MODELING NON-DIFFUSE SOUND FIELDS IN ROOM ACOUSTICS: FROM MURRAY HODGSON'S EARLY WORKS TO THE DIFFUSION EQUATION MODEL

Vincent Valeau[1*], Cédric Foy[†2] and Judicaël Picaut[‡3]
[1]Institut PPRIME UPR 3346, CNRS – Université de Poitiers – ENSMA, Poitiers, France
[2]CEREMA, IFSTTAR, UMRAE, Strasbourg, France
[3]IFSTTAR, CEREMA, UMRAE, Bouguenais, France

Résumé

Le concept de champ diffus en acoustique des salles est l'hypothèse de base de la théorie classique de la réverbération. Cette hypothèse est pourtant fausse dans de nombreuses situations pratiques pour lesquelles le champ sonore réverbéré présente d'importantes variations spatiales dans la pièce. Murray Hodgson a consacré une partie importante de ses activités de recherche à l'étude des champs non diffus, par des études combinant souvent des aspects expérimentaux et de modélisation. Certaines des premières contributions de Hodgson en lien avec ce sujet sont d'abord présentées. Dans une deuxième partie, le papier présente des développements concernant un modèle statistique pour les champs non diffus basé sur un processus de diffusion. Le papier se concentre en particulier sur la modélisation des réflexions diffuses au sein de ce modèle de diffusion, l'application de ce modèle aux locaux industriels, et la modélisation des flux d'énergie en utilisant la loi de Fick. Tous ces développements constituent une suite naturelle des travaux d'Hodgson, concernant de multiples problématiques qu'il a soulevées sur le sujet des champs non diffus.

Mots clefs : acoustique des salles, réverbération, diffusivité du champ sonore, équation de diffusion

Abstract

The concept of diffuse sound field in room acoustics is the basic assumption of the classical theory of reverberation. This assumption is however false in many practical situations where the reverberant sound field undergoes significant spatial variations in the room. Murray Hodgson has dedicated an important part of his research activities to the study of such non-diffuse sound fields, through studies combining generally both experimental and modeling aspects. Some of Hodgson's early contributions in link with this topic are first presented. In a second part, the paper presents some developments concerning a statistical model of non-diffuse sound fields based on a diffusion process. The paper focuses in particular on the modeling of mixed reflections within this diffusion model, the application of this model to industrial workrooms, and the modeling of energy flows by using the Fick's law. All these developments are a natural continuation of Hodgson's works, concerning numerous issues that he raised on the modeling of non-diffuse sound fields.

Keywords: room acoustics, reverberation, sound field diffuseness, diffusion equation

Foreword

The first author of this paper visited Murray Hodgson at the University of British Columbia for the first time in 2005. This visit has been followed by several others, which led to a very friendly relationship, and to numerous and fruitful exchanges, thanks to Murray's great expertise in many fields of acoustics. A collaboration on the development of a statistical model for room acoustics was carried out in the years 2005-2008, and the paper is a review of these works, highlighting the fact that they can be seen as a natural continuation of Murray's earlier works on the modeling of non-diffuse sound fields.

[*] vincent.valeau@univ-poitiers.fr
[†] cedric.foy@cerema.fr
[‡] judicael.picaut@ifsttar.fr

1 Introduction

It is well known that the reverberant sound field in a room can be accurately described by statistical models at medium and high frequencies, provided that there is sufficient modal overlap. In practice, it is considered that such models are valid for frequencies above the so-called "Schroeder frequency" [1]. The classical statistical theory of reverberation is a powerful tool for predicting sound pressure levels and reverberation times based on little information about the room. It is based on the concept of "diffuse sound field", according to which the reverberant sound field at any location in a room is due to uncorrelated waves traveling with equiprobable directions and intensity [2]. Widely used by practitioners for obtaining acoustic predictions within "engineering accuracy" [3], the diffuse field concept is nevertheless limited to restricted practical situations, and is by nature unable to predict spatial variations of the reverberant field in a room. Sound fields

for which such spatial variations are significant will be called "non-diffuse" sound fields in the rest this paper.

Murray Hodgson, since his PhD works in the early 80s on the sound field in industrial workrooms [4], has dedicated a significant part of his research activities to the study of non-diffuse sound fields, through studies combining generally both experimental and modeling aspects. In the years 2000s, Murray Hodgson has been collaborating with the authors of the present paper on the modeling of non-diffuse sound fields, by using a specific statistical model based on a diffusion equation [5]. The objective of this paper is to underline some aspects of Hodgson's research on non-diffuse sound fields, to establish the link with the research activities on the diffusion model, and to make a summary of the collaborative activities between Murray Hodgson and the authors of this paper.

In this purpose, in Section 2, some aspects of Hodgson's research concerning non-diffuse sound fields and the sound field in industrial workrooms are presented. In Section 3, the diffusion model for room acoustics is briefly presented, and the different aspects in which Murray Hodgson has been involved are synthesized, before a brief set of conclusions and perspectives in Section 4.

2 Some aspects of Hodgson's research on non-diffuse sound fields and industrial workrooms

Murray Hodgson has devoted an important part of his research to the study of sound field diffuseness in room acoustics. Several of his papers have had a significant impact on the scientific community working in the field of room acoustics. In his 1996 famous paper, "When is diffuse sound field theory applicable?" [3], Hodgson pointed out that, based on his experience ("*from having measured sound fields in hundred of rooms of any type*"), this theory is generally accurate for describing the reverberation time in real rooms. On the contrary, the prediction of steady-state sound pressure level (SPL) should be limited to rooms with cubic shape and uniform absorption coefficient. If the room shape departs from a cubic geometry, the diffuse sound field theory will be more accurate if the walls have specular reflections [6]. Indeed, Figure 1 shows the reasonable agreement of the diffuse sound field theory with the measured SPL for a squash court (a nearly-cubic room with flat surfaces, i.e., specular reflections), but also demonstrates (along with other examples given in [3]) a general trend of this theory to under-estimate the spatial decay of the SPL for rooms with common aspect ratios. Reference [3] is definitely a paper that has been greatly useful to practitioners, giving accurate guidelines for applying (or not) the well-known diffuse sound field theory. This study definitely demonstrated the need for modeling non-diffuse sound fields with a satisfactory precision.

From the 80's, Hodgson's research has been indeed largely dedicated to the characterization and the prediction on non-diffuse reverberant sound fields, especially by using simulations tools based on ray-tracing, image-source, radiosity models etc. (eg., [6-9]). Hodgson's most cited paper (according to the Scopus database), published in 1991, focused in particular on the influence of the walls' reflection law on the reverberant sound field [8]; in this context, a mixed reflection is defined as a mix of diffuse and specular reflection. The key-parameter is the non-dimensional scattering coefficient (noted down *d* in the following) defining the proportion of specular and diffuse reflections (ranging from 0 for purely specular reflections to 1 for purely diffuse reflections). The need of incorporating the scattering coefficient in ray-tracing simulations was demonstrated experimentally, as illustrated in Figure 2. In the case of a proportionate room (left column in Figure 2), it is shown that the scattering coefficient *d* has no influence on the predicted SPL; whatever its value, the simulation shows a generally satisfactory agreement with the measurement data. On the other hand, in the case of a flat room (an empty factory, right column), the spatial decay of the SPL is very sensitive to the scattering coefficient, and increases with the amount of diffuse reflections. It was concluded that it is generally possible to obtain a best-fit agreement with experiment for a particular value of *d* between the two extremes. This conclusion is now common knowledge among practitioners, and most simulation tools incorporate the scattering coefficient value [10, 11].

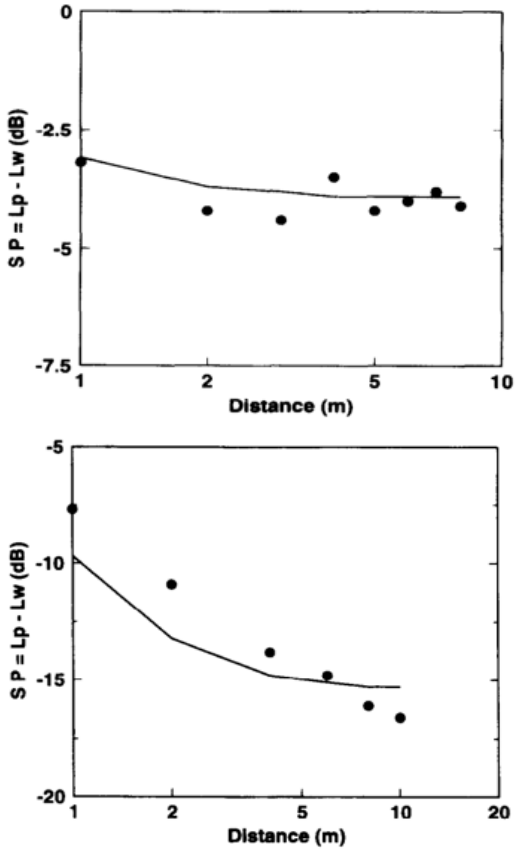

Figure 1 (from [3])**:** Plain line: diffuse sound field theory, (●) measured sound level decay in the 1000 Hz-Octave band, as a function of the distance to the sound source, for: Top: a room with homogeneous dimensions (a squash court , dimensions 10 x 6 x 5 m^3), Bottom: an elongated room (a classroom, dimensions 14 x 8 x 3.5 m^3).

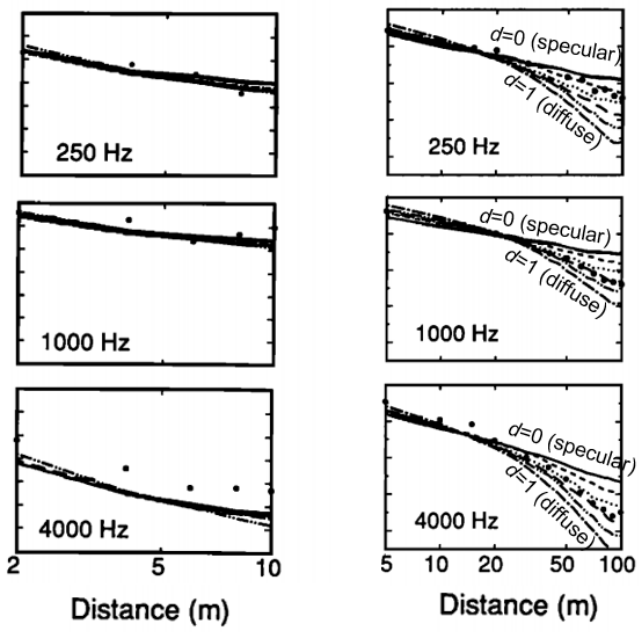

Figure 2 (adapted from [8]): SPL predictions in dB by using the ray-tracing technique, in several octave bands, for different values of the scattering coefficient *d* between 0 and 1, for: a proportionate room (a gymnasium, left column), a flat room (an empty factory, right column). (●) measurement data.

Another important interest of Murray Hodgson was the prediction of the reverberant field in industrial workshops [4]. The presence of "fittings" in the room (which can be called a "fitted room") can potentially enhance the diffuseness of the reverberant field, due to the acoustic scattering by the obstacles. The fittings are generally modeled by a statistical parameter called the fitting density (analogous to a mean free path [12]), and by their absorption coefficient. Many models, often empirical, exist for predicting the reverberation in such rooms, and Hodgson's research in this field has been dedicated to accurate evaluations of such models (e.g., [13-15]), or to assess the correct values for the fitting characteristics (e.g., [16]) by using extensive comparisons between predictions and experiments. Hodgson's publications on the topic of the acoustics of industrial workshops illustrates well how providing reliable tools to practitioners has been a constant goal in Hodgson's research.

3 The diffusion model for room acoustics

Hodgson's works on non-diffuse sound fields truly justifies the need for a model able to describe common practical situations involving non-diffuse sound fields, mixed reflection and scattering by fittings. A solution was proposed with the development of the so-called diffusion model for room acoustics.

The idea of describing the reverberant field in a room by a diffusion process is initially due to Ollendorff in 1969 [17], but the concept was really applied and validated by Picaut et al. in 1997 [5]. The model is based on the sound particle concept [18], *ie.*, on the analogy of the acoustic energy density with a density of "sound particles" propagating at the speed of sound c along straight lines. Many geometrical models (like the ray-tracing technique and its variants) consist in emitting a great number of particles (high enough for reaching the statistical convergence) and following their individual trajectories (the rays).

Conversely, the diffusion model starts from the transport theory developed in statistical physics [19], using the distribution function of the particles in the phase space for modeling the particle dynamics in a global way. Under a set of assumptions, in particular, i) the walls of the room are analogous to a cloud of spherical scatterers located within the room volume, and ii) the phenomena are nearly isotropic, a diffusion equation governing the sound energy density can be obtained [5]. The key-parameter of the diffusion process is the so-called "diffusion coefficient" D (unit m^2/s), and is, in theory, equal to $\lambda c/3$, λ being here the room mean free path, and c the sound speed. In this expression, the classical mean free path of an empty room $\lambda_r=4V/S$ (V and S are respectively the room volume and the area of the room surfaces) is used, which is valid in the case of purely diffuse reflections [2].

This diffusion equation is then associated with an appropriate boundary condition requiring the introduction of an exchange coefficient depending on the absorption coefficient of the walls [20-23]. The advantage of the diffusion model is that it can be rather easily solved numerically [21], and can handle complex cases (eg., complex networks of coupled rooms [24,25]) with a low computational cost compared to geometrical techniques.

The diffusion equation was shown to be an extension of the classical reverberation theory to non-diffuse sound fields [21], and is perfectly adapted for predicting spatial sound decays in rooms such as the ones reported in Figure 1 by Hodgson [3]. In the years 2005-2008, Murray Hodgson was involved in several contributions concerning the development of the diffusion model for room acoustics [21, 26-28], that are reminded in this section.

3.1. Adaptation to mixed reflections

In the validation cases proposed in reference [21], some comparisons were provided by using a ray-tracing code with a value of the scattering coefficient d of 1 (purely diffuse reflections). It was obvious, considering Hodgson's early works (see last section), that the model could only be applied practically if it could handle situations with mixed reflections (d between 0 and 1).

The observation of the effect of the diffusion coefficient value on the simulation results brought a first answer to this problem [26]. In the case of a room with homogeneous dimensions, it was found that the diffusion coefficient value has no effect on the predicted levels; let us remind, from Hodgson's former results in Figure 2, that similarly, the reflection law (through the scattering coefficient d) has no effect on the predicted levels. Let us now define a correction factor K ($K \geq 1$), so that the value of the diffusion coefficient is set to $K \times D$.

As initially observed by Hodgson (Figure 2 [8]), the sound decay in a flat room, predicted by using the ray-tracing technique, is greatly affected by the amount of specular reflections (i.e., the value of the coefficient *d*), as shown in Figure 3. It was then observed, as demonstrated in Figure 3b, that it is always possible to find a correction factor *K* so that a good match can be obtained between the diffusion model predictions and the levels predicted by the ray-tracing technique for different value of the scattering coefficient *d*. It was then concluded that there is an analogous behavior between the effect of the scattering coefficient *d* on the ray-tracing results, and the effect on the diffusion coefficient value $K \times D$ on the diffusion result.

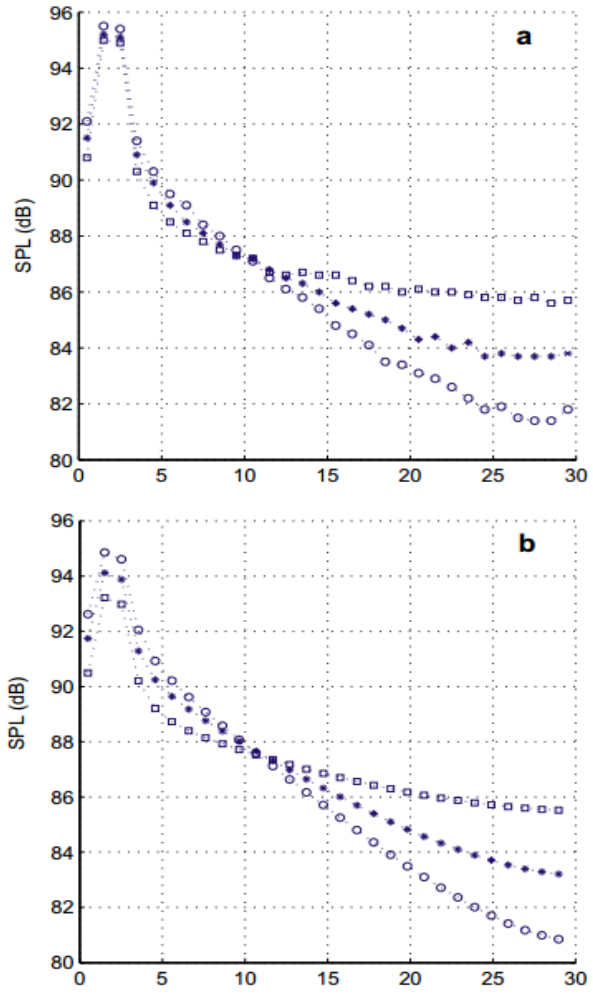

Figure 3 (from [26]): SPL decay in a room of dimensions 30 x 8 x 3.85 m^3 (source at *x*=2); (a) Ray-tracing model: (◦) *d* = 1 (diffuse reflections); (∗) *d* = 0.5; (□) *d* = 0 (specular reflections); (b) Diffusion model: (◦) *K* = 1 (theoretical model); (∗) *K* = 1.8; (□) *K* = 5.

As it will be explained in section 3.3, the coefficient *D* sets the relation between the energy density and the acoustic energy flow through the room (*i.e.*, the intensity). For an elongated room or a flat room, a lower diffusion coefficient means that the diffuse reflections involve a higher resistance to energy flow than specular reflection, likely due to back-scattering.

Some further research was carried out in order to find a general empirical law for the correction factor *K*, which would allow the diffusion model to be applied for a wide range of mixed reflection laws and room aspect ratios [29]. A more satisfying solution was finally derived some years later by working out a theoretical expression of the diffusion coefficient, starting from the transport theory [30]. A new expression for the diffusion coefficient *D* was obtained:

$$D = \frac{\lambda c}{3} \frac{1}{\alpha + (1-\alpha)d} \quad (1)$$

Where α is the absorption coefficient of the room's walls. The dependence to the scattering coefficient *d* appears in the expression, and in the case of purely diffuse reflections (*d*=1), the expression of Eq. (1) logically matches the original value, $\lambda c/3$.

More surprisingly, a dependence of the diffusion coefficient *D* to the absorption coefficient α also appears in Eq. (1). At low absorption coefficient ($\alpha \ll 1$), the value of *D* significantly increases when the amount of specular reflections increases (*ie.*,when *d* decreases), while *D* remains approximately equal to $\lambda c/3$ whatever the value of *d* at high absorption (α close to 1) [30]. The dependence of *D* to the absorption was also observed numerically in the case of elongated rooms [31].

3.2. Predicting the reverberant field in fitted rooms

As mentioned in Section 2, modeling the acoustics of fitted rooms have been a constant goal in Hodgson's research. Fitted rooms are characterized by the presence of a large number of obstacles with different shapes and orientations, and a statistical approach can accurately describe the effect of the fittings, as initially proposed by Kuttruff [12]. The statistical parameter for describing the fittings is the mean free path λ_f of a random spatial distribution of scatterers in the room volume (the fitting density is then defined as $1/\lambda_f$ [6, 32]).

The idea of describing the fittings effect by a diffusion process had been proposed by Kurze in 1985 [33], associated to an image source model for the ceiling and floor. In 2007, a unified model [26] was proposed in order to combine the diffusion by the fittings and by the walls of the room, considering the classical mean free path λ_r of an empty room. The propagation of sound in a fitted room was supposed analogous to the propagation of sound particles through a medium of scatterers accounting for both walls and fittings. In such a medium, the mean free path λ (in meter) of the sound particles is:

$$\lambda = \frac{\lambda_r \lambda_f}{\lambda_r + \lambda_f} \quad (2)$$

So that a diffusion process describing the propagation of sound particles in the fitted room can be defined and solved numerically by adding appropriate boundary conditions [26].

The example of Figure 4 [26] illustrates the efficiency of such a model, by considering the case of a parallelepiped room with specular reflections and half-fitted following two configurations [32] (the absorption coefficient of the fittings

is 0.3). In both cases, the diffusion process matches both ray-tracing predictions and measurement data.

3.3. Predicting energy flows

A diffusion process involves a linear relationship between the gradient of the acoustic energy density ∇w, and the energy flow $\boldsymbol{J}$ (a vector interpreted in acoustics as the acoustic intensity with dimension W/m^2):

$$\boldsymbol{J} = -D\,\nabla w \qquad (3)$$

This law is generally called the Fick's law. From 2008, several studies started using the Fick's law in order to investigate energy flows in single [28] or coupled rooms [34]. Ray-tracing or particle-tracing codes can also be used to evaluate the reverberant energy flow vector, by associating each ray (or sound particle) with an elementary intensity vector; by summing the contributions of the set of rays or particles crossing a given receiving volume, the net intensity vector can be obtained [28, 31].

The energy flow vector is an interesting quantity for investigating the diffuseness of a reverberant sound field. A purely diffuse sound field is composed of many uncorrelated sound waves coming from uniformly distributed directions. By nature, the energy flow should be zero. By considering numerical simulations of the reverberant sound field, it was found that the geometry that can meet rigorously this property is a sphere with uniform absorption [31, 18]. A cubical with homogeneous absorption is known as a favorable configuration for generating a diffuse sound field [3]. Looking closely at the energy flow in a cube, it nevertheless appears that the reverberant intensity vectors describe an organized pattern with significant intensity [31]. Figure 5 displays the intensity vector pattern in the vicinity of the corner of a cubical room, oriented from the source toward the edges of the room, the norm of the reverberant intensity being larger close to the room boundaries. This pattern explains that some significant variations of the sound intensity level close to the walls of the rooms can be observed, whereas the SPL of the reverberant field appears to be rather constant throughout the room [31]. This example demonstrates that the energy flow pattern is an appropriate tool for investigating the diffuseness of a sound field.

The Fick's law is a quite unusual behavior in acoustics (the intensity is proportional to ∇w); indeed for propagating waves, the intensity is proportional to the acoustics energy density w.

The simulation results of Figure 5 tend to indicate that the Fick's law is relevant for a reverberant field in room acoustics, because the particle-tracing results reveal the same intensity pattern as the Fick's law. The Fick's law has been further confirmed in the case of elongated rooms, in particular by using an experimental approach based on a scale model and pressure-velocity probes (for measuring the intensity vector) [35]. The use of the energy flow vector calculated from the Fick's law has also been shown to be very useful for understanding multiple decay phenomena in monumental spaces such as mosques [36].

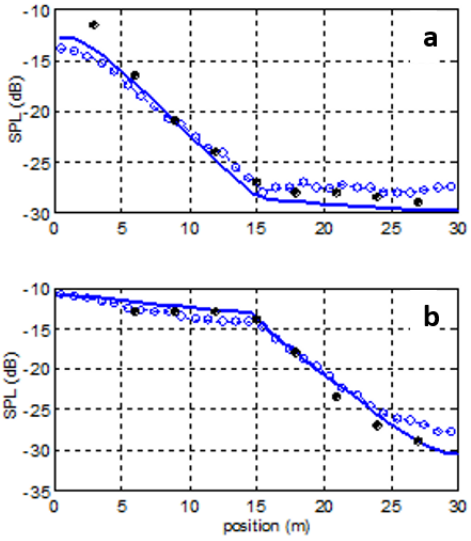

Figure 4 (from [26]**):** SPL decay in a room of dimensions 30 x 8 x 3.85 m^3 (source at x=1.5); (a) room fitted (λ_f = 3.9 m) for x<15 m, empty for x>15 m; (b) room empty for x<15 m, fitted (λ_f = 3.9 m) for x>15 m. Solid line: diffusion model; (o) ray-tracing prediction; (●) measurement data [32].

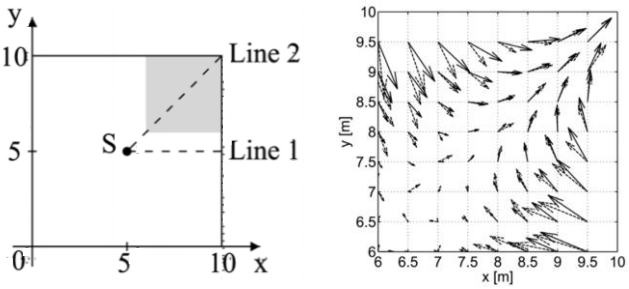

Figure 5 (adapted from [31]): Left: top view of the cubical room (10 x 10 x 10 m^3, source in the room center, purely diffuse reflections); the grey zone indicates the domain in which the energy flow vectors are plotted. Right: energy flow vectors obtained by particle tracing simulations (solid arrows) and the Fick's law (dashed arrows).

4 Concluding remarks

Some remarkable contributions of Murray Hodgson's research on reverberation modeling, and on the effect of scattering objects and wall reflection law have been first presented in this paper. The research works carried out on the development of a diffusion model for room acoustics can be seen as a continuation of Hodgson's work concerning numerous issues that he raised, generally, on the modeling of non-diffuse sound fields. The diffusion model for room acoustics is now applicable to a wide range of practical situations.

However, some aspects still need improvements and developments. In particular, the diffusion coefficient, which is the main parameter of the model, is now known to be varying along the room [31, 35], and this variation would need to be taken into account to accurately model complex situations like flat or elongated rooms with large aspect

ratios. In some cases of networks of coupled rooms (with different aspect ratios or coupled by large apertures), the diffusion model gives some interesting results for physical interpretations, but the quantitative results still need to be improved, possibly because the change of the diffusion coefficient between coupled volumes requires further improvement to accurately model the energy transfers. The question to be answered will be if diffusion, which is an approximation of a more general transport process, has reached its limits, or if some further modeling of the diffusion coefficient is still possible in those cases.

References

[1] Schroeder, M. R. Eigenfrequenzstatistik und Anregungsstatistik in Raümen, *Acustica*, 4: 456-468, 1954. English translation in Schroeder, M. R. Statistical Parameters of the Frequency Response Curves of Large Rooms, *J. Audio Eng. Soc.*, 35: 299-306, 1987.

[2] H. Kuttruff, H. Room Acoustics, 4th ed., *Spon Press*, Oxon, 2009.

[3] Hodgson, M.. When is Diffuse-Field Theory Applicable?, Applied Acoustics, 49(3): 197-207, 1996.

[4] Hodgson, M. Theoretical and Physical Models as Tools for Study of Factory Sound Fields, *Ph. D. Thesis*, University of Southampton, England, 1983.

[5] Picaut, J., Simon, L., Polack, J.-D. A Mathematical Model of Diffuse Sound Field Based on a Diffusion Equation, *Acustica*, 83: 614-621, 1997.

[6] Hodgson, M. On Measures to Increase Sound-Field Diffuseness and the Applicability of Diffuse-Field Theory, *J. Acoust. Soc. Am.*, 95(6): 3651-3653, 1994.

[7] Hodgson, M. On the Prediction of Sound Fields in Large Empty Rooms, *J. Acoust. Soc. Am.*, 84(1): 253-261, 1988.

[8] Hodgson, M. Evidence of Diffuse Surface Reflections in Rooms, *J. Acoust. Soc. Am.*, 89(2): 765-771, 1991.

[9] Nosal, E.-M., Hodgson, M., Ashdown, I. Improved Algorithms and Methods for Room Sound-Field Prediction by Acoustical Radiosity in Arbitrary Polyhedral Rooms, *J. Acoust. Soc. Am.*, 116(2): 970-980, 2004.

[10] Dalenbäck, L. Room Acoustic Prediction Based on a Unified Treatment of Diffuse and Specular Reflection *J. Acoust. Soc. Am.*, 100(2): 899-909, 1996.

[11] Lam, Y. W. A Comparison of Three Diffuse Reflection Modeling Methods Used in Room Acoustics Computer Models, J. *Acoust. Soc. Am.*, 100(4): 2181-2192, 1996.

[12] Kuttruff, H. Sound Decay in Reverberation Chambers with Diffusing Elements, J. *Acoust. Soc. Am.*, 69(6): 1716-1723, 1981.

[13] Hodgson, M. On the Accuracy of Models for Predicting Sound Propagation in Fitted Rooms, J. *Acoust. Soc. Am.*, 88(2): 871-878, 1990.

[14] Hodgson, M. Experimental Evaluation of Simplified Models for Predicting Noise Levels in Industrial Workrooms, J. *Acoust. Soc. Am.*, 103(4): 1933-1939, 1988.

[15] Hodgson, M. Ray-Tracing Evaluation of Empirical Models for Predicting Noise in Industrial Workshops, *Applied Acoustics*, 64: 1033-1048, 2003.

[16] Heereema, N., Hodgson, M. Empirical Models for Predicting Noise Levels, Reverberation Times and Fitting Characteristics in Industrial Workshops, *Applied Acoustics*, 57: 51-60, 1998.

[17] Ollendorf, F. Statistical Room-Acoustics as a Problem of Diffusion (a proposal), *Acustica*, 21: 236-245, 1969.

[18] Joyce, W.B. Exact Effect of Surface Roughness on the Reverberation Time of a Uniformly Absorbing Spherical Enclosure, J. *Acoust. Soc. Am.*, 64(5): 1429-1436, 1978.

[19] Morse, P., Feshbach, M. Methods of Theoretical Physics, *McGraw-Hill*, New York, 1953.

[20] Picaut, J., Simon, L., Polack, J.-D. Sound Field in Long Rooms with Diffusely Reflecting Boundaries, *Applied Acoustics*, 56: 217-240, 1999.

[21] Valeau, V., Picaut, J., Hodgson, M. On the Use of a Diffusion Equation for Room-Acoustic Prediction, *J. Acoust. Soc. Am.*, 119(3): 1504-1513, 2006.

[22] Billon, A., Picaut, J., Sakout, A. Prediction of the Reverberation Time in High Absorbent Room Using a Modified-Diffusion Model, *Applied Acoustics*, 69: 68-74, 2008.

[23] Jing, Y., Xiang, N. On Boundary Conditions for the Diffusion Equation in Room-Acoustic Prediction: Theory, Simulations, and Experiments, *J. Acoust. Soc. Am. El. Lett.*, 123(1): 145-153, 2008.

[24] Billon, A., Valeau, V., Sakout, A., Picaut, J. On the Use of a Diffusion Model for Acoustically Coupled Rooms, *J. Acoust. Soc. Am.*, 120(4): 2043-2054, 2006.

[25] Xiang, N., Jing, Y., Bockman, A. C. Investigation of Acoustically Coupled Enclosures Using a Diffusion-Equation Model, *J. Acoust. Soc. Am.*, 126(3): 1187-1198, 2009.

[26] Valeau, V., Hodgson, M., Picaut, J. A Diffusion-Based Analogy for the Prediction of Sound Fields in Fitted Rooms, *Acta Acustica United. With Acustica*, 93: 94-105, 1997.

[27] Foy, C., Billon, A., Picaut, J., Valeau, V. Sakout, A., Hodgson, M. Diffusion-Based Models for Predicting Sound Fields in Rooms with Mixed Specular and Diffuse Reflections, 19th Int. Cong. On Acoustics, Madrid, 2007.

[28] Valeau, V., Boirlaud, M., Picaut, J. Hodgson, M., Foy, C. The Intensity of a Reverberant Field as an Energy-Density Gradient, Acoustics'08, Paris, 2008.

[29] Foy, C., Valeau, V., Billon, A., Picaut, J., Sakout A. An Empirical Diffusion Model for Acoustic Prediction in Rooms with Mixed Diffuse and Specular Reflections, *Acta Acustica United with Acustica*, 95: 97-105, 2009.

[30] Foy, C., Picaut, J., Valeau, V. Including Scattering within the Rooms Acoustics Diffusion Model: An Analytical Approach, *J. Acoust. Soc. Am.*, 140(4) : 2659-2669, 2016.

[31] Visentin, C., Prodi, N., Valeau, V., Picaut, J. A Numerical Investigation of the Fick's Law of Diffusion in Room Acoustics, *J. Acoust. Soc. Am.*, 132(5): 3180-3189, 2012.

[32] Ondet, A.M., Barbry, J.L. Modeling the Sound Propagation in Fitted Workshops Using Ray Tracing, *J. Acoust. Soc. Am.*, 85: 787–796, 1989.

[33] Kurze, U. J. Scattering of Sound in Industrial Spaces, *J. Sound Vib.*, 98(3): 349–364, 1985.

[34] Jing, Y., Xiang, N. Visualizations of Sound Energy Across Coupled Rooms Using a Diffusion Equation Model, *J. Acoust. Soc. Am. El. Lett.*, 124(6), 2008.

[35] Visentin, C., Prodi, N., Valeau, V., Picaut, J. Experimental Analysis of the Relationship Between Reverberant Acoustic Intensity and Energy Density Inside Long Rooms, *J. Acoust. Soc. Am.*, 138(1): 181-192, 2015.

[36] Gül, Z. S., Xiang, N., Caliskan, M. Investigations on Sound Energy Decays and Flows in a Monumental Mosque, *J. Acoust. Soc. Am., 140(1):* 344-355, 2016.

There's a lot of noise out there.
Rockfon® ceilings provide the style architects want and the high sound absorption you need. Get the facts at www.Rockfon.com.
The Passing Whistler
The Gum Smacker
The Loud Talker
The Coffee Slurper
The Click-Clacker
The Squeaky Roller
Rockfon®
Part of the ROCKWOOL Group

GRAS Sound & vibration

SVS
SOUND & VIBRATION SOLUTIONS CANADA Inc.

SINUS

Hearing Protection Testing

Multifunction Calibrator

New Low-noise KEMAR Manikin

Rugged Microphone
HALT Tested
IP-67

Type I & II
Low Cost SLM
Longest Battery Life

Low Noise
High Sensitivity

Award Winning
Beam Forming
Acoustic Imaging

High Performance Low Cost Acoustic Analysers

Sound & Vibration Solutions Canada Inc.

Integrated Solutions from World Leaders

519-853-4495 ametelka@cogeco.ca www.svscanada.ca