WHEN IS DIFFUSE-FIELD THEORY ACCURATE?

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Diffuse-field theory is used by practitioners to predict sound fields in rooms of every type. Often forgotten is the fact that the theory is based on assumptions which may limit its applicability. If the theoretical assumptions do not hold in the case of a particular room for which predictions are to be done, the predictions may not be accurate.

The objective of this paper is to review what is known about the applicability of diffuse-field theory. This is mainly based on extensive work by Kuttruff ([1] and references therein) and by the author [2, 3, 4, 5, 6], comparing predictions by diffuse-field theory and a ray-tracing model. It will consider two versions of diffuse-field theory - the Eyring and Sabine versions - and the prediction of both sound decay / reverberation time, and steady-state sound pressure level. Note that both diffuse-field theory and ray-tracing are energy-based models which ignore wave effects and thus may be inherently inaccurate at lower frequencies.

I. DIFFUSE FIELDS AND PARAMETERS STUDIED

The discussion will consider the accuracy of diffuse-field theory with respect to the following room-acoustical parameters:

- room shape - as described by the aspect ratio (length:width:height);
- surface absorption - its distribution, and its magnitude as described by the average surface-absorption coefficient;
- surface reflection - as described by the diffuse-reflection coefficient, equal to the proportion of reflected energy which is reflected diffusely [4]. That energy not reflected diffusely is reflected specularly;
- fittings (or volume scatterers) - these are obstacles in the room volume that scatter sound randomly, as described by their volume density.

The basic assumption of diffuse-field theory is that the sound field in the room is diffuse. The sound field is diffuse if the following two conditions apply:

1. At any position in the room the reverberant sound waves are incident from all directions with equal intensity (and random phase relations);
2. The reverberant sound field is the same at every position in the room.

The question that is effectively being asked here is: for what values of the above room-acoustical parameters do the above two conditions hold? Note that it has recently been argued that the first condition is sufficient with respect to sound decay / reverberation time prediction. However, both conditions are relevant to steady-state sound pressure level prediction [6].

The various effects will be discussed qualitatively; space does not permit the use of figures to illustrate each point.

II. ROOM SHAPE

Sound Decay / Reverberation Time - In the case of specular reflection, Eyring prediction is accurate in regularly-shaped (ie quasi-cubic) rooms. As room aspect ratio increases it becomes less accurate. Accuracy increases with diffuse surface reflection and, up to some limit, fitting density.

Steady-State Sound Pressure Level - Eyring prediction is accurate in empty, regularly-shaped rooms with specularly reflecting surfaces. It becomes increasingly inaccurate as the fitting density, room aspect ratio and diffuse surface reflections increase. In particular, levels near a source are increasingly underestimated; those far from sources are increasingly overestimated.

III. SURFACE REFLECTION

Sound Decay / Reverberation Time - Eyring prediction is accurate in regularly-shaped rooms with specularly reflecting surfaces. Its accuracy decreases with increasing aspect ratio. Increasing the diffuse reflection coefficient improves accuracy.

Steady-State Sound Pressure Level - Eyring prediction becomes increasingly inaccurate as the diffuse-reflection coefficient increases from zero (specular reflection). In particular, levels near a source are increasingly underestimated; those far from sources are increasingly overestimated.

IV. FITTING DENSITY

Sound Decay / Reverberation Time - Eyring prediction is accurate only if the fitting density takes an optimum value. This value depends on the room shape and surface absorption distribution. It is low in regularly-shaped rooms with uniformly distributed absorption. It increases with room aspect ratio and the non-uniformity of the absorption. If the fitting density is either lower or higher than the optimum value, the rate of sound decay is lower than that predicted by Eyring;

Steady-State Sound Pressure Level - Eyring prediction becomes increasingly inaccurate as the fitting density increases from zero (empty room).

V. SURFACE-ABSORPTION DISTRIBUTION

Sound Decay / Reverberation Time - In the case of low diffuse-reflection coefficient Eyring prediction is accurate only if the surface absorption is uniformly distributed. Its accuracy decreases with non-uniformity;

Steady-State Sound Pressure Level - Generally speaking, surface-absorption distribution has only a small effect on room steady-state sound pressure levels.

VI. SURFACE-ABSORPTION MAGNITUDE [5]

Sound Decay / Reverberation Time - Eyring prediction can be accurate for any average surface-absorption coefficient. Sabine prediction is only accurate if the average surface absorption coefficient is sufficiently low;

Steady-State Sound Pressure Level - Eyring prediction can be accurate for any average surface-absorption coefficient. Sabine prediction is only accurate if the average surface absorption coefficient is sufficiently low.

VII. SUMMARY

Following is a summary of the conditions under which diffuse-field theory would be expected to be accurate:

Sound Decay / Reverberation Time:	Eyring accurate if	diffuse surface reflection OR optimum fitting density OR specular reflection AND cubic shape AND uniform absorption
Steady-State Sound Pressure Level:	Eyring accurate if	specular reflection AND cubic shape AND uniform absorption AND no fittings (empty)
Sabine cf Eyring:	Eyring accurate Sabine accurate	for any average surface absorption coefficient for low average surface absorption coefficient

VIII. REAL ROOMS

Of fundamental practical interest is the question of how do the above results apply to real rooms. This question is not easy to answer. This is because the applicable values of certain key room-acoustical parameters are not well known for particular rooms. In particular, applicable values for surface-absorption and diffuse-reflection coefficients, and for fitting densities, are not well known.

Here is my personal experience, from having measured sound fields in hundreds of rooms of many types. Note that I am only referring to rooms which consist of a single volume - not coupled spaces. Generally, sound-decay curves are quite linear, and diffuse-field reverberation-time prediction is quite accurate in most real rooms. However, diffuse-field steady-state sound pressure level prediction is seldom accurate in real rooms and can, in fact, be highly inaccurate. These conclusions are consistent with the above conclusions regarding the applicability of diffuse-field theory and the existence in real rooms of many sound diffusing mechanisms (diffusely reflecting surfaces and/or fittings). This is supported by results published elsewhere [4].

It is easy to illustrate how inaccurate diffuse-field theory can be in predicting steady-state sound pressure levels. The figure shows the 1000-Hz sound-propagation curves (the variation with distance from a single omnidirectional point source of the sound pressure level minus the source sound power level) measured in three different rooms - a squash court (9.7 x 6.4 x 5.5 m), an open-plan office (40 x 25 x 2.7 m), and a machine shop (23 x 9 x 4.6 m). Clearly only in the case of the squash court (a good approximation to a reverberation room) does the sound propagation curve level off at large distances as predicted by diffuse-field theory. In all other cases levels decrease monotonically with increasing distance. Eyring theory underestimates levels near the source and overestimates levels far from the source.

IX. CONCLUSIONS

The results of research by Kuttruff and the author, amongst others, have established for what values of certain room-acoustical parameters the sound field in a room would be expected to be diffuse and, thus, predictions by diffuse-field theory accurate. Further research is required to determine exactly how these results apply to real rooms. However, practitioners using diffuse-field theory should be aware that the assumption of a diffuse sound field may seriously limit the accuracy of prediction - particularly of steady-state sound pressure level. Models - such as the method of images and ray tracing - which are accurate in the case of non-diffuse sound fields, are available.

REFERENCES

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FIGURE

1000-Hz octave-band sound-propagation curves as (•) measured and (▬▬) predicted by Eyring theory for: a) a squash court (9.7 x 6.4 x 5.5 m); b) an open-plan office (40 x 25 x 2.7 m); c) a machine shop (23 x 9 x 4.6 m). (——) free-field sound-propagation curve.