Keynote Lecture, Forum Acusticum, Sevilla, 16-20 September 2002.
Proceedings CD-ROM, paper KL-04.

MODELLING IN AUDITORIUM ACOUSTICS – FROM RIPPLE TANK AND SCALE MODELS TO COMPUTER SIMULATIONS

PACS: 43.55.Ka

Rindel, Jens Holger
Ørsted•DTU, Acoustic Technology, Technical University of Denmark
Building 352, DK 2800 Kgs. Lyngby, Denmark
Tel: +45 45 25 39 34
Fax: +45 45 88 05 77
E-mail: jhr@oersted.dtu.dk

ABSTRACT

The paper deals with the tools for the acoustic design of auditoria, and the development of these tools during the last century. Ripple tanks could model the wave nature of sound in a reflecting enclosure, but only in two dimensions. Scale models using high frequency sound waves have been used for testing the design of new auditoria since the 1930es. The development of the room acoustic parameters flourished along with the development of scale model technique. But also the possibility to listen to the sound in the model was a challenge since the early days. The first computer models for room acoustic design appeared around 1967 and during the1990es they have matured. The results became more and more reliable, the calculation speed increased significantly, and new methods for acoustic analysis of the auditorium were developed, one of them being the possibility of producing high quality auralization.

INTRODUCTION

The development of the design tools is described in three sections considering physical models, scale models, and computer models. First is mentioned the early attempts by Sabine and others to use various physical models, primarily to analyse the first reflections in a two dimensional section of a room. Either wave fronts or rays could be modelled. With microphones it became possible to take recordings of sound in scale models, and from the beginning the purpose was to perform listening tests, i.e. what today is called ‘auralization’. The development of the scale modelling technique from the 1930es to the 1970es was mainly to reduce the scale from originally 1:5 to 1:50, and thus making the technique a more efficient tool for the design purpose. The development of computer models has been in the direction of combined hybrid models with emphasis on calculation speed and more reliable results. For the developers of room acoustic computer models it has been very important that a number of international Round Robin comparisons have been organised. From those it has been clear that the modelling of scattering effects is crucial for obtaining reliable results. Thus it may be of great importance for the future development that ISO is now preparing methods for treatment of scattering.

This presentation will focus on the historical development with emphasis on the old and partly forgotten techniques, whereas the newest development in computer models can easily be found elsewhere.

PHYSICAL MODELS

Ultrasonic – Schlieren Photography. In 1913 Sabine published a paper describing the use of ultrasonic waves and Schlieren photography to study wave front reflections from the ceiling and walls in 2D sections of a scale model [1]. The sound source is an electric spark made by the discharge of a condenser. With smoke-filled air and strong light from behind, the wave fronts are made visible and can be registered on a photographic plate. The light is refracted because the wave front is much denser than the surrounding air. The method can visualize effects of diffraction and scattering from irregularities.

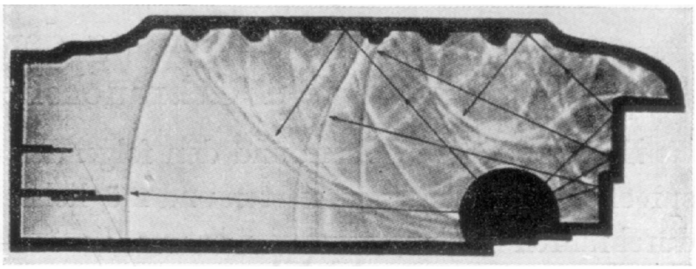

Fig. 1. Schlieren photograph showing reflections of ultrasound wave fronts in a sectional model of the Gewandhaussaal in Leipzig. (Teddington – from Engl, [2]).

Ripple Tank. Very similar pictures can be made by sending light through a water tank with shallow water waves that are created by a mechanic vibrator [3]. A continuous source will create a train of waves and the wavelength can be chosen to represent that of a typical frequency of sound. In a 1:50 scale model the water depth should be approximately 10 mm.

Optical – Light Beam Method. A light source has been used to replace the sound source. One method published in 1929 uses a light source inside a cylinder with a lot of slits. In a 2D model with light reflective surfaces it is possible to get a picture of light beams and their first order reflections. Surfaces that should be absorbing can be painted black to avoid the reflection.

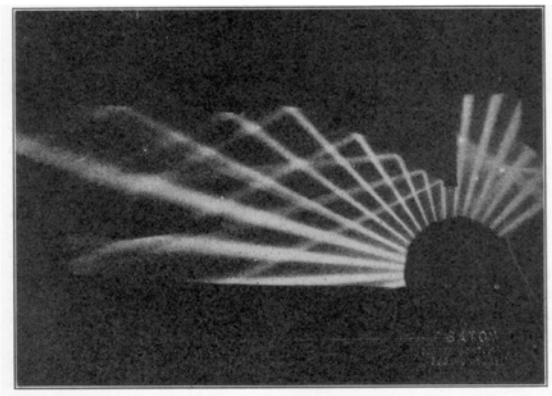

Fig. 2. Light beam investigation of reflections in a sectional model of Okuma Memorial Auditorium. (Satow, 1929 – from Knudsen [4]).

Fig. 3. Optical model of a hall with a concave ceiling. The energy distribution on the floor can be studied on a photographic plate.

Optical – Light Distribution Method. In the 1930es an optical method was used to investigate the energy distribution in an auditorium. An opal glass plate is used to represent the audience. The other surfaces of the room are modelled of sheet aluminium with an optical reflection coefficient of about 50%. With a light source representing the sound source, the brightness of the opal glass indicates the steady-state sound pressure distribution over the seating area. Vermeulen & de Boer [5] used this method for the design of the Philips Theater in Eindhoven.

Optical – Laser Beam Method. In more recent time the laser beam has been used by Nagata Acoustics to investigate first order reflections in a 3D model of Suntory Hall (1986).

	Schlieren method	Ripple tank	Optical - light beams	Optical - distribution	Optical - laser beam
Earliest report	1913	1921	1929	1936	1985
Dimensions	2D	2D	2D	3D	3D
Physics	Ultrasound	Water	Light	Light	Laser
Wavefront	X	X			
Wavelength		X			
Typical scale	1:200	1:50	1:50	1:200	1:10
Early reflections	X	X	X		X
Energy distribution				X	
Surface absorption	X		((X))	((X))	((X))
Scattering effects	X	X			
Diffraction effects	X	X			

Table 1. Some characteristics of physical models.

ACOUSTIC SCALE MODELS

Technicolor Models. In 1934 Spandöck [6] made the first report on a method for subjective assessment of the acoustics of a room by use of three-dimensional models. The scale was 1:5 and he used a wax drum at 60 rev/min to record a sound signal, which was played back at 300 rev/min and radiated into the model. Sound in the model was recorded at the high speed and played back at the low speed. In the following years Jordan [7] improved the method by using a magnetic recorder (the Poulsen Telegraphone) with 20 sec samples of speech. This could demonstrate the influence of sound absorption in the room on the speech intelligibility.

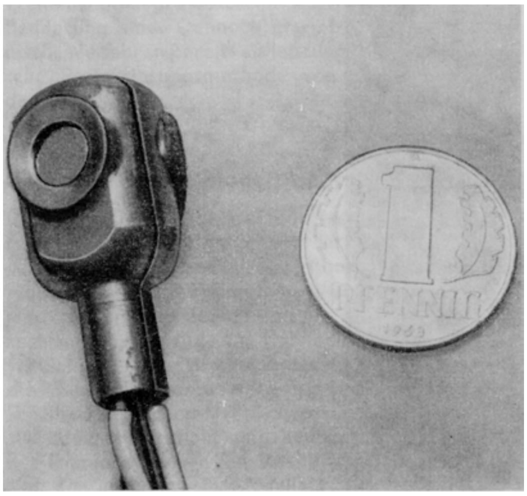

Fig. 4. Dummy head with two microphones in scale 1:20. ([10] fig. 9.69).

Fig. 5. View from a 1:10 scale model of the Major Hall for the Sydney Opera House (not the final design, but the last Utzon design around 1966). ([11] fig. 4.10).

The principle in scale modelling is that all physical dimensions including the wavelengths are reduced by the scale factor. The name ‘Technicolor Models’ as well as the other names used here for scale models was originally proposed by Burd [8]. The reason for this name is the attempt to choose surface materials with the correct absorption coefficients at the scaled frequencies. In the further development by Reichardt [9] and others the scale was reduced to 1:10 or 1:20. In order to minimize the influence of the air attenuation at high frequencies, the air in the model was dried to around 2% RH. Dummy heads in the chosen scale were developed for the recording of binaural signals from the models. The example in Fig. 4 was used for the redesign of the Semper Opera in Dresden.

<u>Half-Tone Models.</u> When the scale model technique is used for the design of a hall, it may be too time consuming and impractical to use listening tests to assess the acoustical quality. Objective room acoustical measurements are faster and more precise. Such measurements are based on the impulse response, which can easily be measured with an electric spark as impulse sound source. During the 1950es and -60es this technique was taken into use for design of opera theatres and concert halls, and in the same period the development of new objective room acoustic parameters flourished [11]. These models are called ‘Half-Tone Models’ because there is no attempt to model the absorption of the surfaces with high precision. Only the audience is modelled with approximately to correct absorption [12]. Other surfaces are made as reflective as possible, and the air attenuation is taken as it is without drying the air. Before the model is taken into use the reverberation time as a function of the frequency is adjusted approximately by adding patches of sound absorbing material in the ceiling or on other suitable surfaces. With a small-scale dummy head it is possible to include an approximate auralization by convolution of a test sound with the measured Binaural Room Impulse Response (BRIR).

<u>Black & White Models.</u> In order to shorten the time needed for model tests, the modelling technique was further developed in the late 1970es for very small models in the scale of 1:50 [13]. In this scale it is very difficult to control the absorption of the materials, and if the surfaces are either reflective or absorptive this may be characterized as ‘Black & White Models’.

	Technicolor models El. dynamic source	Technicolor models Impulse source	Half-tone models	Black & white models
Earliest report	1934	1956	1968	1979
Typical scale	1:8 - 1:20	1:8 - 1:20	1:8 - 1:20	1:50
Source	Loudspeaker	El. spark	El. spark	El. spark
Source directivity	X	(X)		
Microphone receiver	X	X	X	X
Dummy head receiver	X	X	(X)	
Surface absorption	X	X	(X)	((X))
Early reflections	X	X	X	X
Scattering effects	X	X	X	X
Diffraction effects	X	X	X	X
Impulse response	X	X	X	X
Reverberation time	X	X	(X)	(X)
ISO 3382 parameters	X	X	X	(X)
Auralization	X	X	(X)	
Time for construction	12-24 weeks	12-24 weeks	8-20 weeks	3 weeks
Time for measurements	4-8 weeks	4-8 weeks	3-8 weeks	1 week

Table 2. Some characteristics of acoustic scale models. (Partly after Burd [8]).

COMPUTER MODELS

Wave Equation Models. Such models like the Finite Element Method (FEM) and the Boundary Element Method (BEM) are characterized by creating very accurate results at single frequencies. However, since the number of modal frequencies in a room increases with the third power of the frequency, wave models are typically restricted to low frequencies and small rooms.

Image Source Model. This method is based on the principle that a specular reflection can be constructed geometrically by mirroring the source in the plane of the reflecting surface. In a rectangular box-shaped room it is very simple to construct all image sources up to a certain order of reflection [14-15]. But in an arbitrary room the number of possible image sources increases exponentially with the order of reflection, and thus the method is not suitable for rooms like concert halls where reflection orders of several hundred are relevant for the audible reverberant decay.

Markoff Chain Model. The decaying sound in a room can be considered as a process of sound absorption in discrete steps of a time interval that corresponds to the mean free path in a three-dimensional sound field, $dt = 4V/cS$, where V is the volume, c is the speed of sound, and S is the total surface area in the room. This model is based on a probability function for sound travelling from one surface to any other surface in the room. Thus a room averaged decay curve is calculated and the location of absorption material on the different surfaces is taken into account [16].

Particle Tracing Models. A more realistic way to simulate the decaying sound is to trace a large number of particles emitted in all directions from a source point. Each particle carries a certain amount of sound energy that is reduced after each reflection according to the absorption coefficient of the surface involved. As shown in Fig. 6 the result is the average decay curve for the room from which the reverberation time is evaluated [17].

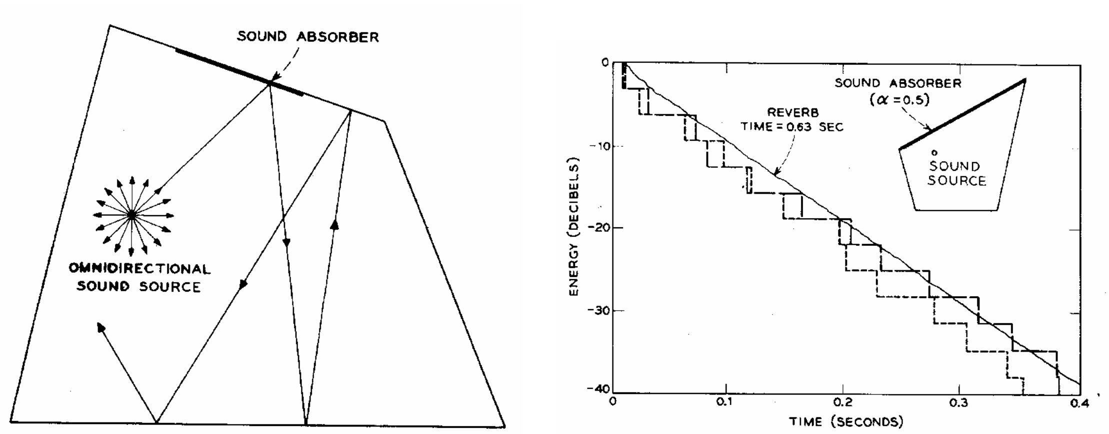

Fig. 6. Particle tracing based on geometrical acoustics. Left: The sound energy follows the path of several hundred rays (only one is shown), and the energy of the particles is reduced when they hit an absorbing surface. Right: Average decay curve. (After Schroeder [17]).

Ray Tracing Models. The first computer model that was used for practical design of auditoria was a ray tracing model [18]. A large number of sound rays are traced from a source point up to high order reflections following the geometrical/optical law of reflection. The main result of this early model is the distribution of ray hits on the audience surface, analysed in appropriate intervals of the time delay. So, this is a qualitative presentation of the sound distribution in space and time. For a closer analysis the direction of incidence of each ray can also be indicated. In order to obtain quantitative results it is necessary to introduce receiver surfaces or volumes for detection of the sound rays. So, an approximate energy-reflectogram can be calculated and used for an estimate of some room acoustic parameters [19-20].

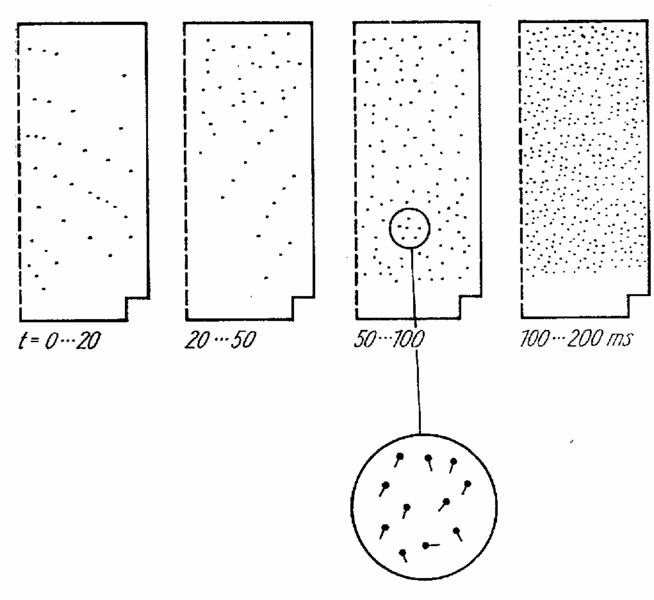

Fig. 7. Example of results from the first ray tracing model [18]. Hit points of sound rays as distributed on one half of the floor, shown in time intervals relative to the direct sound. Some directional information is included, see the enlargement.

	Statictically based equations	Wave equation models	Image source models	Markoff chain models	Particle tracing models	Ray tracing models	Cone tracing models	Radiosity models	Hybrid models
Earliest report	1900		1979	1975	1970	1968	1986	1993	1989
Low frequency model		X	(X)						
High frequency model	X		X	X	X	X	X		X
Point source		X	X	X	X	X	X	X	X
Line source						X		X	X
Surface source						X		X	X
Source directivity			X			X	X	X	X
Point receiver		X	X			(X)	X	X	X
Grid of receivers		X				X	X	X	X
Sound distribution						X	X	X	X
Volume average	X			X	X				
Surface absorption	X	X	X	X	X	X	X	X	X
Early reflections			X			X	X		X
Echo tracing in 3D			X			(X)	(X)		X
Scattering effects					X	X	X	X	X
Diffraction effects		X							X
Coupled spaces		X			X	X	X	X	X
Impulse response			(X)			(X)	(X)	X	X
Reverberation time	X			X	X	(X)	(X)	X	X
ISO 3382 parameters						(X)	(X)	X	X
Auralization			(X)			X	X	X	X
Time for modelling (1-5)	1	5	3	3	3	3	3	3	3
Time for calculations (1-5)	1	5	5	1	1	4	4	3	2

Table 3. Some characteristics of computer models. The time consumption is evaluated on a scale from 1 (very fast) to 5 (very slow).

Cone Tracing Models. An alternative to the receiver volume used in ray tracing models is a point receiver in combination with cones that have a certain opening angle around the rays. Cones with circular cross section have the problem of overlap between neighbour cones [21]. Cones with a triangular cross section can solve this problem [22], but still it is difficult to obtain reliable results with this method.

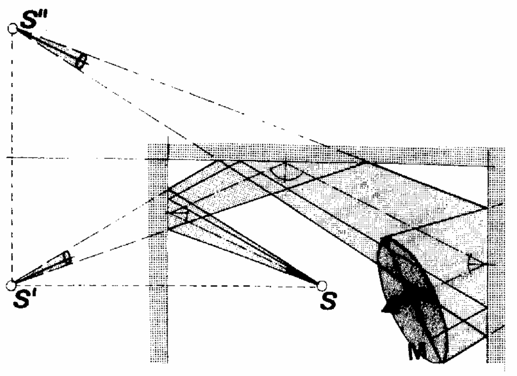

Fig. 8. Tracing of a circular cone from the source S to the receiver M. The first and second order image sources are also shown. ([21] fig. 2).

Radiosity Models. The principle is that the reflected sound from a surface is represented by a large number of source points covering the surface and radiating according to some directivity pattern, typically a random distribution of directions [22]. This method has also been used as an efficient way to model the scattered part of the early reflected sound [30].

Hybrid Models. The disadvantages of the classical methods have lead to development of hybrid models, which combine the best features of two or more methods [22–30]. Thus modern computer models can create reliable results with only modest calculation times. The inclusion of scattering effects and angle dependent reflection with phase shifts has made it possible to calculate impulse responses with a high degree of realism. This in turn has been combined with Head Related Transfer Functions (HRTF) to give Binaural Room Impulse Responses (BRIR), which are convolved with anechoic sound recordings to make auralization of high quality.

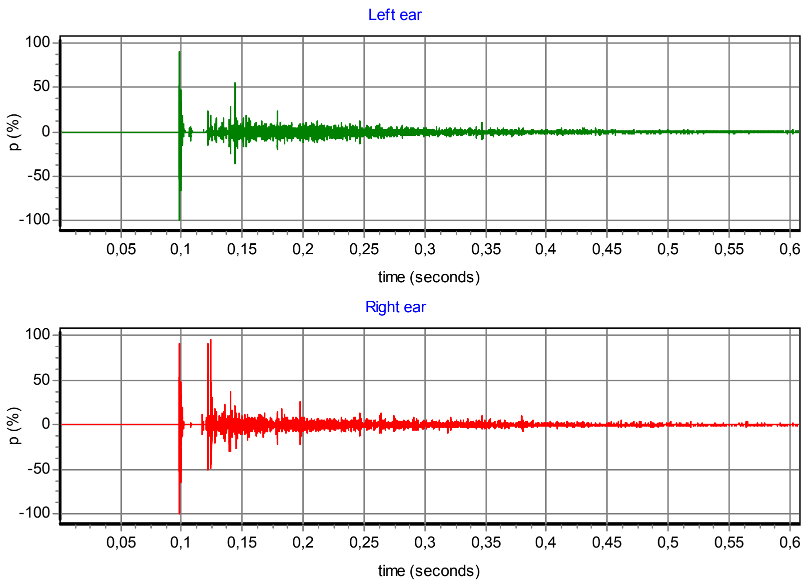

Fig. 9. Examle of a Binaural Room Impulse Response calculated in a new opera house project. The first 600 ms are shown, but in this example the calculated impulse response is 2 s long.

CONCLUSION

During the last century a rich variety of ideas and methods have been created in order to bring the acoustic design of auditoria from a weakly understood art to a scientifically based field of engineering. With the latest development in computer modelling it has been possible to combine the best features of the older methods, to get reliable predictions of objective acoustic parameters, and in addition to offer auralization for subjective listening tests.

BIBLIOGRAPHICAL REFERENCES

[1] W.C. Sabine (1913). Theater Acoustics. The American Architect **104**, 257. Reprinted in: Collected Papers on Acoustics, Harvard University Press, 1922.
[2] J. Engl (1939). Raum- und Bauakustik. Akademische Verlagsgesellschaft, Leipzig.
[3] A.H. Davis & G.W.C. Kaye (1927). The Acoustics of Buildings. London.
[4] V.O. Knudsen (1932). Architectural Acoustics. John Wiley & Sons, New York.
[5] R. Vermeulen & J. de Boer (1936). Philips Techn. Review **1**, 46.
[6] F. Spandöck (1934). Raumakustische Modellversuche. Ann. Phys. **20**, 345.
[7] V.L. Jordan (1941). Elektroakustiske undersøgelser af materialer og modeller. (In Danish). Doctoral Thesis, Copenhagen.
[8] A.N. Burd (1975). Acoustic Modelling – Design Tool or Research Project? Chapter 7 in "Auditorium Acoustics" R. Mackenzie (ed.), Applied Science Publishers, London.
[9] W. Reichardt (1956). Die Akustik des Zuschauerraumes der Staatsoper Berlin Unter den Linden. Hochfrequenztechnik und Elektroakustik **64**, 134.
[10] W. Fasold, E. Sonntag & H. Winkler (1987). Bau- und Raumakustik. Verlag für Bauwesen, Berlin.
[11] V.L. Jordan (1980). Acoustical Design of Concert Halls and Theatres. Applied Science Publishers, London.
[12] B.F. Day (1968). A tenth-scale model audience. Applied Acoustics **1**, 121-135.
[13] M. Barron & C.B. Chinoy (1979). 1:50 Scale Acoustic Models for Objective Testing of Auditoria. Applied Acoustics **12**, 361-375.
[14] J. Allen & D.A. Berkley (1979). Image method for efficiently simulating small-room acoustics. J. Acoust. Soc. Am. **65**, 943-950.
[15] J. Borish (1984). Extension of the image model to arbitrary polyhedra. J. Acoust. Soc. Am. **75**, 1827-1836.
[16] R. Gerlach (1975). The Reverberation Process as Markoff Chain – Theory and Initial Model Experiments. Chapter 9 in "Auditorium Acoustics" R. Mackenzie (ed.), Applied Science Publ. London.
[17] M.R. Schroeder (1970). Digital Simulation of Sound Transmission in Reverberant Spaces. JASA **47**, 424-431.
[18] A. Krokstad, S. Ström & S. Sörsdal (1968). Calculating the Acoustical Room Response by the use of a Ray Tracing Technique. J. Sound and Vibration **8**, 118-125.
[19] U. Stephenson (1985). Eine Schallteilchen-Computersimulation zur Berechnung der für die Hörsamkeit in Konzertsälen massgebenden Parameter. Acustica **59**, 1-20.
[20] P.A. Forsberg (1985). Fully Discrete Ray Tracing. Applied Acoustics **18**, 393-397.
[21] J.P. Vian & D. van Maercke (1986). Calculation of the room impulse response using a ray-tracing method. Proceedings of 12th ICA Symposium, Vancouver, 74-78.
[22] T. Lewers (1993). A Combined Beam Tracing and Radiant Exchange Computer Model of Room Acoustics. Applied Acoustics **38**, 161-178.
[23] M. Vorländer (1989). Simulation of the transient and steady-state sound propagation in rooms using a new combined ray-tracing/image source algorithm. J. Acoust. Soc. Am. **86**, 172-178.
[24] G.M. Naylor (1993). ODEON – Another Hybrid Room Acoustical Model. Applied Acoustics **38**, 131-143.
[25] B.I. Dalenbäck (1996). Room acoustic prediction based on a unified treatment of diffuse and specular reflection. J. Acoust. Soc. Am. **100**, 899-909.
[26] R. Heinz (1996). Zur Modellierung des diffusen Streuverhaltens der Raumbegrenzungsflächen innerhalb raumakustischer Schallteilchen-Simulationen. Acustica – Acta Acustica **82**, 82-90.
[27] U. Stephenson (1996). Quantized Pyramid Beam Tracing – a New Algoritm for Room Acoustics and Noise Immission Prognosis. Acustica – Acta Acustica **82**, 517-525.
[28] K. Nakagawa & H. Shimoda (1997). Hybrid analysis of sound fields in rooms using the Bergeron method and the image source method. Proceedings of ASVA 97, Tokyo, 627-632.
[29] J.H. Rindel (2000). The use of computer modeling in room acoustics. Journal of Vibroengineering, No 3(4) 219-224.
[30] C.L. Christensen (2001). ODEON – A design tool for auditorium acoustics, noise control and loudspeaker systems. Proc. Institute of Acoustics **23** (8), 137-144.