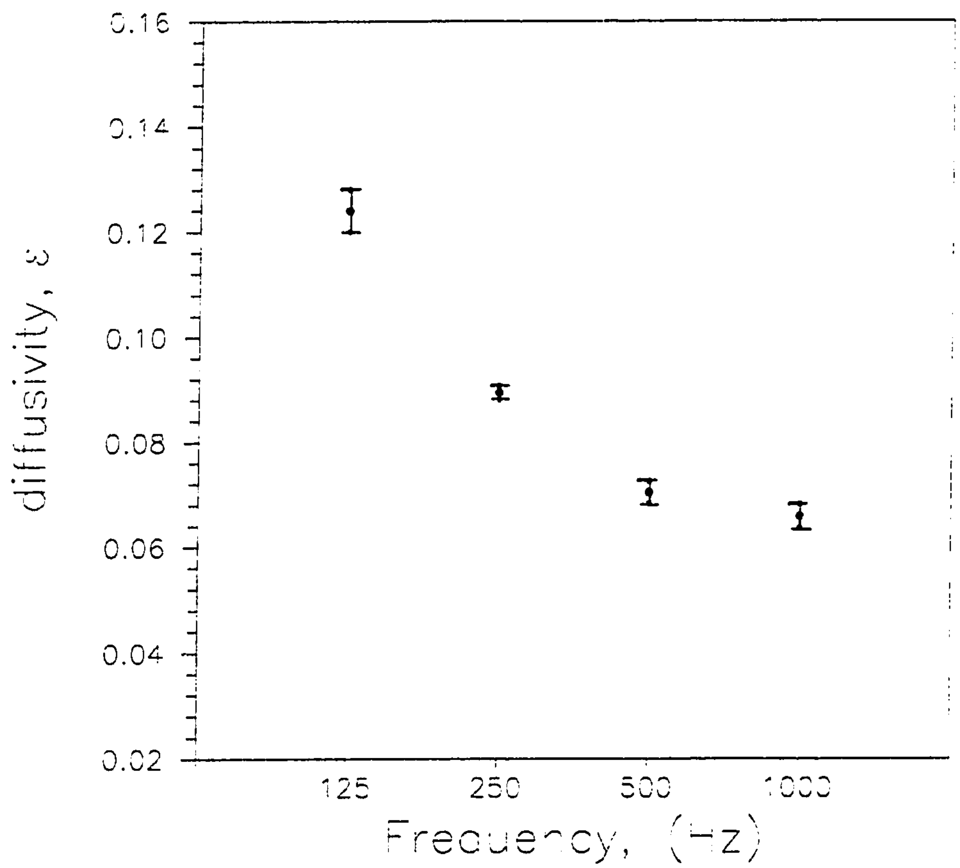


Figure 4.3.1: Diffusion Results for Small Room with Diffusers Out

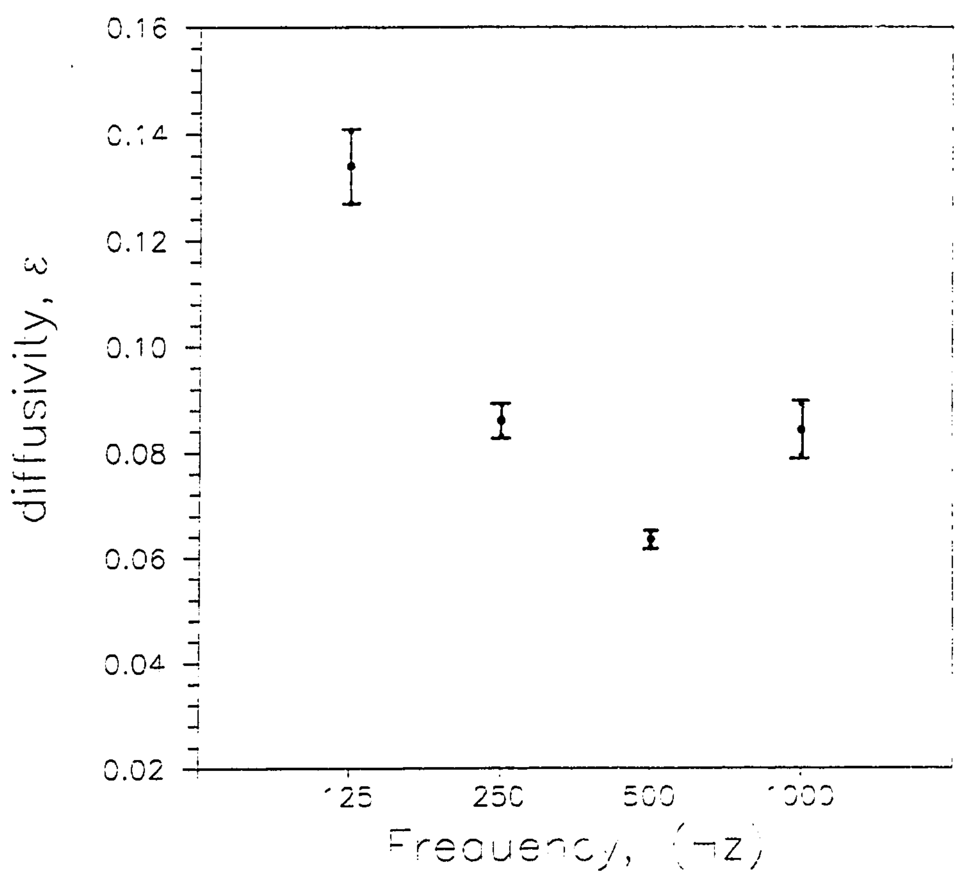


Figure 4.3.2: Diffusion Results for Small Room with Stationary Diffusers

section that the measured diffusivity values seemed particularly sensitive to diffuser orientation at 500 Hz. Why the effect is so strong at 500 Hz is not precisely understood although it is suspected that there may be some interaction between the diffusers and the room that depends upon the relative dimensions of the diffusing panels and those of the reverberation chamber.

The final configuration tested in the small room added an ASTM standard absorption sample in a concentrated patch to the floor [9] in the above case. The results obtained are shown in figure 4.3.5. Compared to the above case with moving diffusers, it is easily noted that the level of diffusion decreases at all frequencies with the addition of the absorption sample although the effect is particularly pronounced at 250 Hz. This is partially explained by looking at the absorption characteristics of the sample, shown in figure 4.3.6. It is reasonable then that the effect of absorption is hardly noticeable at 125 Hz and very noticeable in the 500 Hz 1/3 octave band. The decrease in the level of diffusion measured is no surprise. By adding the absorptive sample a "sink" is effectively placed in the floor which absorbs sound energy. This results in a net energy flow in a specific direction (into the sample) rather than reflecting it back into the room in random directions. The effect is apparent at all measured frequencies as the sample is large enough (2.44m by 2.74m) to be a factor even at 125 Hz.

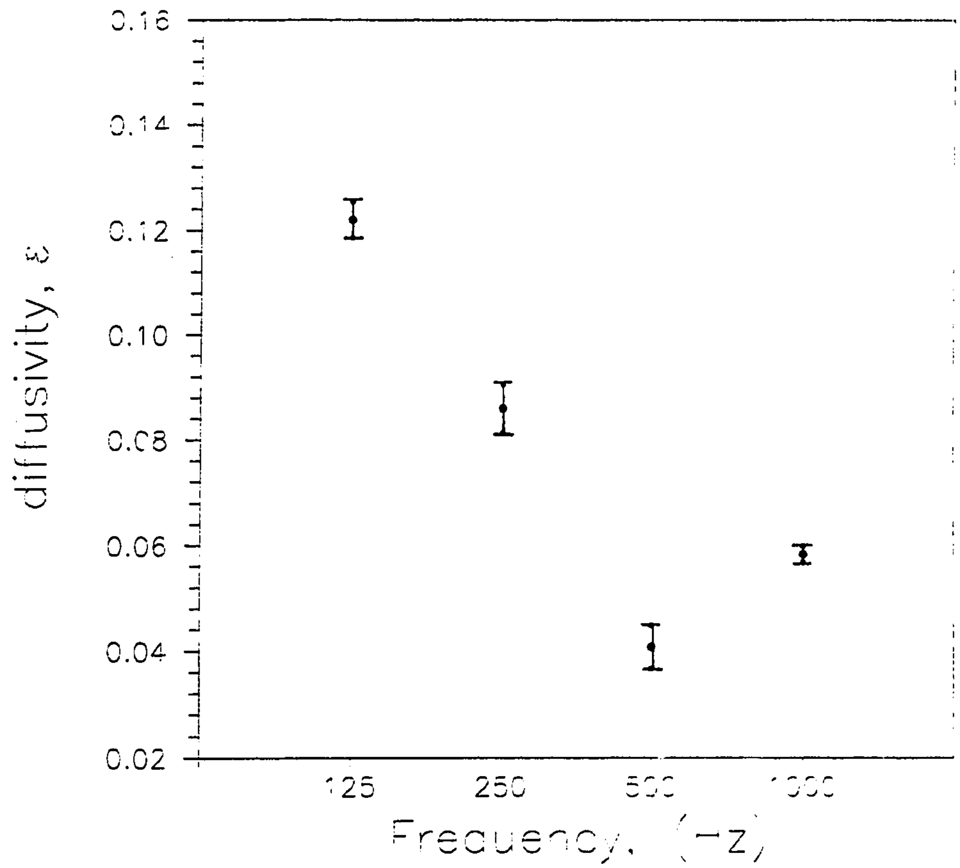


Figure 4.3.3: Diffusion Results for Small Room with Moving Diffusers

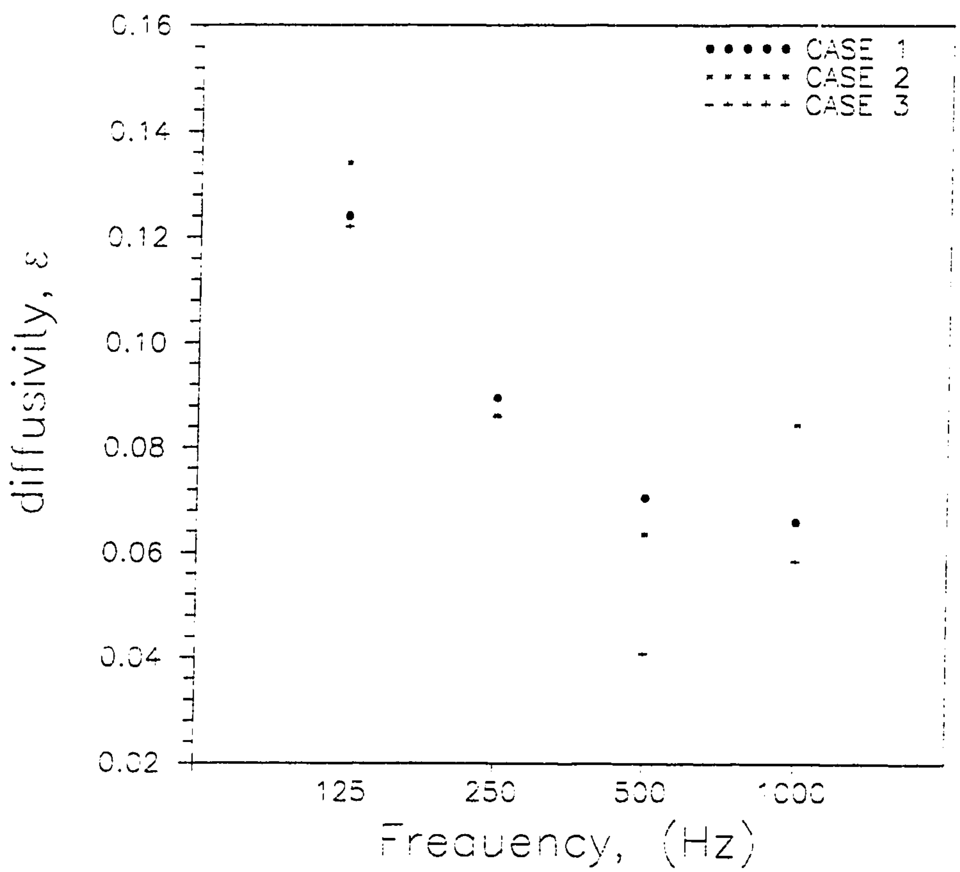


Figure 4.3.4: Comparison of Diffusion Results for Cases 1,2, and 3

In order to partially evaluate the effect of room volume selected testing was done in the large reverberation room. Figure 4.3.7 shows the results for the case without diffusers. When comparing these results to those in the small empty room one notes that the diffusivity has increased at 125 Hz. This is expected as a larger room in general has a higher modal density at a given frequency than a smaller room and would therefore have energy propagating in more directions. This should also be expected at 250 Hz but this was not the case as diffusivity is better at 125 Hz than at 250 Hz in the large room. Also, the diffusivity is better at 250 Hz in the small room than in the large room. The reason for this may be related to the room dimensions and is discussed further below. At 500 and 1000 Hz there is no significant difference in results between the two rooms. This is not unexpected as the modal density at 500 Hz is large enough so that the level of diffusion is relatively unchanged even if the number of room modes present increases.

When moving diffusers are added to the large room the results shown in figure 4.3.8 are obtained. When compared to those in figure 4.3.3 (the small room with diffusers moving), the diffusivity is better in the large room than in the small room at 125 Hz. With moving diffusers, the large room also shows better diffusion than the small room at 250 Hz while the small room has a higher level of diffusion at 500 Hz. This is the main reason an interaction between diffuser panel

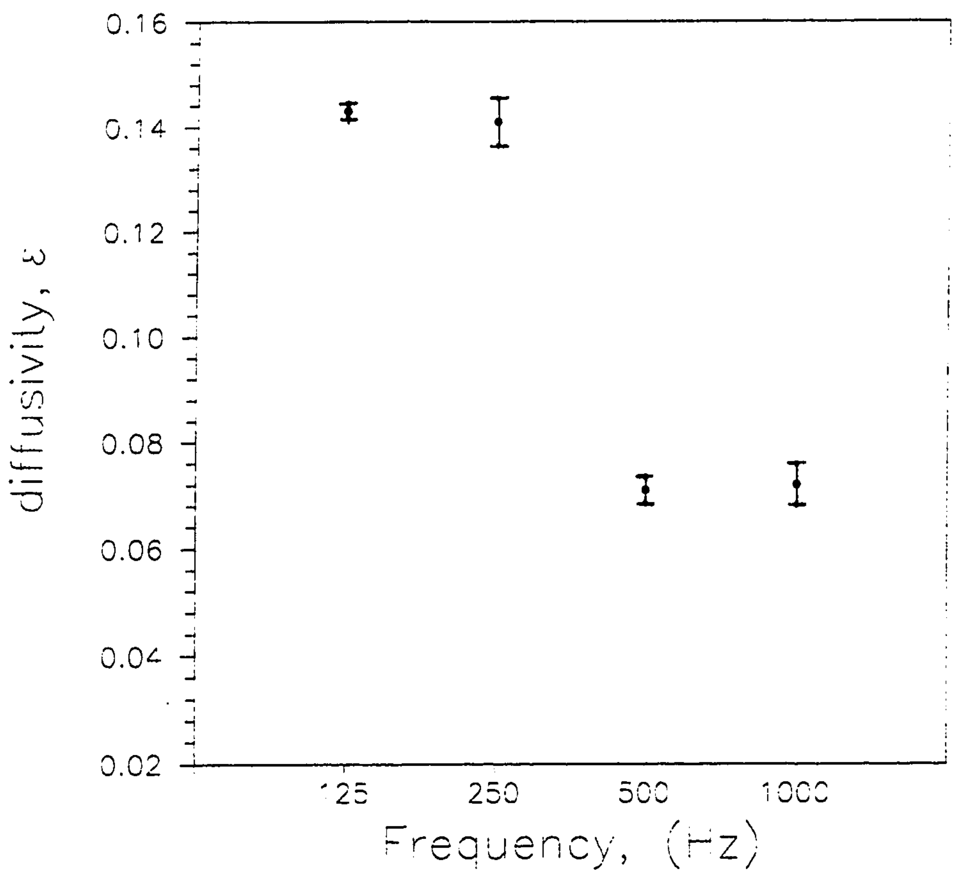


Figure 4.3.5: Diffusion Results for Small Room with Absorptive Sample

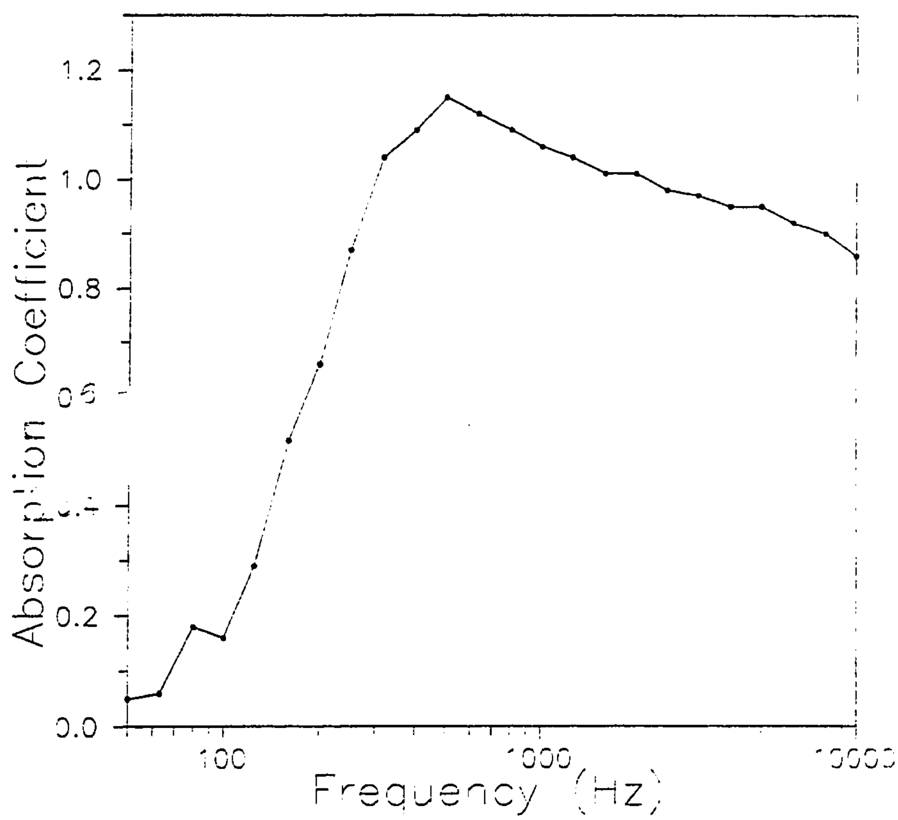


Figure 4.3.6: Absorption Variation With Respect to Frequency for Standard Absorption Sample

dimensions and room dimensions is suspected. If the sensitivity to the addition of diffusers were particularly large at the same frequency in each room it would indicate that it was solely related to the diffuser dimensions or some common factor in room construction. Since the sensitivity occurs at different frequencies, especially since the large room with a larger volume shows a sensitivity at a lower frequency than the small room, a coupled interaction between room and diffuser panels is indicated. This suspicion remains unconfirmed as a numerical model of the situation was prohibitively complicated and only one set of diffuser panels was tested. A marginal increase in the level of diffusion at 1000 Hz was shown in the large room indicating that diffusers may be most effective in the large room at this frequency.

The results included in figures 4.3.1 - 4.3.8 are presented again in a different manner in figures 4.3.9 - 4.3.12., allowing the effects of the different room treatments to be studied at each measured frequency.

A "cross-section" of the diffusion testing results at 125 Hz is given in figure 4.3.9. As noted earlier, only the addition of a large absorptive sample produced any measurable difference in diffusion in the small room. Similarly, the addition of diffusers into the large reverberation room had no measurable effect. The change in room volume in moving from the small to the large room however, did cause a noticeable change in diffusion levels. At 125 Hz, an increase in

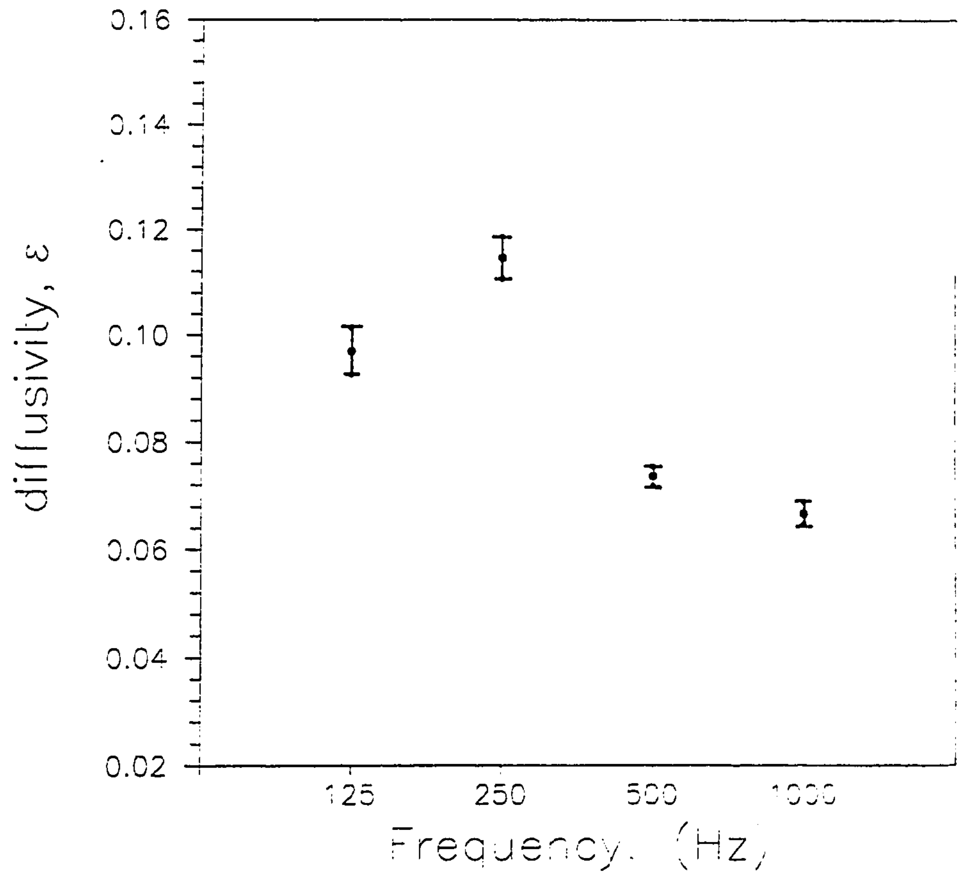


Figure 4.3.7: Diffusion Results for Large Room with Diffusers Out

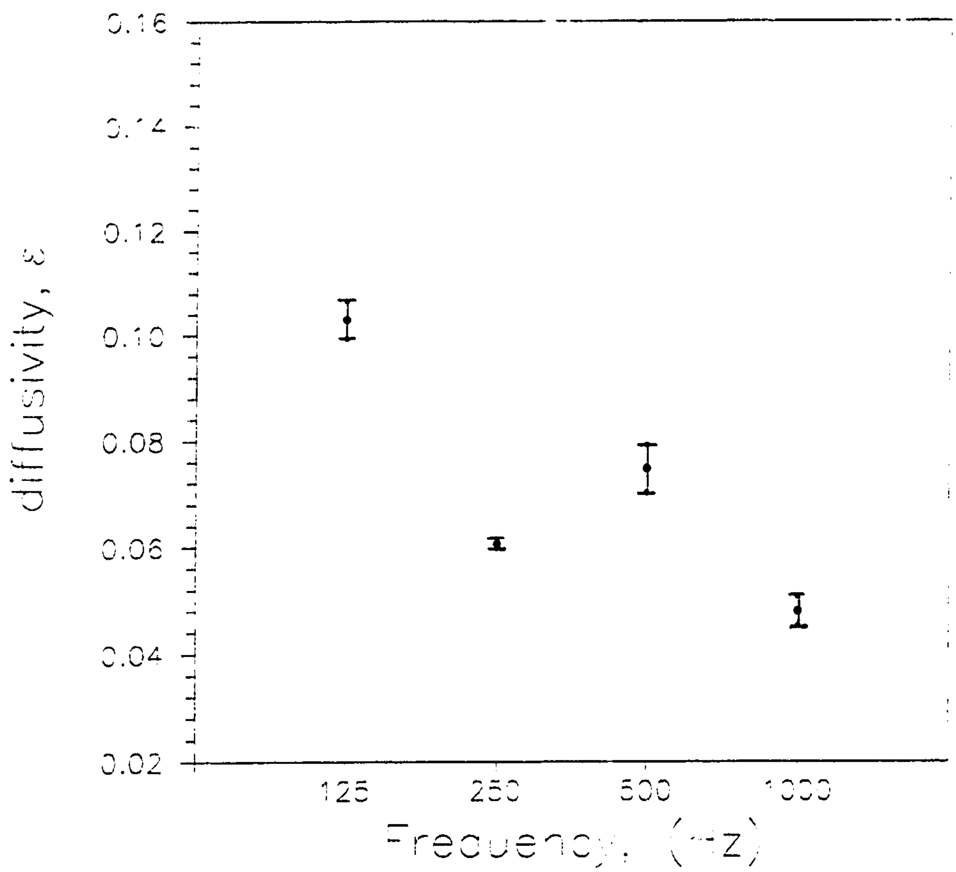


Figure 4.3.8: Diffusion Results for Large Room with Moving Diffusers

absorption in the room caused a decrease in the level of diffusion while an increase in room volume caused an increase in the level of diffusion. The presence or absence of the diffusing panels had no effect on the diffusivity of the room at this frequency.

The 250 Hz diffusion results are shown in figure 4.3.10. As above, it is only the addition of the absorptive sample that causes a distinctly different level of diffusion to be measured although, as previously discussed, the effect is more pronounced at 250 Hz than at 125 Hz . On the other hand, the addition of diffusers to the large room produces a very clear improvement in diffusivity; ε drops from approximately 0.125 to 0.060. Since this diffuser performance is not observed in the small room, this effect is attributed more to a diffuser/room interaction than to the diffusers alone. In general, it can also be said that the level of diffusion improves as the frequency increases from 125 Hz to 250 Hz.

At 500 Hz, the test results begins to show some different behavior. This is seen in figure 4.3.11. Unlike the previous two cross-sections, the diffusing panels are shown to have a measurable effect in the small room, with moving diffusers producing better diffusivity than stationary panels. These stationary panels, in turn, appear to produce better diffusivity than no diffusers at all. The addition of the absorptive sample causes the diffusion levels to drop from those produced by the moving diffusers to those produced with

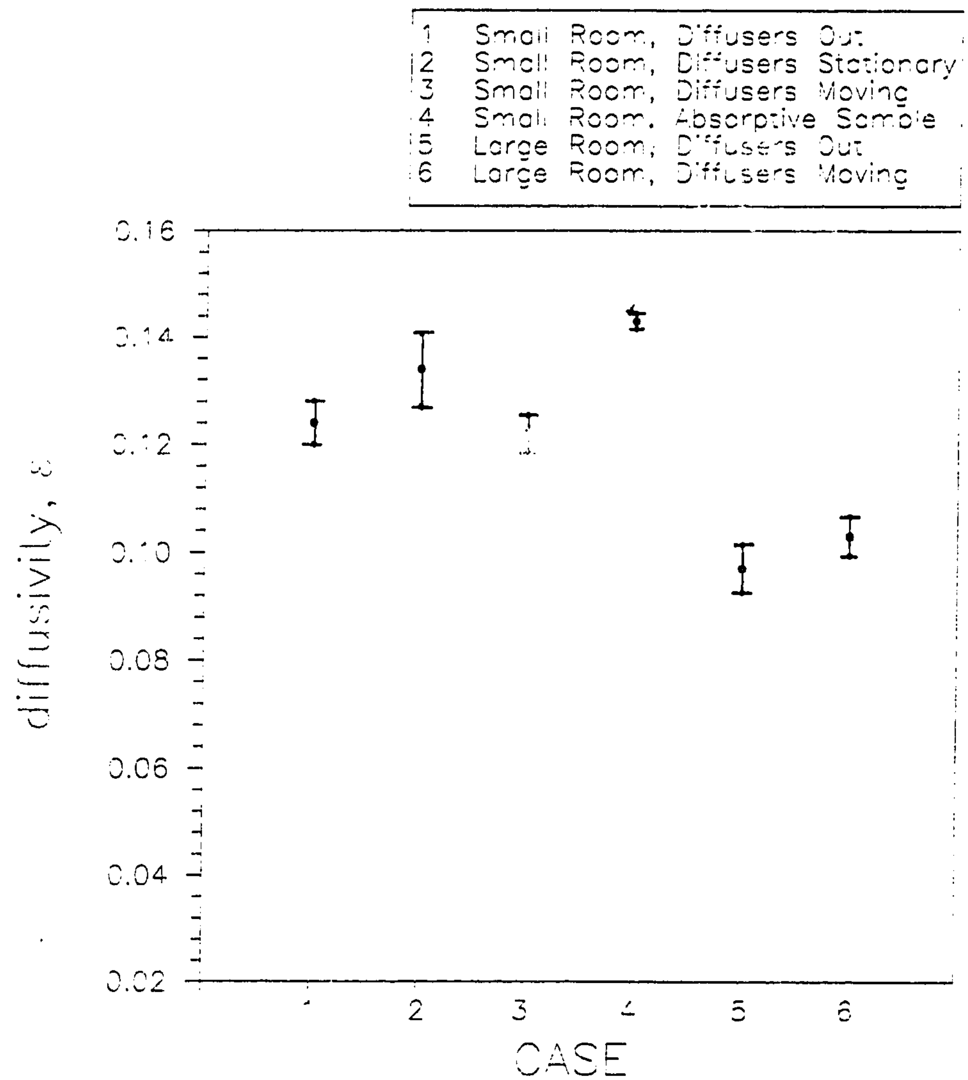


Figure 4.3.9: Comparison of Diffusion Results Between All Cases at 125 Hz

no diffusers present at all. The effect of diffusers is not repeated in the large room at 500 Hz. Again, whether this is some property of the diffusers alone or some room/diffuser interaction is unknown. It may be that the results in the small room are abnormally low or that the results for the large room are abnormally high. The phenomenon seems too complex to draw solid conclusions based on the limited results gathered to date. Figure 4.3.11 also shows the general increase in diffusion levels that comes with an increase in frequency compared to figure 4.3.10.

The last cross-section, for the results at 1000 Hz, is found in figure 4.3.12. It shows a small increase in diffusivity produced by moving diffusers compared with no diffusers for both rooms. In the small room the stationary diffusers do not perform as well as the empty room, however. As noted earlier, the arbitrary orientation chosen for the stationary diffusers could be considerably different from an optimum orientation and cannot be considered representative of all stationary positions. Once more the absorption added to the small room decreases the level of diffusion from those of moving diffuser levels to those of empty room levels.

A final point to be mentioned in the discussion of diffusion results is whether the changing levels of diffusion were in any way related to the modal response of the reverberation rooms. The measured responses shown in figures 4.1[illegible] and 4.1.6 are used for comparison and the relationship

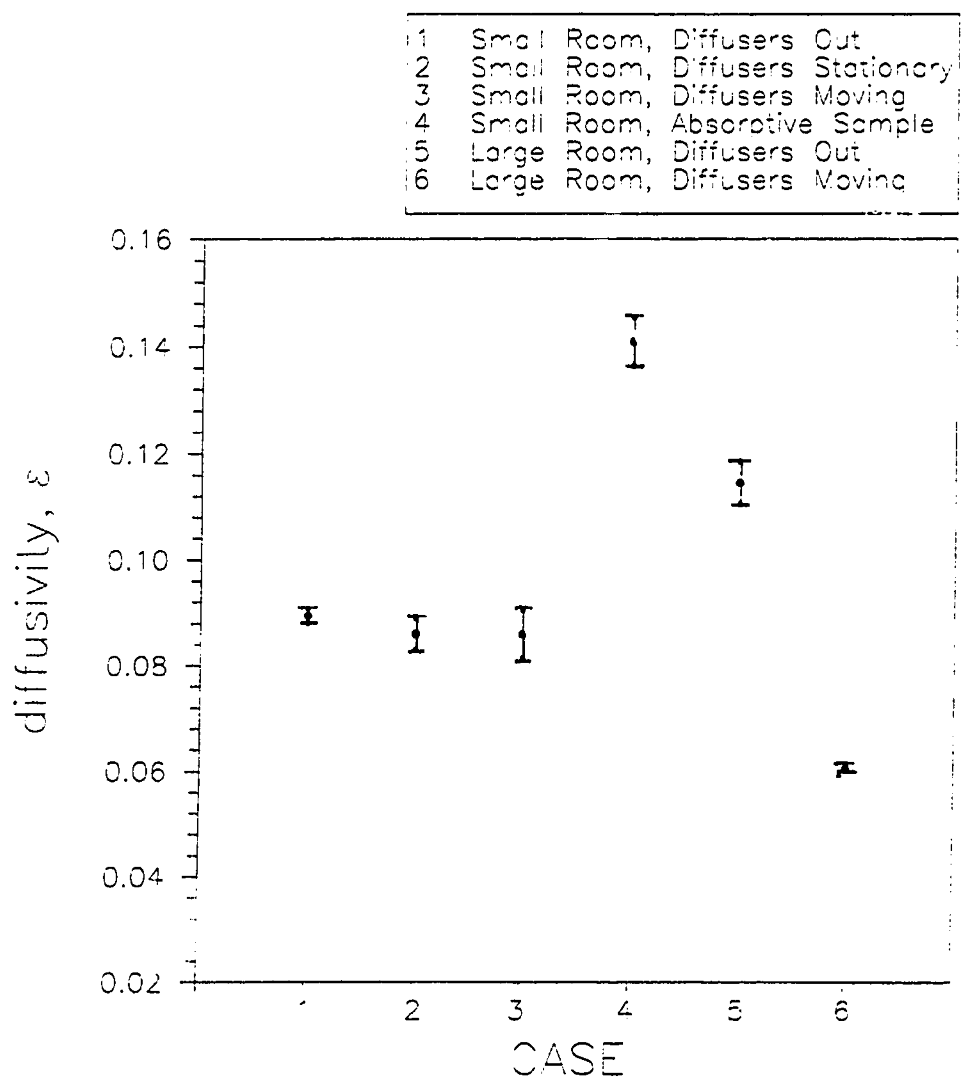


Figure 4.3.10: Comparison of Diffusion Results Between All Cases at 250 Hz

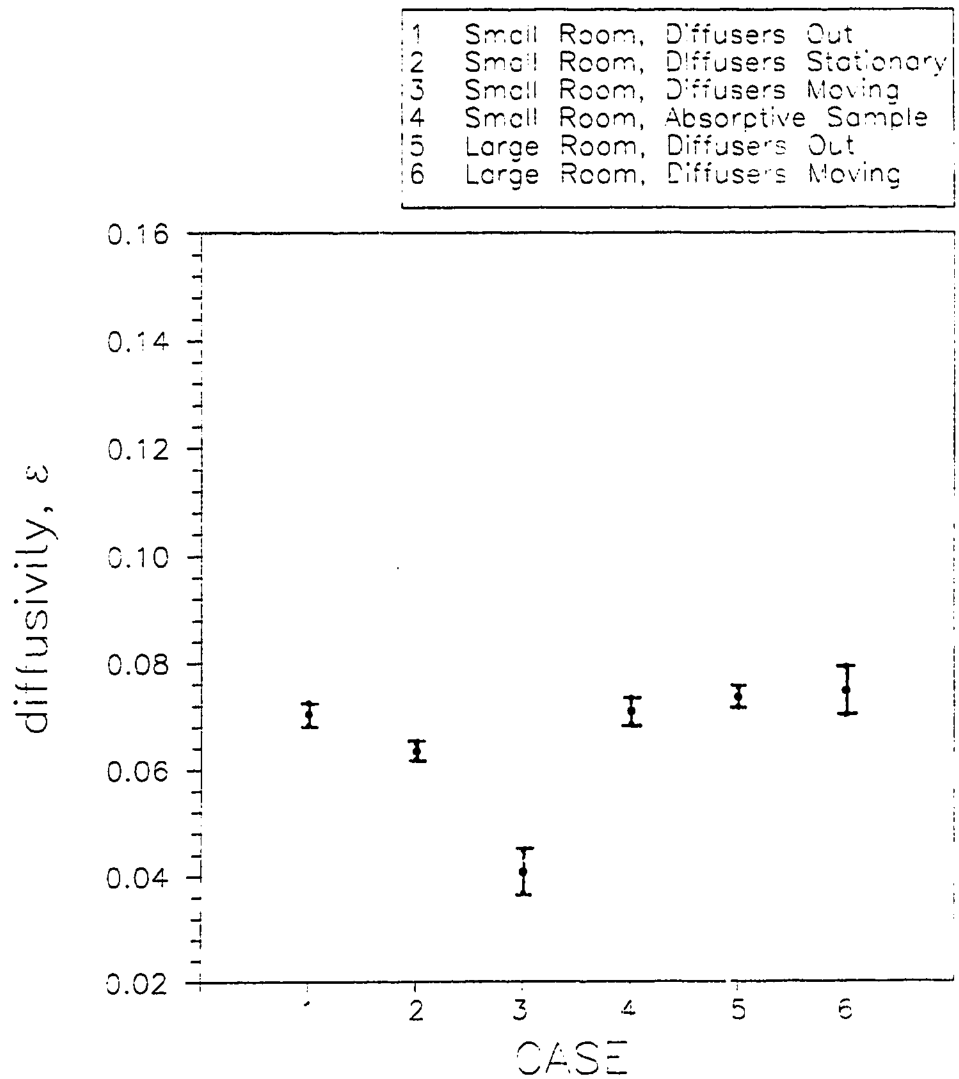


Figure 4.3.11: Comparison of Diffusion Results Between All Cases at 500 Hz

between frequency response and diffusivity is shown in figure 4.3.13. At 125 Hz, the frequency responses indicate the large room with diffusers has the highest response, followed by the large empty room and the small room with diffusers with the lowest response of the three cases. No strong peaks are present in any of the curves at this point and it is difficult to correlate any difference in measured response to the different frequency response curves. At 250 Hz, all three response curves have nearly identical values so that the different diffusion levels measured cannot be caused by differences in room response. At 500 Hz only the large room with and without diffusers cases have differing levels in their frequency response curves and no measurable difference in diffusivity is found between these two cases at 500 Hz. While a very strong peak in a frequency response curve may account for poor diffusion at the peak frequency, it is obvious that room response does not predict the level of diffusivity in these rooms.

4.4 Transmission Loss Testing Results

While it is of interest to understand how the level of diffusion in a room is related to room characteristics or to know how effective different techniques are at achieving

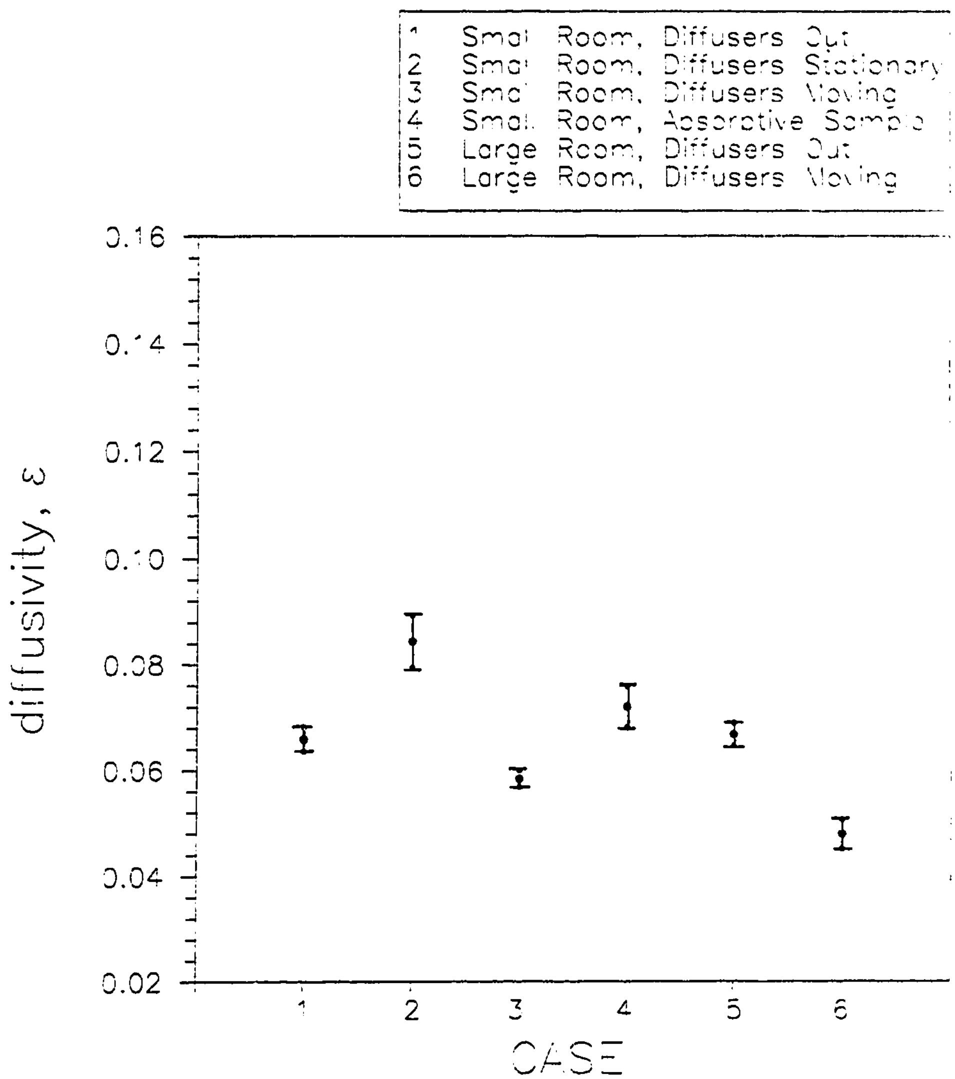


Figure 4.3.12: Comparison of Diffusion Results Between All Cases 1000 Hz

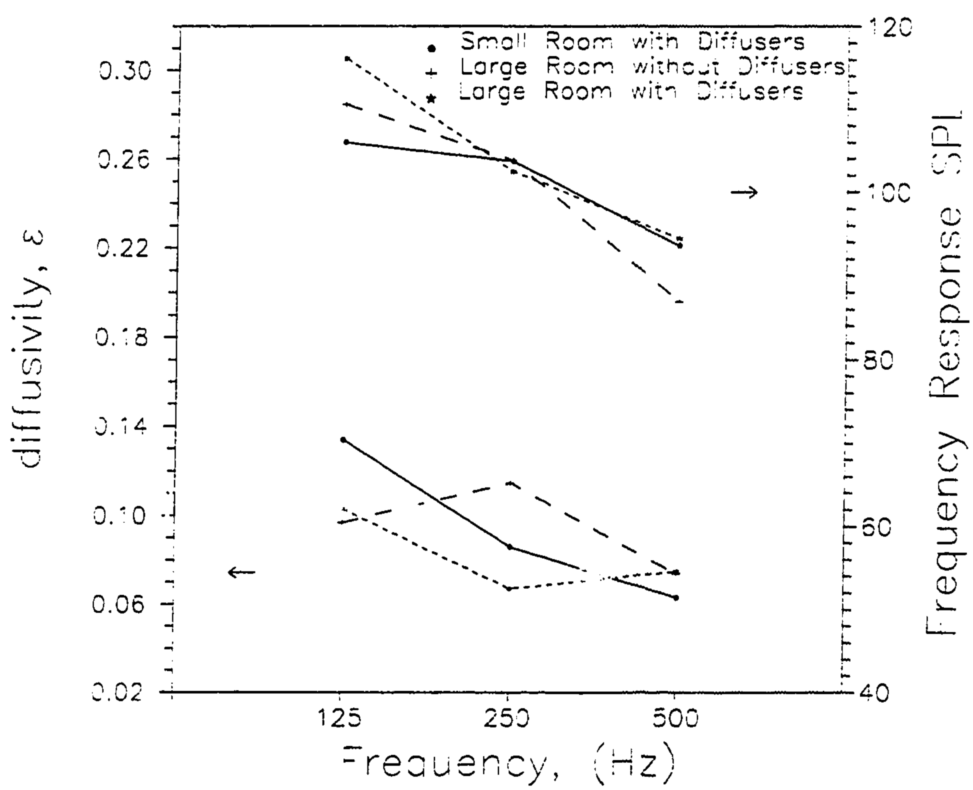


Figure 4.3.13: Relationship Between Room Response and Diffusivity Levels

"high" levels of diffusion, it is more important to know what level of diffusion is necessary to make the assumptions used in common test procedures valid. That is, what is a sufficiently "high" level of diffusion? To assist in answering this question T.L. tests were carried out (on a plug wall used at MEANU to isolate the two reverberation rooms) for each room configuration discussed in the previous section. Since the T.L. test assumes a perfectly diffuse field, variations in diffusion levels could produce measurable changes in T.L. results. If a change in diffusion levels produced no change in T.L. values then the diffusion level would be considered adequate. The results of this testing are discussed below.

The various T.L. values recorded at 125 Hz are shown in figure 4.4.1. It is readily apparent that there is no statistically significant difference in the T.L. values obtained for the different test cases. In all cases the large or small room refers to the source room the receiver room has moving diffusers. The different values of ε measured, from 0.144 in the small room with absorption added, to 0.10 in the large empty room, only produce a variation of [illegible] in measured T.L. This difference is less than the corresponding uncertainties in the values.

At 250 Hz, values of ε range from 0.14 for the small room with an absorptive sample to 0.06 for the large room with moving diffusers. Only a 1 dB difference separates the measured T.L. values for these cases. Actually, all the measured T.L. values shown in figure 4.4.2 are within 1 dB with uncertainties of 1 to 2 dB. Obviously the differing levels of diffusion have no effect on measured T.L. results at 250 Hz.

The measured T.L. results at 500 Hz are shown in figure 4.4.3. In this figure it can be seen that for the cases of the small room with stationary and moving diffusers, statistically different T.L. values were measured. The T.L.'s for these cases were at least 2 dB in mean value lower than those values recorded for the other cases and this separation is greater than the measurement precision. It can be seen from figure 4.3.11 that the two above cases are also the cases with the lowest measured diffusivities although different diffusion levels were measured for the two cases. At 500 Hz at least, differences in ε of only 0.01 corresponds to a measurably different value of T.L.

The measured T.L. results at 1000 Hz are shown in figure 4.4.4. It can be seen that the only case where a statistically different value of T.L. is produced by a differing room configuration is the case of the large room with moving diffusers. The measured T.L. of 67 dB for this configuration is at least 1 dB greater than the values recorded for all other cases. This separation is greater than the measurement error. Figure 4.3.12 shows that the large room with moving diffusers also has the highest level of

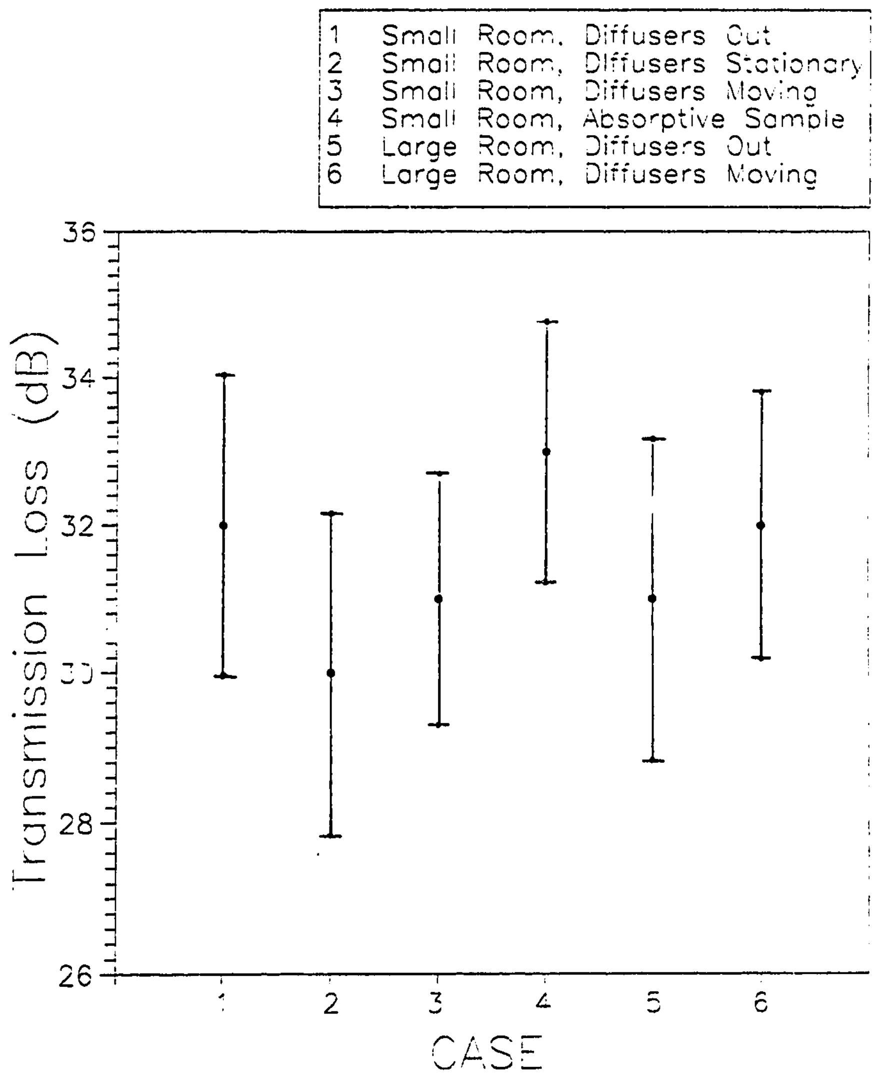


Figure 4.4.1: Transmission Loss Measurements Results at 125 Hz

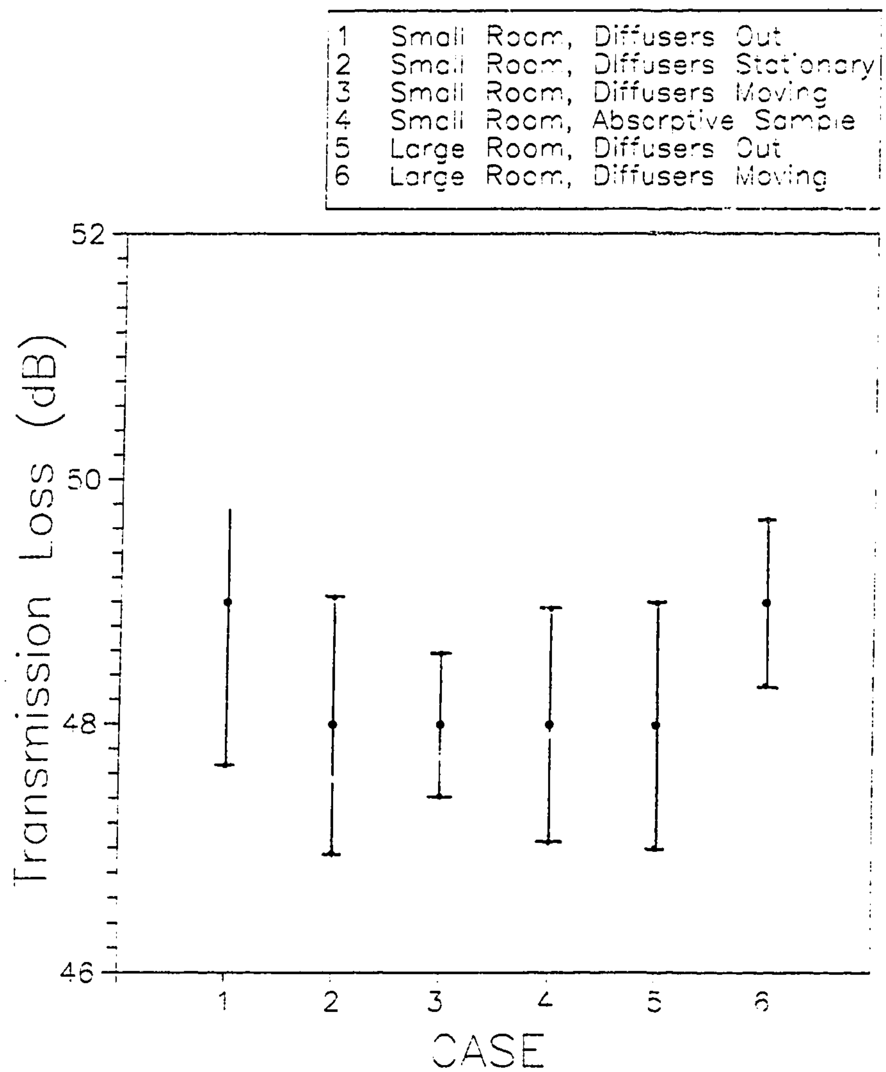


Figure 4.4.2: Transmission Loss Measurement Results at 250 Hz

diffusion of all the cases. Again we see that a difference in ε of only 0.01 corresponds to a measurable difference in T.L. We also see that the effect of diffusivity on T.L. values is not simple. Figure 4.4.3 shows a lower T.L. when diffusivity is best while figure 4.4.4 shows a higher T.L. when diffusivity is best. It is apparent that if the assumptions the T.L. test is based on are not adequately met, the estimate of T.L. produced may be unpredictably high or low.

The preceding results suggest that there is a level of diffusion that must be attained so that the assumptions made in standard acoustical tests remain valid. Furthermore, the results suggest that this level is frequency dependent, with higher levels of diffusion necessary at higher frequencies. Strangely enough, at the low frequencies where diffusion levels were thought to be inadequate, the high uncertainties associated with low frequency measurements insure that even substantial changes in room diffusivity levels produce no significant change in standard test results. For example, figure 4.3.8 shows that at 125 Hz the measured values of diffusivity were less than $\varepsilon=0.14$ and figure 4.4.1 shows that the changing diffusion levels produced no measurable change in T.L. values. From this we can infer that as long as diffusivity levels with ε less than approximately 0.14 are maintained at 125 Hz, test results for this frequency will be unaffected by changing diffusion levels. It is also fortunate that the higher levels of diffusion required at high

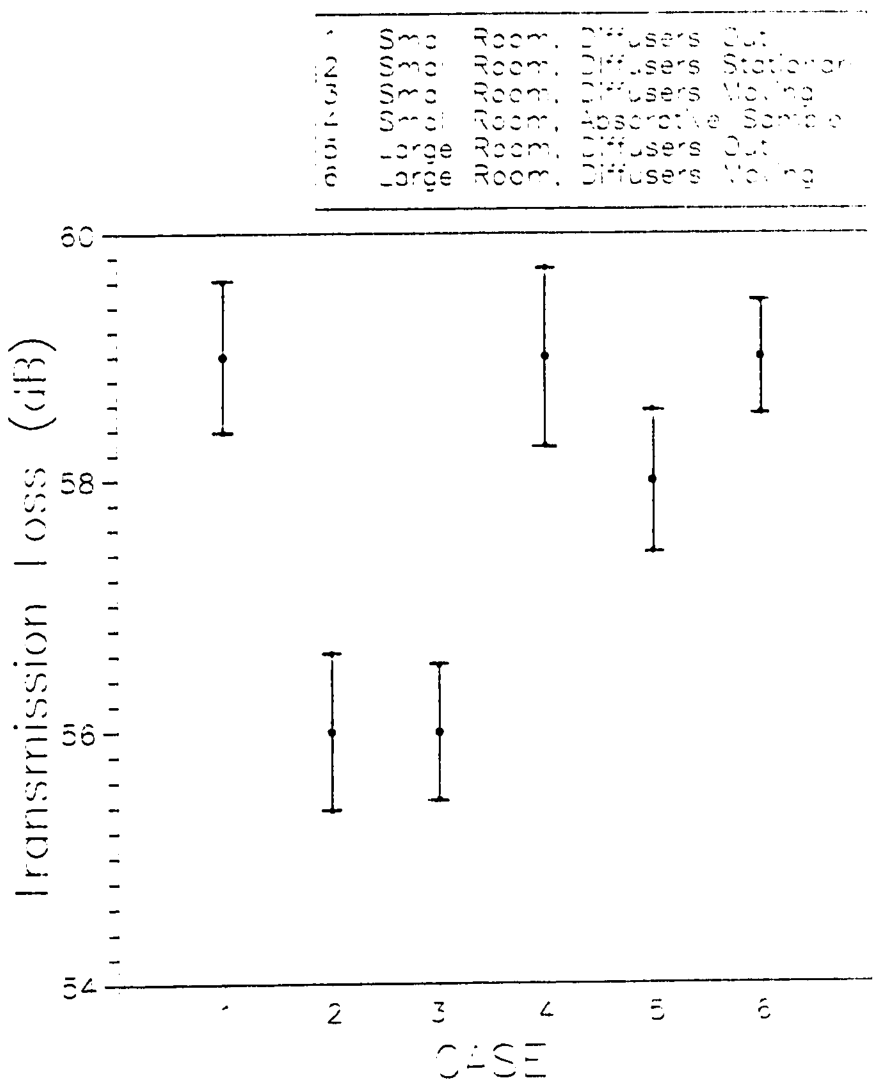


Figure 4.4.3: Transmission Loss Measurement Results at 500 Hz

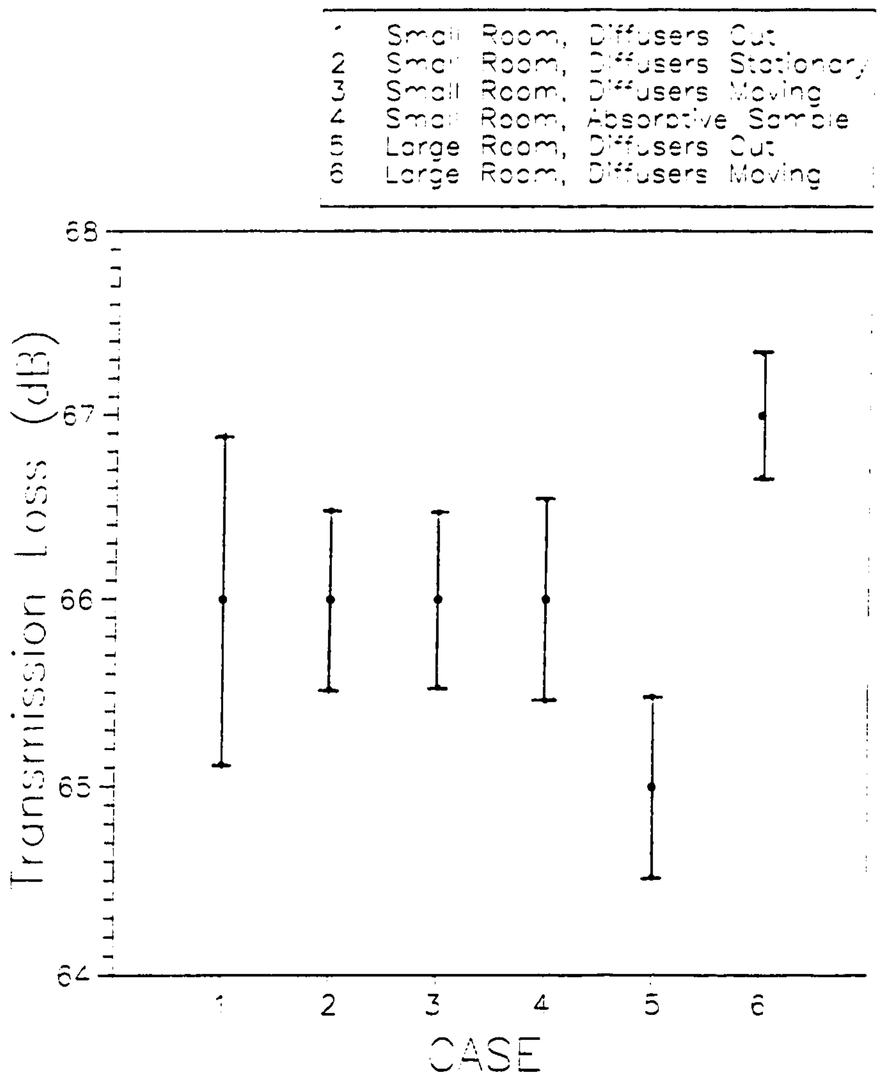


Figure 4.4.4: Transmission Loss Measurement Results at 1000 Hz

frequencies to ensure standard test results are not dependent on the room diffusivity levels arise naturally from basic acoustics theory. The drawback to this however is that to improve diffusion levels at high frequencies one cannot simply add larger or heavier diffusing elements since small, light diffusers are equally effective at these frequencies. More substantial changes in the reverberation chamber would be required to improve diffusivity levels at higher frequencies.

Chapter FIVE

Conclusions and Suggestions

5.1 Conclusions

This study used a cross-correlation technique to evaluate the diffusion levels in MEANU reverberation chambers as a result of various room treatments. The effects of changing diffusion levels on T.L. tests and the use of computer modelling in predicting room frequency response were also investigated. The results gathered lead to the following conclusions.

1) Two dimensional models of reverberation chambers do not accurately predict room frequency response nor does a limp-mass model for diffusing panels accurately predict diffuser performance.

2) Room frequency response cannot be used to predict diffusion levels in a room. While a strongly dominant mode may be the cause of poor diffusion at the mode frequency, a more regular response shows no correlation between modal response and diffusion levels.

3) There is significant spatial variation in diffusion levels in the reverberation suite at MEANU. This spatial variation is more pronounced at some

frequencies than others and may be related to both room dimensions and diffuser design.

4) In general, diffusion levels increase as frequency increases although room and diffuser design can significantly alter the diffusivity.

5) In general, increased room volume produces an increase in diffusion levels but the most noticeable effects occur at low frequencies. Again, room and diffuser designs can be responsible for changes in this trend.

6) Absorption added to a room causes a marked decrease in diffusion levels at all measured frequency. As more absorption is added, the negative effects increase.

7) Diffusing elements were seen to cause an increase in diffusion levels if they were used in their design range. Continuously moving diffusers have better performance characteristics than stationary diffusers. The diffusers currently used at MEANU are ineffective at 125 Hz and marginally effective at the 250 Hz octave band.

8) There appears to be some interaction between diffusers and the reverberation rooms that is related to the relative dimensions of room and diffusing panels. This causes the diffusion levels to be strongly affected at certain frequencies by

the addition of diffusers.

9) T.L. values are affected by changing levels of diffusion and it appears that there exists a level of diffusion such that test values are not affected by changing diffusion levels if they are above the critical level. This critical level is frequency dependent and increases with frequency. That is, higher levels of diffusion are required at higher frequencies.

10) Diffusion levels at MEANU were such that at 125 and 250 Hz, changes in diffusion levels (ε approximately 0.14 or lower) brought about no change in measured T.L values. At higher frequencies, levels of $\varepsilon \approx 0.05$ at 500 Hz and 1000 Hz were not sufficiently high with the result that changes in diffusion produced measurable changes in T.L. values.

5.2 Recommendations for Further Work

The work on this subject is clearly not finished. It remains to establish the critical levels of diffusion required so that standard acoustic test assumptions remain valid. This will involve increasing or decreasing diffusion levels at low frequencies so that changing levels of diffusion result in different measured T.L. values. It may also involve increasing diffusion levels at higher frequencies to reach this critical level.

If it is decided that increased levels of diffusion are required, new diffuser designs must be investigated. A moving diffuser design which consists of large panels with a range of travel significant in comparison to the wavelength of the lowest frequency of interest should be considered. Such a "moving-wall" system would "warp" the room shape much more effectively than the current system and would increase diffusion levels at all frequencies.

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