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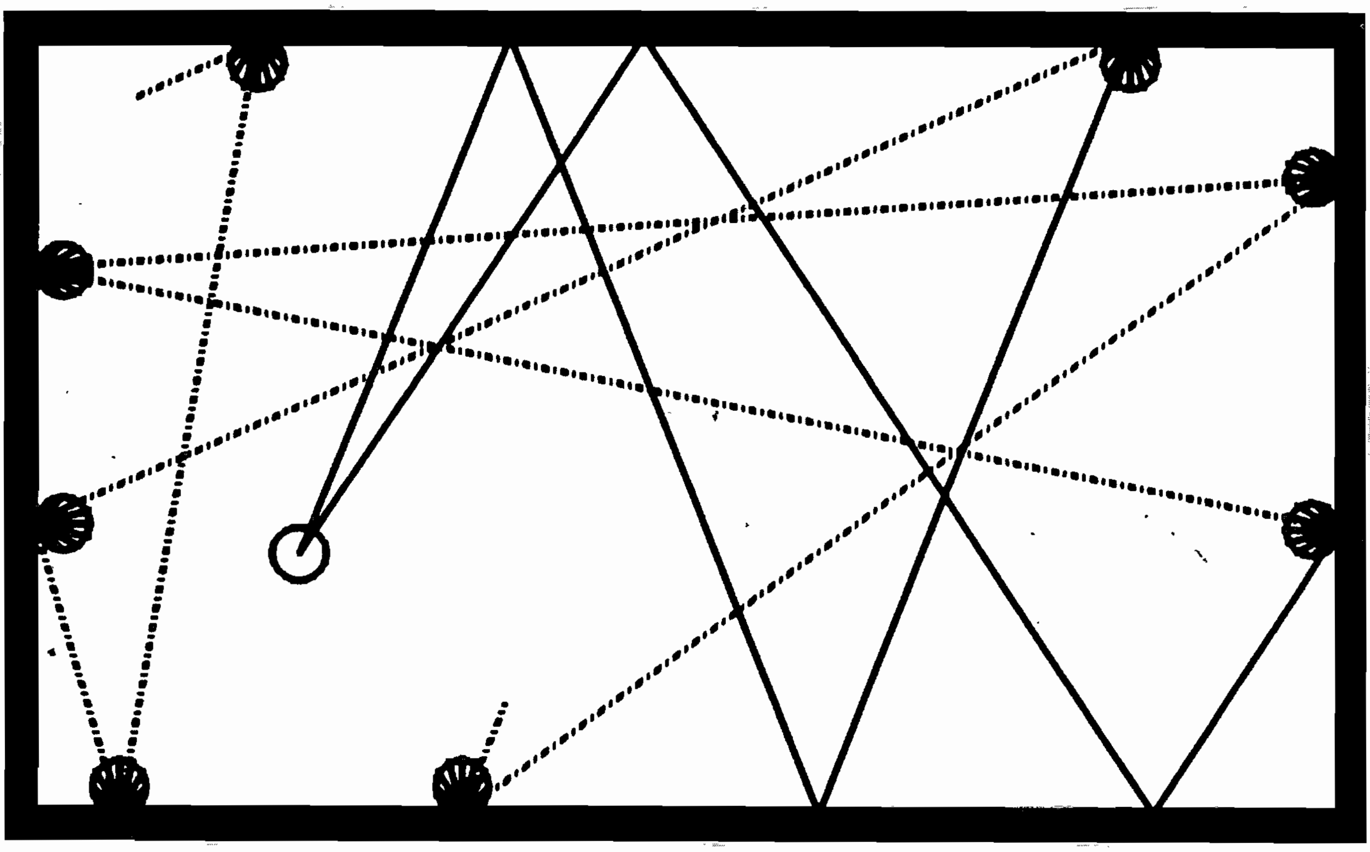

ROOM ACOUSTICS SPECIAL ISSUE

- *Computer Simulation*
- *Sabine Rooms*
- *Neural Networks*
- *Office Acoustics*

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Editorial

It is now just 100 years since the President of Harvard University directed Wallace Clement Sabine, then a young Assistant Professor (i.e. Lecturer) in physics to "propose changes for remedying the acoustical difficulties in the lecture-room of the Fogg Art Museum, a building that had just been completed." How familiar those words sound to the modern acoustical consultant! In the course of remedying those "difficulties", Sabine established the modern science of architectural acoustics. It is pleasing to record that Harvard recognised his contributions and later conferred on him an honorary Doctorate of Science - he had no PhD - and made him the first Dean of the new Graduate School of Applied Science.

In his first published paper in 1898, Sabine wrote: "In order that hearing may be good in any auditorium, it is necessary that the sound should be sufficiently loud; that the simultaneous components of a complex sound should maintain their proper relative intensities; and that the successive sounds in rapidly moving articulation, either in speech or music, should be clear and distinct, free from each other and from extraneous noises." These criteria could hardly be expressed better today, a century later. With only the simplest equipment - remember that microphones and valve amplifiers had not yet been invented - he went on to establish his famous law for reverberation time as a function of volume and surface absorption, and later went on to measure the absorption factors for many materials and surfaces, as well as transmission losses and many other properties of practical interest. His papers were published, for the most part, in architectural and technical journals rather than in the scientific literature, so that they would be available to members of the profession.

Sabine's experimental work was meticulous, and it was said that he "was reluctant to publish the results of an experiment until he was sure it had been done so well that nobody would ever need to repeat it." Consequently the volume of his publications is not very large, though it includes such innovative techniques as the visualisation of acoustic wavefronts using spark photography in small-scale models. He did, however, leave also a memorable collection of buildings for which he contributed the acoustic design. The best known of these is Symphony Hall in Boston, opened in 1890 and still widely regarded as one of the world's great concert halls, as well as the first to be designed using quantitative acoustic principles. He later went on to design the acoustics of many well known buildings, including the Cathedral of St John the Divine in New York, which is the largest Gothic cathedral in the world.

The subject has, of course, progressed a great deal since Sabine's time, but his fundamental insights still stand. In this issue, our contributors show how modern techniques of mathematical analysis and computer modelling can give us both an improved understanding of the acoustic properties of halls and a set of tools not only for improving the acoustics of existing halls but, even more importantly, for optimizing in advance the performance of halls that are still in the design stage.

Neville Fletcher

Computer Simulation Techniques for Acoustical Design of Rooms

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Abstract: After decades of development room acoustical computer models have matured. Hybrid methods combine the best features from image source models and ray tracing methods and have lead to significantly reduced calculation times. Due to the wave nature of sound it has been necessary to simulate scattering effects in the models. Today's room acoustical computer models have several advantages compared to scale models. They have become reliable and efficient design tools for acoustic consultants, and the results of a simulation can be presented not only for the eyes but also for the ears with new techniques for auralisation.

1. INTRODUCTION

In acoustics as in many other areas of physics a basic question is whether the phenomena should be described by particles or by waves. A wave model for sound propagation leads to more or less efficient methods for solving the wave equation, like the Finite Element Method (FEM) and the Boundary Element Method (BEM). Wave models are characterized by creating very accurate results at single frequencies, in fact too accurate to be useful in relation to architectural environments, where results in octave bands are usually preferred. Another problem is that the number of natural modes in a room increases approximately with the third power of the frequency, which means that for practical use wave models are typically restricted to low frequencies and small rooms, so these methods are not considered in the following.

Another possibility is to describe the sound propagation by sound particles moving around along sound rays. Such a geometrical model is well suited for sound at high frequencies and the study of interference with large, complicated structures. For the simulation of sound in large rooms there are two classical geometrical methods, namely the Ray Tracing Method and the Image Source Method. For both methods it is a problem that the wavelength or the frequency of the sound is not inherent in the model. This means that the geometrical models tend to create high order reflections which are much more precise than would be possible with a real sound wave. So, the pure geometrical models should be limited to relatively low order reflections and some kind of statistical approach should be introduced in order to model higher order reflections. One way of introducing the wave nature of sound into geometrical models is by assigning a scattering coefficient to each surface. In this way the reflection from a surface can be modified from a pure specular behaviour into a more or less diffuse behaviour, which has proven to be essential for the development of computer models that can create reliable results.

2. SIMULATION OF SOUND IN ROOMS

2.1 The Ray Tracing Method

The Ray Tracing Method uses a large number of particles, which are emitted in various directions from a source point. The particles are traced around the room losing energy at each reflection according to the absorption coefficient of the surface. When a particle hits a surface it is reflected, which means that a new direction of propagation is determined according to Snell's law as known from geometrical optics. This is called a specular reflection. In order to obtain a calculation result related to a specific receiver position it is necessary either to define an area or a volume around the receiver in order to catch the particles when travelling by, or the sound rays may be considered the axis of a wedge or pyramid. In any case there is a risk of collecting false reflections and that some possible reflection paths are not found. There is a reasonably high probability that a ray will discover a surface with the area A after having travelled the time t if the area of the wave front per ray is not larger than $A/2$. This leads to the minimum number of rays N

$$N \geq \frac{8\pi c^2}{A} t^2 \qquad (1)$$

where c is the speed of sound in air. According to this equation a very large number of rays is necessary for a typical room. As an example a surface area of 10 m² and a propagation time up to only 600 ms lead to around 100,000 rays as a minimum.

The development of room acoustical ray tracing models started some thirty years ago but the first models were mainly meant to give plots for visual inspection of the distribution of reflections [1]. The method was further developed [2], and in order to calculate a point response the rays were transferred into circular cones with special density functions, which should compensate for the overlap between neighbouring cones [3]. However, it was not possible to obtain a reasonable accuracy with this technique. Recently, ray tracing models have been developed that use triangular pyramids instead of circular cones [4], and this may be a way to overcome the problem of overlapping cones.

2.2 The Image Source Method

The Image Source Method is based on the principle that a specular reflection can be constructed geometrically by mirroring the source in the plane of the reflecting surface. In a rectangular box shaped room it is very simple to construct all image sources up to a certain order of reflection, and from this it can be deduced that if the volume of the room is V, the approximate number of image sources within a radius of ct is

$$N_{ref} = \frac{4\pi c^3}{3V} t^3 \qquad (2)$$

This is an estimate of the number of reflections that will arrive at a receiver up to the time t after sound emission, and statistically this equation holds for any room geometry. In a typical auditorium there is often a higher density of early reflections, but this will be compensated by fewer late reflections, so on average the number of reflections increases with time in the third power according to (2).

The advantage of the image source method is that it is very accurate, but if the room is not a simple rectangular box there is a problem. With n surfaces there will be n possible image sources of first order and each of these can create $(n - 1)$ second order image sources. Up to the reflection order i the number of possible image sources N_{sou} will be

$$N_{sou} = 1 + \frac{n}{(n - 2)}[(n-1)^i - 1] \approx (n-1)^i. \qquad (3)$$

As an example we consider a 1,500 m^3 room modelled by 30 surfaces. The mean free path will be around 16 m which means that in order to calculate reflections up to 600 ms a reflection order of $i = 13$ is needed. Thus equation (3) shows that the number of possible image sources is approximately $N_{sou} = 29^{13} \approx 10^{19}$. The calculations explode because of the exponential increase with reflection order. If a specific receiver position is considered it turns out that most of the image sources do not contribute reflections, so most of the calculation efforts will be in vain. From equation (2) it appears that less than 2500 of the 10^{19} image sources are valid for a specific receiver. For this reason image source models are only used for simple rectangular rooms or in such cases where low order reflections are sufficient, e.g. for design of loudspeaker systems in non-reverberant enclosures [5, 6].

2.3 The Hybrid Methods

The disadvantages of the two classical methods have led to development of hybrid models, which combine the best features of both methods [7, 8, 9]. The idea is that an efficient way to find image sources having high probabilities of being valid is to trace rays from the source and note the surfaces they hit. The reflection sequences thus generated are then tested as to whether they give a contribution at the chosen receiver position. This is called a visibility test and it can be performed as a tracing back from the receiver towards the image source. This leads to a sequence of reflections which must be the reverse of the sequence of reflecting walls creating the image source. Once 'backtracing' has found an image to be valid, then the level of the corresponding reflection is simply the product of the energy reflection coefficients of the walls involved and the level of the source in the relevant direction of radiation. The arrival time of the reflection is given by the distance to the image source.

It is, of course, common for more than one ray to follow the same sequence of surfaces, and discover the same potentially valid images. It is necessary to ensure that each valid image is only accepted once, otherwise duplicate reflections would appear in the reflectogram and cause errors. Therefore it is necessary to keep track of the early reflection images found, by building an 'image tree'.

For a given image source to be discovered, it is necessary for at least one ray to follow the sequence which defines it. The finite number of rays used places an upper limit on the length of accurate reflectogram obtainable. Thereafter, some other method has to be used to generate a reverberation tail. This part of the task is the focus of much effort, and numerous approaches have been suggested, usually based on statistical properties of the room's geometry and absorption. One method, which has proven to be efficient, is the 'secondary source' method used in the ODEON program [9]. This method is outlined in the following.

After the transition from early to late reflections, the rays are treated as transporters of energy rather than explorers of the geometry. Each time a ray hits a surface, a secondary source is generated at the collision point. The energy of the secondary source is the total energy of the primary source divided by the number of rays and multiplied by the reflection coefficients of the surfaces involved in the ray's history up to that point. Each secondary source is considered to radiate into a hemisphere as an elemental area radiator. Thus the intensity is proportional to the cosine of the angle between the surface normal and the vector from the secondary source to the receiver. The intensity of the reflection at the receiver also falls according to the inverse square law, with the secondary source position as the origin. The time of arrival of a reflection is determined by the sum of the path lengths from the primary source to the secondary source via intermediate reflecting surfaces and the distance from the secondary source to the receiver. As for the early reflections a visibility test is made to ensure that a secondary source only contributes a reflection if it is visible from the receiver. Thus the late reflections are specific to a certain receiver position and it is possible to take shielding and convex room shapes into account.

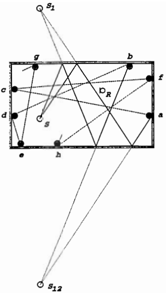

Figure 1. Principle of a hybrid model. Two sound rays create image sources for early reflections and secondary sources on the walls for late reflections.

Figure 1 illustrates in schematic form how the calculation model behaves. In the figure, two neighbouring rays are followed up to the sixth reflection order. The transition order is set to 2, so above this order the rays' reflection directions are chosen at random from a distribution following Lambert's law (see later). The first two reflections are specular, and both rays find the image sources S_1 and S_{12}. These image sources give rise to one reflection each in the response, since they are visible from the receiver point R. In a more complicated room this might not be true for all image sources. The contributions from S, S_1 and S_{12} arrive at the receiver at times proportional to their distances from the receiver. Above order 2, each ray generates independent secondary sources situated on the reflecting surfaces. In the simple box-shaped room these are all visible from the receiver, and thus they all give contributions to the response. In Figure 2 is displayed the response identifying the contributions from the source, the two image sources and the eight secondary sources.

In a complete calculation the last early reflection (from an image source) will typically arrive after the first late reflection (from a secondary source), so there will be a time interval where the two methods overlap. This is indicated on the calculated energy response curve in Figure 3. Also shown is the reverse-integrated decay curve, which is used for calculation of reverberation time and other room acoustical parameters.

In the hybrid model described above it is a critical point at which reflection order the transition is made from early to late reflections. Since the early reflections are determined more accurately than the late reflections one might think that better

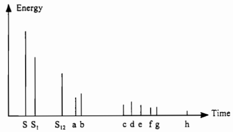

Figure 2. Reflectogram for the receiver R in Figure 1.

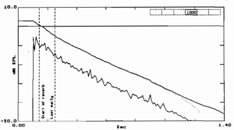

Figure 3. Typical impulse response (energy) and decay curve calculated with a hybrid model.

results are obtained with the transition order as high as possible. However, for a given number of rays the chance of missing some images increases with reflection order and with the number of small surfaces in the room. This suggests that the number of rays should be as large as possible, limited only by patience and computer capacity. However, there are two things which make this conclusion wrong. Firstly, the probability of an image being visible from the receiver decreases with the size of the surfaces taking part in its generation, so the number of reflections missed due to insufficient rays will be much fewer than the number of potential images missed. Secondly, in real life, reflections from small surfaces are generally much weaker than calculated by the laws of geometrical acoustics, so any such reflections missed by the model are in reality of less significance than the model itself would suggest. Actually, the efforts of an extended calculation may lead to worse results.

Recent experiments with the ODEON program have shown that only 500 to 1000 rays are sufficient to obtain reliable results in a typical auditorium, and an optimum transition order has been found to be two or three. This means that a hybrid model like this can give much better results than either of the pure basic methods, and with much shorter calculation time. However, these good news are closely related to the introduction of diffusion in the model.

3. DIFFUSION OF SOUND IN COMPUTER MODELS

The scattering of sound from surfaces can be quantified by a scattering coefficient, which may be defined as follows: The scattering coefficient δ of a surface is the ratio between reflected sound power in non-specular directions and the total reflected sound power. The definition applies for a certain angle of incidence, and the reflected power is supposed to be either specularly reflected or scattered. One weakness of the definition is that it does not say what the directional distribution of the scattered power is; even if $\delta = 1$ the directional distribution could be very uneven.

According to the above definition the scattered power P_{scat} can be expressed as:

$$P_{scat} = \delta P_{refl} = \delta(1-\alpha)P_{inc} \qquad (4)$$

where P_{refl} is the total reflected power, P_{inc} is the incident power and α is the absorption coefficient of the surface. The scattering coefficient may take values between 0 and 1, where $\delta = 0$ means purely specular reflection and $\delta = 1$ means that all reflected power is scattered according to some kind of 'ideal' diffusivity.

We now consider a small wall element dS which is hit by a plane sound wave with the intensity I_0 and the angle of incidence θ relative to the wall normal. The incident power is thus $I_0 dS\cos\theta$. The reflected sound can be regarded as emitted from a small source located on the wall element and the three-dimensional scatter of reflected sound can be described by a directivity $D_{\theta,\phi}$. At a distance r from the wall element the intensity of reflected sound is

$$I_{\theta,\phi} = D_{\theta,\phi}\frac{P_{refl}}{4\pi r^2} = D_{\theta,\phi} I_0 \cos\theta \frac{(1-\alpha)}{4\pi r^2} dS \qquad (5)$$

An omnidirectional source on the wall would have the directivity $D_{\theta,\phi} = 2$, but instead ideal diffuse reflections should follow Lambert's cosine law: in any direction (θ,ϕ) the intensity of scattered sound is proportional to $\cos\theta$, i.e. proportional to the projection of the wall area. The incident power on a surface exposed by a diffuse sound field would also obey Lambert's law, so this must be considered the ideal angular distribution.

If the scattered sound power is assumed to be independent of the azimuth angle ϕ, the angular distribution can be found as a function of the elevation angle θ. For a given θ the sound power is emitted through a ring with height $rd\theta$ and radius $r\sin\theta$, so that

$$dP_\theta = I_{\theta,\phi} 2\pi r^2 \sin\theta \, d\theta = P_{refl} \tfrac{1}{2} D_{\theta,\phi} \sin\theta \, d\theta \qquad (6)$$

which for the Lambert directivity $D_{\theta,\phi} = 4\cos\theta$ leads to

$$dP_\theta = P_{refl} 2\cos\theta\sin\theta \, d\theta = P_{refl}\sin 2\theta \, d\theta \qquad (7)$$

Hence, the angular distribution of ideal diffuse reflections is $\sin 2\theta$.

Diffuse reflections can be simulated in computer models by statistical methods [10]. Using random numbers the direction of a diffuse reflection is calculated with a probability function according to Lambert's cosine-law, while the direction of a specular reflection is calculated according to Snell's law. A scattering coefficient between 0 and 1 is then used as a weighting factor in averaging the coordinates of the two directional vectors which correspond to diffuse or specular reflection, respectively.

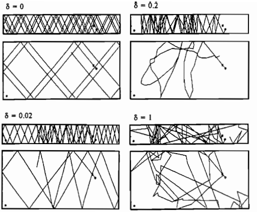

Figure 4. One sound ray in a simple room with different values of the surface scattering coefficient.

An example of ray tracing with different values of the scattering coefficient is shown in Fig. 4. The room is a rectangular box with a relatively low ceiling. All surfaces are assigned the same scattering coefficient. Without scattering, the ray tracing displays a simple geometrical pattern due to specular reflections. A small scattering coefficient of 0.02 changes the late part of the reflection pattern, and a value of 0.20 is sufficient to obtain a diffuse looking result.

By comparison of computer simulations and measured reverberation times in some cases where the absorption coefficient is known, it has been found that the scattering coefficient should normally be set to around 0.1 for large, plane surfaces and to around 0.7 for highly irregular surfaces. Scattering coefficients as low as 0.02 have been found in studies of a reverberation chamber without diffusing elements. The extreme values of 0 and 1 should be avoided in computer simulations. In principle the scattering coefficient varies with the frequencyæscattering due to the finite size of a surface is most pronounced at low frequencies, whereas scattering due to irregularities of the surface occurs at high frequencies. However, today's knowledge about which values of the scattering coefficient are realistic is very limited, and so far it seems sufficient to characterize each surface by only one scattering coefficient, valid for all frequencies.

4. ACCURACY AND CALCULATION TIME

Recently an international round robin has been carried out [11] with 16 participants, most of them developers of software for room acoustical simulations. In an 1800 m^3 auditorium eight acoustical criteria as defined in [12] were calculated for the 1kHz octave band in the ten combinations of two source positions and five receiver positions. For comparison measurements were made in the same positions by seven different participants. Drawings, photos, material descriptions and absorption coefficients were provided. It came out that only three programs can be assumed to give unquestionably reliable results. The results of these programs differ from the average measurement results by the same order of magnitude as the individual measurement results. So, the reproducibility of the best computer simulations can be said to be as good as a measurement, which is quite satisfactory. However, some of the programs produced 5-6 times higher differences. It is interesting to note, that the three best programs (one of which is the ODEON program) use some kind of diffuse reflections, whereas the results from purely specular models were more outlying. It is also typical that the best programs do neither require extremely long calculation times nor extremely detailed room geometries.

5. ADVANTAGES OF COMPUTER MODELS COMPARED TO SCALE MODELS

It is quite obvious that a computer model is much more flexible than a scale model. It is easy to modify the geometry of a computer model, and the surface materials can be changed just by changing the absorption coefficients. The computer model is fast, typically a new set of results are available a few hours after some changes to the model have been proposed. But the advantages are not restricted to time and costs. The most important advantage is probably that the results can be visualised and analysed much better because a computer model contains more information than a set of measurements done in a scale model with small microphones.

5.1 The Reflectogram as a Tool

The reflectogram displays the arrival of early reflections to a receiver. When the early reflections are calculated from detected image sources, it follows that each single reflection can be separated independently of the density of reflections, and in addition to arrival time and energy it is possible to get information about the direction and which surfaces are involved in the reflection path. The latter can be very useful if a particular reflection should be removed or modified.

5.2 Display of Reflection Paths

The reflection paths for all early reflections may be visualised in 3D and analysed in detail. During the design of a room it may be interesting to see which surfaces are active in creating the early reflections. Although it is difficult to extract specific results from such a spatial analysis, it can help to understand how a room responds to sound.

5.3 Grid Response Displays

With a computer model it is straight forward to calculate the response at a large number of receivers distributed in a grid that covers the audience area. Such calculations are typically done over night, and it is extremely useful for the acoustic designer to see a mapping of the spatial distribution of acoustical parameters. Uneven sound distribution and acoustically weak spots can easily be localized and appropriate countermeasures taken.

5.4 Auralisation

In principle it is possible to use impulse responses measured in a scale model for auralisation. However, the quality may suffer seriously due to non-ideal transducers. The transducers are one reason that the computer model is superior for auralisation. Another reason is that the information about each reflection's direction of arrival allows a more sophisticated modelling of the listener's head-related transfer function.

Most of the recent research concerning auralisation has concentrated on the 'correct' approach, whereby each link in the chain from source to receiver may be modelled as an impulse response. See Kleiner et al. [13] for an overview of the technique. However, the convolution technique involved requires either expensive hardware for real-time convolution or long waits for off-line convolution, and often the impulse response is too short to produce a realistic reverberation. An alternative technique for auralisation, which avoids the convolution bottleneck, has recently been proposed [14]. The method is based on an interface between a digital audio mainframe and a room acoustical computer model. This means that auralisation can follow immediately after the room acoustical calculation in a receiving point, and there are no limitations on length of the source signal. The early reflections and the late reverberant reflections are treated by two different techniques. With this technique 40-50 early reflections will usually be sufficient to create a realistic sounding room simulation, and long reverberation time is no problem.

The early reflections are very important for obtaining a realistic auralisation. For presentation through headphones the following three methods are used in order to obtain localization outside the head:

- Interaural time difference. This is the dominant cue for localization of broad band sound in the horizontal plane.
- Interaural intensity difference. The signal to the ear in the direction of the incident reflection is raised up to 6 dB. This is a simplified representation of the reflection effect of the head relative to free field.
- Spectral cues. The spectral peaks and notches due to the outer ear are roughly simulated by filters Although this is known to be the main cue for elevation, the intention at this stage has not been to create a localization for different elevation angles, but rather to avoid the front-back confusion and to improve the out-of-the-head localization.

The auralisation technique offers the possibility to use the ears already during the design process. Several acoustical problems in a room can easily be detected with the ears, whereas they may be difficult to express with a parameter that can be calculated.

6. CONCLUSION

Computer techniques for simulation of sound in rooms have improved significantly in recent years, and for the consultant the computer model offers several advantages compared to the scale model. The scattering of sound from surfaces has appeared to be very important in room acoustical simulation technique, and this has created a need for better information about the scattering properties of materials and structures. Although the scattering can be handled by the model, the knowledge about which scattering coefficients to use is very sparse. So, it can be concluded that there is a need for a method to measure the scattering coefficient of surfaces. Until then there remains an inherent piece of guesswork in room acoustical simulations. On the other hand, it is no surprise that the user can influence the quality of a simulation.

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Predicting the Acoustics of Concert Halls Using an Artificial Neural Network

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Abstract: An alternative approach to the design of concert halls, using artificial neural networks, has been investigated. As part of the study, visiting musicians and conductors were asked to complete a questionnaire on their preferences for over 60 concert halls, most of which were located in Europe and North America. A similiar survey was carried out using members of the Music Critics Association in the USA. These results were used to correlate hall preferences with physical features of the halls. It was found that the single most important feature affecting the acoustics of halls was the diffusion of the interior surfaces. A preliminary neural network analysis showed a high correlation between the predicted and assessed acoustical ratings of halls when only seven geometrical factors were used to describe the halls used in the study. The paper also reports on the comparison of evaluations of concert halls by musicians and music critics and the preferences of both groups for different types of halls.

1. INTRODUCTION

There appear to be several ways in which the complexity of acoustic design of concert halls is handled. One way is to copy or modify an existing building, another is to measure acoustic parameters in existing, model or virtual buildings and then to reproduce these parameters in the new concert hall. None of these is very satisfactory as there are many reasons, not the least of which are cost and inaccurate modelling and measurement, which mean that exact replicas of halls, or exact prototypes, cannot be built (or are not built). Often the acoustic design of a hall comes down to the experience of the designer who over the years gains a feel for what works and what doesn't or who has an innate understanding of what to do.

Sabine's (1900) work on reverberation time was of fundamental importance in the application of science to architectural design. Unfortunately the use of Sabine's work does not guarantee good acoustics and it would seem that despite the best efforts of Beranek (1962) and others to provide an analytic approach to acoustical design, involving factors other than reverberation time, there is still no reasonable expectation that a new concert hall's acoustic will be praised by musicians and audiences.

Concert hall acoustics is a multi-criteria and multi-parameter issue. The requirements for one criteria may be contrary to those for another. For example it is considered that a long narrow hall gives the best conditions for strong lateral reflections which have been shown to be important. The same long narrow hall would not give good conditions for intimacy which is also sought after. A longer than optimum reverberation time may be acceptable in a large hall but unacceptable in a small hall. There is little understanding of these and other interactions and the search for a single measure of acoustics continues with the religious fervour of true believers.

While there is always the hope that some quantity, such as the Interaural Crosscorrelation Coefficient (IACC), will turn out to be a single suitable acoustic measure, it seems unlikely. As described by Ando (1985) the IACC measurement requires a dummy head to face the centre of the stage in an auditorium as the measurement is dependent on direction. In some concert halls the position of the performers can be changed and in all concert halls the members of the audience can move their heads without the perceived acoustic changing. While this anomaly should not rule out the possibility of the success of IACC, or similar binaural measures, it is unfortunate if a measure of performance cannot be directly related to perceived conditions. For this and other reasons, such as the lack of success in applying conventional parametric techniques to auditorium design, it seems worth investigating other approaches.

One such approach which formalizes the successful designer's approach is the use of artificial neural networks to seek out the interrelationships in complex situations. The way in which neural networks operate has been described recently by Baillie and Mathew (1994) and so this will not be covered in this paper. Suffice to say that the use of artificial neural networks obviates the need to specify, calculate and measure acoustic quantities. The acoustics of a space depends on the size, shape and surface finishes of that space and if these factors can be adequately specified and if there are adequate examples of existing concert halls where these factors are known, and where subjective acoustic ratings have been obtained, then artificial neural networks can be used to predict how well a new hall will be perceived.

This paper should only be considered as a first attempt at applying a neural network approach as there are a number of issues which need refining.

2. SUBJECTIVE RATING OF HALLS

For this study a subjective rating of concert halls had to be obtained. It is inordinately difficult to obtain subjective comparisons of different auditoria. This is partly because people have limited knowledge of halls, partly because people tend to prefer the halls they know and partly due to a host of other factors. One of these is that the acoustical conditions in a hall vary from seat to seat and now, with halls having variable acoustics, from performance to performance and even within a performance.

Ideally a group of performers and listeners should be taken blindfolded to many halls around the world and they should play and listen to the same music in each hall and in different seats in each hall. Even this ideal scenario is unlikely to produce much useful information because of the difficulty in remembering the different halls and performances and becoming accustomed to the music. Unfortunately there is no musical equivalent of the speech intelligibility test.

The alternative is to record music played in halls, using a dummy head, and reproduce it in an anechoic laboratory where subjects can make preference judgements between pairs of "halls" without moving and without the use of semantic scales. This has been done by Schroeder (1974), Plenge (1975), Ando (1985) and others but there is always the concern that the virtual acoustics may not be the same as the actual acoustics and that there may be important non-acoustical factors which influence judgements.

Somerville (1953) argued that the best group of subjects for surveys on the acoustical quality of halls are music critics because they gave more concordant answers than performing musicians, engineers, and the general public. But, in his research, only ten concert halls in the U.K. were considered. Parkin (1952) also insisted that the artists tend to evaluate the halls only from their experience on the stage where the acoustic conditions could be quite different from those at the seats of the listeners. Surprisingly there does not appear to have been an attempt to correlate the judgements of musicians and critics about existing concert halls to test these contentions. Such a comparison is reported in this paper.

In practice, if the acoustic evaluation of concert halls is to be extended beyond national borders, to maximize the range of designs studied and minimize prejudices, some of the best people to make these evaluations are internationally acclaimed conductors and soloists as they have the knowledge of halls, the expertise to evaluate them, many opportunities to visit halls, due to regular concert engagements, and the need to consider what the audience hears rather than just the stage acoustics. It could be argued too that if musicians don't like the stage acoustics the acoustics in the auditorium are unlikely to be judged as excellent as the music played in the hall will be adversely affected by the stage acoustics.

Past questionnaire surveys have been of two types: one favouring preference comparisons, the other semantic differential ratings. Preference comparisons were undertaken by Hawkes and Douglas (1971) and Schroeder et al.(1974) whilst semantic scales were used by Wilkens (1975) and Barron (1988).

Parkin et al.(1952) described a subjective investigation of ten British concert halls by means of a questionnaire sent to people who were music critics, music academics and composers. Of the 170 questionnaires sent out 75 were returned. Only 42 of these responses could be used to be evaluate halls because the rest had experience of less than three of the named halls in the questionnaire. This study is the first known attempt to rate the general acoustic quality of halls numerically using subjects from the music profession. The evaluation of the halls was made using a three point scale (good, fair and bad).

Beranek (1962) interviewed 23 musicians and 21 critics to judge the acoustic quality of the 54 halls (ie. 35 concert halls, 7 opera halls and 12 multi-purpose halls) in his study. These acoustic quality judgements were used to construct numerical rating scales of acoustic attributes. The 54 halls were classified into five groups based on the musicians' impressions and evaluations. Beranek interviewed outstanding musicians as a first source of reliable information in his study of halls for music.

In the present study it was decided to ask musicians to evaluate the acoustics of halls using a self-administered questionnaire. The present survey was designed to reassess the acoustics of many halls used in Beranek's study and also to include as many different shapes of halls as possible in order to investigate the effects of hall geometry on the acoustic quality.

3. THE QUESTIONNAIRE

The present work appears to be the first international study of halls, undertaken since Beranek's in 1962, to quantify acoustic quality from systematic subjective responses. The questionnaire used in the study employed a three point scale (like Parkin used) and included concert halls only.

3.1 Questions

In the survey, using a self-administered questionnaire, respondents were asked to express their opinions on the acoustics of up to 75 concert halls. Respondents were asked to make judgements about the acoustics of halls for classical symphonic music. The questionnaire included questions about preferences for music and concert halls. A list of concert halls was included and respondents were asked to rate them acoustically, based on their experience, as either excellent, good or mediocre. The terminologies used for three levels of acoustic quality were suggested by Lawrence (1983).

A three point scale was employed for rating acoustical quality of the halls because it simplifies the subject's task and makes the difference clear. As all the listed halls in the present survey are well known and are regularly used for concerts the acoustics of these halls are not likely to be bad. Thus the ordering scale was designed to start from "mediocre" and used "good" and "excellent" as the other two steps.

3.2 Selection of Halls

Most of the halls listed in the questionnaire were located in Europe and North America. The halls were chosen because information about them was readily available in the literature and because they are well known, so the sample is not a random one. The list of halls includes halls with four different shapes, ie. rectangular, fan, horseshoe and geometric, although categorization into one of these was not always easy. The list of halls was altered slightly during the three years in which the questionnaire was administered so that the number of assessed halls could be maximized. A sample of the concert halls which were listed in the questionnaire, and for which there were sufficient responses to make evaluations, is shown in Table1.

3.3 Respondents

The subjects for this survey were drawn from two groups: musicians who performed in Australia during the 1990, 91 & 92 concert seasons and members of the Music Critics Association in the USA. The music critics' results were used to compare the ratings of musicians with music critics and, to some extent, the stage acoustics with the auditorium acoustics of halls.

Most of the musician questionnaire respondents were conductors and soloists from Australia, Europe, Japan and North America, who have performed as guest artists with many different orchestras in many auditoria in many countries. One of the added advantages of using this cohort of musicians is that the results should not be influenced by local cultural factors. A total of 110 questionnaires were sent to musicians. Thirty five responses were obtained (ie. a 29 % response). The respondents came from 12 countries and comprised 16 conductors, 13 soloists and 3 other musicians. All the musicians were professionals who performed regularly in many auditoria. Among the 32 musicians, 21 performed more than once a week and the rest performed at least once a month.

A second evaluation of concert halls was undertaken using members of the Music Critics Association of the USA. Despite the limitations of a poor response rate (approximately 10%), limited knowledge of halls outside the USA, possible preconceptions and other confounding influences, overall there is a strong correlation between the opinions of the musicians and the critics. Opinions on individual halls did differ between the two groups but the most notable point was the spread of opinions on a number of the halls within each group of respondents.

4. ACOUSTIC QUALITY INDEX OF HALLS

Respondents commented on 60 of the halls listed in the questionnaire. The largest number of halls any individual respondent rated was 41. A total of 805 ratings were obtained from the musicians. The average number of ratings for each hall was fifteen with a maximum of 30 for the Sydney Opera House Concert Hall. For the evaluation of the acoustic quality of a hall at least 5 responses were required.

For estimating the goodness of the halls a value of 1 was assigned to those assessed as 'Excellent', 0.5 to 'Good' and 0 to 'Mediocre'. An acoustic quality index (AQI) for each hall was calculated by averaging the rated values. The "musician" AQI values of halls are distributed in the range 0.22 (Henry & Edsel Ford Auditorium, Detroit) to 0.98 (Grosser Musikvereinssaal, Vienna) while the "critic" AQIs ranged from 0.19 (Gasteig Philharmonie Hall, Munich) to 0.94 (Symphony Hall, Boston). The "musician" AQI values for each hall are listed in Table 1 with the details of the number of responses on which the AQI was based.

The acoustic quality of halls, as rated by the music critics, is compared with the ratings of the same halls by musicians in Fig 1, for the halls for which there were sufficient responses from both groups. The agreement is surprisingly good considering that the acoustics of the stage and auditorium in a given concert hall could be very different. There appears to be better agreement between the ratings of critics and musicians in conventional shaped halls than in fan or geometrically shaped halls such as the Berlin Philharmonie.

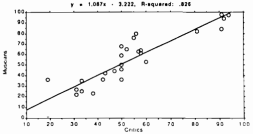

Figure 1. Scattergram of hall AQIs as determined by critics and musicians.

5. ACOUSTIC QUALITY DEPENDENCE ON HALL GEOMETRY

To undertake a neural network analysis it is not necessary to investigate the correlation between different parameters and the acoustical quality of the auditoria but such an analysis is of general interest and so some of the relationships are reported on below. In the present study 28 of the 32 musician respondents said they had a particular preference for hall shape for symphonic music. Regarding the hall type it was found that 21 of the 28 musicians (75%) who answered this question preferred rectangular concert halls. The second most common preference was for horseshoe type halls. This is in accordance with the finding of Gade (1981) who indicated that musicians preferred shoebox type halls as an ideal room shape. Nine of the twenty halls (45%) which have AQI's of 0.60 or better are rectangular in shape whilst only 19 of the 53 halls surveyed were rectangular halls (36%). As might be expected this is a similar trend to that for the musicians preferring rectangular halls.

While the overall acoustic impression of symphonic music played in halls was used to estimate the acoustic quality index of each hall, the appropriate shape of halls for other types of

Table 1. Acoustic quality index of concert halls.

Concert Hall	Hall Type	Total	E (musician responses)	G	M	AQI (musicians)	AQI (critics)
Grosser Musikvereinssaal, Vienna	REC	26	25	1	0	.98	.91
Symphony Hall, Boston	REC	16	15	1	0	.97	.94
Concertgebouw, Amsterdam	REC	26	23	3	0	.94	.92
Carnegie Hall, New York	HSU	28	19	9	0	.84*	.91
Severance Hall, Cleveland	HSU	11	8	2	1	.82	.81
Gewandhaus, Leipzig	GEO	10	6	4	0	.80X	.56
Concert Hall De Doelen, Rotterdam	GEO	17	9	8	0	.77	
Berliner Philharmonie Hall, Berlin	GEO	23	14	7	2	.76	.55
Derngate Center, Northampton	REC	10	5	4	1	.70X	
Herkulessaal, Munich	REC	19	9	8	2	.68	.50
Orchestra Hall, Chicago	HSU	20	7	12	1	.65	.52
Grosser Tonhallesaal, Zurich	REC	18	6	11	1	.64	.58
The Mechanics Hall, Worcester	REC	8	2	6	0	.63	.57
Concert Hall, Haarlem	REC	9	4	3	2	.61X	
Royal Concert Hall, Nottingham	GEO	9	3	5	1	.61X	
Concert Hall De Oosterpoort	FAN	9	2	7	0	.61X	
Philadelphia Academy of Music	HSU	14	4	9	1	.61	.58
Carl Nielsen Hall, Odense	REC	10	2	8	0	.60X	
Neues Festspielhaus, Salzburg	FAN	16	3	13	0	.59	.50
Stadt-Casino, Basel	REC	12	3	8	1	.58	
Oslo Concert Hall, Oslo	FAN	8	2	5	1	.56X	
Concert Hall,Sydney Opera House	GEO	30	6	21	3	.55X	
Concert Hall, Stockholm	REC	12	3	7	2	.54X	
Palais de la Musique, Strasburg	GEO	13	2	10	1	.54X	
Usher Hall, Edinburgh	HSU	18	2	15	1	.53	.60
Liederhalle Grosser Saal, Stuttgart	GEO	14	3	8	3	.50	
St. Andrew's Hall, Glasgow	REC	13	2	9	2	.50‡	
Berwald Hall, Stockholm	GEO	8	1	6	1	.50X	
Lyric Theatre, Baltimore	REC	7	0	7	0	.50	
War Memorial Opera House, S.F	HSU	8	0	8	0	.50	.50
Philharmonic Hall, Liverpool	FAN	18	2	13	3	.47*	
National Concert Hall, Dublin, Eire	REC	13	2	8	3	.46X	
Melbourne Concert Hall, Melbourne	GEO	25	5	13	7	.46X	
Tivoli Koncertsal, Copenhagen	FAN	12	0	11	1	.46	.50
Concert Hall, Kennedy Center	REC	18	3	10	5	.44X	.47
Colston Hall, Bristol	REC	15	1	11	3	.43	
Eastman Theatre, Rochester	FAN	12	0	10	2	.42	.43
Concert Hall, Music Center, Utrecht	GEO	11	0	9	2	.4	
Radiohuset Studio 1, Copenhagen	FAN	9	1	5	3	.39*	
Royal Festival Hall, London	REC	29	6	9	14	.36	.50
Free Trade Hall, Manchester	REC	18	1	11	6	.36	
Palais des Beaux-Arts, Brussel	HSU	18	1	11	6	.36	.42
Gasteig Philharmonie, Munich	FAN	14	2	6	6	.36X	.19
Beethovenhalle, Bonn	GEO	17	2	8	7	.35	.33
Roy Thomson Hall, Toronto	GEO	10	2	3	5	.3	.19
Maison de Radio France, Paris	FAN	16	0	11	5	.34	
Grosser Sendesaal, Berlin	FAN	11	1	4	6	.27	
Avery Fisher Hall, New York	REC	26	2	10	14	.27*X	.31
Boettcher Concert Hall, Denver	GEO	10	0	5	5	.25X	.33
Barbican Concert Hall, London	GEO	26	1	10	15	.23*X	.38
Henry Ford Auditorium, Detroit	FAN	9	0	4	5	.22‡	.31

* All or part of these subjective evaluations may have been made before recent changes in the halls.

‡ Hall no longer exists.

X Hall less than 30 years old.

Where, the abbreviations used in this Table are as follows ;
REC : Rectangular hall FAN : Fan shaped hall HSU : Horseshoe (U shaped) hall GEO :Geometrically shaped hall
Total : Total number of respondents
E: Excellent G: Good M: Mediocre AQI: Acoustic quality index

musical performances was also investigated. The questionnaire respondents were asked to indicate the best shape for three forms of music; symphonic, chamber & solo recital and opera. Table 2 shows the number of respondents who preferred particular hall shapes for particular music forms. The survey showed that more than half the musicians also preferred rectangular halls for chamber music and solo recitals. As expected, horseshoe type halls were preferred for operatic performances. The geometric and arena halls are obviously not popular and this preference should be considered as being more significant than the often expressed preference of musicians for wood lined interiors.

Table 2. Survey results on the preference for hall type for different types of musical performance.

Forms of Music Hall Types	Symphonic	Chamber & Solo Recital	Opera	Suitable for nothing
Rectangular	17	10	2	1
Fan Shaped	4	3	4	4
Horseshoe Shaped	6	3	8	1
Geometric & Arena	4	1	3	10
Sub Total	31	17	17	16

There is a clear preference, shown in Table 2, for rectangular and horseshoe shaped halls compared with fan and geometrically shaped halls. An analysis of preferences for hall shapes in Table 1 also shows this trend but not so clearly. Grouping the rectangular and horseshoe halls together and the fan and geometric halls with AQIs $\leq$ 0.5 and >0.5 and applying a X^2 test to the musician responses shows that the difference is significant at the 1% level (DF=1, X^2=6.878, $0.001<p\leq 0.01$).

The most significant factor, by far, in producing good acoustics appears to be the degree of diffusion by the walls and ceiling. This relationship is a paper topic in itself but an example of the relationship between the acoustic quality index and a subjectively determined area weighted surface diffusivity index (SDI a.w.) is given in Fig 2 for rectangular halls. Further information is given in the following section.

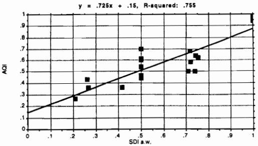

Figure 2. Scattergram of Acoustic Quality Index (AQI) against area weighted Sound Diffusion Index (SDI a.w.) for rectangular halls.

This relationship may have a non-acoustical aspect as well as an acoustical aspect. The design effort required for a hall with surface ornamentation may be an indication of the attention paid to the overall design as well as be visually more stimulating than plainer treatments.

6. OTHER FACTORS INFLUENCING PERCEIVED ACOUSTIC QUALITY

Most concert halls (94% of all halls used in the present work) have a reverberation time of more than 1.5 sec when they are occupied. The mean value of reverberation time of concert halls used in this work is 1.77 sec with the minimum reverberation time of 1.3 sec. It has been acknowledged (Beranek, 1962) that sufficient reverberation time is a crucial requirement for good acoustics. If it is assumed that good halls have adequate diffusion a long reverberation time would not be an essential condition for a diffuse sound field. When the acoustic quality index was plotted as a function of reverberation time of halls, a very low correlation coefficient was obtained (refer to Fig.3) with a large amount of scatter. This indicates that a long reverberation time is not, on its own, a satisfactory indicator of acoustic quality. This point has been made previously eg. Barron (1988) and Beranek (1962). Also it is shown in Parkins' study (1952) where the distribution of reverberation time and volume of halls are very widely scattered, regardless of the quality of halls.

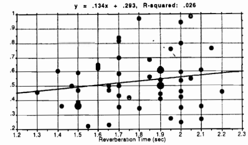

Figure 3. The scattergram of acoustic quality index against reverberation time of halls.

Interestingly, of the halls listed in Table 1, the five top rated halls were all over 30 years old (at the time of the study) and there were only two halls less than 30 years old in the top 10 halls. Of the halls listed, for which there were more than 5 responses, 23 were less than 30 years old and 30 greater than 30 years old. It should be noted that a number of the older halls have been renovated and it it is not clear whether these should be classified as new or old halls and whether the respondents were rating the halls before or after the renovations. However there is a better correlation of acoustic quality with the age of the hall than there is with the reverberation time (see Fig 4).

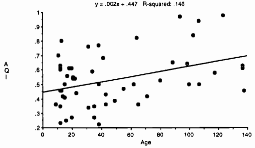

Figure 4(a). Acoustic quality of all halls as a function of age (years).

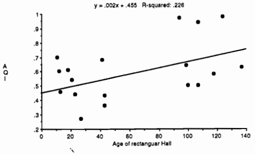

Figure 4(b). Acoustic quality of rectangular halls as a function of the age of halls (years).

It was considered possible that the judged quality of an auditorium might be related to the distance the respondent lived from the hall. There are several reasons for this including a "cultural cringe" factor (halls further away are more highly regarded) and the halls that are most familiar (near halls) being judged to give the best sound. Two analyses were undertaken using information from the music critic survey: a correlation between how good a hall is judged and the average distance away that the hall is (for all the respondents living in North America) and a second test using only the east coast critics and halls. For all the respondents there was a slight correlation (r^2=0.2) with the more distant halls being considered lower quality. The result was significant at the 10% level only and the relationship is considered to be an artifice of the distribution of halls and respondents (most halls and respondents lived on the east coast and most of the better halls used for the study were in the east of the USA).

Of the respondents living in the east and commenting on the east coast halls distance is not important when a Chi-squared test is carried out on two groupings: ≤250 miles distant and >250 miles distant (DF=2, X^2=2.468, $0.20<p\leq0.30$). If the "good" and "mediocre" categories are combined the effect of distance is significant only at the 20% level: DF=1, X^2=2.29, $0.10<p\leq0.20$. It might be useful to correlate judgements with the place where the respondent grew up but one can hardly design using this information and so the only possible value of it would be to indicate how important external factors are in the evaluation of halls.

Using a Chi-squared test there is a $p<.001$ that the hall ratings are from the same populations when a breakdown of halls is used such that the halls in which the five most well known orchestras usually play are separated into one group and the five other best known halls are used as the second group. (Each hall had at least 10 individual ratings and the total number of ratings for each group was 133 and 130.)

Table 3 Comparison of hall ratings with resident orchestras

Hall Rating	A Halls	B Halls	A Halls	B Halls
Excellent	79	23	Boston	Meyerhoff
			Chicago	Avery Fisher
Good	40	68	Severance	San Francisco
			Carnegie	Kennedy Centre
Mediocre	14	39	Philadelphia	Rochester

This is not very convincing evidence that it is the orchestra that determines what respondents think of the acoustics of an auditorium because it could well be that the better orchestras evolve around the better halls and besides it is not known what orchestras were playing in the halls when the respondents made their judgements (the New York Symphony Orchestra plays in the Avery Fisher and the Philadelphia Orchestra plays in Carnegie Hall, for instance, and all orchestras go on tour).

7. NEURAL NETWORK ANALYSIS

For the neural network analysis only the musician responses were used as the music critics did not comment on sufficient halls for which other data was available.

A neural network analysis was undertaken to find the best combination of parameters for the prediction of good acoustics of halls. Neural network analyses are mathematical models of theorised mind and brain activity which learn knowledge on interconnected variables by adaptive simulation. The neural network is applicable to situations where only a few decisions are required from a massive amount of data and situations where a complex nonlinear mapping must be learned (Simpson 1990). In the neural network analysis only geometrical data on the halls were used for the prediction of the acoustic quality of halls.

Geometrical data on 53 concert halls was obtained together with subjective evaluations. The halls used in this study are those for which published data is readily available in publications and for which scaled drawings are available. The plan and section in the 1/400 or 1/500 scale was used to measure the geometric properties of halls. The sample, therefore, is unlikely to be random. The geometrical parameters used are shown in Table 4 with the abbreviation for each.

Hall depth (HD) is defined as the distance between the proscenium wall and the rear wall. HW is the horizontal distance between the side walls in rectangular halls. In the case of non-rectangular halls, the hall width is the average

Table . Auditorium parameters used in the investigation.

No	Geometrical Parameters of Auditorium	Abbreviation	Unit
1	Room Volume	V	m3
2	Number of Audience Seats	N	seats
3	Total Floor Area	St	m2
4	Audience Seating Area	Sa	m2
5	Volume per Seat	V/N	m3/seat
6	Volume per Floor Area	V/St	m
7	Seating Density	Sa/N	m2/seat
8	Hall Depth	HD	m
9	Average Hall Width	HW	m
10	Average Hall Height	HH	m
11	Depth to Width Ratio	D/W	
12	Depth to Height Ratio	D/H	
13	Width to Height Ratio	W/H	
14	Angle of Side Walls	ASW	degree
15	Maximum Rake Angle of Seating	XRA	degree
16	Mean Rake Angle of Hall	MRA	degree
17	Surface Diffusivity of Hall	SDI	

width of the plan which is converted to rectangular one that represents the same area of the original hall where the HW is calculated based on fixed HD. The hall height, HH, is the mean distance between the floor and the ceiling. The angle of the side walls, ASW, is a simple measure of the shape of the halls. ASW is the included angle of the side walls which is 0 for rectangular halls. Two rake angles of the seating were used; the maximum rake angle of the seating, XRA, and the mean rake angle, MRA. The surface diffusivity of a hall is a measure of how irregular the surfaces are. For this study the evaluation of diffusivity of surfaces was undertaken by visual inspection. A simple categorisation was used as it is difficult to subjectively differentiate surfaces using more than a three point scale. Surfaces were placed in one of three categories depending mainly on the irregularity of the surfaces and to a lesser extent on the absorption of those surfaces. The three categories used were high, medium or low diffusivity. The criteria for the classification of diffusiveness of surfaces and weighting procedures are presented in a previous paper (Haan 1993). For numerical evaluation of the effect of diffusivity of the surfaces a value of 1 was assigned to the 'high', 0.5 to 'medium' and 0 to 'low' diffusing surfaces. A surface diffusivity index (SDI_{av}) for each hall was calculated by averaging the diffusivity of the ceiling and walls to obtain an SDI_{av} in the range 0 to 1. It should be mentioned that the categorisation used in the present work is a first attempt at a simple method of defining diffusivity of surfaces and that better ways of defining and categorising of surfaces should be attempted. Likewise, better ways of defining the geometry of halls also need to be investigated.

Using the above, easily determined, parameters a correlation matrix was formed. The parameters with the highest correlations with AQI were used in the subsequent neural network analysis. The correlation matrix is shown in Table 5.

Table 5 Correlation matrix of geometrical parameters and AQI.

	AQI	V/N	Sa/N	D/W	W/H	ASW	MRA	SDI
Acoustic quality index	1							
Volume/seat	-.052	1						
Seating density	-.116	.657	1					
Hall depth to width ratio	.353	-.234	-.352	1				
Hall width to height ratio	-.408	.353	.455	-.592	1			
Angle of side wall	-.425	.282	.093	-.304	.319	1		
Mean rake angle	-.135	.280	.312	-.417	.156	.198	1	
Surface diffusivity index	.783	.078	-.100	.302	-.440	-.240	-.249	1

There are two stages in the procedure of neural network analysis ie. training and testing. The training of a network is the making of a network model which learns the pattern of input data and stores the weights which contain knowledge about the correlation between the network configuration and the characteristics of input data. Fig. 5 illustrates the flow diagram of neural network procedures undertaken in the present study. The geometric data described earlier in this section were adopted as input variables for analysis.

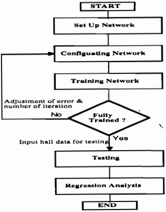

Figure 5. Flow diagram for simulating procedures of a neural network.

The program used in the present study was Dime (version 1.2) which was designed for especially estimation and approximation purpose. The neural network analyses were carried out using a micro Sun workstation.

It is important to have even distribution of sampled data for the both training and testing sets of halls. The data on input and output variables should be evenly distributed in order that the information covers the full range of possible values. Two basic criteria were used to select halls for both the training and testing sets. The percentage of each hall type of hall in each set should be similar (approximately 20%) and the AQI values of halls for testing should cover the AQI range used for network training. Table 6 shows the required number of halls for testing. Ten of the 53 concert halls were chosen as halls for testing networks. And the rest of the halls (ie. 43 halls) were used for training the networks.

Table 6. The number of halls for testing networks.

Hall Type	Number of Halls in Sample	Number of Halls for Testing	Percentage of Halls used for Testing (%)
Rectangular	19	4	21.0
Fan	11	2	18.2
Horseshoe	7	1	14.3
Geometric	16	3	18.8
Sub-total	53	10	18.9

The ten concert halls which were selected for testing networks are listed in Table 7. The geometric halls included one circular hall. The average acoustic quality indices of the both sets of halls are shown in Table 8 with the range of the values.

Table 7. The list of concert halls used for testing the network model.

No.	Hall Name	Type	AQI
1	Concertgebouw, Amsterdam	Rectangular	0.942
4	Carl Nielsen Hall, Odense Concert House	Rectangular	0.600
3	Stadt-Casino, Basel	Rectangular	0.583
2	Royal Festival Hall, London	Rectangular	0.362
5	Tivoli Concert Hall, Copenhagen	Fan shaped	0.458
6	Grosser Sendesaal, Sender Freies Berlin	Fan shaped	0.273
7	Philadelphia Academy of Music, Phil.	Horseshoe shaped	0.607
8	Concert Hall De Doelen, Rotterdam	Geometrical	0.765
9	Berwald Hall, Stockholm	Geometrical	0.500
10	Roy Thomson Hall, Toronto	Circular	0.350

Table 8. The average AQI of both sets of halls used for training and testing networks.

	Halls for Training	Halls for Testing
Number of Halls	43	10
Mean AQI (Std. Dev.)	0.531 (0.183)	0.544 (0.203)
Range of AQI	0.222 - 0.981	0.273 - 0.942

8. RESULTS

The seven major geometrical attributes (highest correlations with AQI) were used as input variables for the neural network analysis. Thus a network function was set up as follows ;

AQI = f (V/N, Sa/N, D/W, W/H, ASW, MRA, SDI)

For the calculation of acoustic quality, based on the geometry of the halls, the data on the geometry of 43 halls were used to train the networks. For the learning procedure the convergence criteria was set to 0.000001 (error margin) and the number of iterations started from 1,000,000 times. If the network converged (ie. the network is fully trained by the input data) the calculated acoustic quality of the trained halls should be the same as the real acoustic quality index of the halls. Fig. 6 shows the training regression line which has an r-squared value of 1. This indicates that the network model used was fully trained that the prediction of acoustic quality of the new halls would be possible to undertake.

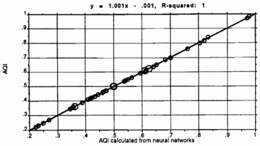

Figure 6. The scattergram of acoustic quality index against calculated acoustic quality of 43 halls which were used for training of the neural network.

Further analysis showed that the highest correlation coefficient was obtained when 5 geometric parameters (D/W, W/H, ASW, MRA, SDI) were used. Except for MRA, all these parameters have a high linear correlation with the acoustic quality of halls. Fig. 7 shows an r^2 value of almost 0.7 (r=0.835) when these parameters were used as input variables for the neural network analysis.

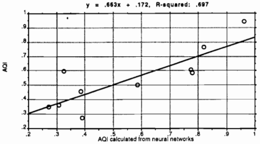

Figure 7. The scattergram of acoustic quality index against calculated acoustic quality of 10 concert halls which were predicted by neural network analysis.

8. DISCUSSION AND CONCLUSIONS

The present study indicates that musicians and music critics have very similar opinions of halls. Previous concerns that the perceptions of players and audience members could be very different do not appear to be justified, with the possible exception of "geometrically" shaped auditoria. What is of more concern is that there are pronounced differences in opinion on the quality of the acoustics of a given hall. In some cases there were approximately equal numbers of musicians (and music critics) rating a hall as "excellent", "good" and "mediocre". Examples of such cases are Berlin Philharmonie

Hall, Berlin, Roy Thompson Hall, Toronto, NHK Hall, Toyko, the Academy of Music, Philadelphia and Joseph Meyerhoff Symphonie Hall, Baltimore. The shape of the hall is significant. There is a marked preference for rectangular and horseshoe shaped halls over fan and geometrically shaped halls. More important appears to be the decoration and surface finishes in the halls which, besides influencing the diffusion of sound, also may be an influence on responses in other ways.

An individual's rating of an auditoria appears to depend on personal experiences and on factors other than just the hall's acoustic characteristics, as indicated by the dependency on the resident orchestra and the distance the respondent is from the hall on the acoustical rating and expressions of preference for rectangular halls. The reverberation time of a hall does not appear to be important though it must be stressed that the range of reverberation times was small. The age of an auditorium is of minor importance with the older halls being considered better.

Whatever acoustical analysis is carried out for the design of a concert hall ultimately there is a need to establish a relationship between the geometry and the acoustic quality of halls. Using an artificial neural network this has been done. The reason for undertaking the analysis in this way is because this analysis is of greater use for designers, at least in the initial stage of the design, as it directly links physical form with acoustic performance. This is, however, at the expense of understanding what is going on and designing within the limits of parameters used in existing auditoria. The analyses carried out indicate that there is a good basis for using hall geometry as a measure of acoustic performance. This paper also indicates the importance of the several geometrical factors on the acoustics of halls. It appears that the present predictions are better than any based on acoustical measures of concert hall acoustics.

It should be also mentioned that most of the halls used in this paper are well known halls which are regularly used for concerts. This means that most of the halls are acoustically good. Although the results clearly show a relationship between acoustic quality of halls and the geometrical properties of halls it should be reemphasized that the halls chosen for this study can not be considered a random sample. The halls are all 'good' halls and so the geometry of these halls can only be considered to influence how good the good halls are. The present paper, nevertheless, shows the importance of shape and other geometrical properties in concert hall design.

There is a need for further work. The most obvious is the need to put objective measures of hall shape and surface finishes into the analysis. This work will be undertaken together with the development of a "music intelligibility test" for auditoria which, if successful, would obviate the need for surveys such as that described early in this paper. Finally, although both musician and music critic opinions were sought for the present analysis, only the musician results were used in the neural network analysis. It would be interesting to extend the analysis for strictly auditorium rather than "stage end" acoustic design but this is also possibly pointless. After the musician survey had been carried out Leo Beranek was critical of it because it was going to be stage-end biased. At his instigation the survey of music critics was carried out. When shown the good correlation between the two surveys Beranek commented to the effect that it was to be expected as music critics formed their opinions based on what they heard from musicians!

ACKNOWLEDGMENTS

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Some Notes On Sabine Rooms

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Abstract: First the classical derivation of the Sabine equation describing the decay of a diffuse sound field in a reverberant enclosed space is reviewed. Next a modal description of sound field decay is proposed and three alternative methods of solution are considered: (a) With appropriate simplifications the Norris-Eyering equation is derived. From the latter equation the Sabine equation is derived as a first approximation. (b) With alternative assumptions the Millington-Sette equation is derived and the open window dilemma, often cited, is resolved. (c) With further argument and one assumption the modal analysis leads to the Sabine equation but not as a first approximation. Experimental verification is demonstrated by making reference to data provided by a CSIRO round robin which was conducted and reported in 1980. It is shown that all of the data obtained in the latter investigation in the seven rooms ranging in size from 106 cubic meters to 607 cubic meters which had sufficient auxiliary diffusion and for all patch sizes tested may be reduced to one line in terms of the calculated statistical absorption coefficient for an infinite patch. A simple empirical expression based upon assumed edge diffraction effects is shown to fairly well describe the data in its mid range. Explanations for departures at low and at high frequencies from the proposed expression describing the results are suggested.

1. INTRODUCTION

When the reflective surfaces of an enclosure are not too distant one from another and none of the dimensions are so large that air absorption becomes of controlling importance, the sound energy density of a reverberant field will tend to uniformity throughout the enclosure. Generally, reflective surfaces will not be too distant, as intended here, if no enclosure dimension exceeds any other dimension by more than a factor of about three. As the distance from the sound source increases in this type of enclosure, the relative contribution of the reverberant field to the overall sound field will increase until it dominates the direct field (Beranek, 1971 see Ch, 9; Smith, 1971 see Ch 3). This kind of enclosed space, in which a generally uniform (energy density) reverberant field, characterised by a mean sound pressure and standard deviation, tends to be established, has been studied extensively because it characterises rooms used for assembly and general living and will be the subject of this paper. For convenience, this type of enclosed space will be referred to as a Sabine enclosure named after the man who initiated investigation of the acoustical properties of such rooms.

All enclosures exhibit low and high frequency response and generally all such response is of interest. However, only the high frequency sound field in an enclosure exhibits those properties which are amenable to the Sabine type analysis; thus, the concepts of the Sabine room are strictly associated only with the high frequency response. For more on this matter reference may be made to Bies and Hansen (1995).

2. TRANSIENT RESPONSE

If sound is introduced into a room, the reverberant field level will increase until the rate of sound energy introduction is just equal to the rate of sound energy absorption. If the sound source is abruptly shut off, the reverberant field will decay at a rate determined by the rate of sound energy absorption. The time required for the reverberant field to decay by 60 dB, called the reverberation time, is the single most important parameter characterising a room for its acoustical properties. For example, a long reverberation time may make the understanding of speech difficult but may be desirable for organ recitals.

As the reverberation time is directly related to the energy dissipation in a room, its measurement provides a means for the determination of the energy absorption properties of a room. Knowledge of the energy absorption properties of a room in turn allows estimation of the resulting sound pressure level in the reverberant field when sound of given power level is introduced. The energy absorption properties of materials placed in a reverberation chamber may be determined by measurement of the associated reverberation times of the chamber, with and without the material under test in the room. The Sabine absorption coefficient, which is assumed to be a property of the material under test, is determined in this way and standards (ASTM C423 - 1984a; ISO R354 - 1963; AS 1045 - 1971) are available which provide guidance for conducting these tests.

In the following sections two methods will be used to characterise the transient response of a room. The classical description, in which the sound field is described statistically, will be presented first and a new method, in which the sound field is described in terms of modal decay, will be presented second. It will be shown that the new method leads to a description in agreement with experiment.

2.1. Classical Description

At high frequencies the reverberant field may be described in terms of a simple differential equation which represents a gross simplification of the physical process but none-the-less gives generally useful results. The total mean absorption coefficient $\bar{\alpha}$, including air absorption, m (dB per 1,000 m), may be written in terms of the volume, V, and total surface, S, of the room as follows.

$$\bar{\alpha} = \bar{\alpha}_w + 9.21x\,10^{-4}\, mV/S \qquad (1)$$

Using the well known expression for the energy density, $\psi = \langle p^2 \rangle / (\rho c^2)$, where p is the root mean square sound pressure, ρ is the density and c the speed of sound in air the following equation may be written for the power, W_a, or rate of energy absorbed:

$$W_a = \psi S c \bar{\alpha} / 4 = \langle p^2 \rangle S \bar{\alpha} / (4 \rho c) \qquad (2a,b)$$

Using the above equation and observing that the rate of change of the energy stored in a reverberant field equals the rate of supply, W_0, less the rate of energy absorbed, W_a, gives the following result.

$$W = V \partial \psi / \partial t = W_0 - \psi S c \bar{\alpha} / 4 \qquad (3a,b)$$

Introducing the dummy variable,

$$X = [4 W_0 / S c \bar{\alpha}] - \psi \qquad (4)$$

and using Equation 4 to rewrite Equation 3, the following result is obtained:

$$\frac{1}{X}\frac{\mathrm{d}X}{\mathrm{d}t} = -\frac{S c \bar{\alpha}}{4V} \qquad (5)$$

Integration of the above equation gives:

$$X = X_0 e^{-S c \bar{\alpha} t / 4V} \qquad (6)$$

where X_0 is the initial value.

Two cases will be considered. Suppose that initially, at time zero, the sound field is nil and a source of sound power W_0 is suddenly turned on. The initial conditions are time $t = 0$ and sound pressure $\langle p_0^2 \rangle = 0$. Substitution of Equation 4 into Equation 6 gives, for the resulting reverberant field at any later time t,

$$\langle p^2 \rangle = \frac{4 W_0 \rho c}{S \bar{\alpha}} \left(1 - e^{-S c \bar{\alpha} t / 4V}\right) \qquad (7)$$

Alternatively, consider that a steady state sound field has been established when the source of sound is suddenly shut off. In this case the initial conditions are time $t = 0$, sound power $W_0 = 0$, and sound pressure $\langle p^2 \rangle = \langle p_0^2 \rangle$. Again, substitution of Equation 4 into Equation 6 gives, for the decaying reverberant field at later time t:

$$\langle p^2 \rangle = \langle p_0^2 \rangle e^{-S c \bar{\alpha} t / 4V} \qquad (8)$$

Taking logarithms to the base ten of both sides of Equation 8 gives the following result.

$$L_{p0} - L_p = 1.086 S c \bar{\alpha} / V \qquad (9)$$

Equation 9 shows that the sound pressure level decays linearly with time and at a rate proportional to the Sabine absorption $S\bar{\alpha}$. It provides the basis for the measurement and the definition of the Sabine absorption coefficient $\bar{\alpha}$.

Sabine introduced the reverberation time, T_{60} (seconds), as the time required for the sound energy density level to decay by 60 dB from its initial value. He showed that the reverberation time, T_{60}, was related to the room volume, V, the total wall area including floor and ceiling, S, the speed of sound, c, and an absorption coefficient, $\bar{\alpha}$, which was characteristic of the room and generally a property of the bounding surfaces. Sabine's reverberation time equation, which follows from Equation 9 with $L_{p0} - L_p = 60$, may be written as follows

$$T_{60} = 55.25 V / S c \bar{\alpha} \qquad (10)$$

2.2. Modal description

The discussion thus far suggests that the reverberant field within a room may be thought of as composed of the excited resonant modes of the room. This is still true even in the high frequency range where the modes may be so numerous and close together that they tend to interfere and cannot be identified separately. In fact, if any enclosure is driven at a frequency slightly off-resonance and the source is abruptly shut off, the frequency of the decaying field will be observed to shift to that of the driven resonant mode as it decays (Morse, 1948).

In general, the reflection coefficient, β, (the fraction of incident energy which is reflected) characterising any surface is a function of the angle of incidence. It is related to the corresponding absorption coefficient, α, (the fraction of incident energy which is absorbed) as $\alpha + \beta = 1$. Let $\langle p(t)^2 \rangle$ be the mean square band sound pressure level at time t in a decaying field and $\langle p_k(t)^2 \rangle$ be the mean square sound pressure level of mode k. The decaying field may be expressed in terms of the sum of the time varying modal square pressure amplitudes $\langle p_k(t)^2 \rangle$, mean reflection coefficients β_k and modal mean free paths Λ_k as follows,

$$\langle p(t)^2 \rangle = \sum_{k=1}^{N} \langle p_k(t)^2 \rangle \beta_k^{ct/\Lambda_k} \qquad (11)$$

where

$$\beta_k = \prod_{i=1}^{n} \left[\beta_{ki}\right]^{S_i/S_k} \qquad (12)$$

In the above equations N is the number of modes within a measurement band. The quantities β_{ki} are the reflection coefficients and S_i are the areas of the corresponding reflecting surfaces encountered by a wave travelling around a modal circuit associated with mode k and reflection from surface i (Morse and Bolt, 1944). The S_k are the sums of the areas of the S_i reflecting surfaces encountered in one modal circuit of mode k.

The modal mean free path Λ_k is the mean distance between reflections of a sound wave travelling around a closed modal circuit and for a rectangular room is given by the following equation (Larson, 1978).

$$\Lambda_k = \frac{2 f_k}{c} \left[\frac{n_x}{L_x^2} + \frac{n_y}{L_y^2} + \frac{n_z}{L_z^2}\right]^{-1} \qquad (13)$$

The quantities β_k are the reflection coefficients encountered during a modal circuit and the symbol $\prod_{i=1}^{n}$ represents the product of the n reflection coefficients where n is either a multiple of the number of reflections in one modal circuit or a large number. The quantity f_k is the resonance frequency given by the following equation for mode k of a rectangular enclosure, which has the modal indices n_x, n_y, n_z.

$$f_k = \frac{c}{2}\sqrt{\left[\frac{n_x}{L_x}\right]^2 + \left[\frac{n_y}{L_y}\right]^2 + \left[\frac{n_z}{L_z}\right]^2} \qquad (14)$$

In the above equation the subscript k on the frequency variable f indicates that the particular solutions or "eigen" frequencies of the equation are functions of the particular mode numbers n_x, n_y, and n_z.

The assumption will be made that the energy in each mode is on average the same, so that in Equation 11, p_k may be replaced with $p_0/\sqrt{N}$ where p_0 is the measured initial sound pressure in the room when the source is shut off. Equation 11 may be rewritten as follows.

$$< p(t)^2 > \; = \; < p_0^2 > \frac{1}{N}\sum_{k=1}^{N} e^{(ct/\Lambda_k)\log_e(1-\alpha_k)} \qquad (15)$$

A mathematical simplification is now introduced. In the above expression the modal mean free path length is replaced with the mean of all of the modal mean free paths, $4V/S$, and the modal mean absorption coefficient α_k is replaced with the area weighted mean statistical absorption coefficient $\overline{\alpha}_{st}$ for the room. The quantity V is the total volume and S is the total wall, ceiling and floor area of the room. In exactly the same way as Equation 10 was derived from Equation 8, the well known reverberation time equation of Norris - Eyring may be derived from Equation 15 giving an expression as follows.

$$T_{60} = -\frac{55.25V}{Sc\log_e(1-\overline{\alpha}_{st})} \qquad (16)$$

This equation is often preferred to the Sabine equation by many who work in the field of architectural acoustics. Note that air absorption must be included in $\overline{\alpha}_{st}$ in a similar way as it is included in $\overline{\alpha}$. It is worth careful note that Equation 16 is a predictive scheme based upon a number of assumptions that cannot be proven, and consequently inversion of the equation to determine the statistical absorption coefficient $\overline{\alpha}_{st}$ is not recommended. With a further simplification, the famous equation of Sabine is obtained. When $\overline{\alpha}_{st} < 0.4$, an error of less than 0.5 dB is made by setting $\overline{\alpha}_{st} \approx \log_e(1-\overline{\alpha}_{st})$ in Equation 16. Then by replacing $\overline{\alpha}_{st}$ with $\overline{\alpha}$, Equation 10 is obtained.

Alternatively, if in Equation 15 the $(1-\alpha_k)$ are replaced with the modal reflection coefficients β_k and these in turn are replaced with a mean value, called the mean statistical reflection coefficient $\overline{\beta}_{st}$, the following equation of Millington and Sette is obtained.

$$T_{60} = -55.25V/Sc\log_e\overline{\beta}_{st} \qquad (17)$$

The quantity $\overline{\beta}_{st}$ is given by Equation 12 but with changes in the meaning of the symbols. β_k is replaced with $\overline{\beta}_{st}$ which is now to be interpreted as the area weighted geometric mean of the random incidence energy reflection coefficients, β_i, for all of the room surfaces; that is,

$$\overline{\beta}_{st} = \prod_{i=1}^{n} \beta_i^{S_i/S} \qquad (18)$$

The quantity β_i is related to the statistical absorption coefficient $\alpha_{st,i}$ for surface i of area S_i by $\beta_i = 1-\alpha_{st,i}$. It is of interest to note that although taken literally Equation 18 would suggest that an open window having no reflection would absorb all of the incident energy and there would be no reverberant field, the interpretation presented here suggests that an open window must be considered as only a part of the wall in which it is placed and the case of total absorption will never occur. Alternatively, reference to Equation 11 shows that if any term β_i is zero it simply does not appear in the sum and thus will not appear in Equation 17 which follows from it.

3. NEW ANALYSIS

When a sound field decays all of the excited modes decay at their natural frequencies (Morse, 1948); the decay of the sound field is modal decay (Lawson, 1978). In the frequency range in which the field is diffuse it is reasonable to assume that the energy of the decaying field is distributed among the excited modes about evenly within a measurement band of frequencies. In a reverberant field in which the decaying sound field is also diffuse, as will be shown, it is also necessary to assume that scattering of sound energy continually takes place between modes so that even though the various modes decay at different rates scattering ensures that they all contain about the same amount of energy on average during decay. Effectively, in a Sabine room all modes within a measurement band will decay on average at the same rate, because energy is continually scattered from the more slowly decaying modes into the more rapidly decaying modes.

Let $\langle p(t)^2\rangle$ be the mean square band level at time t in a decaying field and $\langle p(0)^2\rangle$ be the mean square level at time t = 0. The decaying field may be expressed in terms of a time varying mean square pressure amplitude $p(t)^2$, modal mean square pressure amplitude $B_i(t)$, mean reflection coefficient β_i and modal mean free paths Λ_i. Equation 11 may be rewritten as follows.

$$\langle p(t)^2\rangle = \frac{\langle p(0)^2\rangle}{\Delta N}\sum_{i=N_1}^{N_2} B_j(t)\beta_i^{ct/\Lambda_i} \qquad (19)$$

In the above equation the number of modes within a measurement band bounded below by N_1 and above by N_2 is ΔN. The reflection coefficient β_i is given by Equation 12. It will be noted that Equation 19 is the same as Equation 15 with the exception of the introduction of the modal amplitudes $B_i(t)$.

It may readily be shown (Bies, 1984) that when a reverberant field is diffuse the mean of the modal mean free paths, Λ_i, is the mean free path of the room given by the following expression (Morse and Bolt, 1944).

$$\Lambda = \frac{4V}{S} \qquad (20)$$

Sabine observed that in a room in which the sound field is diffuse decay of the reverberant field is a linear function of time whatever the initial level when the sound source is abruptly shut off. Sabine introduced an absorption coefficient, α_{sab} , which is generally a property of the walls of the room relating the change in sound pressure level and the length of time of reverberation, t. For convenience, a room in which the sound field is diffuse and reverberant sound field decay is a linear function of time will be referred to here as a Sabine room (Fasold, Kraak, and Schirmer, 1984). The room reverberation decay may be written in terms of the room mean free path Λ and the Sabine absorption coefficient α_{sab} as follows.

$$\log_e \frac{\langle p(t)^2 \rangle}{\langle p(0)^2 \rangle} = -\frac{ct}{\Lambda}\alpha_{sab} \quad (21)$$

It will be instructive to consider first the decay of a single mode as given by Equation (19). In this case letting $\Delta N = 1$, $i = j$ and $B_i = 1$ Equation (19) may be rewritten as follows.

$$\log_e \frac{\langle p(t)^2 \rangle}{\langle p(0)^2 \rangle} = \frac{ct}{\Lambda_j}\log_e \beta_j \quad (22)$$

Alternatively, if in Equation (22) $\beta_j = 1 - \alpha_j$ where α_j is small then

$$\alpha_j = -\log_e \beta_j \quad (23)$$

Substitution of Equation (23) into Equation (22) gives an equation formally the same as Equation (21). Evidently, in a Sabine room reverberant sound field decay is formally the same as that for any individual mode. Consequently, it will be convenient to extend the meaning of Equation (23) to define a Sabine reflection coefficient, β_{sab}, and to define the relationship between the Sabine reflection coefficient and a Sabine absorption coefficient. Reference to Equation (22) suggests that the associated Sabine reflection coefficient is a mean reflection coefficient of the excited and decaying modes of the room.

Solving Equation (21) for the Sabine absorption coefficient, a_{sab}, and introducing Equations (19) and (23) gives the following expression.

$$-\log_e \beta_{sab} = -\frac{\Lambda}{ct}\log_e\left[\frac{1}{\Delta N}\sum_{i=N1}^{N2} B_i(t)\,\beta_i^{ct/\Lambda_i}\right] \quad (24)$$

The following Equation is obtained from Equation (24).

$$\beta_{sab}^{ct/\Lambda} = \frac{1}{\Delta N}\sum_{i=N1}^{N2} B_i(t)\,\beta_i^{ct/\Lambda_i} \quad (25)$$

Consideration of Equation (25) shows that in general β_{sab} is a function of time, and the reverberant field decay will not be linear with time. For example, consider the case that all $B_i = 1$ and no scattering of sound energy between modes takes place during sound field decay. If at time zero the amplitudes of all modes were approximately equal and subsequently the modes have all decayed independently of each other, those modes decaying most rapidly will determine the decaying field response initially while those modes decaying least rapidly will progressively dominate the remaining reverberant field response as the field decays. The latter effect is observed experimentally in a reverberant room unless sufficient diffusing elements are introduced in the room. Consequently, it is necessary to introduce the effect of scattering of sound energy from those modes more highly excited to those modes less excited.

In a Sabine room, however, experience shows that β_{sab} is a constant independent of time. For example, Equation (25) may be rewritten as,

$$\beta_{sab} = \left[\frac{1}{\Delta N}\sum_{i=N1}^{N2} (B_i\beta_i)^{ct/\Lambda_i}\right]^{\Lambda/ct} \quad (26)$$

Consideration of Equation (26) shows that in order that there be a solution it is necessary that all terms in the sum on the right hand side of the equation must be equal and in turn each must be equal to the term on the left hand side of the equation.

In the model which has been proposed it is assumed that sound energy is removed from modes least damped through scattering upon reflection at the boundaries and introduced into modes more heavily damped. The amplitude coefficients, B_i, of the latter quantities will be greater than 1 while the amplitude coefficients of the former quantities will be less than 1. Further consideration of Equation (26) shows that there will be some modes which will be unaffected by the assumed energy exchange and in their case the amplitude coefficients are 1. For such modes the above considerations lead to the following conclusion.

$$\beta_{sab} = \beta_i^{\Lambda/\Lambda_i} \quad (27)$$

If it is assumed that the unaffected modes are the modes whose reflection coefficients are the mean of the modal reflection coefficients then it is reasonable to assume that the modal mean free paths are also mean values of the modal mean free paths. In this case the Sabine reflection coefficient is simply equal to the modal mean reflection coefficient.

$$\beta_{sab} = \beta_{modalmean} \quad (28)$$

The modal mean reflection coefficient has the form given by Equation (12).

Consideration of Equation 23 suggests the following relation be assumed to hold for all values of α_{sab} and β_{sab} . That is, it will be assumed that Equation 23 constitutes a definition of α_{sab} in terms of β_{sab}.

$$\alpha_{sab} = -\log_e \beta_{sab} \quad (29)$$

Substitution of Equation 29 in Equation 22 leads to the famous equation of Sabine as follows.

$$T_{60} = \frac{55.25V}{Sc\,\alpha_{sab}} \quad (30)$$

The important difference in the equations derived earlier relating the Sabine absorption coefficient and the reverberation time and Equation 30 is to be noted. Although they are formally identical the earlier expressions are all based upon a number of assumptions which can not be proven while in the latter case the only assumption made is that Equation 23 is true. As will be shown the Sabine equation given by Equation 30 leads to agreement between measurement and prediction when edge diffraction is taken into account in the determination of the Sabine absorption coefficient.

4. CALCULATION OF THE SABINE ABSORPTION COEFFICIENT

It is customary, following Sabine, to calculate absorption as proportional to the area of an absorbing patch of material. On the other hand, where there is a large difference in surface impedances between the absorbing patch and the adjacent wall or floor on which it is mounted, as in the case of the usual reverberation room test, large diffraction effects will take place which in the case of the reverberation room have the effect of considerably adding to the effective area of the patch (Morse & Bolt 1944). Where A_p is the physical area of the patch and A_e is the effective additional area due to edge diffraction the Sabine absorption may be written as follows.

$$A_p \alpha_{sab} = \alpha_\infty (A_p + A_e) \qquad (31)$$

In the above equation a_{sab} is the measured Sabine absorption coefficient and a_∞ is the calculated statistical absorption coefficient for an unbounded surface.

Various authors have considered the calculation of the effective area Ae (Pellam 1940, Morse and Bolt 1944, Levitas and Lax 1951, Northwood et al. 1959, Northwood 1963) with various degrees of success but none are convenient to use and only that of Northwood considers the rectangular patch as considered in the CSIRO tests which will be considered here (see below). The approach which will be taken will be empirical but guided by the observations of Morse and Bolt (1944) and will be limited to showing that a consistent relationship exists between the measurements and theory when diffraction is taken into account.

Following Morse and Bolt (1944) the effective area will be assumed proportional to an effective perimeter of the patch $P' = P - a$, where P is the physical perimeter and a is a constant that is assumed to account for the corners of the patch, multiplied by a wavelength written in terms of the speed of sound c and frequency f as c/f. Equation 31 gives the following postulated functional relationship which will be shown empirically to exist.

$$\left(\frac{\alpha_{sab}}{\alpha_\infty} - 1\right) = F\left(\frac{cP'}{A_p f}\right) \qquad (32)$$

5. COMPARISON OF MEASUREMENTS AND THEORY

In 1980 CSIRO-Division of Building Research published a report describing the results of a round robin conducted in Australia and New Zealand in which the Sabine absorption coefficients of samples of Sillan were determined using the standard reverberation decay method (Davern & Dubout 1980). In all, twenty one reverberant rooms were involved in the tests. The test material, a rock wool batt material of density 100 kg/m³ made by Grunzweig-Hartmann of Germany, was similar to that used in an earlier round robin in Europe (Kosten 1960).

A principal conclusion of the latter report was that those rooms with auxiliary diffusing surfaces equal to or greater than 1.4 times the floor area of the reverberant room gave results consistent among themselves whereas those rooms with less or no auxiliary diffusing surfaces gave results which where inconsistent with all other rooms. Seven rooms ranging in volume from 106 to 607 cubic meters were identified as meeting the diffusing surfaces criterion which gave consistent results for samples ranging in size from 5.0 to 22.5 square meters. Sample sizes were chosen consistent with the size of the room and a sample of 10.5 square meters was tested in all rooms. The data obtained in the latter seven rooms provides the basis for a comparison with prediction.

The referenced report provides four measurements of a 5.0 m² sample, six measurements of a 7.5 m² sample, seven measurements of a 10.5 m² sample, three measurements of a 16.0 m² sample, and one measurement of a 22.5 m² sample in all one third octave bands from 100 Hz to 5,000 Hz. For the purposes of the proposed comparison average values have been determined and recorded in Table 1. Also recorded in the table for convenience of later comparison are calculated values of the statistical absorption coefficient. The statistical absorption coefficient is shown for an infinite locally reactive surface. However, calculations for a bulk reacting surface are only slightly greater at frequencies greater than about 2000 Hz and thus the difference between the two types of surfaces is considered negligible.

Table 1. Absorption Coefficients

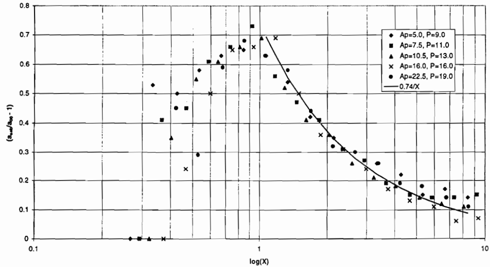
f (Hz)	5.0 m²	7.5 m²	10.5 m²	16.0 m²	22.5 m²	α_∞
100	0.07	0.11	0.11	0.10	0.16	0.1
125	0.26	0.24	0.23	0.21	0.22	0.17
160	0.33	0.32	0.34	0.33	0.35	0.22
200	0.49	0.50	0.50	0.51	0.52	0.31
250	0.67	0.68	0.68	0.68	0.67	0.41
315	0.86	0.90	0.88	0.88	0.82	0.52
400	1.04	1.00	0.97	0.96	0.92	0.64
500	1.14	1.09	1.04	1.01	0.98	0.74
630	1.15	1.14	1.10	1.06	1.05	0.81
800	1.16	1.13	1.08	1.07	1.08	0.86
1000	1.17	1.14	1.09	1.05	1.07	0.90
1250	1.15	1.08	1.07	1.03	1.07	0.91
1600	1.12	1.06	1.05	1.02	1.05	0.92
2000	1.07	1.06	1.04	0.99	1.03	0.93
2500	1.10	1.07	1.04	1.01	1.03	0.94
3150	1.07	1.08	1.05	0.99	1.06	0.94
4000	1.08	1.08	1.05	1.01	1.08	0.94
5000	1.12	1.06	1.05	1.00	1.08	0.94

Use of the data in Table 1 has allowed construction of Figure 1. In turn the figure has allowed determination of an empirical function $F(P'c/A_p f)$ which seems to fairly well describe the data. The empirically determined relationship is,

$$\left(\frac{\alpha_{sab}}{\alpha_\infty} - 1\right) = \frac{0.74}{X} \qquad (34)$$

where

$$X = \frac{A_p f}{c(P - 3.55)} \qquad (35)$$



Plot of measured and normalized sabine absorption coefficients (Table 1) as a function of normalized frequency (equation 35.) See text for discussion.

Consideration of the figure shows generally good agreement over the decade range of the parameter X from about 1.0 to about 10. Above 10. one would expect the edge correction to diminish to zero. It is suggested that the evident departure from the latter expectation at high frequencies may be due in part to the discontinuity in height at the edge between the surface of the absorptive patch and the concrete floor which increases as the ratio of sample thickness to wavelength increases. This has not been considered in any analysis.

Departure at the low frequency end is probably due to failure at long wavelengths of the reverberant rooms to meet the conditions for a diffuse field implicit in the Sabine formulation. At very low frequencies the wide scatter is due to the difficulty of making the necessary reverberation measurements with sufficient accuracy. However, even though the data become quite scattered as the frequency decreases a generally consistent trend can be identified suggesting the possibility of an analytic solution.

6. CONCLUSION

An analysis has been presented which shows that the Sabine equation is correct if it is accepted that the mean modal reflection coefficient and the statistical absorption coefficient are related as proposed. In support of this conclusion the relationship between the calculated statistical absorption coefficient of an unbounded porous material, Silan, and the measured absorption coefficient has been demonstrated in the case that adequate diffusion has been achieved in the test chambers used for the measurements. The demonstration has shown the importance of adequate diffusion and edge diffraction for the determination of the sound absorptive properties of a test material in a reverberation chamber. Conversely, by implication the importance of diffusion and edge diffraction for application of absorptive materials in a Sabine type room have also been demonstrated.

For application to the practice of room acoustics a quantitative measure of diffusion is required which besides identifying adequate diffusion would also identify degree of partial diffusion (Bodlund 1976, 1977a,b). In turn, further investigation is required to determine the quantitative effect of partial diffusion on sound absorption so that it may be taken into account in practice. Additionally, simple procedures are required which will allow estimation of the effect of edge diffraction on sound absorption (Pellam 1940, Morse and Bolt 1944, Levitas and Lax 1951, Northwood et al. 1959, Northwood 1963).

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Notes on Office Acoustics

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Abstract: Based on theoretical aspects of acoustics and years of experience, practical methods of office acoustic design have been determined. When installing partitioning for cellular offices, care needs to be taken to ensure that the sound transmission loss of the partition construction is matched by surrounding constructions and details. When designing open office plans, a careful balance of all of the factors, including sound absorption, distance, shielding and background noise level, is required. The acoustic design of conference rooms must also allow for the modern audio technology associated with such rooms.

1. INTRODUCTION

This paper discusses some acoustical aspects of modern offices. It is intended to summarise some of the conclusions that have resulted from years of experience of the acoustical design of office spaces. It is not intended to be fully comprehensive and the technical basis for some of the conclusions is also not discussed in detail.

Changes which have occurred over the last decade or so in the way offices work have changed the acoustical requirements of office spaces. Such changes as the extensive use of computers, the introduction of audio visual facilities into Conference Rooms and the more common use of Tele-Conferencing and Video-Conferencing facilities. This Technical Note discusses both the acoustics related to the recent changes and conventional office acoustics. In particular, office partitioning, open office plans and conference rooms are discussed in some detail.

2. OFFICE PARTITIONS

To allow flexibility within office spaces, it is common to provide office partitioning using dry construction, as opposed to brick or concrete block. Where acoustical performance is required, the partition is often a stud and plasterboard partition. Such partitions allow medium to good sound transmission loss performance and overall acoustical attenuation in the speech range. This is achieved at a low weight to performance ratio, compared with such materials as brick. Details of plasterboard wall sound transmission loss are readily available from plasterboard manufacturers.

However, where a plasterboard partition is used to separate spaces in an office, the transmission through the partition is not the only noise path to be considered. Noise can also be transmitted up through the ceiling and back down again in the adjacent space as well as through any poor seals at the junctions. The main noise paths are demonstrated in Figure 1.

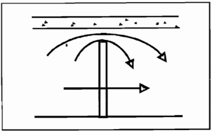

Figure 1. Noise Transmission path through and around an Office partition (section).

Whilst it is relatively easy to obtain good seals through the plasterboard wall at the joints of sheets of plasterboard (since manufacturers have standard taping and setting methods), seals to the ceiling and to window mullions are often difficult to achieve. To maximise the flexibility within office spaces, builders are reluctant to use good acoustic sealants (such as Mastic) between the head of the partition and the underside of the ceiling. Often standard foam strips are used and, whilst these provide better seals than can be provided without such strips, good airtight seals are not possible. This problem is aggravated by the types of acoustic ceilings commonly used in office spaces, such as mineral fibre ceiling tiles laid in a grid or perforated metal pan ceiling tiles also laid in a grid.

It is also common to find poor seals between office partitions and window mullions, where such partitions extend to the building perimeter walls. The expansion and contraction of the window mullion, especially where it is exposed to direct sunlight, tends to crack a standard plaster seal. It is therefore necessary to use a sealant with a degree of flexibility in the joint, such as a non-setting Mastic or a silicone sealant. It also follows that the end of the partition abutting the external wall needs to be constructed so as to follow the profile of the wall and to take account of the window sill and any other construction above and below the window.

In respect of sound transmission from room to room via the ceiling space, the ceiling material needs to be selected so that this path does not become a weak link in the system. Most major ceiling manufacturers have had their ceilings tested to provide room-to-room sound transmission loss performances. For common mineral fibre ceiling tiles, the sound transmission loss is normally in the vicinity of Sound Transmission Class (STC) 35-40. Such a performance is adequate for most standard office partitions, but some form of upgrading is required where a high standard office partition is needed, such as STC 40 or 45. The best way of upgrading the ceiling performance is to install a vertical baffle extending from the ceiling to the underside of the slab above to provide a third barrier between the two rooms via the ceiling. The third barrier is normally so effective that only a single layer of standard building material, such as plasterboard, is necessary to substantially improve the room-to-room sound transmission loss.

Care should be taken where perforated metal pan ceiling tiles exist within the building. Although these tiles commonly have insulation laid over them, they are almost transparent to noise. Accordingly, sound transmission loss via the ceiling space is substantially below that of a low performance partition. This problem can be overcome by again installing a baffle within the ceiling space or, alternatively, by fixing a solid màterial to the back of the tiles (such as single unperforated metal).

Improving the room-to-room sound transmission loss via the ceiling space by the installation of baffles or by backing of tiles will have no effect upon the quality of seal between the partition and the underside of the ceiling. This weakness often limits the performance of office partitions unless the partition extends through the ceiling, preferably to the underside of the concrete slab above.

Whilst the most critical partitions within office spaces are those that separate individual rooms, such as two offices, two conference rooms or an office and a conference room, partitions separating such rooms from corridors can also be of some acoustical importance. However, these walls are often substantially weakened by the installation of doors for access. Since a good solid core door with acoustical seals is unlikely to provide more than STC 30, no benefit is gained by installing a partition with a sound transmission loss greater than STC 40. In fact, little benefit is gained by installing a partition with a sound transmission loss of greater than STC 35.

The frequency characteristics of plasterboard partition sound transmission loss performance need to be considered in some circumstances. As demonstrated in Figure 2, the STC of a stud/plasterboard partition with insulation in the cavity can be as good overall as a single brick wall. However, the sound transmission loss performance in the low and high frequencies is less than that for a brick wall and the low frequency performance particularly can prove important where audio-visual facilities are to be installed. Since all partitions and walls are weaker in the low frequency bands, it can be important to maintain the highest practicable performance in those low frequencies. Accordingly, stud/plasterboard partitions can often result in low frequency noise transmission from rooms with audio-visual facilities to adjacent rooms and, for larger conference rooms, brick construction or heavy plasterboard construction is often required. One should be aware that STC performance does not give a true indication of the overall subjective performance in many instances.

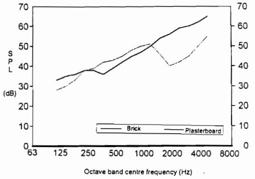

Figure 2. Sound Transmission Loss for 110mm brick wall and 16mm plasterboard each side of 64mm steel studs with 50mm insulation in the cavity (STC 44).

3. OPEN OFFICE PLANS

When developing open office plans instead of cellular offices, one of the most difficult features is establishing sufficient acoustical privacy between workers. The success in this regard depends upon a number of factors:

* Sound absorption in the space.
* Distance between office personnel.
* The degree of shielding between personnel.
* The background noise level.

Sound absorption is most commonly provided by the use of an acoustic ceiling. The perforated metal pan ceiling tile with sound absorbent insulation above provides the best available ceiling absorption and this level of absorption is highly desirable. However, the most common form of acoustic ceiling within modern offices is the mineral fibre ceiling tile. Its sound absorption coefficient is less than the perforated metal pan tile, but it can prove an acceptable compromisee.

Other reflective surfaces, particularly walls, can affect the transmission of sound throughout the open office space. Open plans therefore work best in large areas where reflective walls affect a limited proportion of the office personnel. On the other hand, it is possible to apply sound absorption to reflective walls. Over and above this, all screens to be used within the space should be the sound absorbent type and this limits the selection to a small proportion of commercially available "acoustic" screens.

Obviously, the further apart that office personnel are, the less likely that a lack of acoustical privacy will occur. In practice, a distance of 3 m between personnel orientated back-to-back will prove adequate, but greater distances are required where the personnel are face-to-face. However, shielding by office screens can provide the required privacy at much reduced distances.

The shielding is best provided by free standing screens or screens which form part of work stations. The line of sight between the heads of office personnel must be clearly broken to ensure significant reduction in sound transmission occurs. This means that the screens should be of a height of at least 1.5 m above the floor. Such screens can then reduce the minimum distance between office personnel orientated face-to-face to approximately 1.5 m, depending upon other factors such as sound absorption and background noise level.

Most office spaces have a background noise level generated by operation of the air-conditioning system. This background level can mask the intrusion of sounds from nearby office personnel, thereby reducing the intelligibility and increasing the acoustic privacy. The background noise level is best when sufficient in level and of a spectrum shape to provide good masking, whilst at the same time being subjectively unobtrusive. Figure 3 shows a range of background noise levels which appear to have the correct balance between masking and unobtrusiveness. For convenience the RC curve (say RC40) may be used as an approximation, although the shape of that curve is not tuned to provide the fine balance that is often necessary.

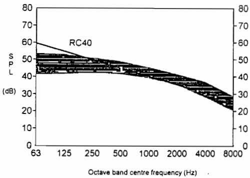

Figure 3. Suggested Background Noise Spectrum.

Air-conditioning systems can be used to specifically create a background noise level similar to the type required for an open office plan. The air outlets can be adjusted or dampered back to provide approximately the correct level and spectrum. However, this method is relatively unreliable and does not give great flexibility in setting the spectrum shape.

The best way of providing the background noise level is by the use of an electronic system. This system commonly incorporates a noise generator, a graphic equaliser, an amplifier and a series of loud speakers installed in the ceiling space. The method of installing the loud speakers in the ceiling space is important in obtaining a good spread of sound throughout the space. Since loud speakers are quite directional in the high frequencies, loud speakers mounted behind standard loud speaker baffles within the ceiling give a substantially different spectrum shape directly under than to one side One of the best ways of overcoming this, whilst at the same time providing a well rounded unobtrusive quality of sound, is to mount the loud speaker above the ceiling tile and allow the sound to be transmitted through the tile. Figure 4 shows a successfully used system for offices containing mineral fibre ceiling tiles.

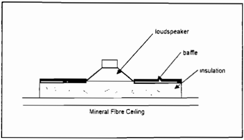

Figure 4. Suggested loudspeaker mounting detail for a mineral fibre ceiling.

4. CONFERENCE ROOMS

The acoustical design of conference rooms to provide a higher degree of intelligibility is widely understood by acousticians. However, the extensive use of tele-conferencing and video-conferencing in today's conference rooms changes the acoustical characteristics required within the room. These systems commonly use microphones which are often located at some distance from the person speaking. Under these circumstances, many existing conference rooms will generate quite reverberant sounds for the receiver at the end of the conference transmission line.

To overcome this, the conference rooms should be designed to be relatively dead acoustically. As a general rule, small conference rooms work relatively well where there is good carpet on the floor and an acoustic ceiling over. However, some sound absorption on wall areas will improve the overall performance.

For larger conference or seminar rooms, a more detailed analysis of reverberation times is required. These rooms should be designed as if they are low standard sound studios (where this is practicable) and it is suggested that a reverberation time somewhere between that recommended for a room for speech and a talk studio would suffice.

5. CONCLUSION

Today's office building occupants are demanding a higher acoustical standard within their offices than they did two decades ago. Acoustical privacy, whether within cellular offices or an open office plan, is the over-riding requirement. With the new office audio-visual aids, providing this privacy is getting harder and harder.

Letters...

I write in answer to Dick Benbow's perplexing problem ("Note" Acoustics Australia Aug 95). It would seem from the precise location of the noise nuisance that we are dealing with an interference effect in 3 dimensions. The homes affected are obviously at anti-nodes on the interference pattern.

How then is the increase in frequency to be explained? I would suggest a second diffraction pattern from a much lower frequency noise with a coincident anti-node. This may be sub-sonic. It may be generated by a different mechanism, from a different array element, from a different structure. My guess is that the second noise would also be wind-driven.

If Dick wants to rest easy at night, he may find a nocturnal excursion on a windy night with appropriate equipment worthwhile.

Neil Clutterbuck MAAS

New Members...

The following are new members of the Society or members whose grading has changed.

Member: Mr G J Cohen (SA), Mr M A Jochelson (NSW)

Student: Mrs D Davis (SA)

News...

NSW MEETINGS
Occupational Noise and Hearing Loss

The NSW Division's third meeting for 1995, held at the NAL auditorium in Chatswood on Wednesday 23 August, gave an overview and update of recent developments in the occupational noise and hearing loss industry. The meeting was very well attended with about 75 (perhaps a record?) to hear the panel of 5 speakers. The audience comprised barristers, solicitors, audiologists, acoustical consultants, researchers, members of insurance and employer groups and government organisations, as well as some individuals with a personal interest. It is estimated that at least half of the audience was from outside the society.

Ken Mikl, of the Workcover Authority of NSW provided a succinct outline of Workcover's role and responsibilities which includes its function as underwriter to the Workers' Compensation insurance industry. He also gave statistics and trends on the severity of occupational hearing loss in NSW including figures on the numbers of compensation claims made per year, overall financial cost and breakdowns of other factors such as age, gender, types of occupation and industry.

Dr John Macrae, of Australian Hearing Services and Chairperson, Standards Steering Committee AV/3, presented an outline of recent research on the accuracy and reliability of hearing loss measurements methods, emphasising the need for regular on-going audiometric testing of employees. He discussed the use of short term hearing threshold shift measurements as a means of determining the effect of occupational noise upon employee hearing loss. He also examined what appeared to be a novel approach to determining the onset of hearing impairment by looking at the summation of hearing loss across a range of frequencies rather than at single frequencies.

Barry Robinson, a barrister from University Chambers in Sydney and a leading advocate of hearing loss claimants, spoke on legislative developments and legal processes. He examined the differences between Workers' Compensation and Common Law claims with the latter requiring proof of employer negligence. He indicated that claims for hearing loss compensation under Common Law can be up to ten times those under Workers' compensation. He also indicated that whilst the majority of claims are made under Workers' Compensation legislation there is a trend towards Common Law claims which can take significantly longer time through the courts but which to his knowledge have been won in 99% of cases. Mr Robinson's presentation on the night was colourful and provoked a strong response from some members of the audience during question time.

Louis Challis, of acoustical consulting firm Challis & Associates and member of the Standards Committee AV/3, spoke principally on Australian Standards AS 1269 and AS 1270 currently under review with draft revisions to be released in either late 1995 or in 1996. He spoke of the various groups represented on the relevant Standards Committees, some of the bases forming the Standards discussed and of noise level and noise dosage limits.

David Eden, of acoustical consulting firm Eden Dynamics (soon to be Acoustic Dynamics) and member of Standards Committee AV/3, spoke on engineering and administrative approaches to occupational noise exposure reduction and control discussing in particular the differences between laboratory and work place performance of hearing protectors. David also introduced his novel concept of a star rating system (up to 5 stars) for rating employer organisations, in terms of their occupational noise environment. This would be based on occupational noise exposure levels and effectiveness of administrative and engineering noise control programs. David indicated that he would like to see more funds directed to controlling noise at its source rather than at the hearing loss compensation industry end.

Following the meeting the majority of those in attendance adjourned to the in house cafe for food, drink and discussion, concluding yet another successful and stimulating meeting.

Capitol Theatre

On Monday 9 October the NSW Division held its AGM in the Dress Circle of the recently restored Capitol Theatre in Sydney's Haymarket, perhaps the grandest and most ornate setting for an Acoustical Society AGM to date? Immediately following the AGM a technical meeting was presented on the architectural and mechanical services acoustics work that went into the restoration. The attendance was around 70, of which approximately a third were from architectural firms.

Peter Knowland, of acoustical consulting firm Peter R. Knowland and Associates Pty Ltd outlined his firm's role, on behalf of Sydney Council, in preparing the brief setting the acoustic performance parameters for the theatre restoration project. Peter also gave a brief history of how the project had come about, indicating that conservation architects Lawrence Nield & Partners had suggested the restoration of the Capitol Theatre in an ideas competition looking at an alternative venue for the Australian Opera which also coincided with pressure at the time for a new lyric theatre having a 2000 seat capacity for opera and ballet performances. It was emphasised that the theatre's original acoustical characteristics were to be preserved including the soft form ceiling, diffusion adjacent to the stage, acoustic volume and a full occupancy reverberation time of around 1.6 seconds. Ambient noise level goals of NR18 and NR25 were respectively set for the audience and stage areas. The winning proposal was provided by Fletcher Constructions.

Barry Murray of acoustical consulting firm Wilkinson Murray Pty Ltd then spoke on the return acoustical design brief and the involvement his company provided in the realisation of the refurbishment works. Barry commenced with a description of issues providing initial design constraints including fire rating, extension in stage size for opera including a raised fly tower, operable ceiling hatches for light projection, installation of a follow spot room above the Dress Circle, and provision of multiple use rooms back of house adjacent to the main theatre space.

Whilst accepting most of the initial tender design brief the only significant departure was in relation to control of train noise. The estimated cost to reduce the initial NR50 train noise levels in the theatre by track isolation would have been $1.5 m. So instead it was decided work on the theatre itself with a combination of structural isolation and principally construction of the raised stage and audience floors and low frequency energy absorbers. Although initially questioned the NR18 design criterion was finally adopted. Barry indicated that the rear wall of the Stalls was brought forward to improve acoustics in this area of the theatre and to allow an increase in foyer size. In order to maintain the existing internal decorative features air conditioning outlets were concealed above the stage proscenium arch and above the back of the theatre, and the house sound system concealed behind the decorations each side of the stage. Acoustical absorption was placed under the ceiling of the fly tower to control reverberation and above the orchestra pit to reduce ceiling reflection. The carpeted floor in the audience area was found to have little effect on space reverberation times.

Much attention was paid to improving the acoustical performance of the building shell with up to 3 skins of brick being used in some places, such as on part of the fly tower, and construction of a new roof 1-3m above the existing roof. Under most rain conditions the roof meets NR18, however, under heavy rain it meets NR25. Barry also explained the innovative approach employed by the Sydney firm Optimus in the provision of air conditioning airflows and noise control to achieve NR18 within the spatial constraints imposed. This was achieved by locating the air conditioning plant room in a building adjacent to the theatre, use of perforated plate on the fan discharge (pointing away from the theatre) to reduce air turbulence and achieve a more uniform air velocity profile, acoustical attenuators principally in the form of internally lined duct at the plant room and theatre ends, and circular duct work which allowed air velocities of up to 7 m/s prior to distribution into the theatre space.

Both Peter and Barry spoke eloquently and informatively with the meeting being very well received by all of those in attendance. Following closure of the meeting approximately a third of the audience adjourned to the nearby Roma Cafe for a pleasant lunch and to catch up on the latest gossip.

Andrew Zelnik

ACT MEETING

Human Vibration

On 24 October, around 40 attended a joint meeting of the ACT Group and the Mechanical Branch of the Institution of Engineers to hear **Dr Hugh Williamson** discuss various aspects of vibrations and people. After explaining the good and bad effects of vibrations he compared the British and the ISO limiting criteria for exposure to vibration. The techniques for measurements, which incorporate transducers but need to minimise any effect on the activity of the person, were discussed. Hugh then outlined some of the projects including a study of various bus driver seats which were to be used in the new local bus fleet. There was some mirth at the thought of a hefty bus driver sitting on a seat pads with embedded accelerometer. The problems of such investigations in adverse environments, such as mines was also discussed. The meeting was well received with much discussion and highlighted the benefits of such joint meetings.

Marion Burgess

VIC MEETING

AMRL Laboratories

The Division's AGM followed a visit on September 20 to the Department of Defence's Aeronautical and Maritime Research Laboratories at Fisherman's Bend, which 23 members attended. The two laboratories opened to the AAS visit were concerned with Human Factors Technology, and Vibration Analysis. Various investigations in progress were demonstrated by aural or visual displays.

In Human Factors Technology, the demonstrations comprised:

i) a binaural technique (using the Aachen system) of 3-dimensional audio recording to simulate the noise of a moving aircraft heard from a fixed location, to enable its direction and height to be identified. The recording technique used a standardised artificial head. Recorded examples were given of a helicopter moving overhead from right to left, and of up to four simultaneous voices, each in a different direction.

ii) the conversion of radar outputs of threats to an aircraft (eg AA activity, and gun location) into coded audio signals for easy recognition and identification.

iii) the development of hearing protection for aircraft crews through noise surveys using an artificial head, filters to simulate human auditory responses, measurement of third-octave and narrow-band sound levels, and various types of noise reduction using a helmet with ear muffs (SLC80 = 18 dB), ear plugs added (unsatisfactory for communication), and active noise reduction using reversed phase noise.

iv) the development of a flight simulator to achieve perceptual rather than physical fidelity in the reception and identification of both visual and non-visual cues. Auditory cues from aerodynamic sources, engine, hydraulic system, runway and weather are recorded for noise location purposes, together with vibration monitoring at the crew's seats, etc.

Demonstrations in Vibration Analysis included the collection of vibration signatures for the purpose of condition monitoring of engine and other critical parts, and the detection of cracks and flaws. The detection of cracks and flaws is the more difficult task, but is aided by the testing of components with deliberately-introduced flaws. Both laboratory and field tests are made using up to 5 accelerometers simultaneously. With regular monitoring, many flaws can be detected up to 10 hours before likely failure time. Recording is generally digital, and comparisons are made in the frequency domain using signal averaging techniques for greater clarity.

All members attending the visit agreed that it was a most interesting and informative afternoon.

Louis Fouvy

NATIONAL VOICE CENTRE

A National Voice Centre, dedicated to excellence in the art, science and care of voice, has just been formed from the faculties of Health Sciences, Medicine, Engineering and the Conservatorium of Music within The University of Sydney as well as the Royal Prince Alfred Hospital and the Australian Opera Auditions Committee. The voice clinic will offer a world class standard of medical care informed by a multi disciplinary team of doctors, artists and scientists. Knowledge about voice will be translated via regular workshops to health workers and voice teachers as well as professional voice users including singers, actors, teachers, business people and the general public. Australian voice research will enhance voice training and medical care.

Fundamental to the concept of the centre is multi-disciplinary medical care, research, voice training, education and the establishment of strong links between the various disciplines related to voice in Australia. Clinical care and voice training initiatives of the Centre, including teacher-in-residence programs, will acknowledge the eclectic nature of voice. It will be routine for a professional voice user to consult a team consisting of a voice or singing teacher, doctor, speech pathologist and voice scientist. Research will be the foundation of much of the Centre's activities. Up to date knowledge and technology can offer valuable insights into the teaching of voice and may reduce the amount of training or therapy time needed. Doctors can work with speech pathologists, voice teachers and scientists to provide a more comprehensive consultative approach to patients with voice problems and to professional voice users who seek advice about optimal vocal performance. This team approach model is well established in centres of excellence overseas.

The Centre will offer on-going up-grading of the skills of voice and singing teachers, speech pathologists and doctors via workshop and seminar programs and a fundamental concept will be to take the clinical and scientific voice knowledge out into the community via regular workshops, seminars, training programs and conferences on voice to professional voice users, teachers, business people and the general public.

Further information: Dr Pamela Davis, Tel: 02 646-6600, Fax: 02 646 6390, email voice@cchs.su.edu.au

SABINE AWARD

Professor Harold Marshall has been selected to receive the Wallace Clement Sabine Award by the Acoustical Society of America. The Sabine Award is presented, on rare occasions, "to an individual of any nationality who has furthered the knowledge of architectural acoustics, as evidenced by contributions to professional journals and periodicals or by other accomplishments in the filed of architectural acoustics". Professor Marshall's citation notes his contributions to the field of architectural acoustics, particularly for the understanding and design of concert halls. In receiving the award, Professor Marshall joins a distinguished group of previous recipients including Leo Beranek (1961) and Lother Cremer (1974). The official presentation took place at the November meeting of the Acoustical Society of America.

Professor Marshall was a founding partner of the acoustical consulting practice of Carr Marshall Day Associates Pty Ltd and is the Director of the Acoustics Institute of the University of Auckland.

AWARD FOR ELECOUSTICS

Elecoustics Pty Ltd of Sydney has recently won an Achievement Award from the Audio Engineering Society for the design of the sound reinforcement system in Courtroom 2 of the High Court of Australia. Difficulties to be overcome in the design included a reverberant courtroom, widely-dispersed seating areas, speakers some distance from microphones, several microphones open simultaneously, strict architectural requirements in relation to the furnishings and fittings in the courtroom, and time and budgetary restraints. Elecoustics received a similar award in 1993 for the design of the sound systems in the House of Representatives and Senate in the Australian Parliament House. The company has also won loudspeaker design awards.

FEEDBACK

The review of the Basic Music Industry Skills, produced by Ausmusic (Acoustics Aust vol 22, no 3, p102 included a comment regarding a lack of emphasis on reducing volume to reduce noise exposure. It has been interesting to note that the latest editions of this package have included more emphasis on the benefits of this simple measure.

INTERNET NEWS

Australian Academy of Science

The Academy of Science has opened a window to the world through a World Wide Web site on the internet: **http://www.asap.unimelb.edu.au/aas/aashome.htm**

This site includes information on the Council of the Academy, committees, publications, and various other activities including the grants, awards and fellowship schemes. One special feature is a virtual bike ride around sites of scientific interest in Canberra.

Acoustics on Internet

An article in a recent issue of Noise & Vibration Worldwide, published by the Institute of Physics in the UK, lists some of the various web sites that include information on noise and vibration. These sites are also detailed on the web page for the journal which would form a good starting point for any "surfers":

http://www.ioppublishing.com:80/mags/nv/index.html

LOW FREQUENCY NOISE

The American Society of Heating, Refrigeration and Airconditioning Engineers (ASHRAE) has awarded a research contract to a team from Vipac, led by **Dr Norm Broner,** to investigate the impact of low frequency HVAC noise on occupants of rooms, offices and auditoria. Current building trends have resulted in an increase in the number and severity of low frequency noise problems at frequencies 250 Hz and below. However very little work has directly addressed the question of how people react to indoor noise in situations where the background sound is established by the noise level of operating HVAC systems. The research objectives are to generate a practical philosophy and procedures for the evaluation of the acceptability of low frequency HVAC sound and to provide the critical basis for development of low frequency design criteria for future publication in ASHRAE handbooks.

Further information: Dr Broner, Vipac, Tel 03 9647 9700, Fax 03 9646 4370.

JOURNALS MERGE

Two European Journal on general acoustics, ACTA ACUSTICA and ACUSTICA will join forces effective January 1996. The 3,000 subscribers will then receive the united journal with about 200 printed pages bi-monthly. The united journal will be edited by the same team of associate editors which now serve ACTA ACUSTICA.

EXCHANGE JOURNALS

A number of exchange arrangements have been established between Acoustics Australia and other Journals from around the world. The Library at the Australian Defence Force Academy has agreed to hold and catalogue these issue on behalf of the Australian Acoustical Society. Access to issues or particular articles can be obtained by normal inter-library loan arrangements. The journals which are received include:

Acoustics Bulletin, Acta Acustica, Applied Acoustics, Aust Journal Audiology, Chinese Journal of Acoustics, Canadian Acoustics, Catgut Acoustical Society Journal, Journal Aust Assoc Musical Instrument Makers, New Zealand Acoustics, Noise News International, Noise and Vibration Worldwide

INTERNOISE 96

This 25th anniversary conference will be held in Liverpool, UK from 30 July to August 2. The theme is "Noise - the Next 25 Years" and every aspect of the legislative and technical assessment and control of noise lies within the purview of the conference.

For further information from Institute of Acoustics, Holwell St, St Albans AL1 1EU, Tel + 44 1727 848195, Fax + 44 1727 850553, email Acoustics@clus1.ulcc.ac.uk

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Peter Karantonis has recently left Eden Dynamics Pty Ltd after 7 years as an acoustical and vibration consultant. He has now joined Renzo Tonin & Associates Pty Ltd where he is head of their Environmental and Industrial Acoustics Group.

Rumour has it that a well known firm of acoustical engineers and scientists recently had an unfortunate incident with one of their noise data loggers in the early stage of a road construction project in the southern part of Australia. Local residents, unaware of the noise monitoring taking place, were alarmed by the strange ticking device in their midst. So they called the police who in turn called the bomb squad. Unsure of what the device was they took a precautionary approach and exploded it!

Ken Scannell has recently joined Sydney acoustical consulting firm Wilkinson Murray Pty Ltd after leaving the Industrial Noise and Vibration Centre in Slough in the UK. Ken has been involved in acoustics since 1976 and has had over 10 papers published on various noise and vibration topics. Ken is looking forward to a bright and sunny future in Australia.

STANDARDS REPORT

The following draft standards were issued for public comment by 30 November 1995:

DR 95366 Description and measurement of environmental noise-Part 1: General Procedures (Revision of AS 1055.1-1989 and revision, in part, of NZS 6801:1991 and NZS 6802:1991).

DR 95367 Description and measurement of environmental noise-Part 2: Application to specific situations (Revision of AS 1055.2-1989 and revision, in part, of NZS 6801:1991 and NZS 6802:1991).

DR 95368 Description and measurement of environmental noise-Part 3: Acquisition of data pertinent to land use (Revision of AS 1055.3-1989 and revision, in part, of NZS 6801:1991 and NZS 6802:1991).

These Public Comment Drafts are the proposed replacements for the current Australian Standards dealing with the description and measurement of environmental noise (AS 1055-1989) and the equivalent New Zealand Standards, NZS 6801-1991: Measurement of sound, and NZS 6802-1991: Assessment of environmental noise.

Standards Australia will also soon be publishing a revised version of AS Z41-1969: Octave, half octave and one-third octave band pass filters intended for the analysis of sound and vibrations. This revision will be a reproduction of IEC 1260-1995: Electroacoustics- Octave-band and fractional-octave-band filters.

Grant Cooper

Housing Code Standards Australia has recently commissioned CSIRO to prepare the initial draft of a performance-based housing code. Committee BD/78-Domestic Construction believes that a performance-based code directed at the specific needs of house construction, is long overdue.

CSIRO, in conjunction with a specialist sub-committee of BD/78, will prepare an initial draft for the committees consideration. The draft will detail performance criteria for both the structural elements of the house, eg. roof, floor, walls etc, and fire resistance, together with utility items such as ventilation, dampness, sound, energy efficiency.

It will specify methods to verify, either by computation or testing, that the required performance criteria have been satisfied. The committee is particularly interested in finding out if the wind and live loading requirements currently applied to all buildings are appropriate when applied to houses.

ANSI Standards

New American National Standards are available as follows:

ANSI S1.26-1995 Method for calculation of the absorption of sound by the atmosphere. ASA Catalogue No. 113-1995. $US80.00 per copy.

ANSI S3.7-1995 Method for coupler calibration of earphones. ASA Catalogue No. 112-1995. $US80.00 per copy.

ANSI S3.20-1995 Bioacoustical Terminology. ASA Catalogue No. 114-1995. $US94.00 per copy.

ANSI S12.2-1995 Criteria for evaluating room noise. ASA Catalogue No. 115-1995. $US72.00 per copy.

ANSI S12.42-1995 Microphone-in-real-ear and acoustic test fixture methods for the measurement of insertion loss of circumaural hearing protection devices. ASA Catalogue No. 116-1995. $US64.00 per copy.

Standards published by the Acoustical Society of America (ASA) are available from: Acoustical Society of America, Standards and Publishing Fulfilment Center, PO Box 1020, Sewickley, PA 15143-9998, USA. Tel +1 412 741 1979. Fax +1 412 741 0609.

New Products...

BRUEL & KJAER

Noise Monitoring Station

The 3571L, environmental noise monitoring station comprises the 2236 SLM and a rechargable battery in a weatherproof, portable case with total weight only 7 kg. A DAT recorder can be included for event recording.

Measuring Amplifier

The 2525 measuring amplifier is a computer controlled level monitor with alarm and safe exposure functions ideally suited to all annual or automated measurement applications. It is a high precision, low noise, single channel measuring amplifier with mounted resonance test feature and menu based user interface.

Evidence Software

The Evidence software type 7696 is a set of reporting and documentation tools to be used on the measurement data downloaded from the 2260 SLM. It enables the user to produce meaningful reports from sound measurements gathered in the field or the laboratory and allows easy operation with other windows based software packages for word processing or spread sheets.

QC Brain

Software WT 9550, or QC Brain, is a smart solution to quality control testing based on the same principles as the human brain. The software can recognise differences in noise and vibration signatures that are otherwise undetectable to tolerance based software. The tolerance and diagnostic masks can be generated, displayed and edited quickly and simply.

Further information: Bruel & Kjaer Aust, PO Box 177 Terrey Hills, NSW 2084 Tel (02) 450 2066, Fax (02) 450 2379.

ACOUSTEX

The sound absorption properties of spray on Acoustex can assist in achieving the quiet intimate atmosphere which is often sought by architects and interior designers. The material can be dyed to match any colour scheme and adheres to all surfaces. It comes in two finishes: standard and architectural. Where the sprayed finish is not practical, Acoustex P/L now has a wide range of panels, baffles and other products.

Further information: Acoustex P/L, 9 Dissik St, Cheltenham, Vic 3192 Tel (03) 9596 5896 Fax (03) 9596 5621

CHARMAC INDUSTRIES

Comprehensive data on the noise emitted from six types of soil pipes currently used in multistorey buildings is now available. The tests were commissioned by Charmac Industries and conducted at the National Acoustics Laboratory using a test wall installed between the two large reverberation rooms. The data allows for the comparison of the performance of the different pipe materials currently used in the sanitary plumbing systems.

Further information: Charmac Industries, PO Box 22 Milperra, NSW 2214 Tel (02) 774 2144 Fax (02) 771 4343

MICROTECH GEFELL

Pistonphone

Microtech Gefell has released the new 5001 Pistonphone, a small mains-independent sound source for precise calibration of sound level meters and complete acoustical measuring set-ups. The pistonphone is supplied in a quality wooden case, which also includes a barometer with special scaling on which the sound level correction values can be read directly. Operation is by a near-silent dc motor which moves two pistons in a pressure chamber to which the microphone being calibrated is attached. The piston movement generates a steady-state sinusoidal alternating pressure at a sound pressure level of 124 dB. The pistonphone allows users to calibrate microphones with capsule diameters of 1 inch, 1/2 inch and 1/4 inch. Correction factors can be taken into account for microphones of different volume.

Further information: Southbank Trading, PO Box 6637, Melbourne, Vic 3000. Tel 03 9804 0432. Fax 03 9804 0449.

VIPAC

Vibration Transducers

1. Monitran Ltd has added a new series of models to their range of LVDT displacement transducers, with miniaturised integral electronics providing a 4-20mA output for use in process control loops. Standard measuring ranges are available from +/-2.5mm to +/-600mm. For differing industrial applications, various construction styles are available. The heavy industrial series has a rugged housing complete with integral mounting bearings, armoured cabling and a waterproof option. A pressurised series has been designed to withstand a pressure gradient of 6000 psi across the transducer body.

2. Monitran's new 1100 series accelerometers have been designed for vibration measurement in the tough operating conditions of temperatures up to 250(C and radioactive emissions to 10^10 rad. Robustly constructed in stainless steel, the piezoelectric devices have measurement ranges up to 250g with a frequency response from 2 to 8000 Hz and a transverse sensitivity of 5%. The compact accelerometers weigh approximately 100 grams and are offered with a choice of mounting styles including threads, studs and magnetic fittings.

3. Monitran has released a range of industrial sensors which will monitor position, displacement, movement, radial vibration and speed without actual contact with the moving target under investigation. The MTN probes have a simple construction consisting of a potted coil assembly which radiates a high frequency signal into the conductive target. Eddy currents are produced which can be monitored as a dc level representing the static gap, or an ac level for the determination of varying profiles in dynamic mode. Several models are available with measuring ranges of 2, 5 and 8.5 mm and a choice of mounting configurations. Designed for measurement of small distances, the probes can also be used to measure speed by monitoring the passage of a hole within the drive shaft assembly. The measuring system is completed with a Monitran probe driver module which operates from a dc supply and provides probe adjustment and calibration controls and an output for data collection systems.

Noisebadge Controller

Larson Davis has released the Model 705RC, a hand held device that permits remote control operation of the LD Model 705 Noisebadge. A user can activate the Model 705 without a computer by sending commands from the 705RC via the serial interface. Connected to the 705, the 705RC can run, stop, calibrate and reset the 705. The 705RC is ideal for users who wish to active the 705 "on the spot - in the field" rather than preprogramming the run/stop time and dates with a computer and 705 software. The dimensions of the 705RC are only 8.25 x 5.71 x 1.91 cm, and it weighs 113 g complete with its 1.5 volt AAA alkaline battery.

Signal Conditioner

Larson Davis has recently released the Model 2204 Microphone/Accelerometer Signal Conditioning Module. The Model 2204 is designed for use with a range of TEAC compact DAT data recorders, facilitating the use of air-condenser microphones, and accelerometers as transducers. The recorder and the signal conditioning module are integrated into a single package with all

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electrical connections internal. Four and eight input channel versions are available, with input types individually selected by channel. The microphone inputs are designed for use with LD air-condenser microphones and LD microphone preamplifiers. Depending on the model of preamplifier, extension cable lengths of up to 150 metres are possible. The dimensions of the combined recorder and signal conditioning unit are 150 x 306 x 280 mm with a total weight of 8.18 Kg.

Computer-based Training Programs

1. MEDIACOUSTIC is a teaching software package for acoustics. The package is based on a central core consisting of four main groups: Physics of Sound; Sound and Man; Acoustics and Buildings; and Noise Control. Each module is illustrated by sound clips, text, pictures, and video animations. The whole system can be consulted like a reference book. MEDIACOUSTIC is available as a CD-ROM, containing around 300 MB of data.

2. Predict/DLI has released a training CD "Introduction to Machine Vibration". The system runs on 386/486 PCs with MS Windows 3.1, CD-ROM reader and 8 MB RAM. Users progress at their own rate and keep track of their progress via randomly generated multiple choice tests. Topics include vibration fundamentals, theory of predictive maintenance, time vs frequency data presentation, FFT analysis and diagnosis of specific faults in machines.

Further details: Ms Pam Sheehan, VIPAC Engineers and Scientists Ltd, 275 Normanby Rd, Port Melbourne, Vic 3207. Tel 03 9647 9700. Fax 03 9646 4370.

COMPUTATIONAL MECHANICS
Beasy

Computational Mechanics Australasia has released a new range of software for solving 3D acoustics problems. Known as Boundary Element Analysis System BEASY-Acoustics, the software has been designed to be able to deal with most, if not all aspects of industrial acoustic problems including interior, exterior or combined interior/exterior analysis. BEASY provides point and line sources along with velocity and impedance conditions of the vibrating structural surfaces for accurate model description. Acoustic domains are represented by zones. Different properties can be defined for each zone allowing analysis of multiple acoustic regions. BEASY provides comprehensive diagnostic capabilities allowing the user to determine the contribution of each sound source to the sound pressure level at any point within the model.

Further information: Computational Mechanics Australasia, Unit 11, 4-8 Queen St BENTLEY WA 6102, Tel (09) 350 6676, Fax (09) 451 1889.

DUNN AIR CONDITIONING
Noise Eater

The Noise Eater active duct silencer system, which can be installed in new buildings or added to existing ducts, includes a proprietary active noise cancellation system integrated with a passive silencer. The unit has been developed by Noise Cancellation Technologies of the USA and works by sampling the sound field at the beginning of the silencer, filtering that data and outputting an inverted version of the sound (180 degrees out of phase) from a loudspeaker near the end of the unit. The anti-noise signal cancels the offending sound and reductions of up to 12 dB have been achieved at 160 Hz.

Further information: Dunn Air Conditioning, PO Box 773, MONA VALE NSW 2103, Tel (02) 9979 7299, Fax (02) 9979 1145.

New Course...

COURSE
Audio Engineering

The Graduate Diploma and Master of Design Science (Audio) have been created to present a study path for those interested in audio profession, to provide a broad audio education, enable continuing self education and to encourage research in audio. The Graduate Diploma can be completed part time in 2 years and the Master of Design Science part time in 3 years or full time in 2 years. Also subjects can be undertaken individually.

Further information: David Bartolo, Dept Architecture and Design Science, University of Sydney NSW 2006, Tel (02) 351 2686, Fax (02) 351 3031 email dads@arch.su.edu.au.

Diary...

CONFERENCES and SEMINARS

* Indicates an Australian Activity

1996

January 10-11, SINGAPORE
Annual Meeting, Society of Acoustics
Details: Dr W S Gan, c/o Acoustical Services Pty Ltd, 209-212 Innovation Centre, NTU, Nanyang Ave, Singapore 2263, Republic of Singapore.
Fax +65 791 3665, Tel +65 791 3242

February 21-23, MELBOURNE
*Aust Cong on Applied Mechanics 96
Details: AE Conventions (ACAM 96), PO Box E181, Queen Victoria Terrace, ACT 2600. Tel (06) 270 6562, Fax (06) 273 2918

February 24-27, SYDNEY
* Occupational Injury Symposium
Details: Occupational Injury Secretariat, Professional Education Program, National Occ Health and Safety Commission, GPO Box 58, Sydney, NSW 2001.
Tel (02) 565 9319, Fax (02) 565 9300

April 1-4, ANTWERP
Forum Acusticum 96
1st Conv. European Acoustics Assoc.
Details: Forum Acusticum, Technological Institute KVIV, Desguinlei 214, B-2018, Antwerpen, Belgium, Tel +32 3 216 0996, Fax +32 3 216 0689

April 26-28, MICHIGAN
Joint meeting of Catgut Acoustical Society and Michigan Violinmakers Assoc.
Details: Catgut Acoustical Soc. Inc., 112 Essex Ave, Montclair, New Jersey 07042, USA. Fax +1 201 744 9197

May 13-17, INDIANAPOLIS
131st Meeting Acoust Society of America
Details: ASA, 500 Sunnyside Blvd., Woodbury, NY 11797, USA. Fax +1 516 576 2377, email elaine@aip.org

May 23-25, MOSCOW
Acoustical Measurements
Details: Russian Acoustical Society, 4 Shvernik St, Moscow 117036 Russia. Fax +7 095 126 8411, email bvp@ asu.acoins.msk.su

May 21-24, AUTRANS
4th Speech Production Seminar
Details: ICP-INPG, 46 ave Felix Viallet, 38031 Grenoble cedex 01, France. Fax +33 76 57 47 10, email etrwspm@icp.grenet.fr

May 27-31, MOSCOW
Intl Symposium on Acoustic Remote Sensing of the Atmosphere and Oceans.
Details: Secretariat ISARS'96, 3 Pyzevsky Line, Moscow, 109017 Russia. Fax +7 095 233 1652, email postmaster@iaph.msk.su

May 28-31, PISA
Noise and Planning '96: Intl conference on Acoustics applied to planning
Details: Guido Lombardi, via Bragadino 2, 20144 Milano, Italy. Tel +39 2 48018833, Fax +39 2 48018839

June 16-20, BARI
13th Intl Congress of Audiology
Details: Audiology and Otology Centre, University of Bari, 70124 Bari, Italy.
Fax +358 460224, email nam96@hut.fi

June 17-21, NANJING
14th Intl Symp on Nonlinear Acoustics
Details: Ronjue Wei, Nanjing University, Institute of Acoustics, Nanjing 210008, China. Fax +86 25 360 5557, email postndi@nju.edu.cn

June 24-28, HERAKLION, CRETE
3rd European Conf on Underwater Acoustics
Details: J S Papdakis, Foundation for Research and Technology, PO Box 1527, 711 10, Heraklion, Crete, Greece. Tel +30 81 210034, Fax +30 81 238868, email conference@iesl.forth.gr

June 24-28, ST PETERSBURG
4th Int Congress on Sound & Vibration
Details: M Crocker, Mech Eng Dept, 201 Ross Hall, Auburn Uni, Auburn, AL 36849-3501, USA. Tel 334 844 3310, Fax 334 844 3306. email mcrocker@eng.auburn.edu

July 30-August 2, LIVERPOOL
INTERNOISE 96 - 25th Anniversary Congress: Noise - The Next 25 Years
Details: Institute of Acoustics, Agriculture House, 5 Holywell Hill, St Albans, Herts AL1 1EU, UK. Tel +44 727 848195, Fax +44 727 850553

September 2-6, CHRISTCHURCH
ROADS 96
Joint Aust/NZ Conference
Details: ARRB Transport Research, 500 Burwood Hwy., Vermont Sth, Vic 3133.
Tel +61 3 9881 1555, Fax =61 3 9887 8104.

September 18-20, LEUVEN
Noise & Vibration Engineering Conference
Details: L Notre, K.U. Leuven-PMA, Celestijnenlaan 300B, 3001 Heverlee, Belgium. Fax +32 16 32 29 87, email lieve.notre@mech.kuleuven.ac.be

September 23-25, ST PETERSBURG
FASE Symposium: Transport Noise
Details: FASE Secretary, K.U. Leuven-ATF, Celestijnenlaan 200D, 3001 Leuven, Belgium. Fax: +32 16 32 79 84, email jan.thoen@fys.kuleuven.ac.be

September 29-October 2, BELLEVUE
NOISE-CON 96
Visions for the Next 25 Years
Details: Engineering Professional Programs, 3201 Fremont Avenue N., Seattle, WA 98103. Tel +1 206 543 5539, Fax +1 206 543 2352

October 3-6, PHILADELPHIA
4th Conf Spoken Language Process
Details: ICSLP96, Sci & Eng Labs, AI du Pont Institute, PO Box 269, Wilmington, DE 19899 USA.
Fax +1 302 651 6895, email: ICSLP96 @asel.udel.edu

November 3-6, SAN ANTONIO
1996 IEEE Intl Ultrasonics Symposium
Details: J S Schoenwald, Rockwell International Science Center, Mail Code A9, 1049 Camono dos Rios, Thousand Oaks, CA 91358, USA. Fax +1 805 373 4810

November 13-15, BRISBANE
*1996 AAS Conference
Making Ends Meet: Innovation and Legislation
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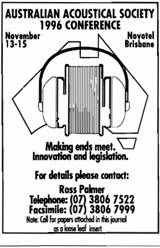

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