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# Standard Diffusion Coefficients


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## 1. INTRODUCTION

One of the legacies of the last decades of the 20th century is an increasing interest in the role of diffusers within auditoria. Advancing techniques for designing diffusers has created a need for a standardised diffusion coefficient to enable the worth of diffusers to be evaluated and design specifications to be enumerated. Another legacy of the late 20th century is the domineering role of computer technology in many walks of life, including auditorium design. Computer based geometric room acoustic models have exploited this technology to enable predictions of auditorium sound fields. A recent round robin test of such models demonstrated that diffusion modelling is a key ingredient in enabling accurate prediction of spaces[1]. Such diffusion modelling usually requires a diffusion coefficient, but presently the values for these coefficients have to be determined empirically[2]. This is another reason why a standard technique for acquiring diffusion coefficients is required. In addition, a diffusion coefficient would create a *language* to describe the degree of diffusion, which it is hoped will improve the understanding of diffuse reflection phenomena. Looking beyond 2000, it is likely that measurement and prediction methods for diffusion coefficients will be enshrined in international standards. Both the International Organisation for Standardisation and the Audio Engineering Society have separate working groups looking at this issue. This paper will discuss the philosophy behind two techniques for determining diffusion coefficients that are likely to form the basis of the standards. The difficulties with specifying a single unified measure will be discussed and the advantages and disadvantages of the two methods will be outlined.

## 2. MOMMERTZ AND VORLANDER

### 2.1 Free field

There are many ways for describing how diffusers behave, and consequently many potential measures for describing the degree of diffusion. The Mommertz and Vorländer method[3] is based on the variation in scattered sound pressure when a test surface is moved, usually by rotation. Figure 1 shows the set up for the free field measurement. If the test surface is plane, as the surface is rotated the sound pressure measured will be constant. If the surface has roughness, however, then rotating the surface produces a varying pressure. If the sound pressure is averaged over a complete rotation, the average pressure measured is the invariant specular component, and the energy lost during the averaging is the non-specular, diffuse component. The diffusion coefficient derived is then the ratio of diffuse to total scattered energy. A drawback of this method is that it is likely to differentiate between redirection and dispersion. The diffusion coefficient will correctly identify energy moving away from specular directions, but does not monitor where the energy goes. Whether this is viewed as a flaw depends on the viewpoint of what diffusion measures are for. From a diffuser designer's point of view, the difference between redirection and dispersion is critical. Diffusers are usually applied to treat first order reflections, for example to prevent echoes from the rear wall of an auditorium. If all the diffuser achieves is redirection, there is a risk that the echo problem will simply move to another place in the hall. On the other hand, if the diffuser achieves dispersion, this has the potential to reduce the echo problem without creating new difficulties for

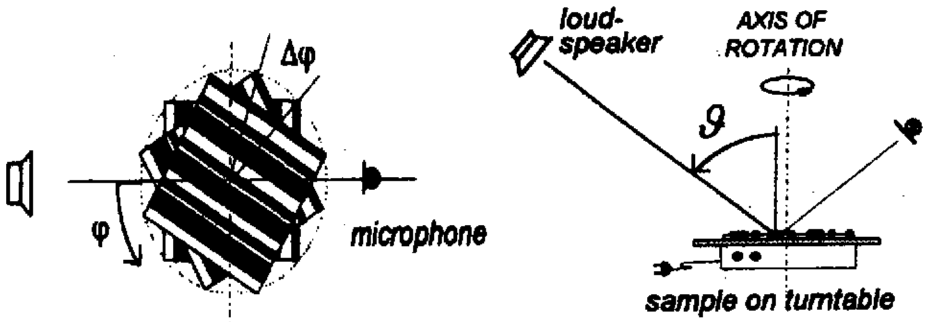


Figure 1. Set up for free field measurement for the Mommertz and Vorländer method, diagram from [1].

other listeners. From other standpoints the difference between redirection and dispersion is less crucial. For example, if a geometric room acoustic model is predicting the sound pressure level, then the difference between redirection and dispersion is less critical as there will be a large number of reflections over which the received pressure is averaged. Given that the free field polar response methods for determining diffusion coefficients can differentiate between redirection and dispersion, it seems reasonable to favour those techniques, and they will be described later.

## 2.2 Diffuse field

The Mommertz and Vorländer method becomes much more attractive when the diffuse field technique is considered. The concept is similar in that the invariant energy is measured as the test surface is rotated. In this case the measurements are performed in a reverberation chamber using standard maximum length sequence techniques. The invariant and variant energies are measured in terms of reverberation times and from this a random incidence diffusion coefficient derived. The advantages of this technique are that is uses mainly standard techniques and facilities and is relatively quick to perform. The remit of the ISO working group is to standardise a *random incidence diffusion coefficient measurement technique*, and as the Mommertz and Vorländer method is the only existing published method, it is likely to be enshrined in the new standard. Measurements using this technique have been carried out at Salford University. Some results are shown in Figure 2; Figure 3 shows some of the surfaces tested. There are several features worthy of note in these results. The plane circle should have a diffusion coefficient of zero for all frequencies. It fails because the sample was not perfectly flat due to bowing about the wood grain leading to small changes in scattered pressure as the sample is rotated. The random arrangement of battens is better than a periodic arrangement - this is evidence that periodic arrangements of diffusers are bad due to lobing effects that occur. The frequencies at which the batten surfaces start diffusing are as expected given their dimensions. Finally, the random arrangement of hemispheres is a remarkably good diffuser, but the coefficient exceeds one at high frequencies. The exact reasons for this are at the moment unclear, but the cause may be that the surface was too deep compared to the circle size. The edges of the sample therefore caused extra scattering, which caused a greater than expected drop in the measured reverberation time and too large a diffusion coefficient. In many ways, this is similar to the problem that occurs when measuring absorption samples of finite size where edge effects lead to coefficients greater than one. In fact the absorption coefficient is a good analogy to draw for other reasons as well. It is extremely difficult to predict the random incidence absorption coefficient for anything but a planar local reacting surface, the random incidence diffusion coefficient is also difficult, if not impossible, to predict. Small surfaces with large surface irregularities will cause difficulties, for that free field methods based on polar responses are more appropriate. The method also has difficulties with surfaces with cylindrical symmetry. For example a single hemisphere will yield a diffusion coefficient of zero as the scattered pressure will not alter with rotation, however, it is well established that isolated hemispheres are excellent diffusers. Figure 2 also includes a measurement carried out by Mommertz and Vorländer on a one dimensional

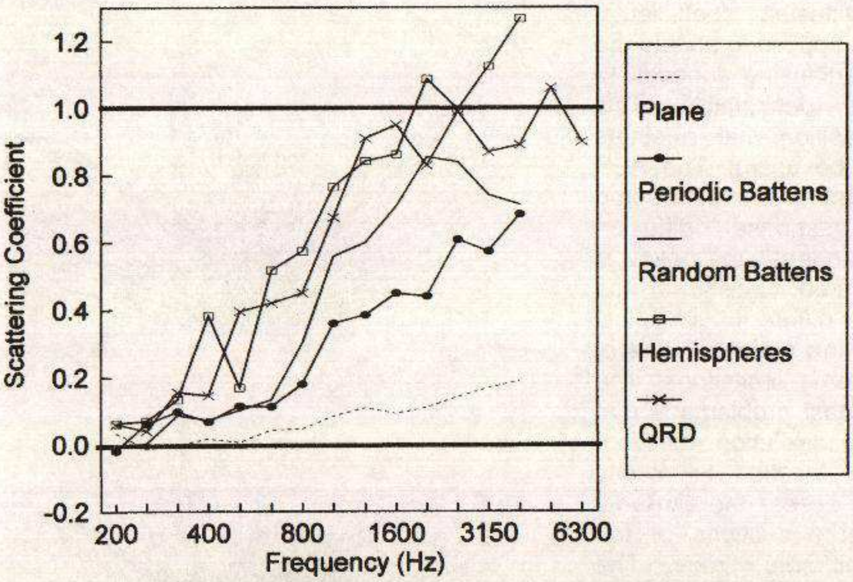


Figure 2 Measurements of random incidence diffusion coefficient for some surfaces. The Quadratic residue diffuser (QRD) was measured by Mommertz and Vorländer and a 1:5 scale assumed.

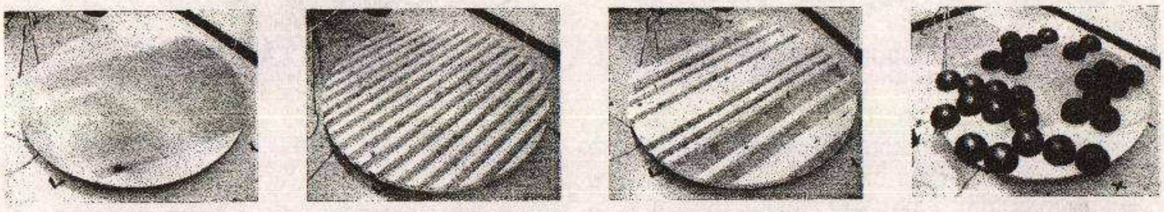

Figure 3 Surfaces tested using diffuse field technique. From left to right: plane, periodic battens, random battens, random hemispheres.

QRD. This surface has very different diffusion in two directions. A polar response about the width of the diffuser will find a reasonable diffuser due to the well depth variation. However, a polar response about the length will essentially see a plane surface and so diffusion will be poor. Surprisingly the diffusion produced by the measurements is relatively high, even though in one plane the scattering will be poor. So the method has difficulties in dealing with scatterers that do not disperse energy in a roughly isotropic manner; these surfaces appear to be better diffusers than they really are.

## 3 POLAR RESPONSE

The majority of literature regarding diffusion coefficients has dealt with those based on polar distributions. These look at the spatial evenness of energy scattering around the surface, in a similar way to how the omnidirectionality of a sound source might be tested. First the scattering from a surface is measured or predicted in terms of a polar distribution. Boundary Element Methods (BEMs) have been shown to be accurate in predicting the scattering from a variety of diffusing surfaces both in two and three dimensions[4,5,6] and so have been used here. Measurements on reflecting surfaces were based on maximum length sequence signals using time gating to separate the reflected from the incident sound. Such a system has been used in the past to enable measurements to be made in a single plane on a semicircle[7]. A capability to measure the surface scattering over the hemisphere using a goniometer was especially developed for this project. Figure 4 illustrates 3D predictions and measurements from a surface. The diffusion coefficient is a frequency dependent, single figure of merit derived from these polar distributions. This can be accomplished by various statistical operations: standard deviation[8,9,10] directivity[11,12], specular zone, spherical harmonics[13] and autocorrelation[14]. In any such data reduction, there is a risk of losing essential detail. Diffusion coefficients, however, have been applied to enable the quality of specialist diffusing surfaces to be evaluated and designed[8,9]. This supports the supposition that a single figure of merit can be useful. The AES working group is likely to enshrine some form of polar response diffusion coefficient into a standard, and below is described the favoured statistic of the authors. All the different statistical operations used to form a single figure of merit suffer from some limitations. The technique with the least problems is that based on the autocorrelation function. The autocorrelation function is mostly used in acoustics to assess the similarity between two or more sections of the same signal at different times. The function can also be used spatially to gauge the similarity between different sections of polar responses. The diffusion coefficient is monitoring the uniformity of the polar distribution. The technique is to first calculate the circular autocorrelation coefficient. A perfect diffuser will have an autocorrelation value of one for all displacements. A complete specular reflector will only have a non-zero value at one point. The circular autocorrelation is then averaged across all displacements to give a single diffusion measure. This is a moderately convoluted calculation, but by luck this procedure reduces to a simple to calculate formulation which bypasses the need to calculate autocorrelation functions. The diffusion coefficient, $d_a$, is given by:

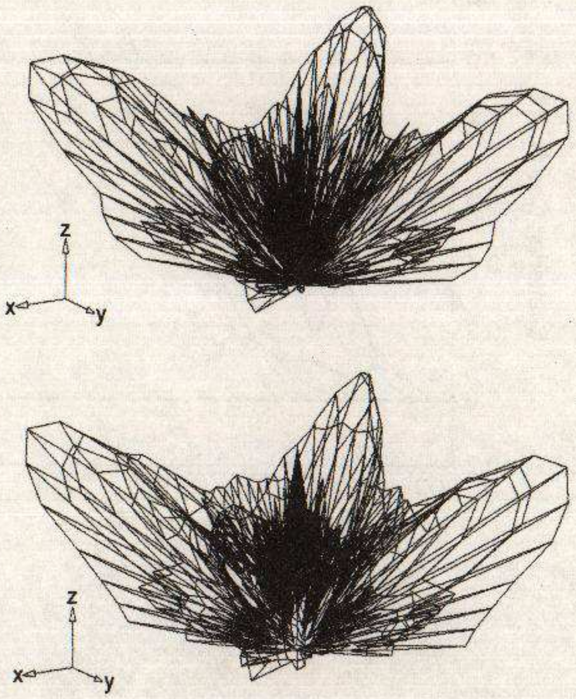


Figure 4 Prediction (top) and measurement (bottom) of scattering from a square based

$$d_a = \frac{\left(\sum_{i=1}^{n} W_i\right)^2}{n \sum_{i=1}^{n} W_i^2} \quad (1)$$

Where $W_i$ is the power scattered into a particular solid angle. This is automatically bounded between 1/n (specular reflection) and 1 (uniform diffusion). A simple scaling can be carried out to make the bounding between 0 and 1.

Most published work in this area has dealt with diffusion in a single plane. Many diffusers are designed to be diffusing in one direction and plane in the other, for example a one dimensional Schroeder diffuser, but others will produce more uniform hemispherical scattering, for example a two dimensional Schroeder diffuser. Consequently surfaces should be tested either for their ability to scatter into a hemisphere or in two orthogonal planes. Two orthogonal planes should be used for cases like the cylinder when the diffuser is expected to display distinct anisotropic behaviour and two diffusion coefficients given. A diffuser that is more approximately isotropic, such as a sphere, requires evaluation over a hemisphere and a single diffusion coefficient is given. All the free field polar response measurements suffer from the same near-far field problem. The polar response varies with source and receiver distances unless the measurements are carried out in the far field. Unfortunately the far field will often be so far from the surface as to make measurements at such a distance impossible. Consequently, a pragmatic approach to measurement distance must be adopted. Polar response measurements are looking at the ability of diffusers to move energy away from specular directions. Therefore to be effective measurements must take both within and outside the specular zone. Measurements at Salford University have typically had eighty percent of measurement positions outside the specular zone. For many auditorium applications, however, real sources and receivers are actually nearer to the surface in the near field. Consequently, it is necessary to also measure at application realistic positions to ensure that focussing at such a distance is not a problem. There is also a tacit assumption that a good far field diffuser is also a good near field diffuser.

In Figure 5 the autocorrelation diffusion coefficient for different surfaces is illustrated as a function of frequency. It can be seen to be ranking the diffusers correctly and separating the different surfaces along the diffusion axis. The coefficient has a clear physical basis in the autocorrelation function, but has the drawback that only the extreme values of uniform diffusion and specular reflection are truly defined. The meaning of intermediate values can not be easily found except that over time, if the diffusion measure becomes used, an understanding for what values mean will naturally develop. Carrying out predictions to enable the evaluation of the coefficient is possible. Measurements on a single plane are relatively easy, but full hemispherical measurements are slow and rather time consuming.

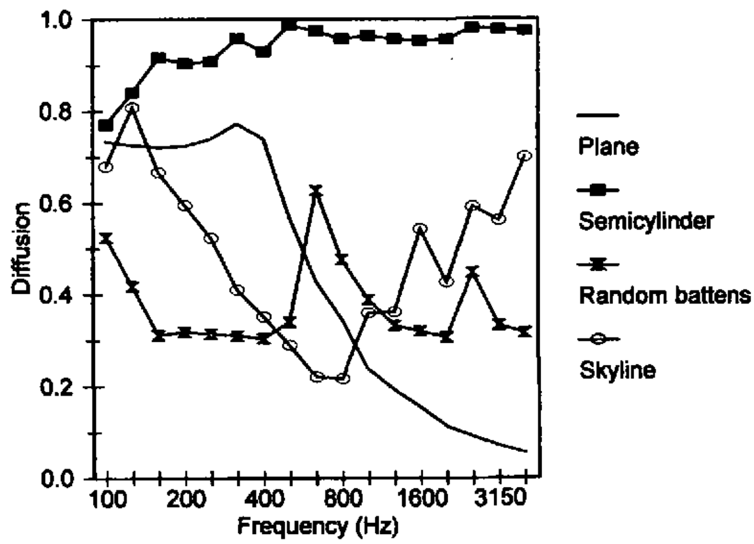


Figure 5 Normal incidence autocorrelation diffusion from various surfaces as a function of frequency.

## 4 DISCUSSIONS AND CONCLUSIONS

At the beginning of the project into diffusion coefficients, the aim was to find a single unified diffusion coefficient that could be used in all situations, Unfortunately, as the project progressed it became apparent that this was not possible. The free field measurement techniques based on polar distributions are more applicable to small to medium sized surfaces, whereas the diffuse field method outlined is for large surfaces with roughness. There is also an important distinction in the philosophy of the two techniques. The polar response measure gauges the ability of a surface to scatter (power) uniformly; it is a strict measure of diffuser quality. The diffuse field method described is more concerned with the ability of a surface to move energy away from specular reflection directions. Whether or not this means that the measure will properly rank diffusers according to quality is uncertain at the moment. In this sense, the two coefficients have different purposes and uses. A familiar analogy would be the absorption coefficient. There are two common techniques for measuring absorption, the impedance tube and the reverberation chamber methods. Both yield useful data for different applications and have contrasting properties, for example impedance tube absorption coefficients are much easier to predict than diffuse field value. The same can be said for diffusion coefficients where free field values are easier to predict than diffuse field values.

There are other methods for evaluating diffusion: one can monitor the effect of diffusers on a non-diffuse space, alternatively the reduction in comb filtering that occurs when a diffuser is added to a plane surface can be measured. Presently, however, none of these other techniques are sufficiently developed or show enough promise to enable them to be recommended as standard techniques.

## 5 ACKNOWLEDGEMENTS

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