The design and implementation of room acoustics – the hall Filharmonie Hradec Králové, FHK

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Abstract: This article comprises the design of acoustic solution of the concert hall incl. orchestra enclosure (shell). The design was made using the newest knowledge of room and architectural acoustic, hereafter the simulation in the EASE program was applied. Impulse responses in selected listening positions were created by auralization process. Then, after installation of designed acoustic elements, measurements of objective criterions of the acoustical quality were taken. The measurement positions coincided with the selected listening positions in the EASE simulation. At the end the single value classification of hall acoustical quality was made.

1. Introduction

In this paper, the implementation of the concert hall of Filharmonie Hradec Králové (hereinafter only FHK) is described, from the initial design, through the own implementation up to the final acoustic measurement and confrontation with the assumed and achieved acoustic values determined on the basis of acoustic calculations. In the following three chapters, the acoustic design will be described, including designed acoustic elements and the orchestra shell, the own hall development and final acoustic measurements.

2. Hall acoustic design

During the hall acoustic design, we were limited by the maximum space volume, which is 6,782 m^3, including the mobile orchestra shell installed in the stage area. With respect to the expected number of visitors - 563, and the priority use for symphony music (permanent stage of the Hradec Králové philharmonic orchestra), the optimum reverberation time was determined, RT_{unocc} = 1.6 s. The determination of other acoustic parameters was based on values recommended in [1] and on acoustic simulations.

2.1. Determination of input parameters

In the acoustic design, acoustic parameters were taken into account that are indicated in Table 1 with the indication of the required values for a single valued classification of the acoustic quality of concert halls according to the methodology indicated in [1].

Apart from these values, acoustic parameters were also considered in Table 2, with the indication of the required values that were determined with the use of [2] and [3].

Table 1. Acoustic parameters for the evaluation according to [1]

	Optimum	Simulation	Measurement
RT_{mid} [s]	1,60	1,64	1,58
[1-$IACC_{E3}$] [-]	1,00	0,58	0,67
EDT_{mid} [s]	1,70	1,69	1,55
SDI [-]	1,00	-	0,70
G_{mid} [dB]	4,5 - 5,5	7,5	7,0
ITDG [ms]	12 - 18	-	18
BR [-]	1,40	1,48	1,44

Table 2. Further observed acoustic parameters

	Optimum	Simulation	Measurement
C_{80} [dB] $_{3\ oct.}$	1 ± 2	0,16	0,80
EK_{music} [-]	< 1,5	< 0,90	< 0,78
T_s [ms] $_{1\ kHz}$	70 až 150	115	108

All values of acoustic parameters are indicated for an empty hall. For the evaluation according to [1], reverberation time parameters, RT_{mid}, and the ratio of bass frequencies, BR, were recalculated to an occupied hall.

2.2. Acoustic simulation

For the own design of acoustic modifications, an acoustic model was used that was created in the EASE simulation program in 4.1.

The ray-tracing method of sound propagation was used in designing the reflection elements and shape of the orchestra shell. For the determination of the values of acoustic parameters with distribution in the reflection planes, Aura module version 2.1 of the Ease simulation program was used in 4.1.

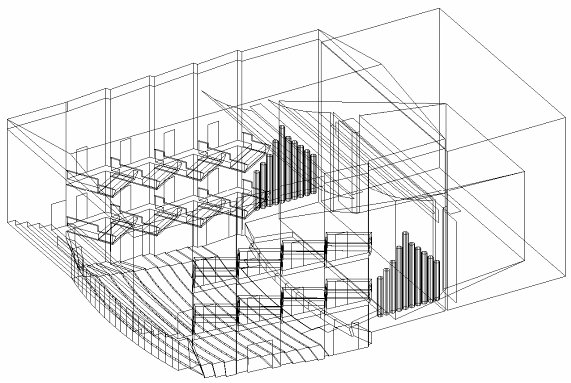

Figure 1. View at the 3D wire model of the FHK hall

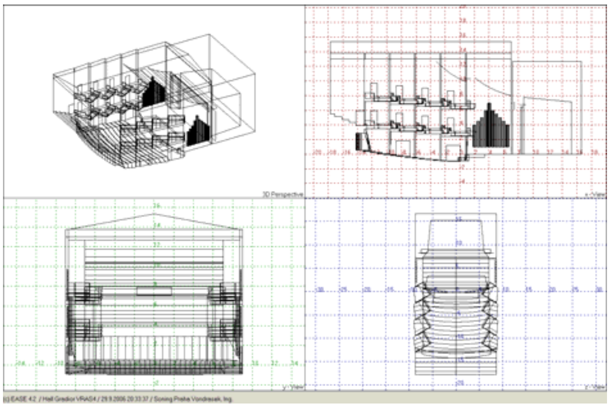

Figure 2. 3D projection of the FHK hall

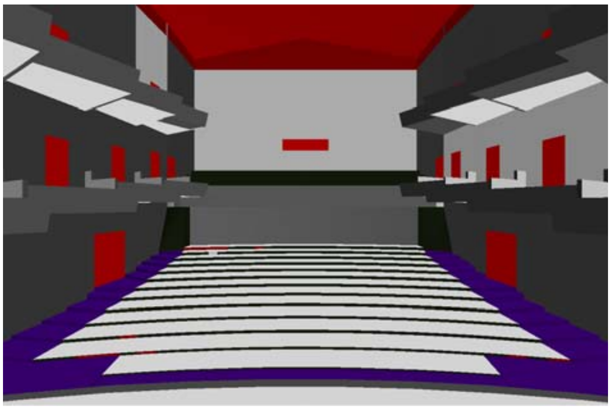

Figure 3. Visualization of the FHK hall space

Figure 4. View to the space of the FHK hall

View at the hall visualizations in comparison with the as made condition is in Figs. 2 to 5..

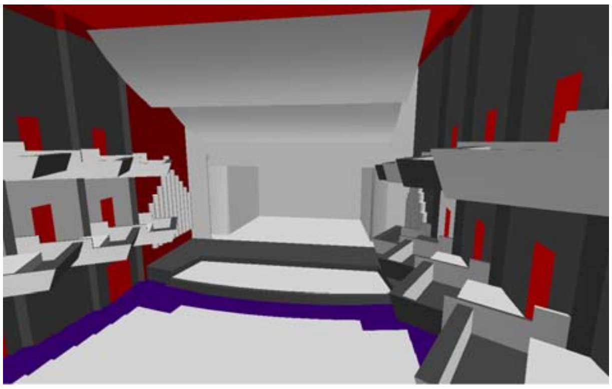

Figure 5. Visualization of the FHK stage space

Figure 6. View to the space of the FHK hall

Figure 7. View to the stage space occupied by the symphonic orchestra

In the preparation of the acoustic model, values of the coefficient of sound absorptivity of the applied materials were used from the database of the Ease program. Scattering values of the designed diffusion elements were obtained on the basis of relations in [8] with the use of the Matlab program.

2.3. Acoustic design of the perimeter walls

The audience assesses best such halls that exhibit the highest possible values of *BQI* (Binaural Quality Index). For this reason, diffuse scattering elements were used in the acoustic design of the hall walls that are supposed to ensure the highest possible *BQI* values. These elements were used in three different modifications that are based on the purpose of use of a given element. The rear wall of the hall is formed by the QRD diffusers that were designed with prime numbers N = 5 and 7. These elements were alternated on the basis of a sequence of the generated MLS signal of order N = 4 of length L = 15. This arrangement guarantees substantially more uniform sound signal scattering than the QRD elements of the same order N repeating in a line.

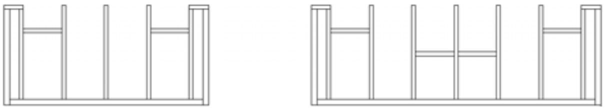

Figure 8. Cross section through the NQRD elements installed on the rear wall and the main balcony parapet

The following relations were used during the calculation of the QRD elements for N = 5 and 7

$$w = \frac{c_0}{2 \cdot f_{\min}} \quad [mm] \tag{1}$$

where c is the speed of sound in air, $f_{\min}$ the upper limit frequency of the diffuser function and w is the width of the individual shaft. The quadratic residue of sequence s_n is given by the following relation

$$s_n = n^2 \cdot \text{mod}\, N \tag{2}$$

where N is the sequence order. For example, for one period of the QRD diffuser with N = 7, the sequence is s_n = {0, 1, 4, 2, 2, 4, 1}. The maximum shaft depth is given by the relation

$$d_n = \frac{s_n \cdot c_0}{2 \cdot N \cdot f_0} \quad [mm] \tag{3}$$

f_0 is the lower limit frequency for which the diffuser is designed, which can be described by the following relation obtained by a modification of (3)

$$f_0 = \frac{s_{\max}}{N} \cdot \frac{c_0}{2 \cdot d_{\max}} \quad [Hz] \tag{4}$$

where $s_{\max}$ is the maximum value in sequence s_n. For N = 7, the value of the ratio is $s_{\max}/N$ = 4/7. The correct function of the QRD diffuser is ensured, if the following inequality is satisfied

$$N >> \frac{c_0}{2 \cdot w \cdot f_0} \quad [-] \tag{5}$$

The side walls of the hall are modified acoustically by the MLS diffusers that are determined on the basis of the MLD sequence of order N = 5 of length L = 31. The depth and width of the elements is determined by using relations (1) and (3), where s_n = 1, because the MLS sequence is formed by values 0 and 1. The cross section through the designed structure is shown in the following figure.

Figure 9. Cross section through the MLS structure of the side walls

The reflection-scattering elements placed on the parapets of the side balconies are designed to meet the following two functions. They should ensure the diffusion scattering of frequencies from 8 kHz to17 kHz. For the order of sequence N = 11, s_n = {0, 1, 4, 9, 5, 3, 3, 5, 9, 4, 1}. For frequencies below the diffusion scattering, they should ensure uniform routing of sound beams into the listening areas in the hall. This is ensured by the designed inclination of 5°. The view of the cross section through the designed structure is in the following figure.

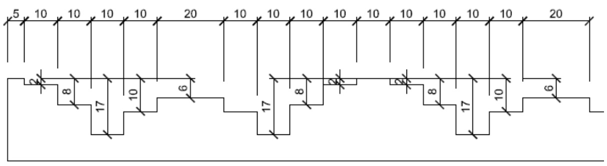

Figure 10. Cross section through the PQRD structure installed on the parapets of the side balconies with an inclination of 5°

All the elements used are made of wood and provided with a special coat complying with the fire safety regulations (flame spread along the surface).

2.4. Podium

There is no general guideline for achieving the optimum values of all the individual criteria of acoustic quality. However, the following conclusions can be deduced from the parameters of the highly assessed halls.

a) The audibility of the own instrument, audibility of other instrument groups, sound colour and space perception are the most important parameters for the podium area. The conductor and soloists have some other requirements with respect to the orchestra.

b) The podium measures and the highly diffuse structure of the ceiling help significantly to mutual audibility and concert. In general, the smooth perimeter walls received worse assessment ("**glare**").

For the podium area, objective criteria *SUPPORT*, *EDT* and *EDTF* correspond to individual subjective attributes; they are defined in the following manner (Gade, 1989):

$$ST1 = 10\log \frac{\int_{20\,ms}^{100\,ms} p^2(t)dt}{\int_{0\,ms}^{10\,ms} p^2(t)dt} \quad [dB] \qquad (6)$$

where $p(t)$ is the hall impulse response

$$ST2 = 10\log \frac{\int_{20\,ms}^{200\,ms} p^2(t)dt}{\int_{0\,ms}^{10\,ms} p^2(t)dt} \quad [dB] \qquad (7)$$

or

$$ST_{late} = 10\log \frac{\int_{20\,ms}^{\infty} p^2(t)dt}{\int_{0\,ms}^{10\,ms} p^2(t)dt} \quad [dB] \qquad (8)$$

The acoustic stage support, *ST*, is defined as the ratio of energies in the following intervals (in milliseconds): {20,100}, {20,200} and {20,∞} with respect to the initial energy in interval {0,10}, expressed on a logarithmic scale. It is determined from the square of the time course of the acoustic pressure of the impulse response, $p^2(t)$, of monoauraul response $p(t)$ (hereinafter only IO), taken by omnidirectional microphone at a distance of 1 m from an omnidirectional source.

Support *ST1* corresponds to the subjective feeling how a musician perceives his/her instrument with respect to other instruments; the soloists' judgmenents correlate better with the *ST2* criterion. ST_{late} is one of the factors of the **reverberance** category and **dynamics.** The second factor is the initial reverberation time, *EDT*, determined from the same impulse responses. The values of criteria are determined as an average of the 250, 500, 1000 and 2000 Hz octave bands.

The *EDTF* criterion is a good measure of the subjective attribute **timbre.** This attribute is related to the feeling how space effects the instrument colour, balance of individual instrument sections and individual instruments in the whole. *EDTF* is defined by the relation

$$EDTF = \frac{EDT_{250} + EDT_{500}}{EDT_{1000} + EDT_{2000}}. \qquad (9)$$

Intimacy (Beranek, 1962) is an important subjective podium attribute. Musicians prefer an intimate environment, they feel better in it and individual instrument groups hear better each other. This undoubtedly has an effect on their performance and concert. The shell dimensions are an objective correlator of intimacy. The shell layout should be within the 19x13 m rectangle. If some dimension exceeds these limits, the medium shell height should be in a range of 9.5 ± 1.5 m.

2.5. Continuation of the podium toward the hall, orchestra shell

The podium, frequently equipped with a concert shell (also dismountable), must help radiate the acoustic energy into the hall by its shape. A sufficient number of initial reflections must be directed to the hall. This can be achieved by the shape design – inclination of the ceiling and trapezoidal layout.

If the opening is small, not only insufficient energy streams into the hall, but multiple reflections also occur between the pairs of almost parallel walls leading to standing wave motion. On the podium, this is perceived by many musicians as an uneven performance of their own instrument and unclear, illegible acoustic reception of the instruments of their mates.

Standing wave motion almost always occurs in case of parallel side walls or horizontal ceilings. In general, musicians value standing wave motion in a very negative manner.

According to Shinichirochan, the shell opening can be characterized by the inclination index *K* defined as

$$K = \frac{\sqrt{\frac{W.H}{\pi}} - \sqrt{\frac{w.h}{\pi}}}{D} \qquad (10)$$

where *W* and *H* is the forestage width and height, *w* and *h* is the width and height of the rear wall and *D* is the shell depth. By a synthesis of the responses of the musicians of the Boston Symphony Orchestra, Das Gewandhaus Orchestra

Leipzig and the New Japan Philharmonic during a tournament through 30 Japanese cities, the author arrived at the following unanimous conclusions:

1) The podium must not be small – for a good symphonic orchestra transmission, it must have at least 1000 m^3.
2) The inclination index must be $K \leq 0.3$.
3) If the scattering properties of the inner limiting walls are distinct, the resulting musicians' impression does not depend so much on the inclination index *K*.

The criteria for the assessment of the podium – hall relation are based on the consideration that the sound of individual instrument groups should be blended and the overall musical expression should be created earlier on the podium than in the hall (Jordan, 1982). For this reason, the average values of the initial reverberation time must be higher in the hall than on the podium. On the contrary, the time clarity must be higher on the podium. The relations can be quantified by means of inverse indices *II*, defined, for example, as

$$II_{EDT} = \frac{Avg(EDT)_{audience\ area}}{Avg(EDT)_{stage}} \qquad (11)$$

or

$$II_{C80} = \frac{Avg(C80)_{stage}}{Avg(C80)_{audience\ area}}. \qquad (12)$$

If the acoustic conditions are to be evaluated as good, the inverse indices must meet condition $II \geq 1$, where the optimum values for the hall are *EDT* in a range of 2 – 2.3 s and C_{80} in a range of 0 ± 1.6 to 2 dB.

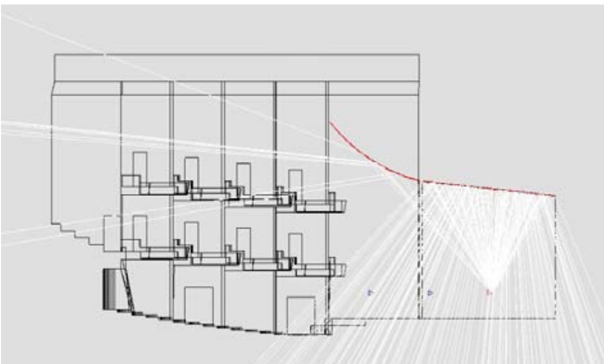

Figure 11. Visualization of the FHK hall space

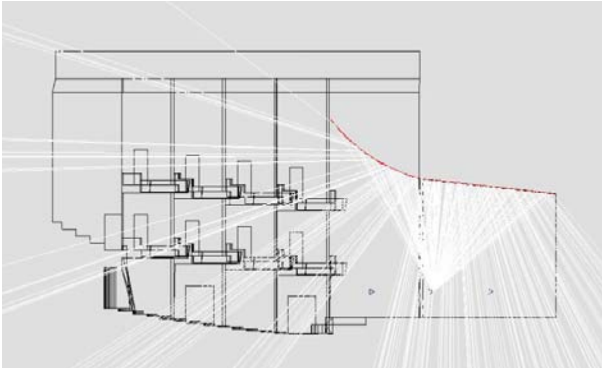

Figure 12. Visualization of the FHK hall space

The ray-tracing method used in the design of the orchestra shell in the hall space of Filharmonie Hradec Králové is illustrated in Figs. 7 to 9. With the help of these simulations, the amount of the sound energy in the shell was determined in relation to the sound energy in the hall area (ensuring such sound volumes in the shell for musicians to play under their common hearing conditions and the *G* – Strength values are at optimum values in the hall). The design of the shape of the reflection plane above the stage space also was part of these simulations. This plane was made of wood with shapes that are obvious from the achieved results. The implemented structure was sufficiently rigid to avoid its vibration.

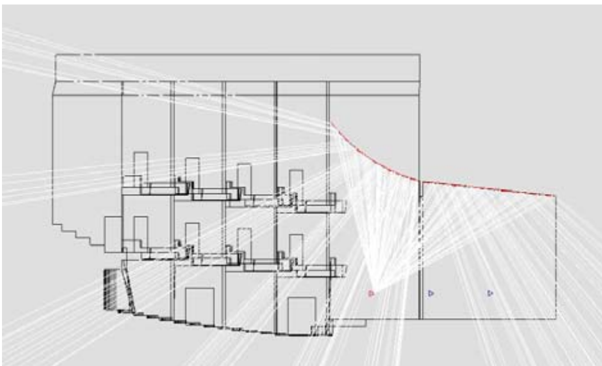

Figure 13. Visualization of the FHK hall space

The acoustic design of the rear and side shell walls is based on the diffusion structure determined by the generated MLS sequence of order N = 5 of length L = 31, where the depth and width of the defined block, which is represented as "1" in the MLS sequence, is calculated according to relation (1) and (3).

View at the design of the structures of the rear and side walls of the orchestra shell.

Figure 14. Cross section through the orchestra shell structure

The greatest demands were laid on the ceiling of the orchestra shell, not only from the point of view of acoustic properties, but also from the point of view of its technical implementation (mobility, ensuring the required inclination, etc.).

Beranek [1] indicates that the surface mass of the shell ceiling should be at least 17 kg/m^2 (weight of panel deck ceiling is 26 kg/m^2) in order to prevent vibrations that might be caused by the orchestra sound. In the design of the scattering structures, a combination of the MLS structures was used that were set in cassettes always turned by 90^0 to one another. The final arrangement is obvious from the following figure.

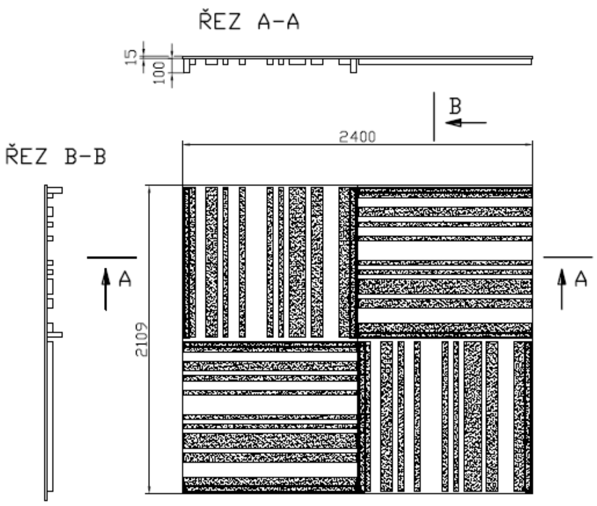

Figure 15. View at the design of the diffuse structure of the orchestra shell ceiling

The structure created in this manner should have sufficient diffusion capacity and thus ensure the required hearing conditions for the orchestra.

The entire concert shell is designed and constructed as a mobile structure, i.e. the ceiling consists of three parts that are suspended on stage lines. The rear wall is split to individual planes; each plane can be turned around its axis and then the black rear flat plane can be used. The side walls are set up of individual parts that can be turned around their axes; the parts can move along defined routes formed by embedded guide rails.

2.6. Results obtained by acoustic simulation

Acoustical characteristics calculations were done both along whole listeners' area fig. 16, 18 and at measured listening positions. Each observed parameter is complemented with value distribution corresponding to surface distribution according to fig. 17, 19.

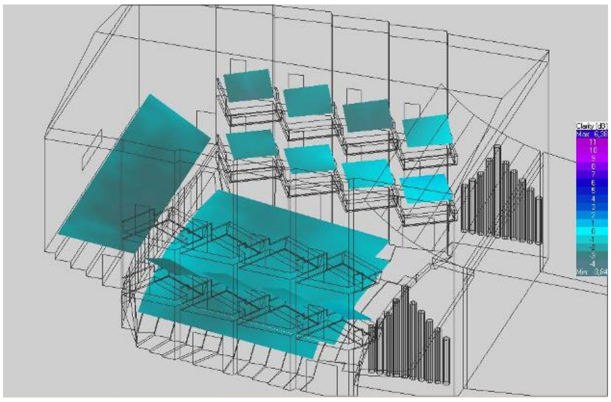

Figure 16. Clarity C_{80} distribution

C_{80} parametr values are within interval -1 ± 2, when worst places are on first balconies.

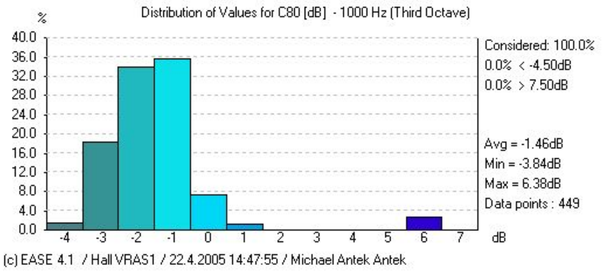

Figure 17. Distribution of Value for C_{80}

Distribution of simulated Total SPL are within interval 95 ± 2 dB that shows uniformly distributed volume level along listening area.

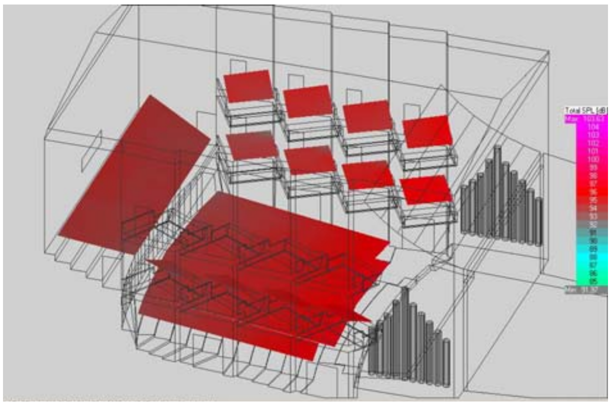

Figure 18. Distribution of the acoustic pressure levels

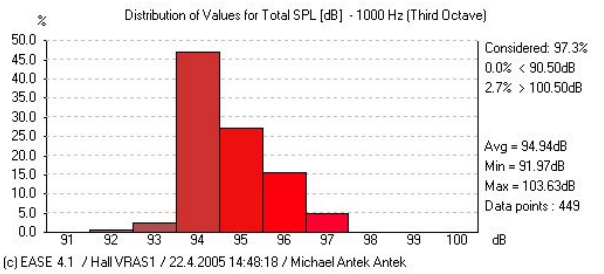

Figure 19. Distribution of Value Total SPL

3. Hall development

The own implementation began after the designed acoustic modifications, preparation of the project and production documentation. Views at the implementation of the own assembly and the details of installed acoustic elements are in the following figures.

Figure 20. Assembly of the QRD diffusers on the rear wall

Anchoring to the hall reinforced walls was greatly emphasized during the installation of all the elements. The elements were bolted and possible unevenness filled with foam to ensure rigid connection to the wall. This measure should prevent possible vibrations or oscillations.

Figure 21. View at the side wall with the MLS structure

All the acoustic elements installed in the hall space are made of wood with the surface modification which meets the requirements for spread of flame index on surface up to 55 mm/min.

Figure 22. View at the dispersed structures on the side balconies

Seats installed in the FHK hall are provided with seat bolsters and back squabs. The rear side of the backrest and the bottom side of the seat are formed by a wooden board with surface modification by coating.

Figure 23. View at the interior acoustic design, detail of the position of the reflective and scattering structures on the side balconies

4. Acoustic measurements

The final acoustic measurements were carried out after completion of the hall interiors. Measurements were carried out in accordance with EN ISO 3382, with the dislocation of the positions of the transmitter – omnidirectional source and receiver – measuring microphone with spherical characteristics for the diffusion field according to the methodology indicated in [7]. The measuring microphone was positioned at a height of 1.2 m, which is the average height of the middle of the ear of a seated listener; the omnidirectional source was positioned at a height of 1.5 m. The measuring positions are indicated in the following figure.

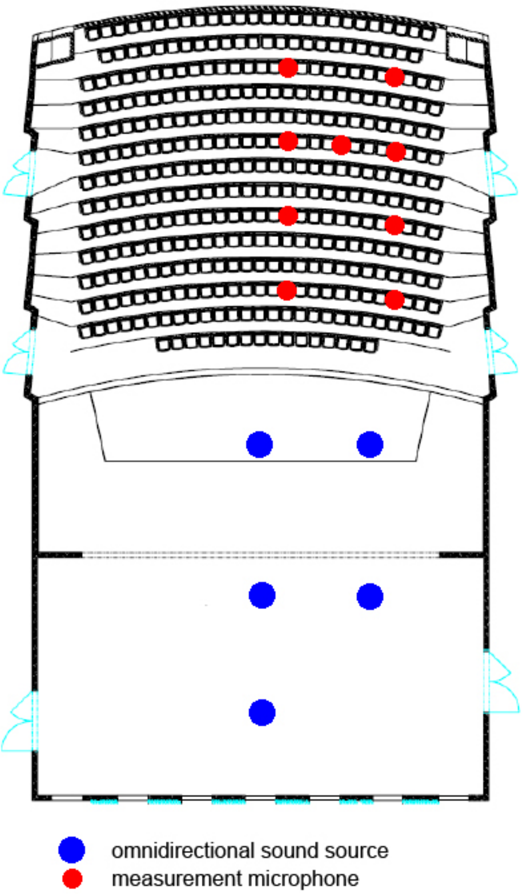

Figure 24. Position of measurement in the hall FHK

4.1. Results of measurements

All measured impulse response have parameter value *INR* - Impulse response to noise ratio in the all three octave bands up to 50 dB, always value parametr *cc* - correlation coefficient comply with requirements ISO 3382. Reverberation time - *T*30 behaviour in three octave bands is illustrated in Figs. 25.

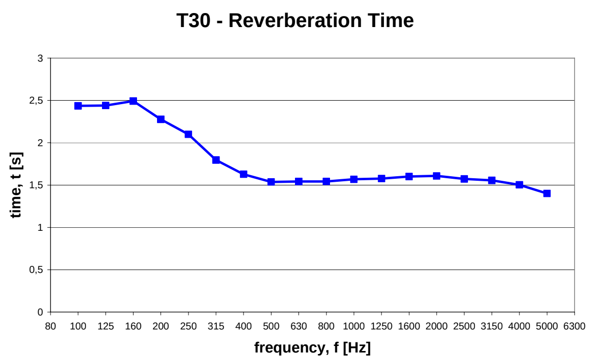

Figure 25. Measured reverberation time

All measurement parameter - *EDT*, *T*10, *T*20, *T*30, *T*s, *C*80, *G* and *IACC* with a single valued classification the are indicated in the tables and also in the graphs appendix.

5. Evaluation

This article deal with complex design description of hall of "Filharmonie Hradec Králové". Acoustical measurement results and contemporary subjective tests indicates very good acoustical parameters of the hall which are valued as B+ on the subjective scale.

Acknowledgement

This work has been solve together with project No. 1M6138498401, which is supported The Ministry of Education, Youth and Sports. I also wish to thank Ing. Michal Antek for his expert help during the implementation of the acoustic design of the FHK modifications and last but not least, RNDr. Vaclav Derner, the FHK director for his helpful and cooperative approach during the design, implementation and acoustic measure-ments.

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Appendix

	(Full Octave)					
f [Hz]	125	250	500	1000	2000	4000
EDT [s]	2,49	2,12	1,56	1,55	1,58	1,47

	Average 500 Hz a 1000 Hz
EDT_{mid} [s]	1,55

	(Third Octave)																	
f [Hz]	100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000
EDT [s]	2,24	2,56	2,59	2,27	2,17	1,72	1,61	1,60	1,48	1,49	1,56	1,61	1,60	1,59	1,55	1,58	1,48	1,35

	(Full Octave)					
f [Hz]	125	250	500	1000	2000	4000
T10 [s]	2,42	2,12	1,62	1,57	1,59	1,49

	(Third Octave)																	
f [Hz]	100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000
T10 [s]	2,41	2,43	2,47	2,26	2,12	1,82	1,72	1,61	1,58	1,56	1,62	1,57	1,61	1,61	1,59	1,54	1,50	1,40

	(Full Octave)					
f [Hz]	125	250	500	1000	2000	4000
T20 [s]	2,44	2,13	1,59	1,57	1,58	1,49

	(Third Octave)																	
f [Hz]	100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000
T20 [s]	2,40	2,40	2,48	2,26	2,07	1,78	1,66	1,56	1,55	1,55	1,59	1,58	1,61	1,60	1,57	1,55	1,50	1,39

	(Full Octave)					
f [Hz]	125	250	500	1000	2000	4000
T30 [s]	2,46	2,15	1,59	1,57	1,59	1,49

	Average 500 Hz a 1000 Hz
$T30_{mid}$ [s]	1,58

	(Third Octave)																	
f [Hz]	100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000
T30 [s]	2,44	2,44	2,49	2,28	2,10	1,80	1,63	1,54	1,54	1,54	1,57	1,58	1,60	1,61	1,57	1,56	1,50	1,40

	(Full Octave)					
f [Hz]	125	250	500	1000	2000	4000
Ts [s]	192	159	111	102	110	102

	(Third Octave)																	
f [Hz]	100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000
Ts [s]	182	215	218	195	170	129	120	119	106	100	102	108	111	113	110	112	104	94

	(Full Octave)					
f [Hz]	125	250	500	1000	2000	4000
C80 [s]	-3,0	-1,9	0,5	1,3	0,6	1,0

	(Third Octave)																	
f [Hz]	100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000
C80 [s]	-0,9	-3,2	-4,1	-3,4	-2,5	0,2	0,3	0,0	1,2	1,7	1,4	0,8	0,7	0,4	0,6	0,4	0,9	1,5

	(Full Octave)					
f [Hz]	125	250	500	1000	2000	4000
G [dB]	9,6	8,4	6,9	7,2	7,0	6,9

	Average 500 Hz a 1000 Hz
G_{mid} [dB]	7,0

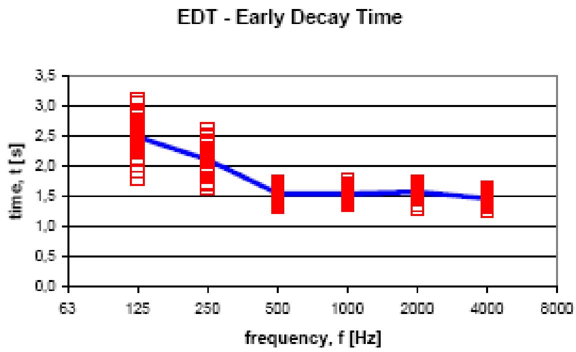
	(Full Octave)					
f [Hz]	125	250	500	1000	2000	4000
IACC 0,80 [-]	0,94	0,79	0,37	0,29	0,32	0,31

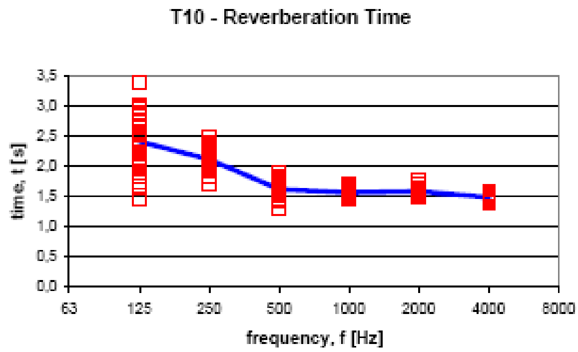
	Average 500 Hz až 2000 Hz
$IACC_{E3}$ [-]	0,33

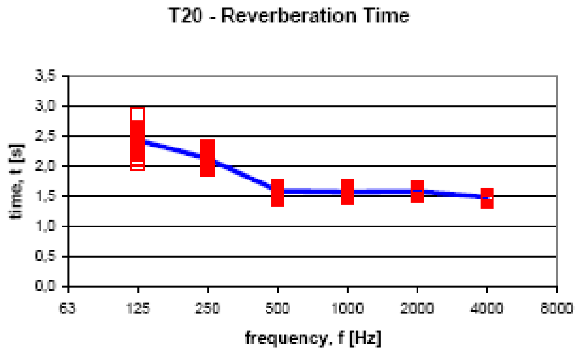
ITDG [ms]	17

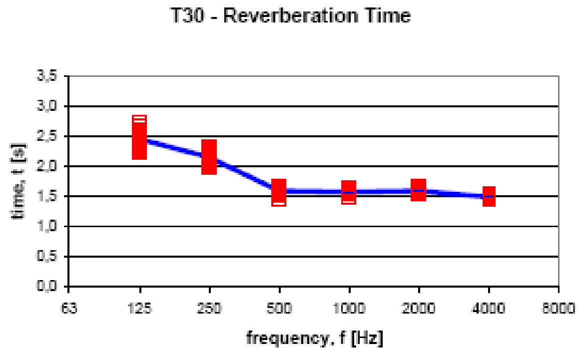
SDI [-]	0,7

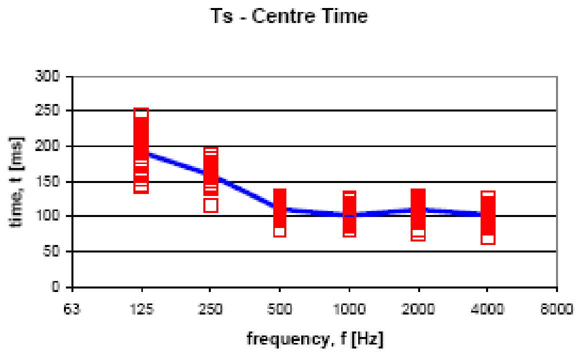
BR [-]	1,44

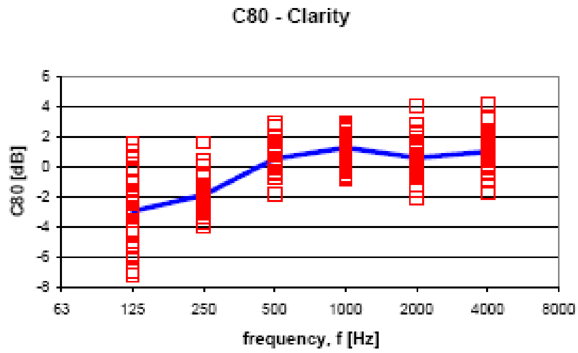

EDT - Early Decay Time
time, t [s]
3,5
3,0
2,5
2,0
1,5
1,0
0,5
0,0
63
125
250
500
1000
2000
4000
8000
frequency, f [Hz]

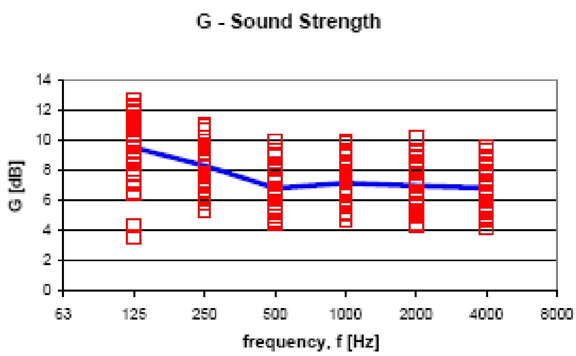

T10 - Reverberation Time
time, t [s]
3,5
3,0
2,5
2,0
1,5
1,0
0,5
0,0
63
125
250
500
1000
2000
4000
8000
frequency, f [Hz]

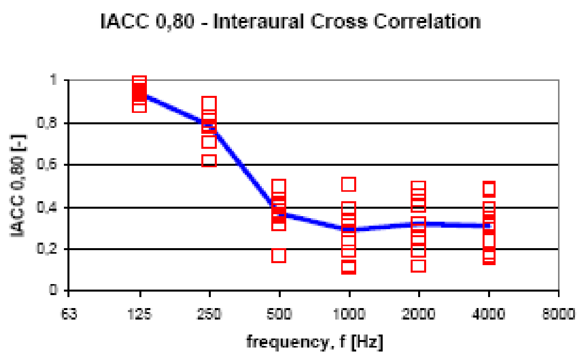

T20 - Reverberation Time
time, t [s]
3,5
3,0
2,5
2,0
1,5
1,0
0,5
0,0
63
125
250
500
1000
2000
4000
8000
frequency, f [Hz]


T30 - Reverberation Time
time, t [s]
3,5
3,0
2,5
2,0
1,5
1,0
0,5
0,0
63
125
250
500
1000
2000
4000
8000
frequency, f [Hz]


Ts - Centre Time
time, t [ms]
300
250
200
150
100
50
0
63
125
250
500
1000
2000
4000
8000
frequency, f [Hz]


C80 - Clarity
C80 [dB]
6
4
2
0
-2
-4
-6
-8
63
125
250
500
1000
2000
4000
8000
frequency, f [Hz]


G - Sound Strength
G [dB]
14
12
10
8
6
4
2
0
63
125
250
500
1000
2000
4000
8000
frequency, f [Hz]


IACC 0,80 - Interaural Cross Correlation
IACC 0,80 [-]
1
0,8
0,6
0,4
0,2
0
63
125
250
500
1000
2000
4000
8000
frequency, f [Hz]