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Energy- and wave-based beam-tracing prediction of room-acoustical parameters using different boundary conditions

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A beam-tracing model was used to predict the transient responses of rooms. The model is wave-based and can be applied to rooms with extended-reaction surfaces. Room surfaces can be modeled as multiple layers of solid, fluid or poro-elastic materials with acoustical properties that are calculated using Biot theory. Both wave-based and energy-based versions of the beam-tracing model have been applied to various room configurations to study the effects of using different boundary conditions (local vs. extended reaction and phase changes on reflection) on room-acoustical parameters. Very significant differences occurred in all parameters when interference effects were taken into account, whether partly (ignoring phase change on reflection) or entirely (wave-based modeling). Modeling surfaces as of local or of extended reaction was found to be significant for surfaces that consist of multiple layers, specifically when one of the layers is air. For multi-layers of solid materials with an air-cavity, significant differences occurred around their mass-air-mass resonance. While these changes affected reverberation times and sound strengths in most room configurations, their effect on Rapid Speech Transmission Index remained mostly insignificant. The results have been explained in part by considering the absorption and reflection characteristics of the test surfaces used in each configuration.

1 Introduction

This paper discusses the prediction of sound fields in rooms under different conditions. Room-acoustical prediction models attempt to find the temporal and spatial distributions of sound pressure or energy (pressure squared) inside an enclosed space according to the source and boundary conditions of the room. Geometrical acoustics methods are traditionally energy-based, neglecting the wave properties of sound. Nevertheless, when the wavelength of sound becomes comparable to the dimensions of the room, the wave behavior of sound, such as interference, becomes too important to be neglected. Interference effects can be modeled effectively (and easily) if sound energy is replaced by complex pressure amplitudes, which include phase information from the propagation path. Using wave-based modeling, the true phase spectrum of a room's transfer function can be constructed, which is important for calculating the impulse response of the room. Another advantage of modeling phase is that phase shifts due to surface reflections can be modeled.

Regardless of the method of prediction, the interaction of sound waves with the boundaries of a room has a significant effect on the room sound field. The traditional boundary condition used in (energy-based) geometrical models is a frequency- and angularly-invariant absorption coefficient for the room surfaces. An improvement to this boundary condition is to use octave-band-varying absorption coefficients. Another important characteristic of absorption coefficients of real surfaces is their dependence on the angle of incidence.

A widely-used boundary condition in room-acoustics is the surface impedance. In general, the acoustical impedance of a surface is a function of both frequency and the angle of incidence. In this case, the surface is said to be of extended reaction. A common simplifying assumption is to ignore the angular dependence of the surface impedance; the surface is said to be of local reaction in this case. Local reaction is encountered whenever the wall itself or the space behind it is unable to propagate waves or vibrations in a direction parallel to its surface [1]. This is generally a reasonable assumption for walls made of simple absorptive materials with high flow resistivity, because they dissipate the energy of acoustic waves effectively. On the other hand, local reaction is not a realistic assumption for walls having predominantly elastic properties due to wall vibrations, or for multilayer walls containing a fluid layer.

Although the assumption of local reaction is very widely used in room acoustics, there are a limited number of studies addressing the validity of this assumption and its effects on the room sound fields. It is the intent of this work to study the effects of different surface-reaction models on the steady-state characteristics and temporal variations of the sound-pressure fields in various room configurations. This has already been done in part by Hodgson and Wareing [2], who investigated the effects of modeling surfaces as of local or of extended reaction on steady-state sound-pressure levels in twelve room configurations. The aim here is to revisit the configurations used by Hodgson and Wareing [2] and investigate them further in terms of their transient response and associated room-acoustical parameters. Moreover, the significance of modeling interference effects is investigated: in the first stage, only phase changes on surface reflection are ignored; in the second stage, all phase effects are ignored (energy-based modeling).

2 Prediction Model

A beam-tracing model is used for predicting the steady-state and transient responses of rooms. The model is based on an existing wave-based triangular-beam-tracing model developed for predicting steady-state sound fields in empty rooms with specularly-reflecting, extended-reaction surfaces [3]. Room surfaces can be modeled as multilayer surfaces of fluid, solid or poro-elastic materials, and Biot theory is used in the transfer-matrix formulation of the poro-elastic layers. The existing model was upgraded to calculate the pressure impulse responses of rooms, making the calculation of derived room-acoustical parameters possible. Moreover, energy-based modeling was implemented in the new model, so that energy-based impulse responses and room-acoustical parameters could be compared with those obtained using wave-based modeling. A full description of the new beam-tracing model and its additional features (e.g. sound diffraction) can be found in [4].

The beam-tracing model calculates the complex transfer function of a room. Pressure impulse responses are then computed via Fourier trans-formation. The room-acoustical parameters are then derived from the impulse. In the case of energy-based modeling, on the other hand, the echogram is used as an approximation to the energy impulse response; an echogram is obtained at a receiver point by plotting the energy of the received beams versus their arrival times.

3 Application of the New Model

Predictions were made of the acoustical responses of three rooms with different bounding surfaces using the new beam-tracing model. One or more of the room surfaces were assigned a multilayer structure. The reflection coefficients of the multi-layer surfaces were calculated from their surface impedance assuming planar sound waves. In the case of local reaction, the normal impedance of the surface was used at all angles of incidence. In order to investigate the significance of modeling phase change on reflection, predictions were made using the absolute value of the reflection coefficients as well; this was done for both the local- and the extended-reaction cases. Moreover, all results were compared with those obtained from energy-based predictions.

3.1 Test Configurations

Three room configurations representing a small, empty office (Room 1: dimensions 3 x 3 x 3 m3), a corridor (Room 2: dimensions 10 x 3 x 3 m3) and a small, empty industrial workshop (Room 3: dimensions 3 x 3 x 10 m3) were studied by Hodgson and Wareing [2]. They used various multilayer boundary conditions for the surfaces of these rooms, based on which twelve room configurations were considered. The acoustical properties of the surfaces with multilayer structures were calculated using the transfer-matrix algorithm. All other surfaces of the rooms were assigned an average diffuse-field absorption coefficient of 0.1, invariant with the incident angle and the frequency. Room surfaces were assumed to be specularly-reflecting.

A large window was modeled on one wall in each of the rooms with a single glass panel (G1, G2, and G3). Carpet on a hard backing was used as the floor surface in Rooms 1 and 2 (C1 and C2). The four walls of Rooms 1 and 2 were modeled with double-drywall panels with a 100-mm air cavity (D1 and D2). A suspended acoustical ceiling was modeled with a 12-mm layer of glass-fiber, 457-mm layer of air and a rigid backing, and was applied to the ceiling of Rooms 1 and 2 (SAC1 and SAC2). The ceiling in Room 3 was modeled in two ways: using a double-steel panel (SC3), and using a 100-mm glass-fiber layer with a rigid backing (FG3). The four walls of Room 3 were modeled with double-steel panels with a 100-mm air cavity (SW3).

In addition to an average diffuse-field absorption coefficient of 0.1 used in every test configuration, seven other boundary conditions were used. For ease of reference, the seven test surfaces are abbreviated as follows: SGP for single-glass panel, used in configurations G1, G2 and G3; DDW for double-drywall panel, used in D1 and D2; DSP for double-steel panel, used in SW3 and SC3; CAF for carpeted floor, used in C1 and C2; FGR for glass-fiber on a rigid backing, used in FG3; FGA for glass-fiber on an air cavity, used in SAC1 and SAC2. All configurations were the same as the ones used by Hodgson and Wareing [2].

All predictions were performed using the same input-parameter values as Hodgson and Wareing [2]: constant source-power level of 80 dB at all frequencies; source positioned at the center of the wall at x = 0, 0.5 m in front of it and at a constant height of 2 m; receiver positioned at the center of the wall at x = Lx, 0.5 m in front of it and at a constant height of 1.8 m. Predictions were made using 4500 beams, which were traced for 80 reflections. A frequency range of 0.5 to 5600 Hz was used to obtain results up to the octave band centered at 4000 Hz, using 0.5-Hz increments. Calculation times for all configurations were typically 35 to 40 minutes on a PC with a 2.40 GHz CPU and 1.97 GB of RAM.

3.2 Room-Acoustical Parameters

Three room-acoustical parameters were studied: a measure of the steady-state characteristics of the sound field (sound strength), a measure of the temporal variations of the sound field (reverberation time), and a measure of how well the sound field transmits speech (RASTI). These parameters, defined in ISO 3882-1 and [1], were calculated from octave-band impulse responses. Variations in these parameters due to changes in configuration and prediction type were considered significant only if they were audible: greater than 1 dB, 5% and 0.03 for sound strength, reverberation time and RASTI, respectively.

4 Results and Discussion

The results of the beam-tracing predictions of the three room-acoustical parameters in the twelve test configurations are presented in this section. In each case, test surfaces were modeled as of extended and of local reaction, and the results compared. Moreover, energy-based and wave-based models are compared, and the effects of phase change on reflection considered. Three types of predictions were made for each configuration: wave-based with complex reflection coefficients (WBC); wave-based with real reflection coefficients (WBR); energy-based with inevitably real reflection coefficients (EBR). For ease of reference, extended-reaction modeling of test surfaces is referred to with the suffix 'ext'; likewise, the suffix 'loc' indicates local-reaction modeling of test surfaces. Moreover, the difference between the parameters predicted with the test surfaces modeled as of local and extension reaction is referred to as the "L-E difference"; likewise, the difference between predictions made using real and complex reflection coefficients is referred to as the "R-C difference".

In what follows, it is assumed that the WBC-ext model gives the most accurate results. Other models are therefore assessed with respect to WBC-ext. Moreover, only the results for sound strength are presented and discussed here; full results can be found in [4].

Predicted sound-strength values for six of the twelve test configurations are shown in Fig. 1. Only these six are shown because the results from the other six configurations have, in general, similar trends to the ones shown. The six sets of results that are not shown, however, are discussed based on their similarities to those shown.

The L-E difference is inaudible (below 1 dB) for all cases in configuration G2. Moreover, it can be seen that phase change on reflection has no audible effect on sound strength. However, energy-based predictions are very different from wave-based predictions. No audible changes in the energy-based predictions of sound strength are observed over the frequency range considered. Configurations G1 and G3 show similar trends and are not shown. These results are consistent with those reported by Hodgson and Wareing [2].

The only audible L-E differences in configurations D2 occurred in the 63- and 125-Hz octave bands. In general, sound strength is slightly overestimated in the local-reaction case. At 63 Hz, all models underestimate the sound strength by 3 to 4 dB. This is because of the mass-air-mass resonance of the double drywall. Configuration D1 (not shown) gave similar results.

In configuration C2, no audible differences in the sound strength were associated with phase change on reflection. As the frequency increases, on the other hand, the L-E difference increases. The local-reaction model under-estimates the absorption coefficients for the CAF test surface, with the difference between the two models increasing with frequency. As a result, the local-reaction models overestimate the sound strength, with the L-E difference increasing with frequency. Similar trends are seen in configuration C1 (not shown).

In configuration SC3, the workshop with double-steel panels as its ceiling, audible L-E differences occurred in the 63 to 500 Hz octave bands. The local-reaction models underestimate the sound strength at 125 Hz, but overestimate it at 250 Hz. This can be explained by considering the absorption characteristics of the DSP test surfaces; the local-reaction model overestimates the absorption coefficient at 125 Hz, but underestimates it at 250 Hz. At 500 Hz, the local-reaction model underestimates the absorption coefficient, and the corresponding sound strengths are accordingly overestimated. The WBR-ext model underestimates the sound strength, which shows the importance of modeling phase; this is most significant near the resonance frequency. When DSP is used as the four walls of the workshop in SW3 (not shown), L-E differences are audible at 125 and 250 Hz only. This suggests that the locations of the test surfaces significantly influence the sound strength in the 63 and 500 Hz octave bands.

No audible L-E differences occurred in configuration FG3. However, phase changes due to reflection have the most significant influence on sound strength in this configuration; of course, this is only predictable using the wave-based models. In octave bands from 63 to 250 Hz, the WBR models overestimate the sound strength by 5 to 7 dB. Following Hodgson and Wareing [2], this difference is explained by studying the characteristics of the reflection coefficient of the test surface, which correspond to the angle of incidence of the first-order reflection path. The R-C difference can be explained by the opposite signs of the real and imaginary parts of the reflection coefficient at frequencies below 230 Hz. As the real part of the reflection coefficient goes to zero from 0.5 to 230 Hz, the imaginary part of the reflection coefficient becomes more significant, and the R-C difference increases. Above 230 Hz, however, this difference decreases, as the real and imaginary parts of the reflection coefficient have the same sign. The difference also decreases with frequency as the imaginary part of the reflection coefficient decreases.

The most significant L-E difference is observed in configurations SAC2, at the lowest frequencies. SAC1 (not shown) gave very similar results. In the 63- and 125-Hz octave-bands, the WBC-loc model predicts sound strengths that are, respectively, more than 10 and 5 dB lower than other wave-based models. As frequency increases, however, the difference between the models becomes smaller. The L-E differences at lower frequencies are explained by considering the angular variations of the real part and the absolute value of the reflection coefficients of the FGA test surfaces. At 45 Hz, the real part of the local-reaction reflection coefficient is greater than the extended-reaction reflection coefficient at all angles of incidence, with their difference increasing with angle of incidence. Most importantly, the real parts of the two reflection coefficients have opposite signs for incident angles greater than 40º. As frequency increases to the upper frequency limit of 90 Hz, this transition of the sign of the real part of the reflection coefficient happens at a lower incident angle. Consequently, for the majority of the local-reaction reflection coefficients in the 63-Hz octave band, their real part has a different sign than the extended-reaction reflection coefficients. This is particularly important when we consider that the first-order reflections in the SAC1 and SAC2 configurations occur at 42.3º and 76.3º, respectively. As frequency increases, the real part of the extended-reaction reflection coefficient gradually becomes negative as well; the real parts of the reflection coefficients have different signs only for incident angles greater than 44º at 125 Hz and 61º at 180 Hz. This is consistent with the fact that sound strengths predicted by the WBC-loc model are significantly different from those predicted by the other methods at 63 and 125 Hz.

In the case of the energy-based model, the local-reaction sound strengths are lower than those with extended-reaction at the lowest frequencies, with the difference decreasing with frequency. This general trend can be explained by considering the absorption coefficient of the FGA test surface: as frequency increases, the difference between the local- and extended-reaction absorption coefficients decreases. The same explanation applies to the WBR model.

Following is a summary of the results obtained for all three parameters [4]:

- Wave-based predictions showed significant variations in sound strength and reverberation time with frequency. Energy-based predictions, on the contrary, showed much smoother and smaller variations with frequency for both parameters;
- For configurations with a single solid panel, different surface-reaction models made no audible differences in any of the three parameters, except for the reverberation time of the corridor at the lowest frequency, which is most likely due to interference effects;
- In the case of configurations that included solid double-panel partitions with an air gap, the only audible effects of changing the surface-reaction model occurred around the mass-air-mass resonance frequency. This is because local- and extended-reaction models predict significantly different reflection characteristics at the resonance frequency, both in magnitude and phase. These differences influenced sound strength and reverberation time, but not RASTI values;
- When a single layer of porous material on a rigid backing was used as a test surface, significant differences occurred only at lower frequencies and due to phase change on reflection. Modeling with the local-reaction model made no audible effects on any of the parameters studied;
- When a second layer of porous material was added to the test surface, significant differences were made in all parameters. Local-reaction modeling of the test surfaces underestimated the absorption coefficient, which contributed to significant differences in sound strength and reverberation time at frequencies above 500 Hz. While phase change on reflection made no audible differences in sound strengths, it made significant changes to reverberation time in the 125-Hz and higher octave bands, with the reverberation times underestimated. The most

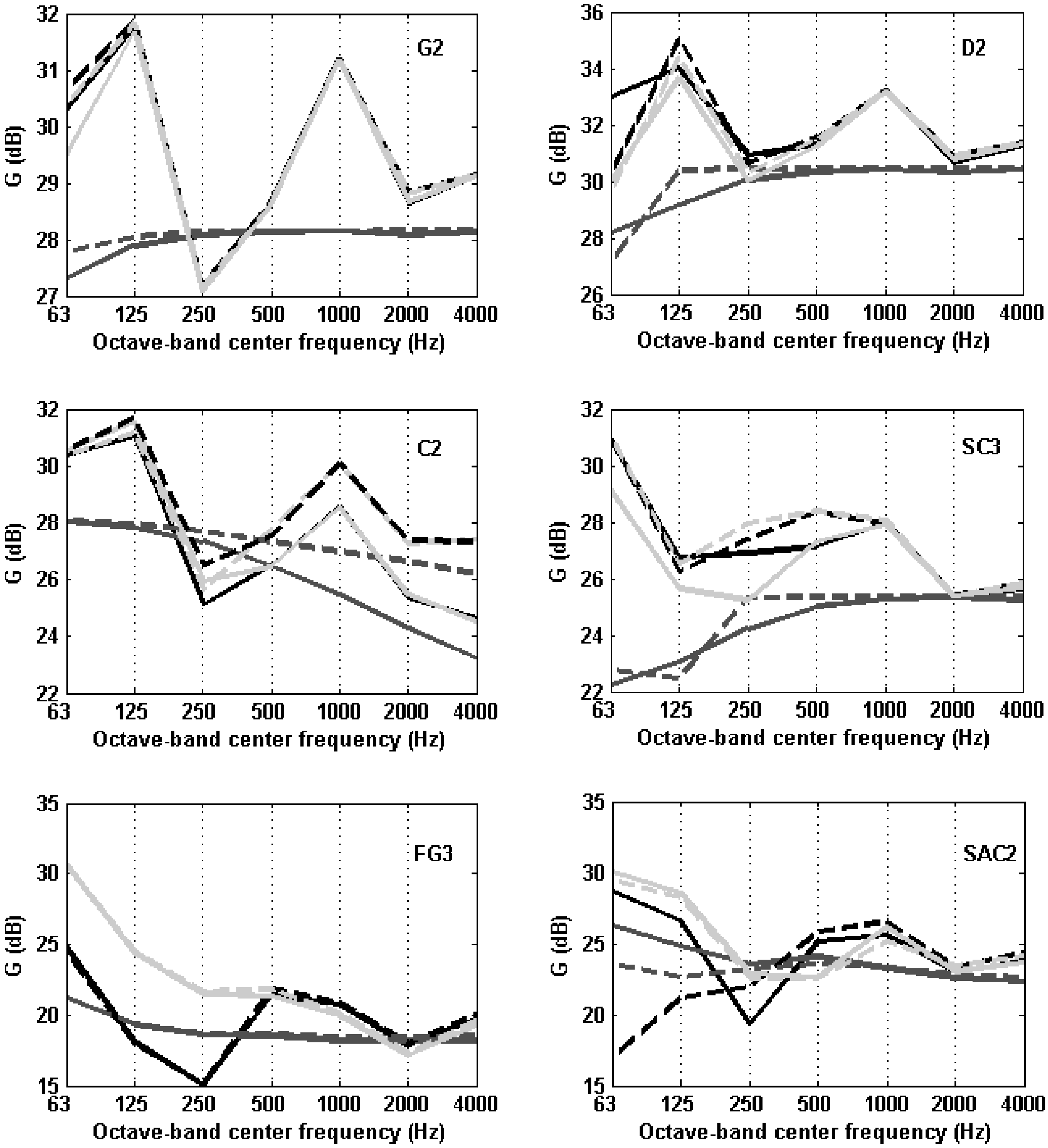

Figure 1: Predicted octave-band sound strength, *G*, for configurations G2, D2, C2, SC3, FG3 and SAC2. Solid lines: extended reaction; dashed lines: local reaction. Black lines: WBC; light grey lines: WBR, dark grey lines: EBR.

significant differences in energy-based predictions occurred for this configuration, for all parameters studied;

• The most significant difference between local- and extended-reaction modeling of test surfaces was in the case of a porous layer with an air gap. This was explained by the fact that the local-reaction assumption is not valid for a fluid layer. As a result, significant differences in both reverberation time and sound strength were observed at low frequencies. At higher frequencies, phase change on reflection made significant differences in predicted reverberation time, but not in sound strength;

• The energy-based model consistently over-estimated the RASTI values. Moreover, RASTI values are generally predicted to have a negative correlation with the size of the room. In both cases (higher absorption and smaller rooms), lower speech intelligibility is most likely due to high reverberation times.

5 Conclusion

The following remarks summarize the findings on the significance of predicting the acoustical parameters using different models:

• *Energy-based and wave-based modeling*: Very significant differences occurred in all three parameters when interference effects were ignored, whether partly (ignoring phase change on ref-lection) or entirely (tracing sound pressure squared instead of sound pressure). Further, accounting for phase changes due to distance traveled was found to be far more significant than phase change on reflection. With the wave-based model, predicted reverberation time and sound strength changed significantly with frequency; in the case of energy-based prediction, these variations were less significant. When predictions were energy-based, the room-acoustical parameters were less significantly influenced by a change in the surface-reaction model. The energy-based model consistently predicted higher RASTI values than the wave-based models;

- *Local and extended reaction of surfaces*: Modeling surfaces as of local or of extended reaction is significant for surfaces that consist of multiple layers, specifically when one of the layers is air. This affects the corresponding reverberation time and sound strength significantly – changes in RASTI are, however, mostly inaudible. For double layers of solid materials with an air cavity in-between, significant differences occurred only around their mass-air-mass resonance frequency, where the local-reaction model highly overestimates the absorption co-efficient. The local-reaction assumption is highly inaccurate for a porous layer on an air gap; this inaccuracy becomes less significant when working with octave-band absorption coefficients. For single-layer surfaces, whether made of porous or solid materials, local- or extended-reaction modeling of the surface is generally insignificant. For solid walls, the coincidence phenomenon is only predictable with the extended-reaction model;
- *Phase change on reflection*: Modeling phase change on reflection was found to be significant in the case of surfaces for which the real part of their reflection coefficients changes its sign. At frequencies at which the sign of the real and imaginary parts of the reflection coefficient are different, significant changes were observed due to modeling phase change on reflection. For the configurations studied in this research, modeling phase change on reflection had no audible influence on predicted RASTI values.

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