Relationship between room shape and Early Lateral Energy Fraction in rectangular concert halls

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Introduction

In recent years, computer simulation became a popular method to predict acoustics of rooms including that of concert halls [1, 2, 3]. This method is particularly valuable, when predicting the influence of changes in the hall geometry on it's sound field. Also, a large number of source and/or receiving position can be easily analyzed. Compared to scale model measurements, computer simulations are simple and easy. Compared to measurements in real halls, simulation is a 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 the risks - results from simulations can be realistic only, if the hall geometry, absorption, diffusion and also other factors in the computer model reflect that of real hall. The risk is even greater, because as for now, none of the commonly used programs takes care of wave effects like interference and diffraction. It is then recommended to compare results from simulation with real hall measurements, whenever possible.

In the 80's several researches [7, 8, 9] started making systematic measurements surveys in real concert halls, by measuring objective parameters specified in ISO 3382 standard. Results from those measurements, combined with halls geometrical data were used for creation of simple design/acoustic relationships [10, 11, 12]. Those relationships were presented as linear regression models, from which the acoustic effect of changes in certain design variables can be easily calculated.

This paper presents results from computer simulations of Early Lateral Energy Fraction (LF_{80}) made in 24 models representing rectangular concert halls [13]. LF_{80} is known to correlate well with perceived Apparent Source Width, one of the two spatial effect identified so far in concert halls [21]. In those simulations audience and stage area were 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 compares the hall-average results of LF_{80} from simulations with ones calculated for the same room geometry, but according to linear regression models discussed above. Other parameters from ISO 3382 like Clarity (C_{80}) and Strength (G) were discussed in paper [14].

Method

Simple models of concert halls, rectangular in plan, have been modelled in Odeon version 8. In those models only two variables were changed: volume (V) and length-to-width ratio (L/W). Three volumes were analyzed: 8 000 m^3, 12 000 m^3 and 16 000 m^3, each in eight length-to-width ratios (L/W=1.10; 1.43; 1.77; 2.10; 2.43; 2.77; 3.10; 3.43). Room plans for all 24 created models are shown in Fig 1.

All simulations were made with the following assumptions:

- for models in one volume floor area was constant;

- stage area was fixed at 190 m^2 in all models;

- audience area equalled floor area minus stage area;

- audience floor was horizontal in all models;

- stage height was 1.0 meter.

For all models, realistic figures of absorption and diffusion were used. Scattering coefficient of 0.65 was used for audience and stage area 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 [2]. Such a high value was chosen based on suggestion of positive correlation between preference and high level of diffusity of room boundaries [23]. This was also consulted with Odeon developers.

Room height for all models was 14 meters, which resulted in reverberation time of approx. 2.0 sec in all models.

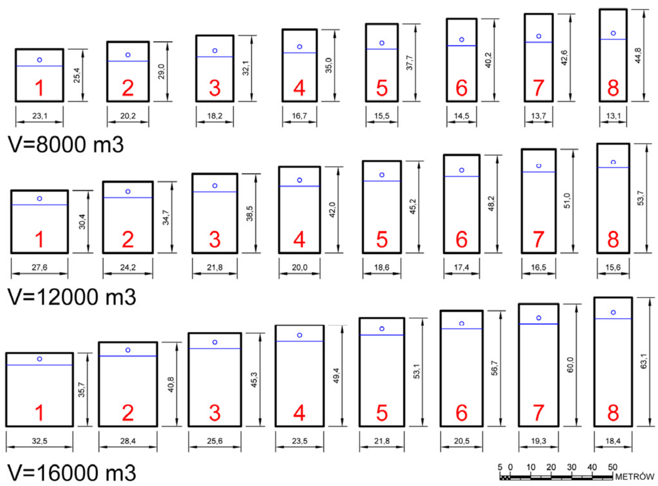

Figure 1: Room plans of all analyzed computer models.

Omnidirectional source was positioned centrally, 1.2 m. over stage, 3 m. away from stage front.

In each model a grid of receivers was created 1.2 m. over audience area, based on 1x1 meter grid. In total approx. 300 receivers were created in models with smallest volume, and approx. 850 in models with biggest volume. No receivers were less then 1.0 from walls/stage front.

Detailed description of simulation method is given in [22].

For all receiving positions in all 24 models, eight objective parameters have been calculated. Only Early Lateral Energy Fraction (LF_{80}) is discussed here.

Based on measurements in 53 concert halls simple relations between room geometry and objective acoustical parameters have been found [8, 9] and presented in the form of linear regression models. Regression model used in this paper for comparison with simulation results is shown in Table 1.

Room acoustical parameter	Regression model: F (theory, geometry)	Correlation coefficient	% of variance	STD residuals
Early Lateral Energy Fraction LF_{80}	0.39 – 0.0061 W	0.70	49%	0.05

Table 1: Linear regression model used in this paper for comparison with simulation, where: W – hall width.

Results

To simplify the presentation, results of LF_{80} reported here are the average of 125Hz, 250Hz, 500Hz and 1000Hz as recommended in [13]. For all results, only receivers positioned more than 10m from source are included, unless stated otherwise.

LF_{80} - room averaged values

Simulation results show, that in analyzed models room-averaged LF_{80} is between 0.20 to 0.27. In rooms with shape close to square (model 1), room-average LF_{80} is close to 0.25, and decrease to 0.20 with elongation of room. This is shown in Fig.2.

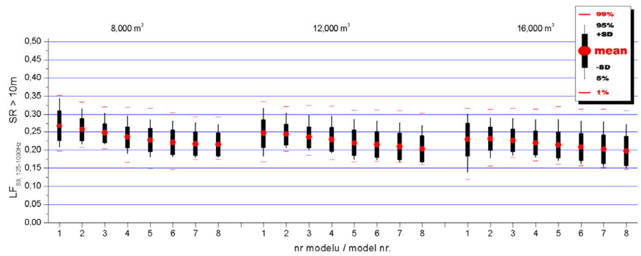

Figure 2: Comparison of room-averaged Early Lateral Energy Fraction $LF_{80,\ 125\sim1kHz}$ calculated by Odeon (grid response) in all analyzed volumes and models. Models n° - see Fig.1

Standard deviation is rather small in all models (0.03 ~0.04), compared to measurements in real halls [16], where SD is typically in range 0.05 to 0.10. This is due to lack of wave effects in computer simulations [17]. On the other hand within-hall variations of LF are huge, reaching 50% in some models. This makes traditional room-average values of little use, if they are not supplemented with additional information, like histograms or percentage of seats falling into particular range.

Comparison of simulation results and figures calculated based on LF regression model from Table 1 is shown in Fig.3. Additionally to linear regression from Table 1, in Fig.3 second regression was added, given in [17]. When simulation results are grouped by volume, it is clearly visible, that the relation between LF and room width is not as expected. Simulation results show LF increase with width, while both regression models predict the opposite!

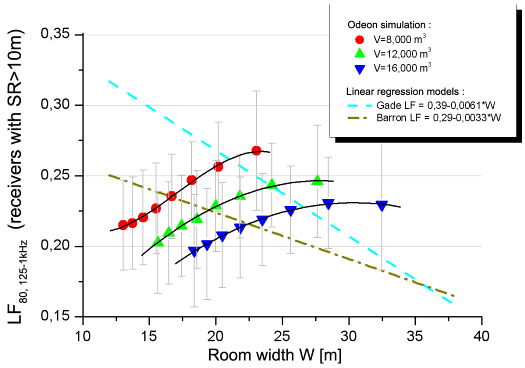

Figure 3: Relation between LF_{80} and room width shown for Odeon simulation and for two regression models (by Gade and Barron) grouped by models volume

Discrepancy between prediction and simulation results shown in Fig.3 was discussed in details in [18]. One possible explanation was, that width and length are both responsible for changes in magnitude of Early Lateral Energy Fraction in concert halls, as changes in height are known to have rather low influence on LF [19]. A different presentation of results from Fig.3 is shown in Fig.4.

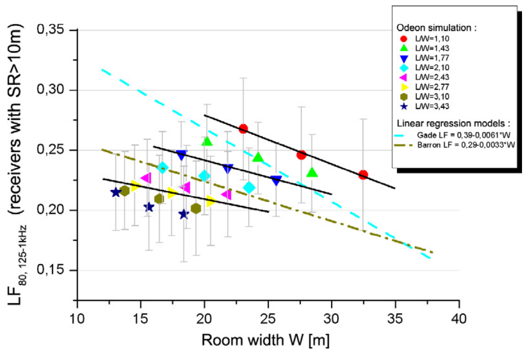

Figure 4: Relation between LF_{80} and room width shown for Odeon simulation and for two regression models (by Gade and Barron), grouped by models length-to-width ratio

This time results from simulation were grouped not by volume, but by length-to-width ratio of analyzed models. The decrease in LF with width is clearly visible now (marked in Fig.4 with three black lines representing best fit linear regression for L/W ratio of 1.1, 1.77 and 2.77), and its slope is similar to both linear regression models. But it is also clearly seen, that increase in width always lowers LF only in rooms with similar L/W ratio. It also explains why rooms with same width can have much different LF values, and also, why rooms with different width (like Amsterdam Concertgebouw and Vienna Gr. Musikvereinssaal) can have similar LF.

The relationship between room length-to-width ratio and LF_{80}, shown in Fig.4 can be presented in numerical form, as equation, having room width (W) and room length (L) as variables. It is shown below [13]:

$$LF_{80} = 0.22395 + 0.39148 * e^{\frac{-L}{W*1.03755}} - W * \left(0.00193 + 0.01081 * e^{\frac{-L}{W*0.6763}}\right) \quad (1)$$

where: W - room width in meters; L – room length in meters.

Equation (1), together with two linear regression models shown in Fig.4 were used to calculate expected values of LF_{80} in 16 existing rectangular concert halls with volume 4 000 ~ 20 000 m^3, where LF measurement data exist [10, 12, 20]. For each of three well known classical concert halls [16] both measured values, given in [20] were used. Differences between predicted and measured values were compared, and shown in Table.2 as mean prediction error.

prediction model	mean error	Std. Dev.
Eq.(1)	0,035	0,028
0.39-0.0061*W (Gade)	0,046	0,029
0.29-0.0033*W (Barron)	0,039	0,031

Table 2: Comparison of 3 prediction models expressed as mean error between predicted and measured values of $LF_{80, 125\text{-}1kHz}$ for 16 rectangular concert halls

Results from Table 2 shows, that mean error and standard deviation of eq.(1) are slightly smaller then in other prediction models, but the improvements is marginal, while eq.(1) is being much more complicated then other two. More test results from rectangular halls are required to test this relation further.

LF_{80} – distribution within the room

Histograms of simulation results for LF_{80} in all simulated models and volumes and all receiver positions are shown in Fig. 5. It should be noted, that none of the models has a normal distribution of LF_{80} values. It seems, that smaller and squarer models are characterized with highest LF_{80} values and most condensed distribution.

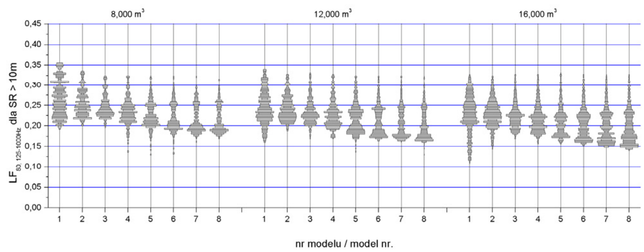

Figure 5: Histograms comparison of Early Lateral Energy Fraction $LF_{80,\ 125\sim1kHz}$, calculated by Odeon (grid response) in all analyzed volumes and models. Models n° see Fig.1.

When LF_{80} results are plotted against Source-Receiver (SR) distance (Fig. 7) one can see, that even the maximum values are similar in all volumes and the influence of direct energy is decreasing LF_{80} close to source, there are more receiver positions with lower LF_{80} values when SR distance is increased.

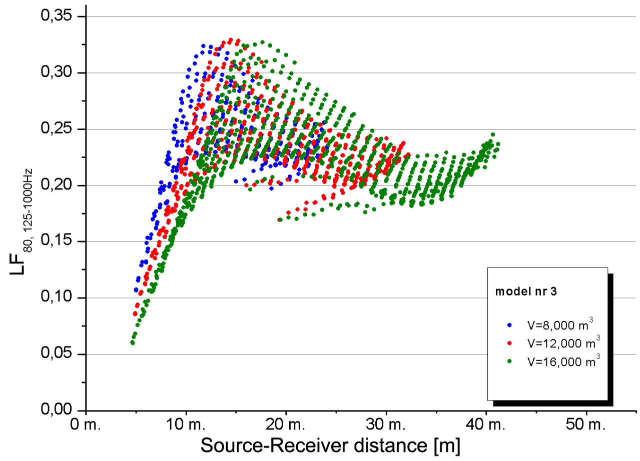

Figure 6: Relation of Early Lateral Energy Fraction $LF_{80,\ 125\sim1kHz}$ from Source-Receiver distance, for model 3 in all analyzed volumes (including receivers closer then 10m from source). Models n° – see Fig.1.

For better understanding of Early Lateral Energy Fraction distribution within the room LF_{80} values were presented in Fig.7 as grid responses drawn over floor plans. When Fig.7 is analysed together with Fig.6 one can see, that areas of biggest concentration of high values are located approx. at 1/2 to 1/3 of hall length close to side walls, while lowest values are located approx 10m from back wall across the hall width.

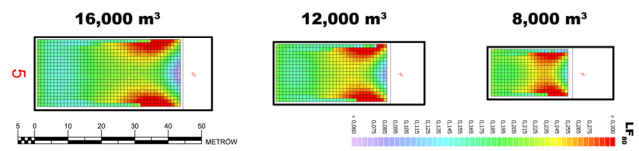

Figure 7: Comparison of distribution of Early Lateral Energy Fraction $LF_{80,\ 250Hz}$, calculated by Odeon (grid response) in model 5 in all volumes. Models n° – see Fig.1.

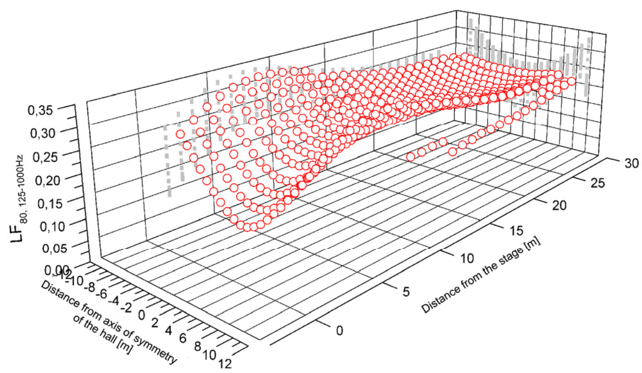

Figure 8: Typical "tongue-shape" distribution of Early Lateral Energy Fraction $LF_{80,\ 250Hz}$ in rectangular rooms (model 5, Volume 12,000 m^3). Models n° – see Fig.1.

Fig. 8 shows distribution of LF_{80} over the audience area, presented as 3-dimensional graph, with room width on X axis, room length on Y axis, and LF_{80} on Z axis. It's shape can be described as "tongue-shape" due to it's similarity to human tongue. All models in all volumes have similar shape as the one shown on Fig.8.

Conclusion

The results of this paper permit conclusion concerning strong influence of room shape on acoustics of "shoe-box" type concert halls. This paper confirm that in rectangular concert halls having identical volume and absorption/diffusion characteristic, room shape is an important factor influencing acoustics. Even with similar Reverberation Time in all rooms, acoustical parameters like Early Lateral Energy Fraction (LF_{80}) are sensitive to changes in room geometry.

The hall width only was found to be insufficient to describe the LF_{80} behaviour in simulated rooms. A formula for predicting of LF_{80} in rectangular halls has been proposed, which takes into the account both width and length of hall.

Results from simulation shows, that LF_{80} values vary greatly depending on receiver position. This information is lost, if only room-averaged values are used to describe the acoustic of particular concert hall. It is then recommended to describe concert hall acoustics with more information, than just mean values. 3-dimensional graphs, histograms, or just stating percentage of seats falling into particular range could be useful.

It was found, that the distribution of LF_{80} in rectangular rooms is similar in shape to human "tongue", with peaks on sides, lower values in centre and lowest close to source and back wall.

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