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Computer modelling and simulation of sound field in 24 rectangular concert halls

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Extensive acoustics computer simulations have been made using Odeon computer simulation software. From 300 to 850 measurements positions have been analysed in 24 rectangular rooms representing "shoe-box" type concert halls with volumes of 8 000 m^3, 12 000 m^3 and 16 000 m^3. In total 14 000 receiver positions have been analysed. For each receiver position eight objective measures have been calculated, in particular Reverberation Time (T_{30}), Early Decay Time (EDT), Clarity (C_{80}), Strength (G, G_{early}, G_{late}), Early Lateral Energy Fraction (LF_{80}) and Late Lateral Strength (G_{LL}). Most of measures have been calculated in six octave bands from 125Hz to 4000Hz. Extensive amount of generated data required developing of new methods for processing, comparing and graphical presentation of results. Those methods together with description of modelling and simulation procedures are described in this paper.

1 Introduction

In recent decades, computer simulation became a popular method to predict acoustics of concert halls [1, 2, 3]. This method is especially valuable, when predicting the influence of hall geometry on the sound field, as changes in geometry are easily made. It can be also utilized when a large number of sources and/or receiving positions are to be analyzed. Compared to scale models, computer simulations are simple and easy. Compared to measurements in real halls, simulation are low-cost and fast alternative. Modern computer simulation software like Odeon [4] offer a reliable level of prediction, which - to some extent – can substitute real hall measurements [5, 6]. It is however not without a risk – as results from simulations are realistic only, if the hall geometry, absorption, diffusion and also other factors in the computer model reflect those of the real hall. The risk is even greater, because as for now, none of the programs mentioned above take care of wave effects like interference and diffraction.

This paper presents modelling and simulation procedures used in acoustical computer simulations of 24 models representing rectangular concert halls [7]. In those simulations audience and stage area was kept constant, but room proportions were gradually changed from square to elongate rectangular. Simulations were repeated in three different room volumes to allow for extension of results on greater number of halls. This paper also shows methods for processing, comparing and graphical presentation of results generated in those simulations.

2 Simulations

2.1 Creation of models

Using Odeon version 8, simple computer models of "shoe-box" type concert halls have been created, like shown in Fig 1. Each model was programmed using Odeon parametric language [4]. By changing just two variables in describing model geometry .par file, namely length-to-width ratio (L/W) and floor area (S), all model variants were created. Eight models were representing each of three analyzed volumes: 8 000 m^3, 12 000 m^3 and 16 000 m^3. Length-to-width was calculated according to simple formula:

$$L/W = n/3 + 0.1 \qquad (1)$$

where $\boldsymbol{n}$ was a number from 3 to 10. Length-to-width ratio calculated according to Eq.(1) was equal in successive models from the same volume to L/W=1.10; 1.43; 1.77; 2.10; 2.43; 2.77; 3.10; 3.43. This was to avoid L/W being integer number, which has no influence on computer simulation (due to lack of wave effects), but could impact planned verification of simulation in scale models.

All models were made with the following assumptions:

- for models in one volume floor area (audience+stage) was constant, and equal to 585 m^2 for 8 000 m^3, 840 m^2 for 12 000 m^3 and 1 160 m^2 for 16 000 m^3 models;
- stage area was 190 m^2 in all models;
- audience area equals floor area minus stage area;
- audience floor was horizontal in all models;
- stage height was 1.0 meter.

Room height was identical in all models and equal to 14 meters. This should result in reverberation time of approx. 2.0 sec. according to simple Kosten [8] formula. This formula is widely used for preliminary room dimensioning during early design phase, so it was chosen as a reference for models height.

Room plans for all models are shown in Fig 2. Example of .par file describing one of the models is shown in Fig.3.

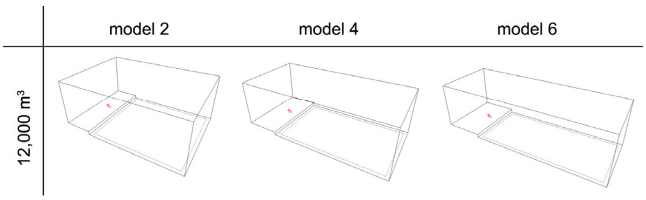

Fig.1 Three examples of simulated "shoe-box" halls in one of the analyzed volumes (V=12 000 m^3). L/W ratio equals 1.43 (model 2); 2.10 (model 4); 2.77 (model 6).

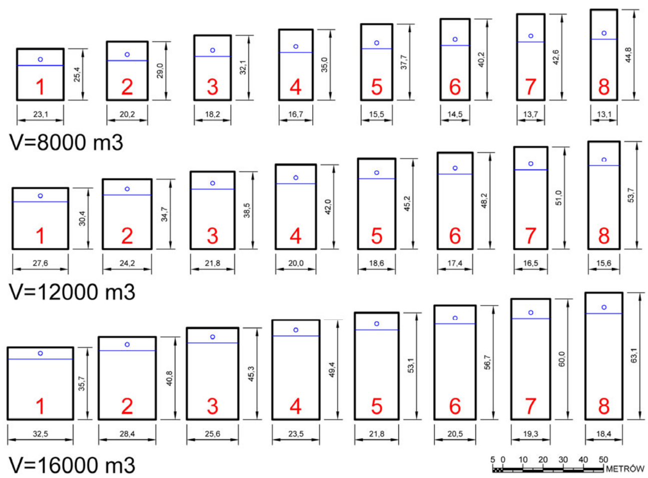

Fig.2 Room plans of all analyzed models.
Model 1 has L/W ratio=1.10. Model 8 has L/W ratio=3.43

```
###
MReset
MRotateZ 90
;.par file for model 2

const M 4
const LW M/3+0.1

;S - floor area
;AUD - Audience area
;STG - Stage area 190 m2
;H - room heigth
;L - room length
;AU_H - audience height at rear
wall
;H_STG - stage height
;ST - stage depth
;AU - audience depth
;LW - Length to Width ratio
(3/3 4/3 5/3 6/3 7/3 8/3 9/3
10/3)+0,1 for 8 models

const S 840
const STG 190
const AUD S-STG
const H_STG 1
const AU_H 0

const H 14
const W sqrt(S/LW)
const L (AUD+STG)/W
const ST STG/W
const AU L-ST

;ceiling
Pt   10   -ST   W/2 H
Pt   20   -ST   -W/2 H
Pt  50  AU  -W/2 H
Pt  60  AU  W/2 H

;stage
Pt   11   -ST   W/2   H_STG
Pt   21   -ST   -W/2  H_STG
Pt  31  0  -W/2 H_STG
Pt  41  0  W/2 H_STG

;audience
Pt  42  0 W/2 0
Pt  32  0 -W/2 0
Pt  52  AU -W/2 AU_H
Pt  62  AU W/2 AU_H

;grid_audience - virtual
audience for grid offset 1 m
from side, rear wall and stage
front
Pt  420  1 W/2-1 0
Pt  320  1 -W/2+1 0
Pt  520  AU-1 -W/2+1 AU_H
Pt  620  AU-1 W/2-1 AU_H

Surf  1 ceiling
 10 20 50 60
Surf 2 stage
 11 21 31 41
Surf 3 audience
 42 32 52 62
Surf 4 wall_stage
 10 20 21 11
Surf 5 wall_back
 60 50 52 62
Surf 6 stage_front
 41 31 32 42
Surf 7 side_wall
 10 11 41 42 62 60
Surf 8 side_wall
 20 21 31 32 52 50
Surf 99 grid_audience
 420 320 520 620

###
```

Fig.3 Example of Odeon parametric file (.par) for model 2 in 12 000 m^3 volume.

2.2 Absorption and diffusion

Results from simulations were suppose to be compared with real hall measurements, so for all models, realistic figures of absorption and diffusion were used. Audience was modelled as fully occupied. Stage was modelled with orchestra. For walls and ceiling the material with properties averaged from 15 halls was used. Absorption coefficients for audience, stage, ceiling and walls for all models are given in Table 1.

<table>
<tr><th>Surface</th><th colspan="6">Material / sound absorption coefficients</th></tr>
<tr><td rowspan="3">Audience</td><td colspan="6">Audience, heavily upholstered seats (Odeon mat. no. 907, Ref.: Beranek & Hidaka 1998)</td></tr>
<tr><td>125</td><td>250</td><td>500</td><td>1000</td><td>2000</td><td>4000</td></tr>
<tr><td>0.72</td><td>0.80</td><td>0.86</td><td>0.89</td><td>0.90</td><td>0.90</td></tr>
<tr><td rowspan="3">Stage</td><td colspan="6">Orchestra with instruments on podium, 1.5 sq.m per person (Odeon mat. No. 900, Ref.: Bobran 1973)</td></tr>
<tr><td>125</td><td>250</td><td>500</td><td>1000</td><td>2000</td><td>4000</td></tr>
<tr><td>0.27</td><td>0.53</td><td>0.67</td><td>0.93</td><td>0.87</td><td>0.80</td></tr>
<tr><td rowspan="3">Walls / Ceiling</td><td colspan="6">Walls, average total residual absorption of 15 halls (Odeon mat. No. 2354, Ref.: Dalenbäck 2000)</td></tr>
<tr><td>125</td><td>250</td><td>500</td><td>1000</td><td>2000</td><td>4000</td></tr>
<tr><td>0.14</td><td>0.12</td><td>0.10</td><td>0.09</td><td>0.08</td><td>0.07</td></tr>
</table>

Table.1 Sound absorption coefficients used in simulations.

For audience and stage area scattering coefficients of 0.65 was used, equal in all frequencies 125~4000 Hz. For walls and ceiling scattering coefficients were frequency dependent and set as 0.30 for key diffraction frequency 707 Hz [4]. These values were chose based on suggestion of positive correlation between preference and high level of diffusity of room boundaries [9]. This value was also consulted with the Odeon developers.

2.3 Source and receivers

Omnidirectional source was positioned centrally over the stage, at a height of 1.2 meter and 3 meters away from the stage front. Source overall gain was set at 31dB to allow Strength (G) calculations.

In each model a grid of receivers was created 1.2 meters over audience area. Grid size was 1 x 1 meter. This value is close to typical seating row distance (~0.9m.), and distance between every second seat in row (2 * ~0.55m).

Odeon version 8 restrict receiver grid size to be equal in both directions, so number of receivers was slightly different from model to model, due to different L/W ratio. For models with 8 000 m^3 there were between 304 to 315 receivers, for 12 000 m^3 between 525 to 546, and for 16 000 m^3 – 816 to 840.

To keep receivers at least 1m from walls and stage front, a rectangular surface was created, at floor level, with edges moved 1m inward compared to walls/stage front. When setting up grid, this surface was selected, so no receivers were less then 1.0 from walls/stage front. This surface was made transparent in Odeon material properties, so had no influence on results.

2.4 Odeon 'room setup'

Odeon calculation parameters (Room Setup) were set as shown in Fig 4. *Number of rays* used in calculation was set to 50 000, even then minimum value, recommended based on room geometry complexity, was 1000. *Impulse response resolution* was set to 1ms and *angular absorption* set to 'all materials'. Several tests were made, with different settings, which showed, that artefacts visible in T_{30} and EDT grid response, created by transition from discrete early reflections to reverberation, are no longer visible, if above settings are used. Additionally, *transition order* was 2, *desired late reflection density* (in grid response) was set as 999999/ms. Temperature was set at 20°, relative humidity at 50%.

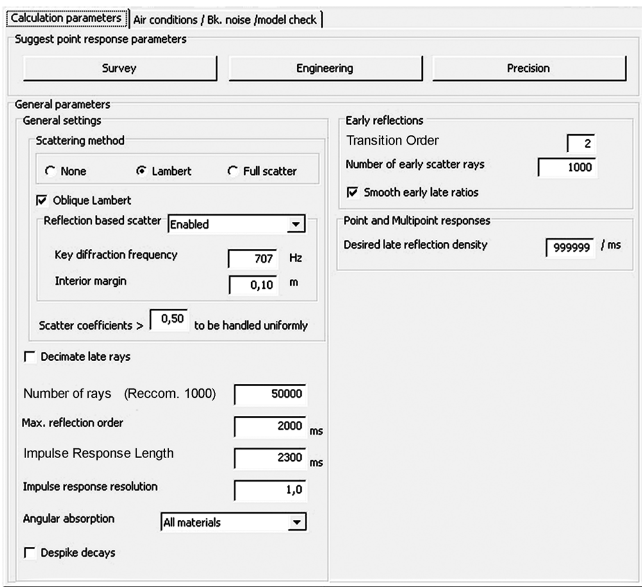

Fig.4 Odeon room setup for simulations.

3 Processing of results

3.1 Many measures

For each receiver, six objective parameters have been calculated by Odeon: Reverberation Time (T_{30}), Early Decay Time (EDT), Clarity (C_{80}), Strength (G), Early Lateral Energy Fraction (LF_{80}) and Late Lateral Strength (G_{LL}). Early and late level (G_E, G_L) were calculated manually based on Strength and Clarity results from Odeon according to the following equations:

$$G_E = G - 10 * \log(1 + \frac{1}{10^{\frac{C_{80}}{10}}}) \qquad (2)$$

$$G_L = G - 10 * \log(1 + 10^{\frac{C_{80}}{10}}) \qquad (3)$$

where ***G*** is Strength (total relative sound level), and ***C_{80}*** is Clarity (early to late sound index).

Additionally, for each receiver position a Source-Receiver distance (SR) was calculated manually, based on Pythagoras's theorem and source/receiver coordinates given by Odeon.

3.2 Many frequencies

Reverberation Time (T_{30}), Early Decay Time (EDT), Clarity (C_{80}), Strength (G), Early Lateral Energy Fraction (LF_{80}) and early and late level (G_E, G_L) were calculated in 6 octave bands (125~4000 Hz). Late Lateral Strength (G_{LL}) was given automatically by Odeon as single value, which was an average of 125~1000 Hz. To simplify the analysis and presentation of simulation results, they were averaged over individual frequency range, as recommended in [10]. Some parameters were averaged over more then one frequency range (like T_{30} or EDT). Details of averaging are shown in Table.2.

parameter	**mean of**
Reverberation Time T_{30}	500/1000 Hz 125/250/500/1000/2000 Hz
Early Decay Time EDT	500/1000 Hz 125/250/500/1000/2000 Hz
Clarity C_{80}	500/1000/2000 Hz
Strenght G	500/1000/2000 Hz
Eearly Lateral Energy Fraction LF_{80}	125/250/500/1000 Hz
Late Lateral Sound Level G_{LL}	125/250/500/1000 Hz

Table.2 Averaging of results by individual frequency ranges used in simulations [10].

3.3 Many positions

In all 24 models 13 645 receiver positioned were analyzed. In each position eight measures and the source-receiver distance were calculated. Most of measures were calculated in 6 octaves (125~4000Hz). The total number of single values, which needed to be evaluated, was a little more then 600 000! That would be hard to make without a computer and good processing tools.

3.4 Few processing tools

Processing of all results was done with just two programs: GAWK and PASTE. Both are free. GAWK [11], made under GNU public license, is the utility which interprets a special programming language that makes it possible to handle simple data-reformatting jobs with just a few lines of code. PASTE is just a command line tool for merging multiple text files.

Before using GAWK, several attempts were made to process the results with the use a combination of MS Word (for pre-processing of text files) and MS Excel (for averaging and calculation). Even then those attempts cannot be called “unsuccessful”, workflow with Word and Excel was not good enough in author’s opinion.

In preparation for using GAWK, in all Odeon models the function “*ASCII output all grid parameters*” was used. This function allowed Odeon to generate for each model a simple text file containing all the results for all receivers in grid (so called “*grid response*”). Before, Odeon was set up to export ASCII files separated with <*space*> character, and not with tabulator or comma, as that was required by GAWK. Text file with results was placed in the same folder where each model parametric file was located. Example of that text file is shown below:

results.txt

```
GRID RESPONSE ENERGY PARAMETERS for job 1
Grid receiver 1 at (x,y,z) = (-9,4, 1,8, 1,2)
PARAM 63 125 250 500 1000 2000 4000 8000
EDT 1,94 1,86 2,02 2,14 2,15 2,13 1,81 1,02
T30 1,99 1,91 2,14 2,24 2,20 2,10 1,70 0,96
SPL 7,0 6,6 6,8 6,5 5,6 5,5 4,7 2,0
C80 1,4 1,8 1,4 0,8 1,1 0,7 1,7 6,0
D50 0,42 0,45 0,44 0,43 0,45 0,44 0,49 0,69
Ts 112 104 114 123 118 120 96 44
LF80 0,251 0,247 0,260 0,247 0,216 0,199 0,193 0,176
SPL(A) 12,1
LG80* 4,5
STI 0,52
Grid receiver 2 at (x,y,z) = (-9,4, 2,8, 1,2)
PARAM 63 125 250 500 1000 2000 4000 8000
...
```

To use the presented above text file in GAWK, it was first necessary to remove brackets and extra commas from receiver coordinates. GAWK needed to have all values separated only by spaces, so the three receiver coordinates (x, y, z) should be just numbers. Additionally, to allow GAWK differentiate the “SPL” values from “SPL(A)” (both have the same first 3 letters), the later was preceded with “X” letter. Both modifications were done with simple GAWK program. If Odeon developers could consider slight change in original file structure, to eliminate that problem, that would be welcome.

The main processing of Odeon grid response text file was done with simple GAWK program:

program1

```
/receiver/ { print $3 > "receiver_number.txt" }
/x,y,z/ { a = $7 ; b = $8 + 3 ; c = sqrt (a^2 + b^2) ; z = $9 ;
d = (z - 2.2) ; sr = sqrt (c^2 + d^2) ; print sr >
"source_receiver_distance.txt" }
/x,y,z/ { x = $7 ; print x > "coordinate_x.txt" }
/x,y,z/ { y = $8 ; print y > "coordinate_y.txt" }
/T30/ { sum = $5 + $6 ; avg = sum / 2 ; print avg >
"t30_500-1khz.txt" }
/EDT/ { sum = $5 + $6 ; avg = sum / 2 ; print avg >
"edt_500-1khz.txt" }
...
```

This program (*program1*) seeks for particular text at the beginning of each line (like T30, EDT, …), and when found, makes necessary calculations on values from that line (like summing, averaging, computing SR distance, etc.) and finally saves the result into a separate text file (ie. t30_500-1khz.txt, edt_500-1khz.txt, etc). Symbols $1, $2, $3 … $n are references to 1st, 2nd, 3rd … nth segment in each line of Odeon grid response text file.

All files generated with GAWK had the same order of receiver positions, as in original Odeon grid response text file. That allowed to merge selected parameters (with PASTE command line tool) into one text file, with parameters in columns and receiver positions in rows. It was also used to merge results of one parameter from all simulated models into one file.

4 Analysis

Analyzing of the pre-processed data was done in OriginPro version 7.5 from OriginLab [12]. Text files with parameters were imported into OriginPro using *Multiple ASCII Import* option, which placed each imported text file into separate columns of single spreadsheet. Then spreadsheet was sorted, typically based on Source-Receiver distance. When required, rows with receivers located closer then 10m from source were selected and excluded from analysis with simple *Mask* function. All required statistical analysis were made from within the program, including linear and non-linear curve fitting.

5 Presentation of results

Large amount of data, which needed to be presented and intention to relate results of simulation to models geometry, required multiple ways of presentation. Five main types of graphs were used. Four of them were generated directly from the software used for analysis described earlier (OriginPro). In this paper, examples of graphs with results from simulation of Early Lateral Energy Fraction were used. LF is probably the most geometry-related acoustical parameter, which needs special graphical representation, so its behavior within the hall can be understood.

First type of graph was showing the room-averaged mean value of a parameter combined with +/- Standard Deviation and 1st, 5th, 95th and 99th percentile. Example of this graph is shown in Fig.1 for Early Lateral Energy Fraction ($LF_{80,\ 125\text{-}1kHz}$) calculated by Odeon (grid response) for all model in all volumes, for receiver positions with Source-Receiver distance greater then 10 meters. This type of graph was generated directly in OriginPro.

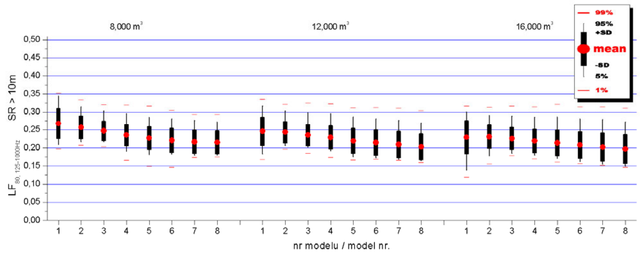

Fig.1 Comparison of room-averaged Early Lateral Energy Fraction $LF_{80,\ 125\sim1kHz}$ calculated by Odeon (grid response) in all analyzed volumes and models. Models N^{o} – see Fig.2.

Second type of graph was showing the histograms of a parameter. Example of this graph is shown in Fig.2 for Early Lateral Energy Fraction ($LF_{80,\ 125\text{-}1kHz}$) calculated by Odeon (grid response) for all model in all volumes, for receiver positions with Source-Receiver distance greater then 10 meters. This type of graph was generated directly in OriginPro.

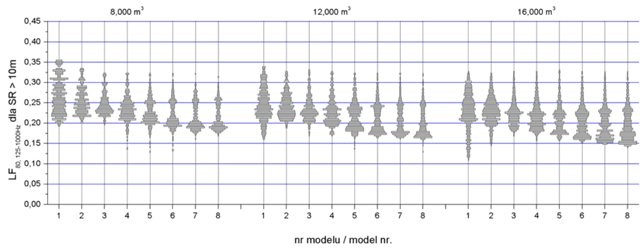

Fig.2 Histograms comparison of Early Lateral Energy Fraction $LF_{80,\ 125\sim1kHz}$, calculated by Odeon (grid response) in all analyzed volumes and models. Models N^{o} – see Fig.2.

Third type of graph was showing the distribution of a parameter within the audience area. Example of this graph is shown in Fig.3 for Early Lateral Energy Fraction ($LF_{80,\ 250Hz}$) calculated by Odeon (grid response) for model 5 in all volumes. This type of graph was created in Adobe Photoshop, by merging Odeon grid response with the plans of the models, drawn in Autodesk AutoCAD, and exported to Photoshop via Adobe Acrobat PDF Writer.

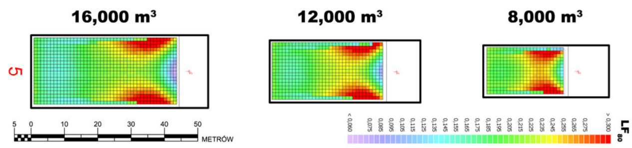

Fig.3 Comparison of distribution of Early Lateral Energy Fraction $LF_{80,\ 250Hz}$, calculated by Odeon (grid response) in model 5 in all volumes. Models N^{o}. – see Fig.2.

Fourth type of graph was showing the relation of a parameter from Source-Receiver distance. Example of this graph is shown in Fig.4 for Early Lateral Energy Fraction ($LF_{80,\ 125\text{-}1kHz}$) calculated by Odeon (grid response) for model 3, in all volumes. This type of graph was generated directly in OriginPro.

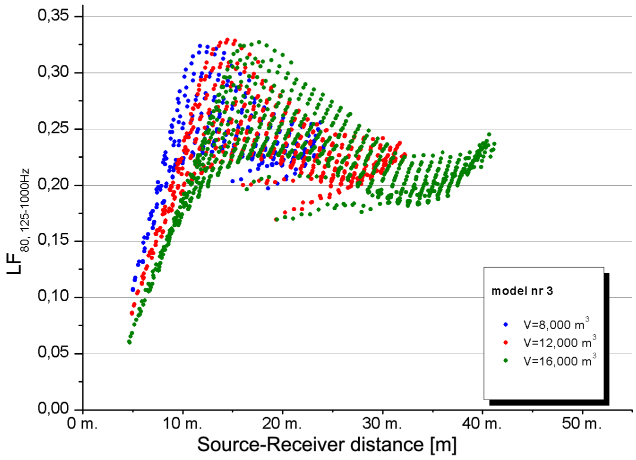

Fig.4 Relation of Early Lateral Energy Fraction $LF_{80,\ 125\sim1000Hz}$ from Source-Receiver distance, for model 3 in all analyzed volumes. Models N°. – see Fig.2.

Fifth type of graph was showing the 3-dimensional representation of distribution of a parameter within the audience area. Example of this graph is shown in Fig.5 for Early Lateral Energy Fraction ($LF_{80,\ 125\text{-}1kHz}$) calculated by Odeon (grid response) for model 3 in 12 000 m^3. This type of graph was generated directly in OriginPro based on receivers coordinates (x, y) and LF value.

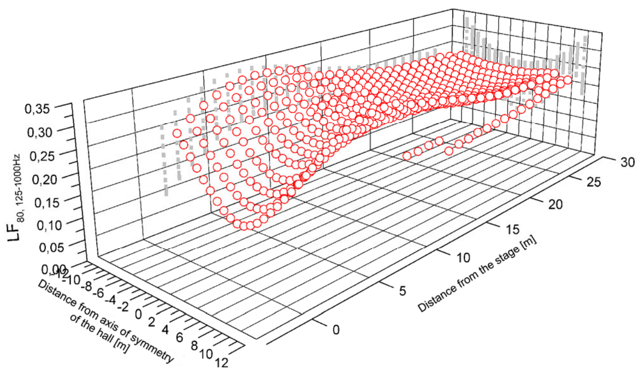

Fig.5 Typical "tongue-shape" distribution of Early Lateral Energy Fraction $LF_{80,\ 250Hz}$, in rectangular rooms (model 5, volume 12 000 m^3) Models N° – see Fig.2.

Those main five types of graphs were used to describe most of the behaviour of all analyzed parameters within simulated rectangular concert halls, and therefore can be recommended for use in similar types of research.

6 Conclusion

This paper presented in details the procedures used for modelling and simulation together with the methods for processing and presentation of results used in acoustical computer simulations of 24 models representing typical "shoe-box" type concert halls. Described procedures and methods can be easily incorporated and transferred into other research tasks.

Example of Early Lateral Energy Fraction, calculated in Odeon for analyzed models, was used to demonstrate the complexity of its "tongue-shape" distribution within the room, together with a group of graphs, which the author found useful to present this complexity. If only room-averaged values are used to describe behavior of such an acoustical parameter, a lot of information would be lost. It is then recommended to describe concert hall acoustics with more information, than just mean values. Examples of graphs showed in this paper, like histograms or 3-dimensional representation of parameter distribution within the hall could be used for that.

Acknowledgments

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