Evaluating Physical and Aural Accuracy in Computed Early Room Impulse Responses

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Abstract

If one of the goals of computational room acoustics is auralization, then one must also define physical accuracy criteria in terms of what is audible. Some types of errors, such as neglect of low-frequency modes and edge diffraction, may be so clearly audible that sophisticated psychoacoustic evaluation is sometimes unnecessary. On the other hand, computations of surface scattering may have errors on the order of 1 - 3 dB. One may ask when such errors are aurally significant. For example, small spectral changes audible for single scattering from a rough surface may not be audible in a room impulse response, depending on the density and decay rate of the reflections (and the corresponding degree of comb-filter effects), the similarity to frequency spectra of other reflections, the effects on the early or late parts of the impulse response, and the input signal that is used in a given auralization. This paper examines various room scattering computations and describes subjective methods for evaluating them in terms of aural adequacy. The tests for aural-adequacy employ time-frequency analysis, ABX listening tests, and multi-dimensional analysis of listening experiments to evaluate differences in numerical results.

1. Introduction

In auralization of room sound fields, most conventional approaches base their computations on geometrical-acoustics assumptions, which lose validity at lower frequencies (or for scattering from small facets) due to the neglect of edge diffraction and to coarse approximations of surface scattering. This paper discusses physical and subjective effects of three approaches to modeling surface scattering: Lambert surface scattering from rough surfaces, edge-diffraction, and surface-scattering by hemispherical bosses.

The degree to which each of these methods is “accurate,” however, depends on the metric used. A conventional approach is to compare frequency spectra or time-frequency plots of impulse responses obtained from different models or measurements, although it is not clear exactly what defines an acceptable error for purposes of auralization, e.g., a certain decibel deviation over a given frequency range, for a given input signal. Thus, it is helpful to complement these physical plots with structured listening tests that measure the aural perception of differences. This paper, moreover, explores physical and perceptual aspects of constructing and evaluating models of scattering in room acoustics computations.

2. Edge Diffraction

2.1. Physical and perceptual evaluation of high-accuracy computations

To minimize computational demands of including scattering in auralization, one may study how many orders of scattering must be included. Edge diffraction can be considered an elementary form of surface scattering and is in this sense the first major correction to geometrical acoustics. A previous study [2] incorporating Svensson’s edge-diffraction computations [1] found that higher orders and combinations of edge diffraction components were not usually as significant as first-order diffraction components when the receiver was visible to the source. This corresponded in frequency spectra to deviations less than 1 dB above 150 Hz.

These physical measures, however, were complemented by ABX listening tests. Impulse responses with different diffraction-orders and diffraction-components were convolved with various anechoic signals. The test taker specified whether sound “X” was the same as sound “A” or “B” where “A” might include diffraction and “B” might not. The probability of guessing correctly was assumed to follow a binomial distribution, and a significance level of 0.05 was utilized to indicate an audible difference.

It was surprising that although the total computed diffraction had small effect on numerical parameters (i.e., 1-2 dB), it was nevertheless audible for certain input signals. This suggested that conventional...
numerical parameters without complementary listening tests were not sufficient to describe the perceived field.

2.2. Perceptual Approximations to Edge Diffraction

One can also use such physical analysis and perceptual testing to construct perceptual approximations to edge diffraction, e.g., by modeling edge-diffraction parametrically by physical phenomena. Such approximations could be useful, e.g., for medium-resolution fast virtual-reality applications.

A parametric approach to modeling edge-diffraction is discussed and compared with the high-accuracy model. We do this by computing simplified finite impulse response (FIR) filters that approximate the spectral and phase characteristics of first-order edge-diffractions. Our six input parameters are the source and receiver positions (each described by two cylindrical coordinates), the wedge angle (e.g., 0 for a knife-edge and $\pi$ for a half-plane), and the wedge length. The four output parameters that describe the diffraction are the level, diffraction cutoff frequency (which resembles a low-pass filter), slope of the response above the cutoff frequency, and the phase/polarity of the diffraction (which controls the cancellation effects of the diffraction on the specular reflection).

One should note that the reference geometry from the previous section was conservatively composed of large flat walls whose dimensions were larger than most of the wavelengths of interest [2]. More realistic rooms, however, do not consist of large, bare walls but include smaller-scale surface irregularities, e.g., facets for which audible wavelengths are typically a similar order or larger. To most clearly illustrate the effect of calculating varying orders of diffraction, we initially consider only the scattering (reflection + diffraction) from a single long rectangular panel (1.2 m wide), with source and receiver at angles of 38.7 degrees to the centerline of the panel.

Figure 1 shows the directivity and polarity of the edge-scattering functions as a function of angle. There are three zones corresponding to the existence of the direct sound (I and II), specular reflections (I), and diffraction alone (Zone III “shadow” region). The directivity plot and frequency responses show that there are diffraction singularities at the zone boundaries but a continuous total sound field (with all components summed). It also shows how the diffraction component resembles a low-pass filter, depending on position.

If one then approximates the edge-diffraction as a low-pass filter and superposes this with the specular reflection, this approximation of the total scattering may be compared to the higher accuracy computation (Fig. 3). It is important that the polarity of the diffraction impulse response is correct, since the total scattering must reflect the correct interference among the individual (direct, reflected, and diffracted) components. Figure 2 shows that the total scattering seems to be modeled relatively well, with up to 3 dB errors for this configuration.

Figure 1. Upper figure: directivity and polarity of first-order edge diffraction. Lower plot: frequency response as a function of scattering angle.

Figure 2. Frequency response of total scattering (reflection + edge diffraction). The dotted lines represent the high-accuracy solution; the solid lines depict the parametric approximation.
3. Surface Scattering

3.1 Boss-Scattering in Early RIR

Edge-diffraction models are not optimized, however, to model scattering from individual scatterers such as hemispheres on a plane. Such scattering can be calculated using so-called boss models, where a boss is simply a protuberance from a surface.

We calculate the scattering from two parallel walls, where the boss size and density are varied and the boss positions can be dithered, described further below. The incident and reflected non-specular scattering from the sphere is calculated according to the following image-implementation of the classical solution for scattering from spheres \[3-4\]. Here, the total sound field is regarded as a sum of the direct sound \(p_r\) and the scattered sound \(p_{sc}\), which itself is composed of the “specular” (image-like) reflection from the flat plane \(p_r\) and the “non-specular” boss-scattering of the incident and reflected sound, \(p_{inc}\) and \(p_{refl}\).

\[
p_{inc}^m(r) = -\frac{ikA_0}{\pi} \sum_{l=0}^{\infty} \sum_{m=-l}^{l} \frac{j_l(kr)}{j_l(ka)} h_l(kr) \times \sum_{n=0}^{\infty} \epsilon_n S^n_m \cos(\delta_n) \cos m(\varphi - \varphi_n)
\]

\[
p_{refl}^m(r) = -\frac{ikA_0}{\pi} \sum_{l=0}^{\infty} \sum_{m=-l}^{l} \frac{j_l(ka)}{j_l(kr)} h_l(kr) \times \sum_{n=0}^{\infty} \epsilon_n S^n_m \cos(\delta_n) \cos m(\varphi - \varphi_n)
\]

Figures 3 and 4 show some results from these calculations, where only first-order non-specular scattering is included. In particular, the early decay and level of the reverberation is clearly dependent on the boss number and size.

Multi-dimensional scaling (MDS) of initial listening tests using pair comparisons indicate that variations in either of these factors (boss size and density) are statistically significant in causing audible changes in the binaural room impulse response. The cases shown in Figure 5 correspond to the following boss sizes and densities on the side walls: (1) 2x3 bosses, \(a = 0.37\) m; (2) 5x7 bosses, \(a = 0.37\) m; (3) 8x8 bosses, \(a = 0.10\) m; (4) 8x8 bosses, \(a = 0.10\) m, dithered; (5) 8x8 bosses, \(a = 0.23\) m; (6) 8x8 bosses, \(a = 0.23\) m, dithered; (7) 8x8 bosses, \(a = 0.37\) m; (8) 8x8 bosses, \(a = 0.37\) m dithered. Plots of the data on three axes \((x, y, z)\) suggests that two dimensions \((x, y)\) are related to varying the boss size and the boss density, respectively. The third dimension may be related to dither, but the correlation the z-axis was not clearly evident in the plotted data (not shown).
3.2 Lambert Scattering in RIR with Reverberation

The previous two cases gave examples of room impulse responses (RIRs) with calculations of early-order scattering. However, full room auralizations typically include reverberant tails. We thus examine such cases where RIRs vary due to variations in Lambert scattering coefficient.

Some major limitations of a Lambert-based scattering model [7] are that (1) it does not simulate well the complex scattering directivity from two-dimensional scattering geometries such as edges of finite planes and cylinders, and (2) it does not explicitly account for phase, neglecting interference effects between specular and non-specular scattering. This latter effect is especially important at non-specular angles of surface scattering to the receiver. Nevertheless, despite its oversimplification of surface scattering, Lambert-scattering can still function as a perceptually-based approximation to surface scattering where phase is neglected.

Figure 6 shows results of listening tests [5] that investigated the perceived difference in changes of the Lambert scattering coefficient from 10% to 60% over different frequency ranges. These figures showed that changes in scattering coefficient are audible in all frequency regions tested, where the relative audibility is related to the input signal. Moreover, for perceptual (i.e., aural) accuracy, scattering must be treated with frequency dependence (not all auralization programs do this), and with models appropriate to each frequency. Such conclusions on the perceptual aspects of surface scattering are not immediately obvious from time-frequency spectral plots or other conventional numerical parameters.

4. Conclusions and Future Work

This paper demonstrates the value of complementing the physical metrics of numerical accuracy with psychoacoustical listening tests in order to judge aural accuracy more effectively. For medium-resolution applications in virtual reality, one can also use listening tests to create better perception-based scattering models, such as the construction of simplified scattering filters described above, based on few parameters for faster computation of edge diffraction.

Additional numerical investigation and subjective testing is also needed to determine how best to model scattering parametrically from hemispherical bosses. One should also investigate how best to characterize spatial and timbral effects of scattering and to what extent late reverberation influences such perceptual effects in the early room impulse response.

5. References