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Issues for computer modelling of room acoustics in non-concert hall settings

Yiu Wai Lam*

Acoustics Research Centre, School of Computing Science and Engineering, University of Salford, Salford M5 4WT, UK

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Abstract: The basic principle of common room acoustics computer models is the energy-based geometrical room acoustics theory. The energy-based calculation relies on the averaging effect provided when there are many reflections from many different directions, which is well suited for large concert halls at medium and high frequencies. In recent years computer modelling has become an established tool in architectural acoustics design thanks to the advance in computing power and improved understanding of the modelling accuracy. However concert hall is only one of many types of built environments that require good acoustic design. Increasingly computer models are being sought for non-concert hall applications, such as in small rooms at low frequencies, flat rooms in workplace surroundings, and long enclosures such as underground stations. In these built environments the design issues are substantially difference from that of concert halls and in most cases the common room acoustics models will needed to be modified or totally re-formulated in order to deal with these new issues. This paper looks at some examples of these issues. In workplace environments we look at the issues of directional propagation and volume scattering by furniture and equipment instead of the surface scattering that is common assumed in concert hall models. In small rooms we look at the requirement of using wave models, such as boundary element models, or introducing phase information into geometrical room acoustics models to determine wave behaviours. Of particular interest is the ability of the wave models to provide phase information that is important not only for room modes but for the construction of impulse response for auralisation. Some simulated results using different modelling techniques will be presented to illustrate the problems and potential solutions.

Keywords: Computer simulation, Room acoustics

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1. INTRODUCTION

The application of energy-based computer modelling to concert hall settings is well established nowadays. Its accuracy has been tested through a series of international round robin tests, e.g. [1,2], and it has been accepted by many architectural consultants as a design tool. Although there are a large variety of computer models available for concert hall acoustics, most are based on energy based, straight-line propagation geometrical room acoustics, with some forms of diffuse reflection algorithm to account for surface scattering. The energy based geometrical prediction works well in concert halls because of the relatively well proportionate geometry, large room volumes, and usually medium to high frequency settings, in which the number of reflections is large and the distribution of reflection directions is well mixed. However in the design of room acoustics, there are many room types other than concert halls that are also important to the community. Small performance spaces such as studios and listening room, to large disproportionate enclosures such as offices, factory workplaces, and underground stations all present different classes of problems to the modelling of their internal acoustics. A street canyon can also be considered as a special semi-enclosed space in which the modelling of sound propagation is also important. In these spaces the sound propagation can be very directional and/or significantly affected by different types of wave behaviours. In these cases the geometrical models will need to be modified to take them into account.

This paper examines some specific modelling issues associated with some common non-concert hall spaces, especially disproportionate workplaces and small performance spaces. Adaptation of the usual geometrical models to these spaces will be discussed, and the application of wave

*e-mail: y.w.lam@salford.ac.uk

based numerical models will also be demonstrated. In particular the possible requirements for modifications to account for directional propagation, inclusion of volume scattering to account for large objects in the space, and the introduction of pressure reflection coefficients to account for phase information in the geometrical models will be examined.

2. LARGE DISPORTIONATE SPACES

Large workplaces, such as factories or open plan offices have three characteristics that are very different from concert halls and are important to the modelling of acoustics: — the presence of noise screens, disproportionate shapes, and the presence of volume scatters. First there are generally noise screens in the workplaces. The diffracted pressure over the screen tops needs to be calculated in addition to the geometrical reflections to gain a correct prediction. Usually it is sufficient to calculate only the first order diffractions from nearby geometrical images to give a satisfactory prediction. Some recent modelling examples can be found in Wang and Bradley [3,4].

2.1. Disproportionate Rooms — Directional Propagation

The second aspect of concern is the disproportionate geometry usually found in workplaces. In a proportionate room, the distribution of sound reflections is fairly mixed and the "diffuse field" or random incidence absorption coefficient and scattering coefficient used in energy based geometrical room acoustics models are appropriate. In a disproportionate room, the sound field is distorted and the inherent errors of the energy based geometrical assumption can also be amplified in certain propagation directions. Table 1 shows a comparison of the predictions of *RT* by a hybrid room acoustics model with diffuse reflection energy re-distribution facility [5] on two scale-model rooms. Both rooms are made of the same material but one has a very high aspect ratio. Using the same absorption coefficient, the disproportionate room requires a significantly higher scattering coefficient for the prediction to converge to the measured *RT*. Similar behaviours were also found when other geometrical room acoustics models were applied to these rooms, although the value of the scattering coefficient for the best prediction varied depending on the diffuse-reflection algorithms used. The result shows that the value of scattering coefficient of a wall required for computer modelling can change significantly in disproportionate rooms, and the random incidence scattering coefficient may not be appropriate for this type of spaces.

Table 1 *RT* (s) at 630 Hz predicted by a energy-based hybrid room acoustics model.

Scattering coefficient d	Room 1: $7.5\,\text{m} \times 27.5\,\text{m} \times 27.5\,\text{m}$	Room 2: $110\,\text{m} \times 55\,\text{m} \times 5.5\,\text{m}$
$d = 0$	9.18	11.90
$d = 0.1$	8.65	6.60
$d = 0.25$	/	5.20
$d = 1$	8.64	5.0
Eyring	8.8	5.0
Measured	8.7†	5.4†

†from Fig. 2 of Hodgson *et al.*, *J. Sound Vib.*, **113**, 260 (1987).

The cause of this problem is due to the different propagation directions created by the disproportionate room shape. Sound propagating in the long direction suffers substantially less reflections and therefore retains its energy for a much longer time. A purely geometrical model over-emphasises this aspect, resulting in a long reverberation tail that is dominated by the propagation in the long direction. In reality surface scattering and other wave effects re-distribute the energy away from the long direction. Hence the application of a suitable scattering coefficient is necessary to model this behaviour. However the amount of re-distribution in the real room is dependent both on the material property of the surface as well as wave propagation characteristics, which is in turn influenced by the disproportionate geometry. Hence a different scattering coefficient is required for significantly directional propagation.

Interestingly, the effect of the disproportionate geometry is mainly on the energy in the reverberant tail and as such does not have too big an effect on the sound pressure level. The difference between predictions using different scattering coefficients, shown in Fig. 1, are quite small and all predictions are close to the measured values when the scattering coefficient used is below 0.25. This can be

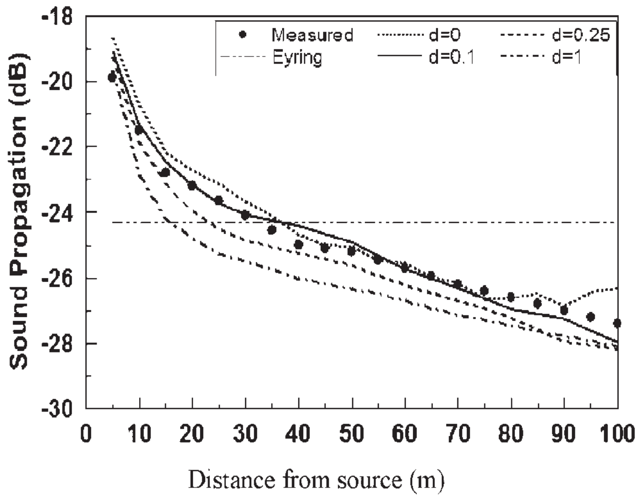

Fig. 1 Sound pressure level variation with distance in an empty long flat room of size $110\,\text{m} \times 55\,\text{m} \times 5.5\,\text{m}$. Predictions by an energy-based geometrical room acoustics model with different surface scattering coefficient d.

considered as an indication that the absorption coefficient used is appropriate. A significant under-prediction of the sound level is observed only when the scattering coefficient is set at a large value of 1.

There are also other cases of directional propagation created by, for example, a 2-dimensional diffuser or a large opening such as an open roof. In some cases there may not be sufficient amount of reflections in certain directions to justify the type of omni-directional averaging or randomisation algorithms commonly adopted in room acoustic models for dealing with surface scattering. Computer models and probably the specification of material properties may need to be modified to account for directional changes.

2.2. Volume Scattering

The third aspect of difficulty in modelling workspaces is the presence of scattering objects or obstacles in the volume of room. In a concert hall, although the audience area is highly scattering it is also absorptive and can be adequately represented by a flat surface with a high scattering coefficient. In workplaces such as a factory there are large machineries and the sound propagation in between these scattering objects is also important. In theory one could model each object individually by appropriate geometrical shapes but in practice it is not always feasible due to the large number of objects involved. Figure 2 shows a comparison of the sound propagation prediction by a geometrical acoustics model in a tube-like room that has an aspect ratio of 7.8:2.1:1 (30 m × 8 m × 3.85 m) and has many scattering objects on the floor. The room and the configuration of the scattering objects are those of "configuration (b)" in Reference [6]. Essentially the objects are 0.5 m × 0.5 m × 3 m rectangular blocks that are placed on the floor in regular intervals (2 per 3 m in the direction of the longest dimension of the room and 1 every meter in the other direction). Different surface scattering coefficients were used on the floor to try to simulate the effect of the scattering effect of the objects. As a comparison the prediction by a ray tracing model using a randomised volume scattering method [6] is also shown. In the volume scattering method, the proportion of energy that is scattered from the obstacles within a volume of space is described by the "scattering cross-section density" q m^{-1} (also known as the "fitting density") which is calculated from the surface area per fitting S_{si} contained within volume V:

$$q = \frac{\sum S_{si}}{4V} \tag{1}$$

A ray passing through the volume is attenuated by the absorption of the fitting and scattered into different directions using a randomisation process based on this parameter. Details of the method and the absorption and fitting data that were used for this analysis can be found in Reference [6].

It can be seen from Fig. 2 that the geometrical prediction using surface scattering is quite good at short to medium distance from the source, and provides a considerable improvement over the simple diffuse field prediction, but it significantly over-predicts the sound pressure level at long distance. In other words the cumulative scattering effect of the volume scatters is under-predicted over a long distance. Using higher scattering coefficients on the floor surface only slightly improve the prediction but could not match the continuous drop of sound pressure level at longer distances. In contrast the volume scattering model seems to predict the drop fairly well. It should be noted that the fitting density used in the configuration of Fig. 2 is very high and the height of the obstacles (3 m) is nearly the height of the room (3.85 m) and is much higher than the source height (0.85 m) and receiver height (1.5 m). Hence this is a situation that actually emphasises the effect of volume scattering. In general whether the surface scattering method can approximate the effect of obstacle scattering will be strongly dependent on the height of the obstacles. For example if the height of the obstacle is significantly lower than the source and receiver heights, such as in the case of audience seating in a concert hall, then the surface scattering method should work well. However in the case of a factory where the height of machinery is higher than the receiver height then the volume scattering method should produce better predictions.

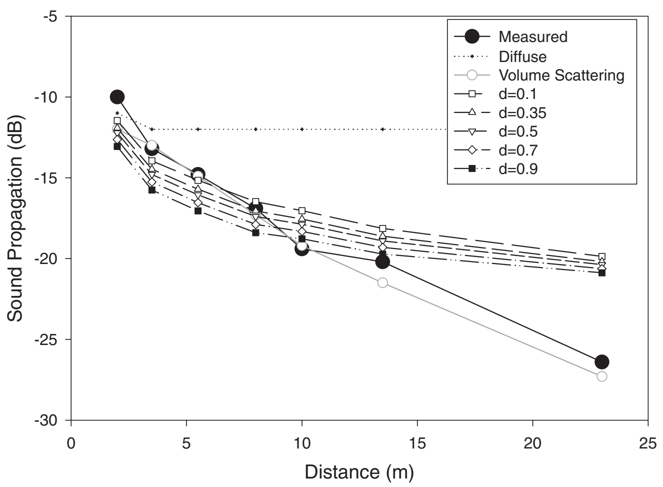

Fig. 2 Predictions of sound propagation in a tube-shape room of aspect ratio 7.8:2.1:1 using surface scattering and volume scattering algorithms. The measured data, geometry of the room, and the details of the scattering objects are taken from A. M. Ondet and J. L. Barbry's "configuration (b)" experiment [*J. Acoust. Soc. Am.*, **85**, 787–796 (1989)].

3. MODELLING PHASE AND TRANSIENT RESPONSE

The acoustics of a small space at very high frequencies is similar to that of a large concert hall and can be adequately modelled by the usual energy based geometrical room acoustics models if only energy parameters such as *RT*, clarity index and sound level etc. [7] are required. However for small studios the influence of wave behaviour of the sound can become important at the lower end of the audio frequency range. The phenomenon of room modes at low frequencies is well known and can be easily predicted for simple rectangular rooms with near rigid walls. The sound field in such simple rooms can be calculated by an infinite series of the contribution from each of these modes — the wave solution. For rooms with more complicated shapes or distribution of absorptive materials wave based computer models are necessary to obtain reliable predictions when room modes are important. Even in concert hall settings, the inclusion of phase information in the prediction will be advantageous for the production of the true transient impulse response of the room, which is often required for producing realistic auralisation, or simply as a possible means of improving prediction accuracy. There are some well established numerical models, such as the finite element method (FEM) and the boundary element method (BEM), that are flexible and accurate for predicting wave fields in a room. Unfortunately they are still too expensive to apply in practice. Following the concept of geometrical acoustics, one could consider modifying existing energy based geometrical room acoustic models by incorporating a pressure wave based reflection algorithm rather than the simple energy absorption and scattering approximation to model the complex sound pressure reflection phenomenon. Together with the phase information from the propagation path, a full phase model can be used to model the room acoustics. The ray path information generated by a ray tracing or an image model will be sufficient to calculate the sound pressure reflection if the reflecting surface is locally reacting and has no edge effect, such as in the case of an infinite plane or a surface in a perfectly rectangular room. There are two obvious possibilities to model the complex sound pressure reflection. If one takes the same assumption as in ray tracing that the sound can be approximated by plane waves then a plane wave reflection coefficient can be constructed from the reflection geometry and the surface impedance. An arguably more accurate representation, for propagation from a point source, is to retain the spherical wave front and construct a spherical wave reflection coefficient. There is however an underlying assumption that the spherical wave remains essentially spherical after the reflection, i.e. the images are also point sources. This is not entirely accurate for soft reflecting surfaces since the wave front will be modified by the impedance of the surface.

In here we will look at the accuracy obtained by introducing these two pressure reflection coefficients into geometrical acoustics models such as the ray tracing and image methods. Of particular interest is the accuracy of adopting a plane wave reflection coefficient, which can be easily done if the impedance of the surface is known, in the geometrical models to obtain phase information.

3.1. Numerical Methods

Traditionally, accurate prediction of the wave behaviour of a sound field relies on numerical models such as FEM and BEM. In finite element modelling of room acoustics the entire interior region of the room is discretised into finite acoustic elements with the surface impedance of the wall acting as boundary conditions. The disadvantage is that, since the entire 3D region is modelled, the number of elements required is very large. The BEM on the other hand only requires the discretisation of the boundary walls and hence requires much less elements than the FEM. The boundary integral formulation is also theoretically exact and it has been proved to be a highly accurate method in many acoustic problems. However the application of these numerical methods is only advisable in practice at frequencies up to a few hundred Hz for a typical size listening room. They are generally too computationally demanding to use routinely in practice for room acoustics. Nevertheless in this research the BEM provides an exact theoretical formulation that can be used as a reference to determine the accuracy of other geometrical room acoustics models. In this study, the element size in the BEM models is set to below 1/6 of a wavelength to keep the numerical errors small.

3.2. Wave Based Geometrical Acoustics Models

Because of the high cost of numerical methods such as BEM, an attractive alternative to predicting the wave nature of room acoustics is to modify the geometrical ray tracing and image method in such a way that phase information is retained in the ray tracing process or in the generation of the images. Since one way of considering the ray tracing model is to consider the ray as representing the propagation of elemental plane waves, it is therefore logical to consider using a plane wave reflection coefficient to model the reflection of the wave at impedance surfaces. The plane wave reflection coefficient is given by:

$$R_{\mathrm{p}} = \frac{\cos\theta - 1/\beta}{\cos\theta + 1/\beta} \qquad (2)$$

which is only a simple function of the reflection angle θ, measured from the normal, and the surface admittance β. Note that for a plane wave reflection to occur the plane should be infinite and the surface admittance should be constant over the surface.

The implementation into a ray tracing or image model is straightforward. The coefficient R_p is simply applied to each reflection in turn. The increase in computation time due to complex arithmetic should not be too high, except that the calculation is now calculated at single frequencies rather than over octave bands as in a conventional energy based geometrical model. An example of using this approach to generate the Green's function inside a rectangular room with a point source has already been demonstrated in [8].

Unfortunately although the plane wave approximation may be adequate at high frequencies and at normal incidence on a nearly rigid wall, the spherical wave front from a point source has a significant effect when the surface impedance is far from rigid and the angle of incidence is far from normal. Suh and Nelson [9] investigated the difference between the plane wave reflection and the spherical wave reflection assumption on a single reflection from a plane surface in 1999. They subsequently implemented a phase image model using the plane wave reflection coefficient to calculate the impulse response in two small to medium size rooms. Although significant improvements were seen relative to an equivalent energy based model, there were also significant differences between the phase image model prediction and measurements. Whether these errors came from the assumption of plane wave reflection or from measurement uncertainties is not clear. In here we will determine more clearly the accuracy of the plane wave reflection assumption in geometrical room acoustics modelling by comparing it with a model that uses the spherical wave reflection coefficient, and with the wave based numerical method of boundary integrals.

Formulations of the spherical wave coefficient are well established in outdoor sound propagation e.g. [10]. The spherical wave coefficient Q can be written as:

$$Q = R_p + (1 - R_p)F(w) \qquad (3)$$

where R_p is the plane wave reflection coefficient as given previously in Eq. (2), $F(w) = 1 + jw\sqrt{\pi}e^{-w^2}erfc(-jw)$ is the boundary loss factor due to the spherical wave front, and $w = \sqrt{jkR_2/2}(\beta + \cos\theta)$ is called the numerical distance. The distance R_2 is the total path length of the reflected path. *erfc* is the complimentary error function.

The spherical wave reflection coefficient is again applied to each reflection in turn in the ray tracing or image method. However its implementation in room acoustics is a lot more complicated than the plane wave equivalent. Since Q depends on the locations of the source and receiver as well as the reflection plane geometry (through R_2) and its calculation involves an infinite series (the *erfc* term), the model calculation time will be increased significantly. It would therefore be of interest to see if it provides significant improvements over the plane wave reflection coefficient to justify its implementation in practice.

3.3. Measurements

To provide some basic validation of the accuracy of the numerical models, sound field measurements were carried out in two rooms. One is a small reverberation chamber (3.95 m × 3.15 m × 2.38 m) with hard walls and the other is a standard listening room (6.9 m × 4.6 m × 2.8 m) fitted with carpet. The outline geometries of the two rooms are shown in Figs. 3 and 4. The sound source is a loudspeaker. Since a direct measurement of the sound power of the loudspeaker is difficult at very low frequencies, the acceleration of the driver cone was measured and used

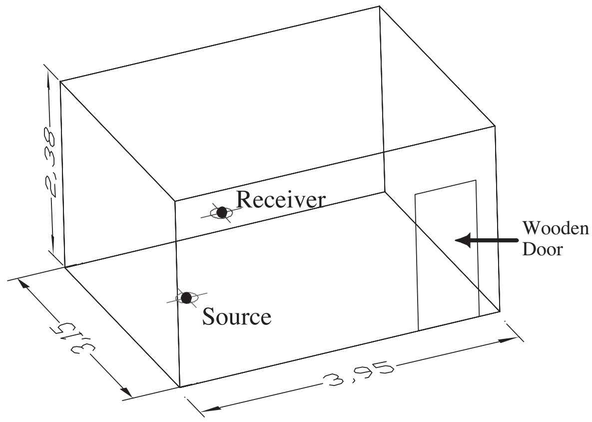

Fig. 3 3D view of the reverberation room measured and the source and receiver locations used. The door is made of heavy wood and is assumed to be acoustically the same as the surrounding walls in the prediction models.

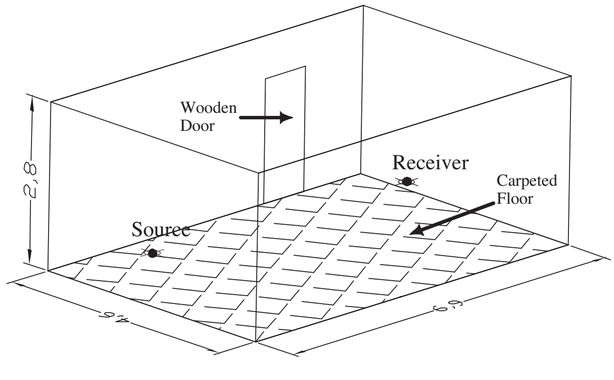

Fig. 4 3D view of the listening room measured and the source and receiver locations used. The door is made of heavy wood and is assumed to be acoustically the same as the surrounding wall in the prediction models. The acoustic property of the carpeted floor is estimated and modelled separately from the other walls.

instead as a representation of the sound power in the normalisation of the sound pressure. This is satisfactory at the lower frequency end (below 100 Hz in our case) where the cone behaves like a rigid piston with near omni-directionality. The sound pressure levels were calculated to a source strength that gives a free field sound pressure amplitude of $1/4\pi$ at 1 m from the source. The normalised admittance values of the wall surfaces were determined from the decay time of the first few clearly separated room modes within the 20 to 100 Hz frequency range, using the wave solution for rectangular rooms with nearly hard walls [11]. This assumes that the admittance is real and is acceptable when the wall impedance is high, which is the case for the hard walls and the carpet below 100 Hz. The admittance values are assumed to stay constant within the frequency range of 20 to 100 Hz unless otherwise stated. In the followings "admittance" refers to normalised admittance values.

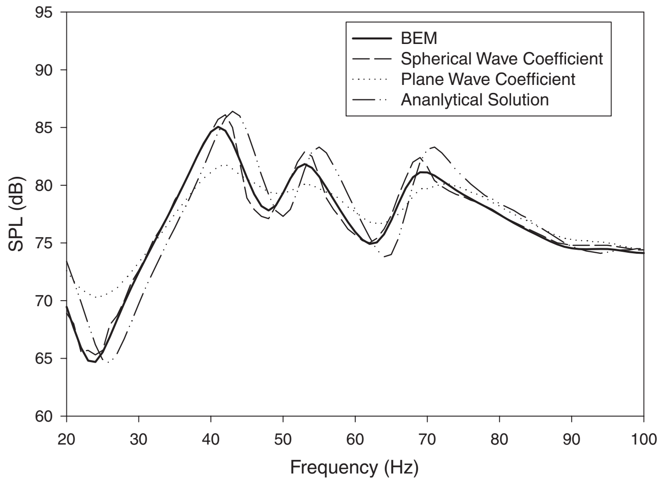

Fig. 6 Comparison of wave based room acoustics models for predicting complex sound field in the same room as in Fig. 5 but with absorptive walls (admittance = $(0.2, 0.2i)$).

3.4. Reverberation Room Comparisons

Figure 5 shows a comparison of the different prediction method against the measured data in the reverberation room with hard walls. The source location was (0.2, 0.2, 1) and the receiver was at (1, 1, 1.5). Also shown is the analytical solution for rectangular rooms with nearly rigid walls [11]. This is labelled as "Analytical Solution" in Figs. 5 and 6. It can be seen that all the prediction methods work very well. This is not surprising since the wall surfaces are very hard with a normalised admittance value of only 0.007, which corresponds approximately to a random incidence absorption coefficient α_{ran} of 0.056. This fits the near hard wall assumption of most of the models well. The discrepancy at frequencies below 40 Hz is due to measurement errors caused by the low signal strength of the loudspeaker at such low frequencies. The accuracy of the reference numerical model BEM is confirmed to be very good.

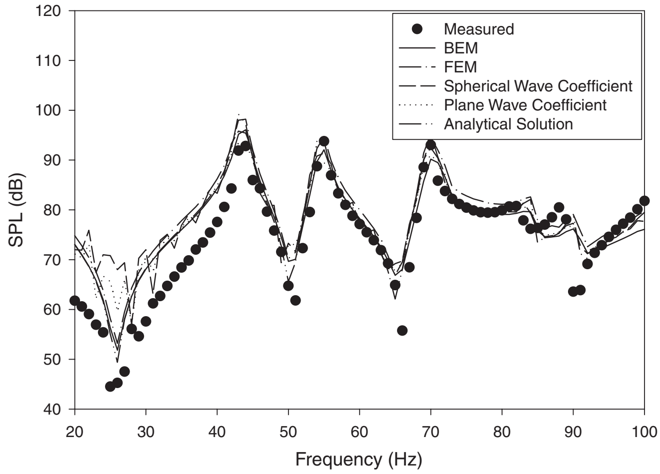

Fig. 5 Comparison of BEM and wave based geometrical room acoustics computer models with measurements for predicting complex sound field in a reverberation room with hard walls.

When modified with a complex reflection coefficient, either based on the plane wave or spherical wave formulation, the geometrical image model using complex sound pressure also produced very good predictions for the reverberation room. The peak values are predicted very well. The values at minima have more noticeable errors. This is because in the geometrical models only contributions from images with amplitude within −30 dB of the direct sound were used. This corresponds to roughly half the *RT* of the room. Hence the very low values at destructive interferences cannot be accurately calculated. Nevertheless these very low values should not be important in practice. Overall it seems that a complex pressure geometrical acoustics model is a viable method for modelling the complex sound field in a room. The convergence rates of the complex pressure models are however lower than the corresponding energy based model. This is due to the complex pressure interference that produces significant oscillations when the contributions from the images are summed. This is more significant at the lower frequency end as can be seen from the fluctuations of the wave based geometrical predictions at frequencies below 40 Hz in Fig. 5. At higher frequencies the phase change becomes more rapid and the convergence is faster and sufficiently smooth results were obtained with this cut-off criterion. It is also worth noting that geometrical prediction using the spherical wave reflection coefficient is more susceptible to this convergence problem.

The good accuracy of the geometrical model using the plane wave reflection coefficient is very encouraging for computer modelling of acoustics in small rooms and at low frequencies, since this coefficient is easy to calculate and easy to implement in a ray or image model. In Fig. 5 the use of a spherical wave reflection coefficient only seems to provide a small improvement. However it should be noted that the reverberation room of Fig. 5 has very hard walls, and the accuracy of the plane wave reflection model may not be as good in rooms that have softer walls. This is demonstrated by a simulation using a room with an assumed admittance of (0.2, 0.2*j*), which corresponds to an estimated random incidence absorption coefficient of about 0.7. The result is shown in Fig. 6. The ray model with spherical wave reflection coefficient still agrees well with the BEM but the one with plane wave reflection coefficient now has substantial errors.

3.5. Listening Room Comparisons

The reverberation room used in the last section has uniform and hard walls, which is not a common room type. In order to test the performance of the computer models in more realistic surroundings, comparisons were also made in a bigger and more realistic listening room. The walls of the listening room are fairly hard with an estimated admittance value of 0.009. The floor was fitted with a carpet. The admittance of the carpet was determined from the decay time of the first two room modes to be 0.02, which corresponds to an estimated random incidence absorption coefficient of about 0.16. The same admittance value is assumed over the frequency range of 20 to 100 Hz for the calculation. It is expected that this assumption will not be valid in the real room at frequencies significantly above the first two room modes (above 100 Hz in this case). It is used here simply to provide a means for comparison between prediction models. As a comparison, an energy based geometrical room acoustics model was also used to calculate the sound pressure level. Since the admittance, and hence the absorption coefficient was assumed to be constant over the calculation frequencies, the sound pressure level predicted by the energy based model is the same for all frequencies. The source location was (1, 3.3, 0.4) and the receiver was at (4.7, 1.4, 1.2).

Figure 7 shows the narrow band results from 20 to 100 Hz for comparison with measured values which are only available up to 100 Hz. All predictions are calculated at a 1 Hz frequency resolution. Generally the computer models all agree well with the measured data within this frequency range. Once again errors in the complex pressure geometrical models are noticeable at the minima of the sound pressure level frequency spectrum because of the −30 dB cut-off limit for the geometrical contributions. Otherwise the model using the spherical wave reflection coefficient agrees very well with both measurements and BEM.

The plane wave reflection formulation worked largely

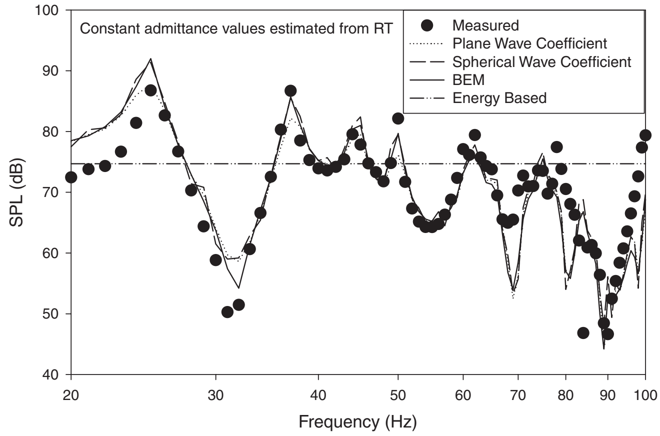

Fig. 7 Comparison of wave based room acoustics models with measurements for predicting complex sound field in a standard listening room with hard walls and a carpeted floor.

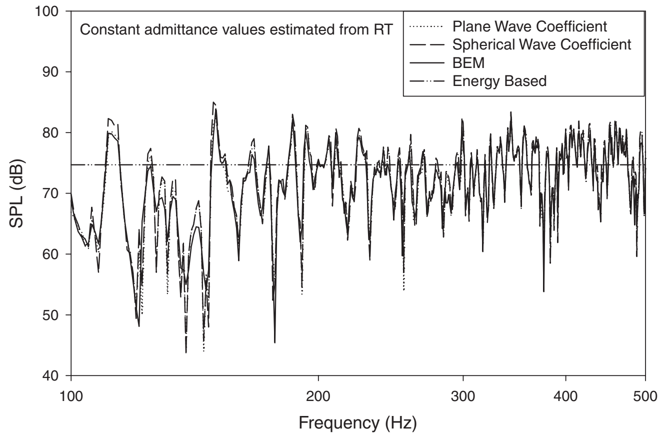

Fig. 8 Comparison of wave based room acoustics models for predicting complex sound field in the standard listening room for the frequency range from 100 to 500 Hz. The admittance values are taken as the same low absorption values as those estimated from the lower (below 100 Hz) frequency range.

as well as the spherical wave reflection formulation in this listening room. Some noticeable errors are seen in the predicted peak values at the lower end of the frequency spectrum. It seems that the higher value of the admittance of the carpet is having an effect. However the overall shape of the sound pressure level spectrum is still well predicted. In fact even the errors at the peak values seem to diminish as frequency increases. This can be better seen in Fig. 8 which shows the predictions in the 100 to 500 Hz frequency range. Note that the admittance values used in the predictions did not change from the values used for the 20 to 100 Hz frequency range so that the only change is the higher frequencies in the predictions. The prediction using the plane wave reflection coefficient is virtually indistinguishable from the ones using the spherical wave reflection coefficient and the BEM at frequencies above 200 Hz. This indicates that, for a fixed value of admittance, the plane wave reflection formulation is more accurate at higher frequencies.

The energy based prediction obviously could not predict the fluctuations in the frequency spectrum of the sound pressure level, but at higher frequencies the average values of the wave based predictions seem to approach the trend of energy based prediction. Note that the Schroeder frequency of this listening room is estimated to be about 250 Hz.

As in the case of the reverberation room, we wish to see the effect of increasing the admittance to a more absorptive value. In this case only the admittance value of the carpet is changed while the walls remain fairly hard. This is to simulate the effect of having only one highly absorptive surface, such as commonly encountered in rooms with audience. The admittance value chosen is once again (0.2, 0.2*i*) which corresponds to a random incidence absorption coefficient of about 0.7. This value is used for all frequencies. Figure 9 shows the simulations from the different models. The calculations were done from 10 to 500 Hz at 1 Hz intervals. Again the geometrical prediction using the spherical wave reflection coefficient agrees remarkably well with the highly accurate BEM. On the other hand, even with just one absorptive surface, the plane wave reflection formulation shows substantial errors at the lower end of the frequency range. However since the admittance value remains constant through the frequency range, the error in the plane wave reflection formulation decreases at higher frequencies and becomes fairly small at frequencies above 200 Hz.

For room acoustics at high frequencies one may not be interested in the details at single frequency but the level in 1/3 or full octave bands. Figure 10 shows the 1/3 octave band comparisons calculated for the case with the highly absorptive carpet. The narrow band predictions from the wave based models were energy-averaged into 1/3 octave bands. The advantage of the spherical wave reflection model is clear below 125 Hz but the plane wave reflection model provides equally well predictions in the 1/3 octave band above 125 Hz. The better accuracy of the plane wave model at higher frequencies for a fixed admittance is clearly shown. Incidentally the advantage of wave based models in frequency bands below the Schroeder frequency, 250 Hz, is clear but the energy based model seems acceptable from about 200 Hz onwards.

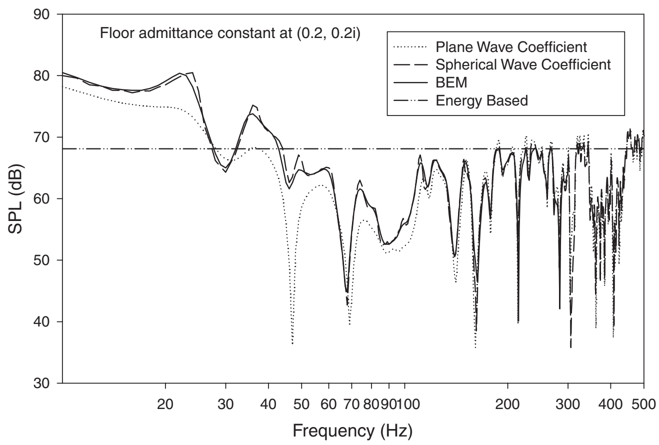

Fig. 9 Comparison of wave based room acoustics models for predicting complex sound field in the standard listening room for the frequency range from 10 to 500 Hz with an assumed frequency independent absorptive admittance value of (0.2, 0.2*i*) for the floor.

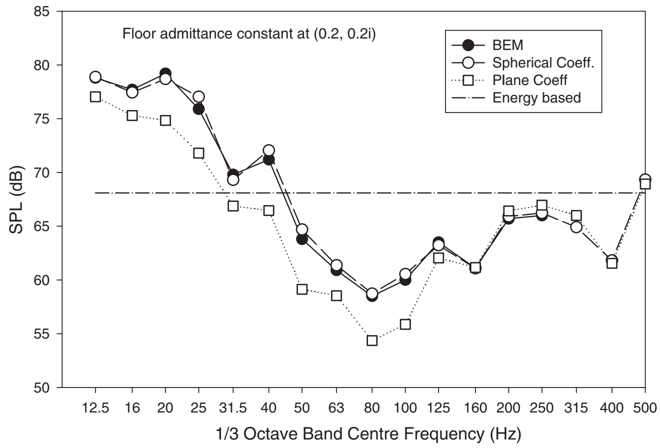

Fig. 10 1/3 octave results of Fig. 9.

The above simulations use an admittance values that are independent of frequency, which is not realistic for most, and especially absorptive room surfaces. A further simulation was therefore carried out by simulating the admittance of the floor based on the impedance behaviour of an assumed fibrous material. The frequency dependent admittance value is calculated from Delany and Bazley's empirical single parameter impedance model for fibrous materials [12]. The flow resistivity, $\sigma = 150$ (kPa/m^2), of the material and the thickness (50 mm) of the cover were chosen to match the carpet's admittance value of 0.02 as estimated from *RT* measurements in the real room. Figure 11 shows the simulated impedance values from 10 Hz to 1,000 Hz. Note that the admittance value at 500 Hz is about (0.1, 0.1*i*) which is about half of the fixed value of (0.2, 0.2*i*) assumed in Figs. 9 and 10 for the highly absorptive case. The predictions of the sound pressure level spectrum using this simulated admittance behaviour is shown in Fig. 12. Note that this time the calculations were performed at a frequency resolution of 2 Hz. Again the spherical wave reflection formulation agrees very well with BEM throughout the frequency range while the plane wave reflection formulation shows noticeable errors at low frequencies which diminishes at higher frequencies. The situation can be seen more clearly in the 1/3 octave results shown in Fig. 13. In this case the higher error at higher

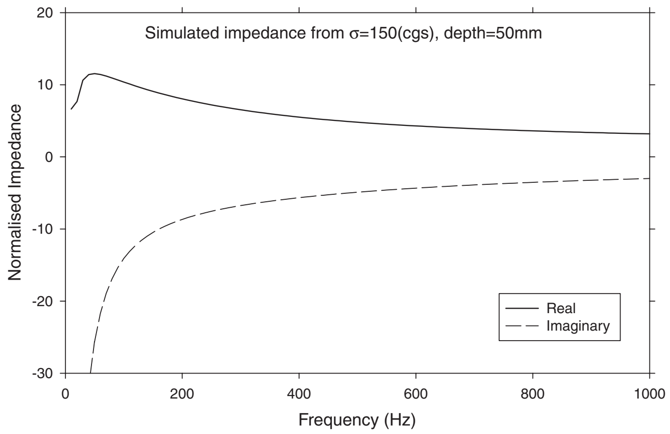

Fig. 11 Calculated impedance data of a 50 mm fibrous cover with a flow resistivity of 150 kPa/m^2. The calculation is based on Delaney and Bazley's empirical model [*Appl. Acoust.*, **3**, 105–116 (1970)].

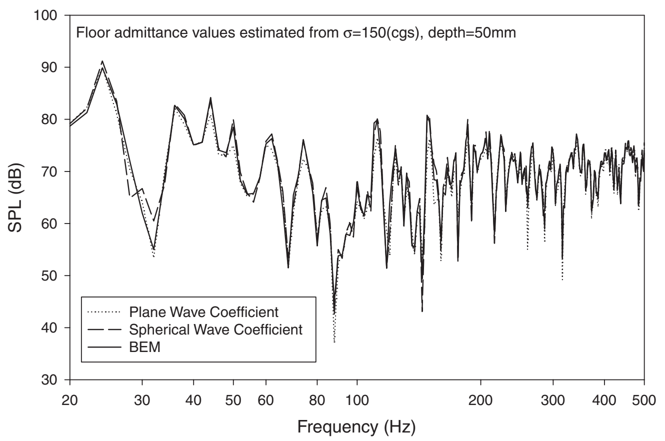

Fig. 12 Comparison of BEM and wave based geometrical room acoustics computer models for predicting complex sound field in the standard listening room with the simulated frequency dependent admittance of Fig. 11.

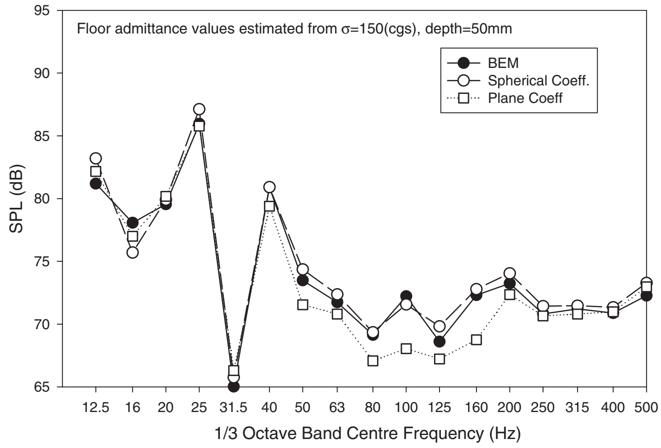

Fig. 13 1/3 octave results of Fig. 12.

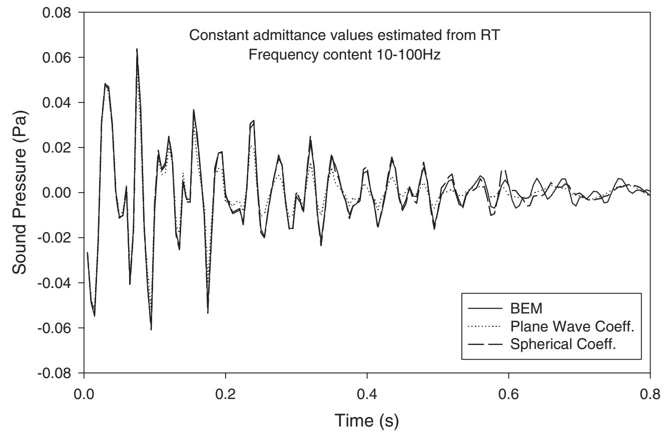

Fig. 14 Impulse responses constructed from the wave based predictions with a 10–100 Hz frequency content for the listening room with admittance values estimated from the measured *RT* in the same frequency range.

admittance, which increases with frequency, is somewhat compensated by the better accuracy of plane wave reflection at higher frequencies. Thus the largest error is observed in the middle of the frequency range, from about 63 to 200 Hz. The result confirms that the error in the plane wave reflection approximation is larger at lower frequencies and on more absorptive surfaces (larger admittance).

3.6. Impulse Response Simulations

One advantage of including phase in the geometrical room acoustics model is the ability to construct a true impulse response. It is therefore of interest to determine the accuracy of the different complex sound pressure reflection models in providing predictions of room impulse responses. The simulations for the low absorption case (floor admittance fixed at 0.02) and high absorption case (floor admittance fixed at $(0.2, 0.2i)$) were done at 1 Hz frequency resolution which allows the construction of impulse responses to a time length of 1 s, which is roughly the *RT* of the actual listening room at around the 100 Hz 1/3 octave band. The impulse responses were constructed from the complex frequency domain data using the inverse Fourier Transform function in MATLAB.

The impulse responses constructed from the 10–100 Hz data for the low absorption case are shown in Fig. 14, with the BEM result taken as reference. Again the one using the spherical wave reflection formulation is virtually identical to that by BEM up to about 0.5 s. The fine details of the time domain data are faithfully reproduced, demonstrating the extremely high accuracy of the spherical wave reflection model in both amplitude and phase. Above 0.5 s the geometrical models start to differ because only images within a time limit of about 0.5 s (about half of the *RT*) were included in the image model calculations due to the −30 dB cut-off limit. The plane wave formulated

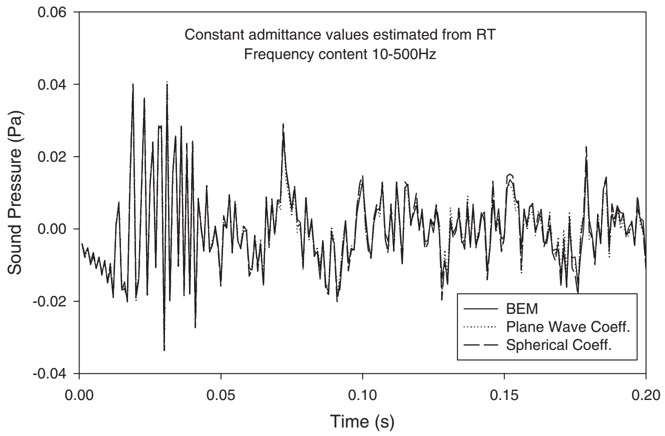

Fig. 15 Impulse responses from the wave based predictions with a 10–500 Hz frequency content. The frequency independent admittance values of Fig. 14 are used throughout the frequency range.

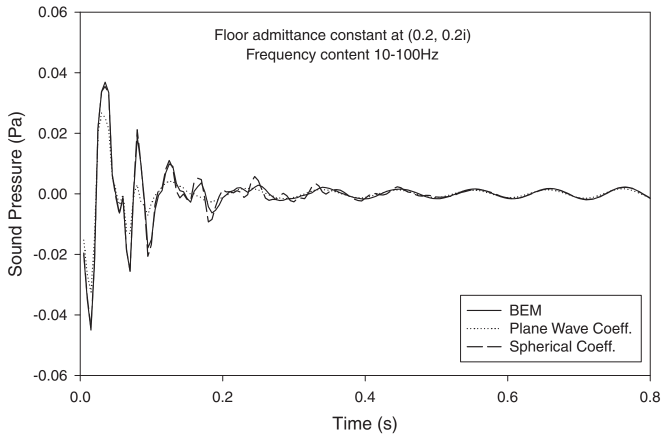

Fig. 16 Impulse responses from the wave based predictions with an assumed frequency independent absorptive admittance value of (0.2, 0.2i) for the floor. Frequency content 10–100 Hz.

impulse response shows similar structure to both BEM and spherical wave formulated responses but the amplitudes of the peaks and troughs seems to be less and less accurate at longer delay time, i.e. for higher order images. This is because the errors in the plane wave reflection approximation build up with more and more reflections.

When the impulse responses are constructed using data from the full 10–500 Hz frequency range they are virtually indistinguishable from each other, even in a close up look within the 0 to 0.2 s time frame, as shown in Fig. 15. The errors in the plane wave reflection formulation are not as noticeable as in the lower frequency impulse response, which is consistent with the frequency domain comparisons which show that the accuracy of the plane wave reflection formulation is better at higher frequencies.

In the high absorption case (floor admittance = (0.2, 0.02i)) the impulse responses constructed from the 10–100 Hz data clearly show the effect of the higher absorption, with the responses damped out almost completely by 0.4 s, as can be seen in Fig. 16. The spherical wave reflection formulation still matches the BEM well, while the plane wave reflection formulation again shows significant errors especially in the peaks and troughs.

The impulse responses constructed from the simulated frequency dependent floor admittance, using a 2 Hz frequency resolution from 10–500 Hz, shows that the plane wave reflection approximation matches well with BEM and spherical wave reflection formulations at short time delays but has progressively more noticeable errors at delays longer than 0.2 s, as shown in Fig. 17.

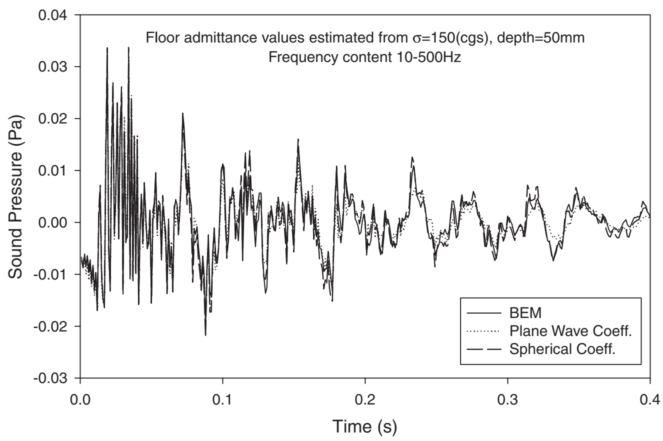

Fig. 17 Impulse responses from the wave based predictions with the simulated frequency dependent admittance from Fig. 11 for the floor. Frequency content 10–500 Hz.

4. CONCLUSIONS

In non-concert hall settings, there are many modelling issues that cannot be dealt with adequately by the usual energy based geometrical room acoustics models. In large workplaces or offices, the existence of noise screens requires the addition of sound diffraction calculations into the computer models. When the room is highly disproportionate, the paper has shown that a surface scattering coefficient higher than the usual random incidence surface scattering coefficient will be required to provide accurate predictions. This is a result of the highly directional propagation property of the sound field, which is created by the disproportionate geometry. In rooms with many internal large scattering objects, such as machineries in a factory, the results shows that the surface scattering model cannot accurately predict the reduction in the sound pressure level at long distance from the source, and a volume scattering algorithm will be needed for the modelling. This effect is likely to be more pronounced for more disproportionate rooms.

In small rooms at low frequencies, the existence of wave induced room modes is well known and wave based computer models are necessary for the prediction of the sound field. Using the well established and highly accurate numerical model, namely the BEM, as a reference, this paper has shown that incorporating complex sound pressure propagation and reflection in the geometrical image model can also provide accurate prediction of the complex sound field. The spherical wave reflection model was found to produce predictions in both frequency and time domains that are virtually identical to those by BEM, showing that the spherical wave reflection formulation in a geometrical acoustics model is a valid and accurate model. The plane wave reflection model was found to have noticeable errors at higher admittance (absorptive) values and at longer delay time (higher order reflections). The accuracy was shown to improve at higher frequencies when the admittance is kept constant. However the errors was found to be not excessive in a case where the admittance of the floor is simulated by a fibrous cover that has admittance increases to about (0.1, 0.1i) (corresponding absorption coefficient 0.5) at 500 Hz. Only when the admittance is increased to about (0.2, 0.2i) (corresponding absorption coefficient 0.7) then the error becomes substantial in both the frequency and time domains. It suggests that the use of a plane wave reflection model may not be suitable for rooms that have highly absorptive surfaces, such as purposely built absorbers.

Although the spherical wave reflection model has been shown to have virtually the same accuracy as the theoretically exact BEM, this study is limited to rectangular rooms with each room surface having a uniform admittance. In more complicated room the accuracy of the spherical wave model will be affected by at least three other considerations:

a) In a rectangular room the mirrored surfaces form an infinite plane in each of the coordinate planes. This means that the effective reflecting surfaces are all plane with uniform admittance, which is a situation that creates no edge effects and matches well with the configuration assumed by both the plane and spherical wave reflection coefficients. In a room with complicated geometry this will not be true and edge effects will reduce the validity of the pressure reflection coefficients.
b) If the wall surfaces have non-uniform distribution of admittance then the boundaries between the admittance changes will diffract sound and reduces the accuracy of the reflection models.
c) Lastly the effect of surface roughness has not been accounted for in these models. Surface roughness has been known to create both coherent and incoherent scattering that can affect both low and high frequency reflections. At low frequencies the effect is mostly confined to near grazing incidence and could be approximated by an effective change in the admittance value that is dependent on incident angle. At high frequencies the geometry of the roughness produces incoherent scattering that has been well studied and modelled by current state-of-the-art energy based room acoustics models.

In summary, this study has shown that the concept of using spherical wave reflection coefficient in a geometrical acoustics model to predict the complex sound field is fundamentally sound and theoretically has the same accuracy as the BEM. However the situation in realistic rooms is more complicated and will need to be further studied. The plane wave reflection model provides a reasonable match to the BEM and spherical wave reflection model except when there is a highly absorptive surface ($\alpha > 0.5$). However considering the possible errors due to edges effects, admittance discontinuities and surface roughness the error in the plane wave reflection approximation may not be the dominant factor. This could be very interesting since the plane wave formulation is much faster and easier to implement in practice. This requires further studies.

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