

## Application of Fitted to Measurements Sound Reflection Model in Geometrical Acoustics Simulations

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### ABSTRACT

Geometrical acoustics (GA) is commonly used in room acoustics simulations. One of important factors in all GA simulations is reflection handling. Commonly used sound reflection models are mostly based on combination of Lambert diffusion and specular reflection, yet these models have significant limitations. In this work we present an alternative approach based on Room Acoustics Rendering Equation and fitted to measurements Phong reflection model. The ray tracing results obtained with commonly used and proposed methods are evaluated by comparison to measurements of simple structures, reference reflection patterns modelled with Boundary Elements Method and in full room acoustics simulations.

**Keywords:** Ray tracing, BRDF, simulations, room,

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(see <http://i-ince.org/files/data/classification.pdf>)

### 1. INTRODUCTION

A geometrical acoustics is most common method of room acoustics prediction. The acoustic rendering equation formalized by Siltanen et al. [1] provides a mathematical framework for a wide variety of geometrical acoustics methods. It is a universal set

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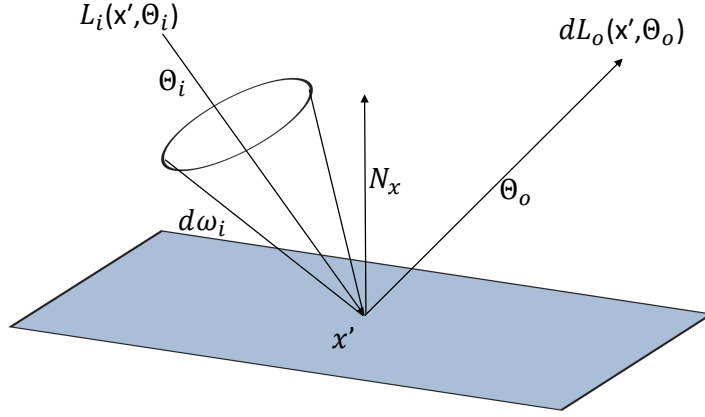


Figure 1: Graphical representation of BRDF definition

of equations which can be used to derive any geometrical acoustic method [2]. An important factor significantly affecting the simulation results, shared by all the methods is a reflection handling.

The acoustics rendering equation introduces an acoustic bidirectional reflectance distribution function (BRDF). The most common reflection model combines ideally specular and perfectly diffuse reflection. The ratio between the two is defined by the scattering coefficient [3]. This approach yields significant problems, firstly the assumptions of ideally specular reflection and ideally diffuse reflection weighted using scattering coefficient seems questionable [4] moreover the ideally specular component of the BRDF can cause problems in some applications [2].

The aim of this research was to provide an alternative, fitted to measurements reflection model that can be sampled for diffuse and specular contribution for any combination of incidence and reflection angle.

## 2. PHONG REFLECTION MODEL FITTED TO MEASUREMENTS

### 2.2.1. Model description

In general a bidirectional reflectance distribution function can be written as [1, 5]:

$$f(x', \Theta_i, \Theta_o) = \frac{dL_o(x, \Theta_o)}{L_i(x, \Theta_i) |N_x \cdot \Theta_i| d\omega}, \quad (1)$$

for a point  $x'$  on a surface with normal  $N_x$ ,  $L_o$  is the radiance outgoing along the direction  $\Theta_o$  and  $L_i$  is an incoming radiance incident through a differential solid angle  $\omega_i$  along the direction  $\Theta_i$  (figure 1).  $|N_x \cdot \Theta_i|$  is the cosine of angle between surface normal and incidence direction. The BRDF describes the amount of energy reflected in given direction as a result of an incoming energy.

Based on the equations above the classical reflection model combining ideally specular reflection with Lambert diffusion can be written as:

$$f(x', \Theta_i, \Theta_o, \alpha, s) = (1 - s_m)(1 - \alpha) \frac{\delta(\Theta_s - \Theta_o)}{|\Theta_o \cdot N_{x'}|} + s_m(1 - \alpha) \frac{1}{\pi}, \quad (2)$$

where  $\Theta_s$  is specular reflection direction. The classic model depends on material absorption coefficient  $\alpha$  and scattering coefficient  $s_m$  (we use  $s_m$  instead of  $s$  to differ the

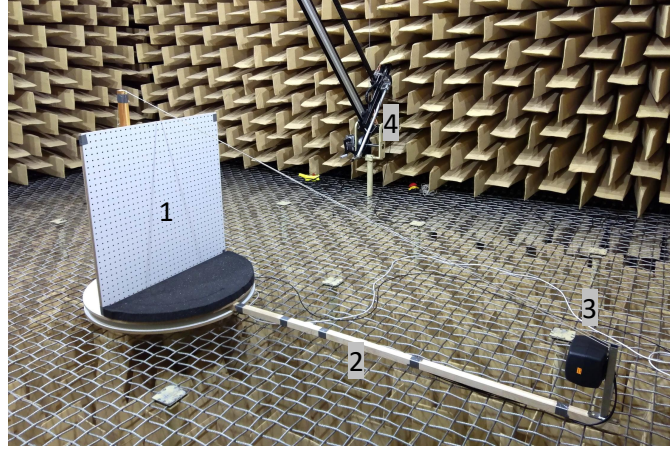


Figure 2: Photograph of sample on a measurement stand. 1 - measured sample, 2 - arm with the speaker, 3 - speaker, 4 - manipulator with microphone

measured scattering coefficient  $s$  from the coefficient which is an input to the reflection model  $s_m$ ) which are provided by the user. Using the classic model it is problematic that for given angle of incidence there is only one outgoing direction  $\Theta_o$  where specularly reflected part is nonzero. This limits its applicability in ray tracing techniques such as bidirectional path tracing [6] or path tracing with diffuse rain [7].

To overcome this limitation an adaptation of commonly used in computer graphics Phong reflection model [8] is proposed. In Phong model the ideally specular reflection is replaced by cosine of angle between specular direction  $\Theta_s$  and outgoing direction  $\Theta_o$  raised to  $n$ th power:

$$f(x', \Theta_i, \Theta_o, \alpha, s, n) = (1 - s_m)(1 - \alpha) \frac{1}{\rho(x, \Theta_i, n)} |\Theta_s \cdot \Theta_o|^n + s_m(1 - \alpha) \frac{1}{\pi}. \quad (3)$$

Due to energy conservation principle a normalization factor  $\rho(x, \Theta_i, n)$  is required. Its calculation is not straightforward as part of the specular lobe may be below the reflecting plane. This part is neglected from calculations, but it should also be omitted in normalization factor calculation. In this paper a recursive relation for  $\rho(x, \Theta_i, n)$  provided by Arvo [9] was used.

### 2.2.2. Measurement stand

Phong model introduces new parameter  $n$  related to the width of a specular reflection lobe. As the parameter is unknown it should be fitted to measured reflection patterns, therefore new measurement stand was designed and build (figure 2).

The measured sample and a speaker on an arm are mounted on a rotary table in an anechoic chamber. The relative position of the sample and the speaker is constant during a measurement. The speaker and the microphone are placed 2.2 m from the sample centre. For 2D measurement the microphone is above the speaker to avoid collisions and shadowing caused by the speaker. Arm position can be adjusted to achieve incidence angles between 0 – 90 deg. The microphone is placed on a manipulator responsible for measurement on arch perpendicular to table rotation plane. The combination of table rotation, manipulator movement and arm angle adjustment allows for measurements of full 3D hemispherical reflection patterns for any given angle of incidence.

### 2.2.3. Phong model fitting

Based on measurement results, the normalized diffusion coefficient  $d_n$  [10] and scattering coefficient  $s$  were calculated. To obtain a scattering coefficient from free field measurements we used procedure proposed by Mommertz [11]. Because we were interested in scattering due to surface structure, low frequency results must have been rejected.

The Phong model as in equation (3) is a "point reflectivity function" [12], so for a point source a total surface reflectivity pattern is obtained by integration BRDF over reflective surface area and over the solid angle subtended by the receiver:

$$\Phi = \int_A \int_{\Omega} L(x', \Theta_i) f(x', \Theta_i, \Theta_o) |\Theta_o \cdot N_x| dx d\omega. \quad (4)$$

$L(x', \Theta_i)$  is the incoming radiance at point  $x$  from the direction  $\Theta_i$  and  $f(x', \Theta_i, \Theta_o)$  is the BRDF function. This formulation neglects the propagation time as only total energy is required for directivity pattern calculation.

To find optimal values for  $n$  coefficient an optimization algorithm was used. For each sample and frequency a simulated reflection patterns were optimized to minimize the root mean squared error (RMSE) between the simulation and the measurement. To allow the RMSE calculation both the simulated and the measured patterns were normalized so that total reflected energy is equal to 1. The optimization was made both for scattering coefficient  $s$  and diffusion coefficient  $d_n$  used as the model scattering coefficient  $s_m$ .

## 3. RESULTS AND CONCLUSIONS

Phong model can fitted to measured data using proposed Monte-Carlo approach (figure 4). It should be noted that for  $n$  approaching infinity the Phong model becomes a classic model (equation 2). This leads to straightforward method of verification weather the proposed model fits to measurement better than the classic. If the error function ( $RMS E(n)$ ) contains a minima in, the Phong model for that case will be better fitted. We found that for most cases the  $RMS E(n)$  has a minima for  $n$  in range between 0 and 1000 (figure 3) and the Phong model provided better fitting than the classic model (figure 4).

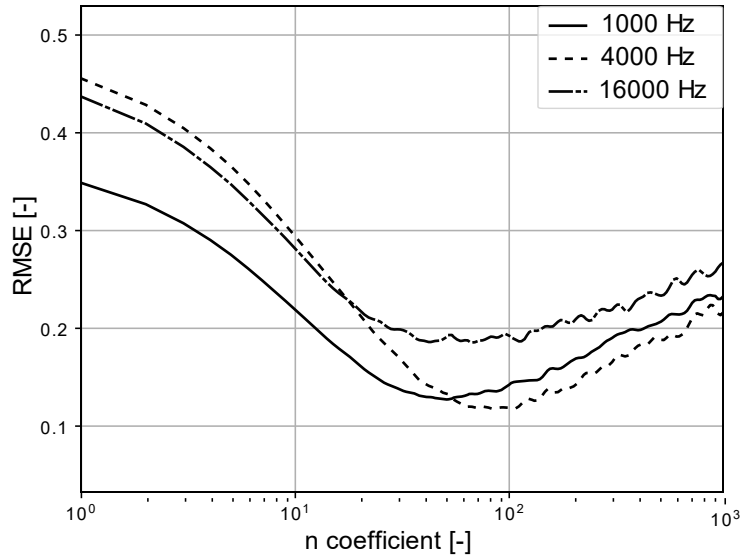


Figure 3: Example of RMSE dependence from  $n$  coefficient for selected frequencies

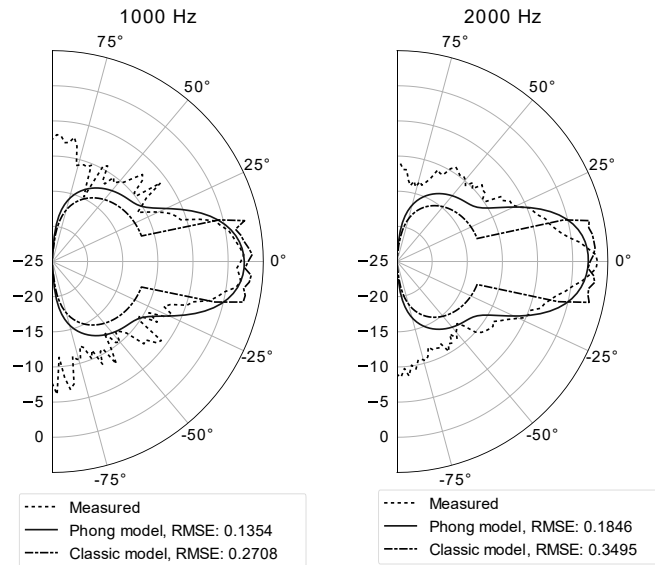


Figure 4: Example comparison of Phong model and classic model fit, log scale

We also verified that the Phong model can be fitted to reflection patterns obtained from wave based methods. This allows to replace the measurement with BEM/FEM simulation and simplifies the fitting process.

The Phong model can be used as a replacement for classic reflection model. It can be sampled for any combination of incidence and reflection angle and it shows better agreement with measured data than the classic model however, the evaluation in complete room acoustics scene is still to be made.

#### 4. ACKNOWLEDGEMENTS

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## 5. REFERENCES

- [1] Samuel Siltanen, Tapio Lokki, Sami Kiminki, and Lauri Savioja. The room acoustic rendering equation. *J. Acoust. Soc. Am.*, 122(3):1624–1635, 2007.
- [2] Lauri Savioja and U. Peter Svensson. Overview of geometrical room acoustic modeling techniques. *The Journal of the Acoustical Society of America*, 138(2):708–730, aug 2015.
- [3] ISO 17497-1:2004 Acoustics – Sound-scattering properties of surfaces – Part 1: Measurement of the random-incidence scattering coefficient in a reverberation room, 2004.
- [4] Stefan Drechsler and Uwe M Stephenson. Diffusivity Coefficients Caused by Edge Diffraction of Arbitrary Polygonal Reflectors. In *AIA-DAGA*, pages 1419–1422, Merano, 2013.
- [5] Eric P Lafortune. *Mathematical Models and Monte Carlo Algorithms for Physically Based Rendering*. PhD thesis, Katholieke Universiteit Leuven, 1994.
- [6] Chunxiao Cao, Zhong Ren, Carl Schissler, Dinesh Manocha, and Kun Zhou. Interactive sound propagation with bidirectional path tracing. *ACM Transactions on Graphics*, 35(6):1–11, 2016.
- [7] Dirk Schröder. *Physically based real-time auralization of interactive virtual environments*. 2012.
- [8] Eric P. Lafortune and Yves D. Willems. *Using the Modified Phong Reflectance Model for Physically Based Rendering*. PhD thesis, Department of Computing Science, K.U. Leuven, 1994.
- [9] James Arvo. Applications of Irradiance Tensors to the Simulation of Non-Lambertian Phenomena. *Computer Graphics (SIGGRAPH '95 Proceedings)*, pages 335–342, 1995.
- [10] ISO 17497-2:2012 Acoustics – Sound-scattering properties of surfaces – Part 2: Measurement of the directional diffusion coefficient in a free field, 2012.
- [11] E Mommertz. Determination of scattering coefficients from the reflection directivity of architectural surfaces. *Applied Acoustics*, 60(2):201–203, 2000.
- [12] Bengt-Inge Dalenbäck, Mendel Kleiner, and Peter Svensson. A Macroscopic View of Diffuse Reflection. *Journal of the Audio Engineering Society*, 42(10):793–807, oct 1994.