ARCHIVES OF ACOUSTICS
32, 4 (Supplement), 227–233 (2007)

ANALYSIS OF SOUND FIELD IN DOMINICANS' CHURCH IN CRACOW

Magdalena PLEWA

AGH University of Science and Technology
Al. Mickiewicza 30, 30-059 Kraków, Poland
e-mail: mplewa@student.agh.edu.pl

(*received July 15, 2007; accepted October 27, 2007*)

This publication presents the results of sound field analysis: simulation using ray method, finite element model below 200 Hz and real reverberation time measurements in band 125–8000 Hz, executed in Dominicans' church in Cracow. Effects of calculations and measurements show that big part of energy is accumulated in low frequencies what causes significant influence of this band on the acoustics of analyzed interior. Results of ray-method simulation and MLS measurements allowed to receive the values of reverberation time in octave bands. Big architectonical dimensions caused difficulties in sound field analyzing but designers of basilica achieved magnificent acoustic effect without present theoretical knowledge. This article, using computer-aided methods, analyzes results of their work.

Keywords: acoustics, church, ray method, finite elements method.

1. Introduction

Acoustics of old Christian temples is often delightful, although designers did not have theoretical knowledge about the nature of sound waves. Now, using simulation and measurements methods we can describe some parameters of sound field. Analysis of the acoustic field is a good basis for designing acoustic adaptation of the interior. Applying acoustic field simulation gives the possibility to analyze both the interior already existing and the interior designed. It allows for easy introduction of changes in the architectonic dimensions and acoustic elements of the room modeled. If there is a possibility of carrying out acoustic measurements, the values obtained are compared with the simulation. In this way one may draw conclusions concerning the correctness of the model used in the calculations, as well as "adjust" it to the data obtained.

Geometrical methods allow for achieving good results for bands above the border frequency, calculated with the Schröder formula.

$$f_{gr} = 4000\frac{T}{V}\,. \tag{1}$$

This frequency is interpreted as the boundary below which wave phenomena dominate in the acoustic field [1, 2]. The ray method does not take account of these phenomena, therefore calculations for low frequencies obtained with this method are burdened with errors. The Schröder frequency for the interior under analysis is approximately $f \approx 100$ Hz.

2. Target and method of research

Dominicans' church in Cracow is a gothic basilica consisted of three aisles and presbytery. Inside the temple take place many concerts in many kinds of music. Acoustic analysis of interior was realized for the sake of monumental character of building, various concert use and planned change of electroacoustic installation.

After conducting simulations with the ray method, the results obtained for the octave band of a middle frequency of 125 Hz are hardly accurate. For octave bands 125–8000 Hz, the ray method was applied. To conduct a simulation of the acoustic field in the full range of audible frequencies, the results shall be complemented with additional calculations. For frequencies below 200 Hz there shall be used one of the methods of approximate wave equation solving – the finite elements method. The band common for both methods shall be 125 Hz.

3. Measurements

Registration of impulse response and reverberation time was made using the MLS method, in an empty church. For measurements an Ego Sys U2A sound card, Beyma GU50 loudspeaker, Rduch MW – 4 K amplifier and Behringer ECM 800 microphone were used. The program Sample Champion 3.0. was used to generate noise, register data and analyze the results The input function was an MLS signal of 256000 sound samples. The loudspeaker emitting the noise was placed in two points. The measuring microphone was placed (Fig. 1):

- in 4 locations for the first sound source no. 1,
- at 9 points for the second sound source no. 2.

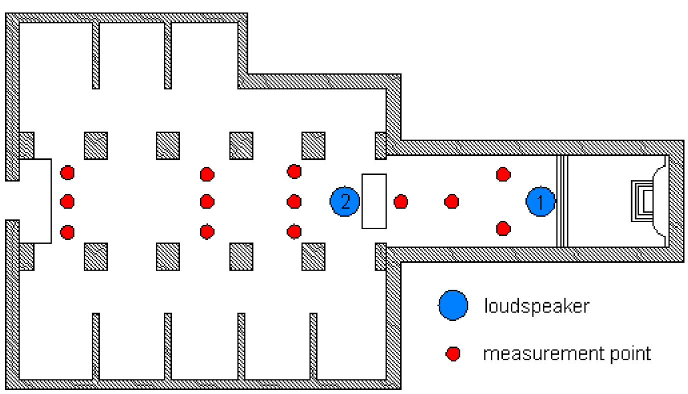

Fig. 1. Location of measurement points.

In Fig. 2 there has been presented an impulse response of the interior, registered in one of the measurement points, for the loudspeaker located in item 2 (Fig. 1). In the chart one may see a distinct initial rebound, which suggests that it has a substantial influence on the acoustics of this interior.

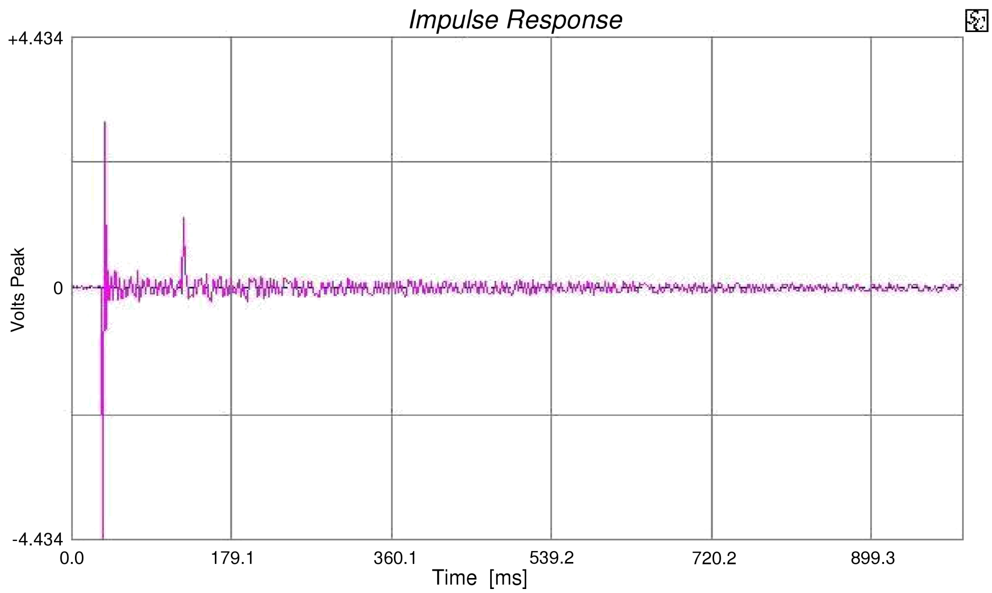

Fig. 2. Impulse response.

In Figs. 3 and 4 present envelope curves for frequency data fading, along with T60 values calculated using Sample Champion software.

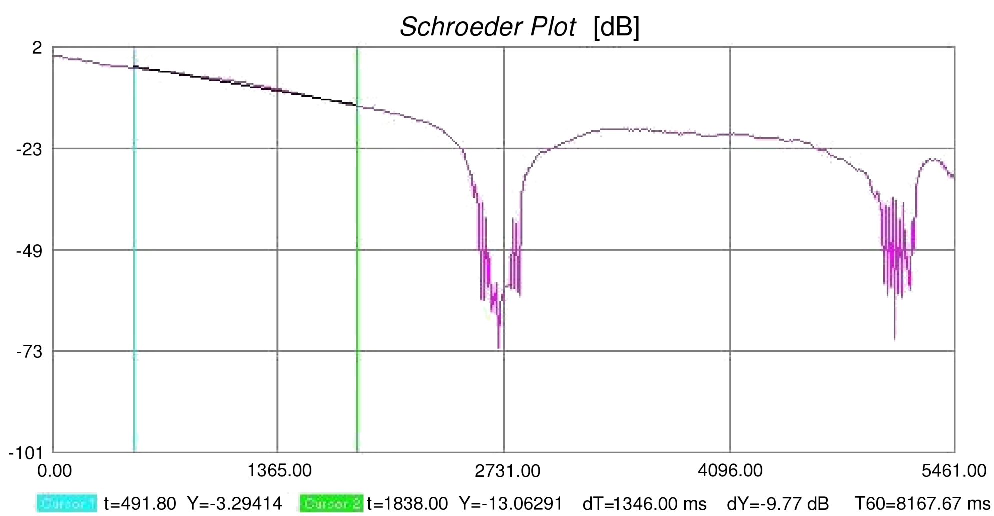

Fig. 3. Decay curve for frequency 125 Hz.

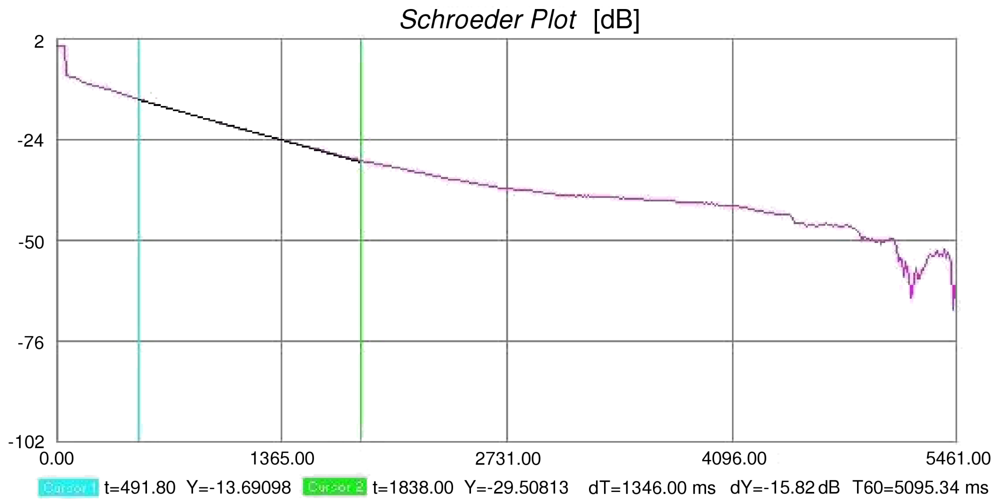

Fig. 4. Decay curve for frequency 2 kHz.

4. Ray method

In the ray method, a continuous acoustic wave is represented as a discrete set of "sound rays", which propagate at sound speed. All of the rays carry the same portion of the energy emitted by the source and lose it gradually after subsequent rebounds, in proportion to the absorption factors [2, 3].

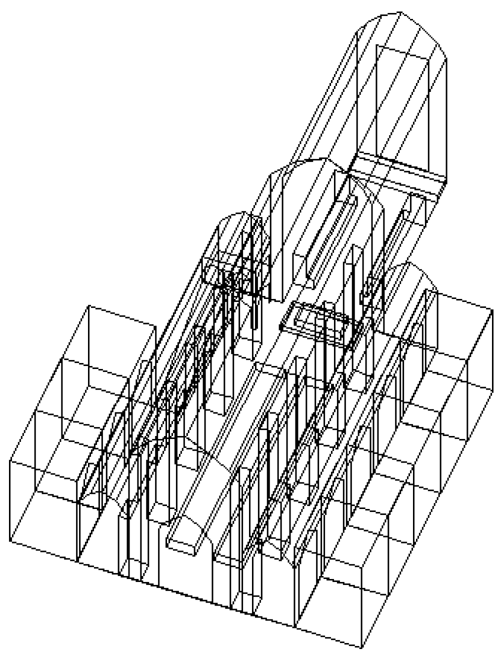

Fig. 5. Model of church used in RAYNOISE.

Ray method simulation has been carried out using RAYNOISE 2.1 software. The geometric model of the church (Fig. 5) has been prepared taking account of more details than in the case of the finite elements method.

Acoustic scattering on objects of complicated shapes, such as benches, stalls, altars, portal and organ, is also an important factor. Abounding sculpture causes, that acoustic field is dispersed and close to diffuse. It is one of the elements which state about good acoustics of old, sacral buildings. Absorption of above mentioned elements is also important, but difficult to estimate and because of presented earlier aspects of sound field diffusion, less significant. By reason of that the values of absorption factors, mostly in bands 1 and 2 kHz, have been additionally "adjusted" (increased by 50–70%) to the measurement results.

In simulation sound sources and receivers have been placed as in the case of real measurements.

5. Finite elements method

Finite elements method bases on approximate solution of acoustic wave equation:

$$\nabla^2\psi - \frac{1}{c^2}\,\frac{\partial^2\psi}{\partial t^2} = 0. \tag{2}$$

The interior under analysis is treated as a system of elements joined together by nodes, described by a system of algebraic equations (for static issues). These equations describe generalized movements of the nodes. By determining, through the use of limiting conditions, the coefficient values of interpolating functions in nodes on the outer edges of the model, and next, on the basis of assumptions of continuity of the functions, the coefficients of other elements are received. By solving the equation system, the values of generalized coordinates are obtained. Next, using interpolating functions, the acoustic parameters inside the elements are calculated [4–6].

For the purposes of the model used in the finite elements method (Fig. 6), the interior of the church has been diagrammatically replicated, as a combination of four acoustic volumes: main aisle, side aisles and presbytery. Moreover in simulation was also used more complicated model, completed with columns situated between the naves. The arched shape of the vaulting has been preserved, while other architectonic details of the interior such as columns, side altars etc., have been omitted due to their negligent influence on the results obtained using the finite elements method. The FEM Procedure was conducted for frequencies below 200 Hz, and so the minimum length of the wave under consideration is $\lambda = 1.7$ m. Projection accuracy of objects which are comparable with the length of the wave and objects much smaller than the interior, has a negligent effect on the results of the calculations. The model was prepared using AutoCad 2007 software, in the dxf format.

In Table 1 are presented FEM simulation parameters.

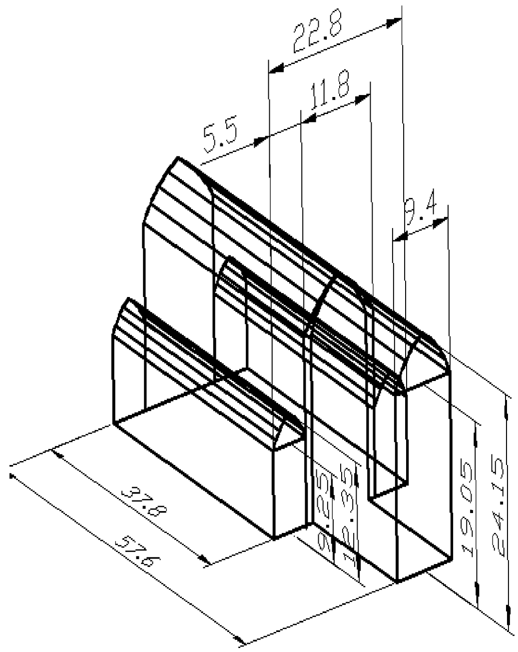

Fig. 6. Model of church prepared for infinite element method.

Table 1. FEM simulation parameters.

Application	Velocity of sound	Air density	Basic model		Model with columns	
SYSNOISE	$342\frac{\mathrm{m}}{\mathrm{s}}$	$1.223\frac{\mathrm{kg}}{\mathrm{m}^3}$	Amount of elements	Amount of nodes	Amount of elements	Amount of nodes
			52310	52491	54743	57121

6. Comparison of results

Table 2 presents reverberation times obtained from measurements and calculations in the ray method. Results of reverberation time measurements in particular measurements are averaging, after rejection of two extreme values. Probably discrepancies in the results result from the inaccuracy of the model used for simulations in RAYNOISE. The model was created based on dimensions obtained with a laser measuring device, because no architectonic documentation of the church exists. The absorption coefficients assumed in the simulation also contribute to the inaccuracy, as they have been determined on the grounds of their values for similar materials.

The most important conclusion founded on results of FEM simulation is big modal density for low frequencies. First 250 modes are contained in range 10–50 Hz.

Table 2. Values of reverberation time in octave-bands.

Frequency	Reverberation time (MLS)	Reverberation time (RAYNOISE)
125	8.24	9.62
250	4.62	4.83
500	5.31	5.01
1000	5.2	4.89
2000	4.55	4.31
4000	3.47	3.2
8000	2.4	2.03

7. Inference

Above mentioned large modal density in low-frequency band exercises significant influence on acoustic of analyzed interior. Moreover in church are placed organs, which can generate sound with first harmonic circa 30 Hz, so problem of low frequencies is really important.

Thanks to science and technique development it was possible to catty out presented research. A juxtaposition of all the results gives a good basis for designing acoustic adaptation, including the electro-acoustic system envisaged for the church. However people who build the basilica achieved magnificent acoustic effect without present theoretical knowledge. Presented analysis allows us to come a little bit closer to this superb combination of architecture and acoustics, which we admire till today.

References

[1] ENGEL Z., *Ochrona środowiska przed drganiami i hałasem*, PWN, Warszawa 2001.

[2] KULOWSKI A., *Akustyka sal*, WPG, Gdańsk 2007.

[3] GOŁAŚ A., *Metody komputerowe w akustyce wnętrz i środowiska*, AGH, Kraków 1995.

[4] SHUKU T., ISHIHSEA K., *The analysis of the acoustic field in irregularly shaped rooms by the finite element method*, Journal of Sound and Vibration, **29**, 1, 67–76 (1973).

[5] OLSZEWSKI R., *Zastosowanie MES i MEB do analizy pola akustycznego*, AGH, Kraków 2005.

[6] PANUSZKA R., *Stosowanie metod całkowych i elementów skończonych w akustyce*, PTA, Kraków 1995.

[7] MEYER J., *Kirchenakustik*, Verlag Erwin Bochinsky, Frankfurt am Main 2003.

[8] ENGEL Z., ENGEL R., KOSAŁA K., *Analiza porównawcza oceny akustycznej obiektów sakralnych*, Zeszyty Naukowe Politechniki Białostockiej, Budownictwo, Seria: Budownictwo Sakralne i Monumentalne, 2006.