International Symposium on Room Acoustics
Satellite Symposium of the 19th International Congress on Acoustics
Seville, 10-12 September 2007

VARIABLE ACOUSTICS OF THEATRE “DE SPIEGEL” IN ZWOLLE (NL)

PACS: 43.55.Cs-Mc

Luykx, Maarten[1]; Metkemeijer, Rob[2], Vercammen, Martijn[1]
[1]Peutz Consult, Mook, the Netherlands; m.luykx@mook.peutz.nl
[2] Peutz Consult, Zoetermeer, the Netherlands; r.metkemeijer@zoetermeer.peutz.nl

ABSTRACT
In 2006 the new theatre in Zwolle (NL) has been completed which can be considered as a next step in variable acoustics. The hall is not only suitable for intimate plays (850 seats) but also for opera and symphonic concerts (1000 seats), in all situations with natural acoustics. The variable acoustics necessary are obtained by altering the very compact volume of the theatre (about 4100 m^3) into about 11000 m^3 for symphonic music. Using 370 m² of movable ceilings an additional volume of about 4100 m^3 above the hall is realised using an 7m high gallery. Additionally, an orchestra shell of 2800 m^3 can be applied. A 1:12 scale model has been used in the design phase to verify the acoustic behaviour. Reactions of listeners and critics are very positive (“Masterpiece of variability”). The acoustics of the real hall have been measured in May 2007, revealing interesting properties. RT values are 0.9 s for theatre up to 2.1 s for symphonic music. Average $C_{80}(3)$ values range from 0 dB for concert use, 4 dB for opera up to 7 dB for theatre. The hall combines the sightlines of a theatre and its intelligibility with the reverberation of a concert hall, making it an excellent opera house as well.

Introduction and brief
In june 2006 a new theatre in Zwolle (NL) has been completed. For its design challenging demands were set in the brief. It had to be suitable for theatre, opera, ballet, musical, and symphonic music, in all situations with natural variable acoustics. In an early stage, Peutz became involved as acoustic advisor with the description of the main acoustics properties, including the main dimensions, in order to stringently guide the architectural design and to guarantee the final result. Amongst these requirements were demands for the number of seats (850-1000), for the acoustic volume (<4800 up to >12000 m^3), for RT values of the hall (0.9–2.0 s) and the stage tower, for the loudness or gain (G=5 dB concert), speech intelligibility, values of C80(3), LEF and ST, viewing distances (<25 m for theatre, <35 m for opera/concert) and for the basic dimensions for the room (<23 x 20 x 12 m (dxwxh) and for the stage opening (18 x 14 m (wxh)).

Design
The idea of Peutz, based on experience with the Royal Albert Hall, was to combine these different requirements by starting with a very compact acoustic volume for the 850 seat theatre situation (max. ca. 4800 m^3) and to add additional acoustic volumes to it, formed by a 4000 m^3 gallery above and around the hall and a 3300 m^3 orchestra shell on stage. Besides additional reverberation for opera and symphonic music the gallery should at the same time supply 150 additional seats to sum up to a total of 1000 seats for opera, symphonic concerts and musical. Application of ca. 400 m² acoustic curtains on the gallery level should be effective as variable absorption to reduce the reverberation of the gallery for musical use. By using large moving ceilings it should be possible to close off the gallery volume from the hall and make the hall’s acoustic volume as small as possible, as required for theatre situation, where sufficient loudness for natural speech of actors and a good speech intelligibility are the key demands.

Scale Model
Using a 1:12 scale model, acoustic studies have been performed during the design phase regarding the variable acoustics, sound distribution and echo-reduction, including subjective evaluations through auralisation [1]. The results were used to design the diffusive wall and ceiling elements.

Description of the theatre: sizes and volumes
The theatre has different settings for symphonic music (concerts), opera, musical and theatre. In figure 1 to 4 the maximum variation of more than 250% in acoustic volume (indicated by red area) is illustrated in the plan and cross sections of the theatre situation and the concert situation.

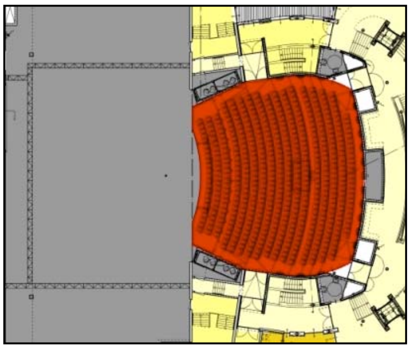

Figure 1.- Plan theatre mode (ground floor)

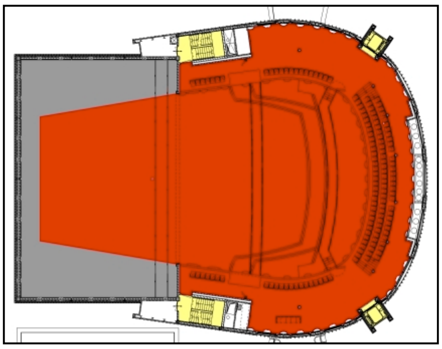

Figure 2.- Plan concert mode (gallery level)

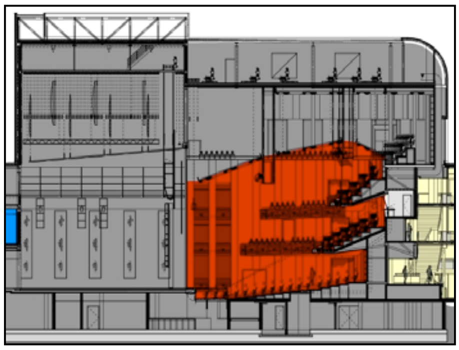

Figure 3.- Longitudinal section theatre mode

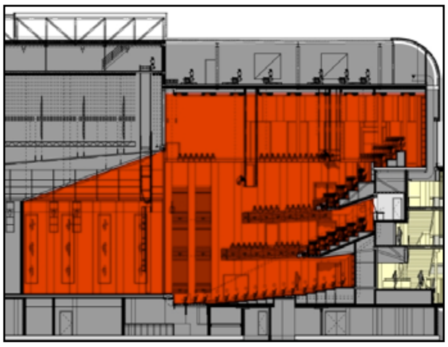

Figure 4.-Section hall in concert mode

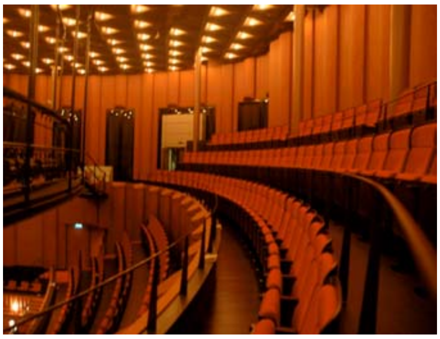

Figure 5.- View on Gallery level

Figure 6.- View on orchestra shell in use

The architects of Greiner van Goor Huijten Architects Amsterdam (NL) have designed a very compact theatre, with a basic horse shoe shape, curved rows and good sightlines, fulfilling all the demands set. The maximum room depth is between 18 m on the ground floor to 19.5 m on the balconies, and width is between 18 to 21 m. On ground floor the furthest seat is within 17 m of the proscenium opening, and on the second balcony this is 23m. To get sufficient acoustic coupling between the orchestra environment on stage and the hall, a large stage opening of 14 m high and 18 m wide is applied. Inside the hall itself the front side walls including box-seats can be rotated inwards to a width of 15 m, to adapt the walls visually to a smaller proscenium opening in theatre mode (12 m).

To limit the volume and the height in the theatre situation sightlines, have been optimised with a gradually sloped floor and alternating rows of seats have been applied. Due to the important demand for theatre use sightlines are still significantly better than in average shoebox concert halls. The depth of the balcony overhangs has been limited to the height underneath in order to maintain sufficient height and acoustic conditions for seats under the balconies in the concert situation [2].

The movable ceiling has a gross surface of 370 m² and consists of three independent, electrically operated parts which are intersected by lighting bridges (Fig. 3). Due to these fixed bridges the sight of the gallery seats to the stage with opera/musical/concert use is somewhat limited (see fig. 5), but movable bridges were considered too expensive. The bridges also limit the lowest height of each ceiling, as well as does the furthest row of the 2nd balcony. Both result in a average ceiling height of 13.5 m above ground floor in the theatre situation, resulting in an acoustic theatre volume of 4125 m^3 including the volume under the balconies. In their lowest position these ceilings connect close to the walls of the second balcony of the auditorium, leaving a small gap to the wall, and thereby reduce the acoustic volume. The openings between the ceilingparts themselves, which have gaps of 1-1.5m, act as additional absorption. The gallery volume behind it is "deadened" using acoustic drapes and absorption on the back of the movable ceilings.

To fullfill the demand for an additional reverberation volume of at least 4000 m^3 and 150 additional seats, a gallery has been implemented around the theatre above the 2nd balcony level (Fig 2,5). It has an average depth of 6 m, a usable floor surface of 290 m², and a height of 6.7m and a volume of 1850 m^3. Together with the volume of 2250 m^3 above the movable ceilings, that can be raised over max. 6.0 meters up to the height of the gallery ceiling (19.5m+) this leads to a total gallery volume of 4100 m^3. Intermediate ceiling settings can be applied for other types of use, for instance for musical or opera.

For concert use, a flexible orchestra shell of 9 m high aluminium sandwich panelling, build by Sorba (NL), has been designed with similar appearance and diffusors as the walls of the halls (see Fig. 6 and 10). It has a width of 14-18m, a depth of 14,5m and a height of 10-14m, giving a volume of 2800 m^3. All together a total acoustic volume in the concert situation of 11000 m^3 results.

Description of the theatre: materials

The internal wall and ceiling finishes had to fulfil certain weight requirements (>20 kg/m²) to minimize (low frequent) sound absorption in the concert situation. The fixed and movable ceilings are for 50% of their surface cladded with triangular elements of 1560 x 1560 mm (Fig. 7). These are formed by semi-cylindrical hollow diffusors with a width of 300 mm and height of 200 mm, build out of two 12.5mm curved gypsum boards bend over a wooden structure.

The flat ceiling elements are made of 18 mm multiplex and 12.5 mm gypsum board. In their highest position the movable ceilings have to level with the fixed ceiling parts, setting a strict demand for the thickness of the moving ceilings. A total height of 1004 mm is taken by these ceilings between concrete roof and bottom of the diffusors, including the 200 mm diffusor height. The motors for raising and lowering the ceiling as well as the air handling units have been positioned on a 300 mm heavy concrete floor directly above the hall.

Figure 7.- Detail of the ceiling

Figure 8.-Theatre situation (low ceilings)

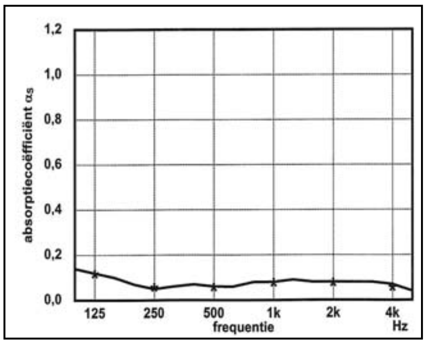

Figure 9.- Sound absorption of wall section

The walls of the theatre on all levels consist of a structural wall of 150 mm heavy limestone, with an interior finish of diffusive vertical convex elements placed in an alternating pattern with the flat parts, 1:1 on the (curved) rear walls and 1:2 on the (curved) side walls (see Fig. 8). The flat walls parts consist of 0.8 mm Resopal glued to 12 mm Fipro-plate (fire resistant plate) on 12.5 mm gypsum board, on an air space of 75 mm with metal supports and 50 mm mineral wool. The surface mass is 22 kg/m².

The wall diffusors are semi-cylindrical elements of 750-800 mm wide with a depth of 150 mm placed 100 mm in front of the walls (total depth 250 mm), extending over all the height of the theatre. They consist of 0.8 mm high density fibreboard (Resopal) glued on 3 mm mdf on 2 plates of 12.5 mm curved (slotted) gypsum board, bend over a wooden frame. The total surface mass is 23 kg/m². The hollow inside of the diffusors is left empty, but is carefully sealed to prevent any unwanted sound absorption by slots. The sound absorption of 10 m² wall part including diffusors has been measured in Peutz' laboratories, resulting in values of about 10% or less (Fig. 9) as considered acceptable. Originally, 200 m² variable wall absorption was projected to ensure the desired RT-variations, but it was skipped for cost and architectural reasons. Instead, the acoustic advisor was allowed to decide on 60 m² of fixed wall surface to be either absorbent or reflective. Based on measurements 60 m² of wall absorption was replaced by a reflective wall after the hall was finished.

The sound absorption of the diffusive balcony edge has been measured to be below 10-15%. As additional sound absorption, 500 m² of acoustic curtains are projected on a rail in front of the gallery walls, to be used in musical and theatre situations. The curtains can be stored in boxes to eliminate their absorption in concert situations. Carpet is applied in the aisles, other floor parts are finished with linoleum.

The sound absorption of the chairs (both empty and occupied) was carefully specified and measured in the reverberation chamber to ensure that the RT value of 2.0 s for the occupied concert situation could be met, and to keep a minimal RT difference between occupied and unoccupied conditions. Therefore, an additional slotted perforation of the seat bottom has been applied.

Figure 10.- View towards stage concert situation

Figure 11.- Concert hall with simulated audience.

Measurements

To investigate the individual and combined acoustic effect of the variable parameters of this theatre, measurements have been performed on 7th and 8th May 2007. In total 11 different settings have been measured, of which the specifications are given in table 1. The main variable elements are: the occupancy of the seats, the stage surrounding (theatre drapes or an orchestra shell), the position of the movable ceilings (high or low or intermediate), the acoustic curtains on the gallery, the orchestra pit (opera). Four concert configurations, one theatre setting, four musical settings and two opera settings have been measured. The first concert situation (ZC1) was measured with empty seats, all other situations were measured with a standard method for simulated audience occupation (see Fig. 11) using specific cloth hung over the seats [3,4].

Table I.- Desciption of variants measured and RT values measured

Var.	Type	"Occupied"	Ceilings	Curtains gallery	Orchestra shell/pit	Stage opening	Measured average RT values (s)		Volume (m^3)
							1 kHz	0,5-2 kHz	
ZC1	Concert	no	High (19m+)	none	Shell	18x14m	2.1-2.3	2.1-2.2	11000
ZC2	Concert*	yes	High (19m+)	none	Shell	18x14m	1.9-2.2	1.9-2.1	"
ZC3	Concert	yes	@14m+	none	Shell	18x14m	1.6-1.7	1.6-1.7	7400
ZC4	Concert	yes	@14m+	yes	Shell	18x14m	1.5-1.6	1.5-1.6	7300
ZT1	Theatre*	yes	@9-13m	yes	None	13x7m	0.9	0.9**	4100
ZM1	Musical	yes	9,13,19m+	yes	None	13x7m	0.9	0.9	5300
ZM2	Musical*	yes	9,19,19 m+	yes	None	13x7m	0.9	0.9	6200
ZM3	Musical	yes	All high	yes	None	13x7m	0.9-1.0	0.9-1.0	8200
ZM4	Musical	yes	All high	no	None	13x7m	1.9	1.8	"
ZO1	Opera*	yes	All high	no	Pit + curtain	13x7m	1.5-1.9	1.4-1.9	"
ZO2	Opera	yes	14,19,19	no	Pit + curtain	13x7m	1.3-1.6	1.3-1.6	7400

* main variant used

RT measurements

Reverberation time measurements have been performed using a 9 mm calibre alarm pistol as an omnidirectional source, with a sufficient S/N ratio down to the 63 Hz octave band. The shots have been recorded at different positions in the hall, an octave analysis is performed afterwards. RT values are deduced from -5;-35 dB according [2], although 0;-60 dB would usually have given similar results because of the large S/N ratio. For each level (ground floor, 1st balcony, 2nd balcony, gallery (or 3rd balcony)) at least 5 shots have been recorded and their RT octave values have been averaged. In total 220 shots have been recorded. In table 1 average RT values are given, and in figures 12-15 several results are presented as a function of the frequency. Some conclusions are given in the last chapter.

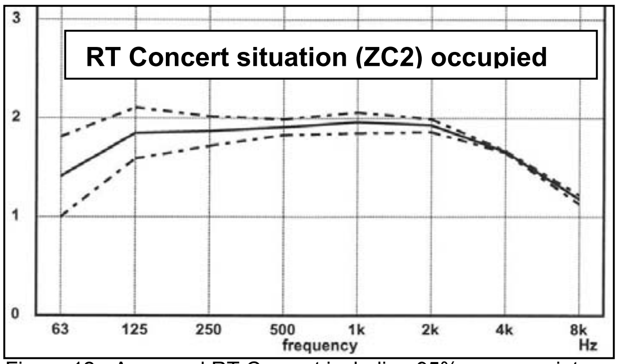

Figure 12.- Averaged RT Concert including 95% accuracy intervals

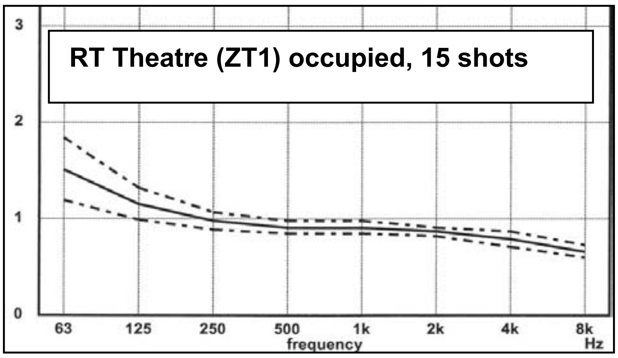

Figure 13- Averaged RT Theatre including 95% accuracy intervals

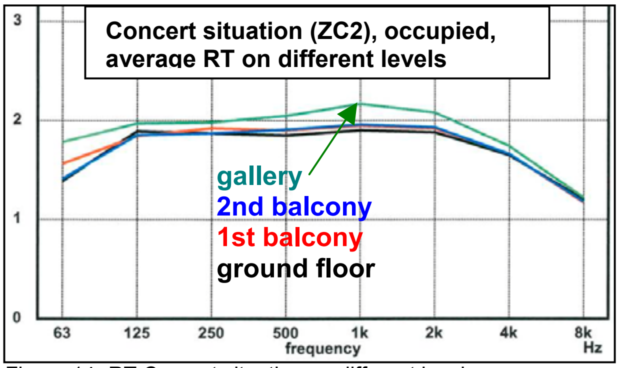

Figure 14- RT Concert situation on different levels

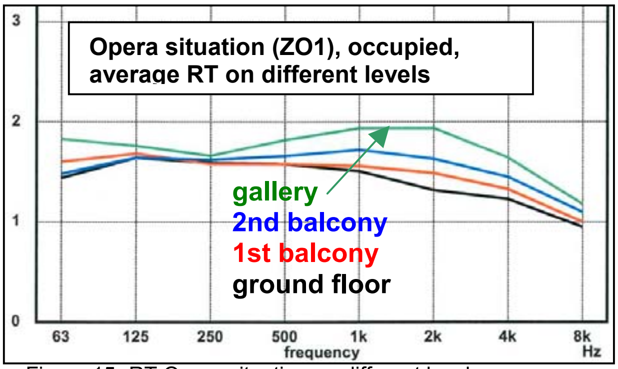

Figure 15- RT Opera situation on different levels

Impulse response measurements

Impulse response measurements have been performed in 7 different configurations of the hall (table 1) with a standard Maximum Length Sequence (MLSSA). To evaluate energy-time curves and acoustic parameters an omnidirectional noise source (cone) and a omnidirectional microphone (B&K 4007) have been used. Two source positions are used on stage, as well as 16 microphone positions distributed over the hall and stage (see Fig 16, 17), comparable with those used in the scale model and complying with a standard Peutz layout. In the opera situation, additional source and microphone positions have been applied in the orchestra pit (Fig. 17). In total more that 300 i.r.-measurements have been performed. Additionally, an octaeder source and an artificial head (AKG) have been used for binaural impulsresponse measurements and auralisation.

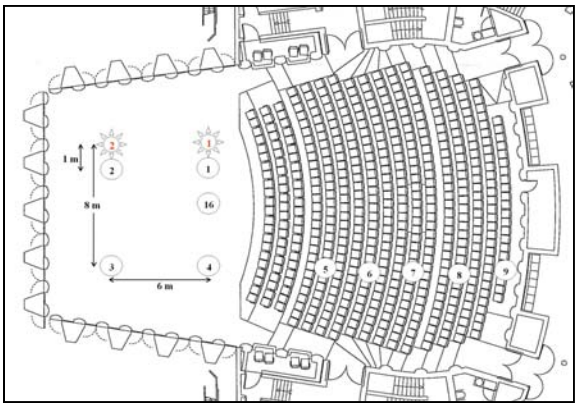

Figure 16.- Source and mic positions groundfloor plan concerthall

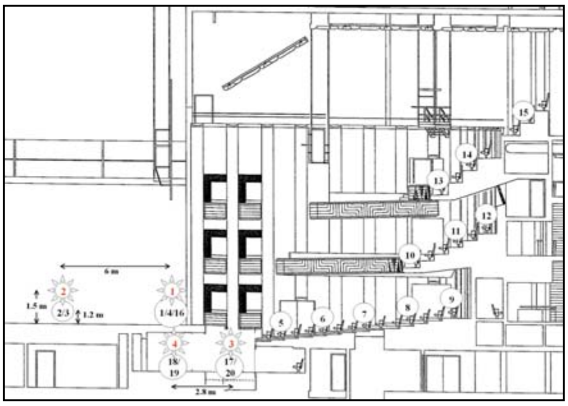

Figure 17- Source and mic positions in cross-section opera.

Based on the measured impulse responses, the Energy Time Curves (ETC) have been calculated. A filter (20 ms) is applied to simulate the time-filtering effect of the human ear. Combining two ETC's of different variants but with similar source and microphone position in one graph can be used to illustrate and investigate the difference in (perceived) sound energy with time, due to the variable parameter to be studied. Two examples (concert vs. theatre) are given in figure 18 and 19. The large addition of early and late sound energy due to the orchestra shell and the gallery is clearly visible (and audible).

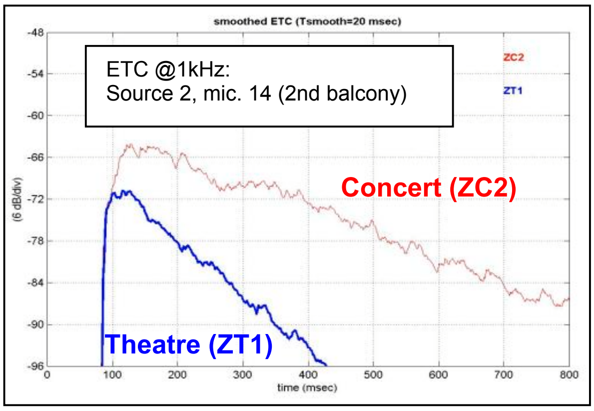

Figure 18.- Energy-time curve Concert vs. Theatre rear balcony

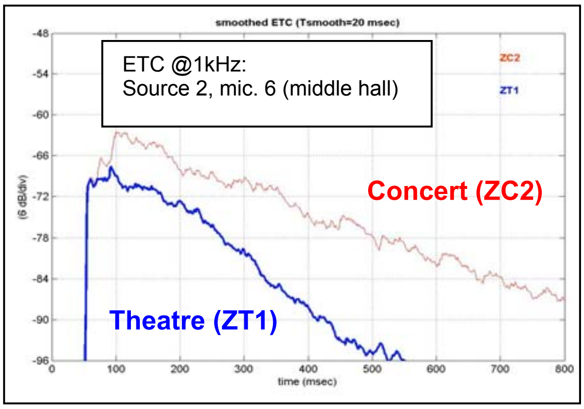

Figure 19- Energy-time curve Concert vs. Theatre middle hall

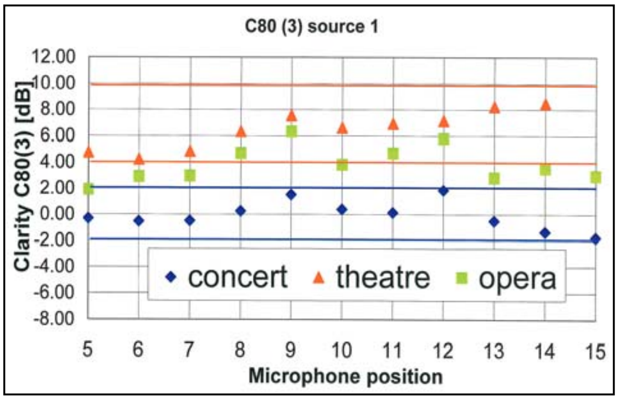

Figure 20.- C_{80}(3) values for three main variants, source 1

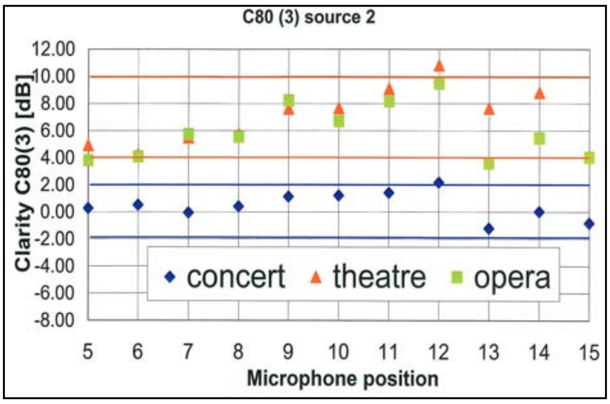

Figure 21- C_{80} (3) values for three main variants, source 2

Acoustic parameters

From the (omnidirectional) impulse responses measured several acoustic parameters have been calculated. Such as Dir/reverb-ratio, C_{50}, C_{80}, D_{50}, D_{80}, ST1, ST2, EEB, T_{center}, EDT, T_{30}, S/N. In concert mode, the ST1 (1kHz) values on stage are -13 and -9 dB. The background noise level in the hall is 23 dB(A) (NR-16). A graphical presentation of the $C_{80}(3)$ values for the main variants, averaged over 0.5, 1 and 2 kHz octaves, is presented in the figures 20 and 21. In figure 22, $C_{80}(3)$ data measured for the opera situation for 4 different source positions are given, including the values for the stage and the orchestra pit.

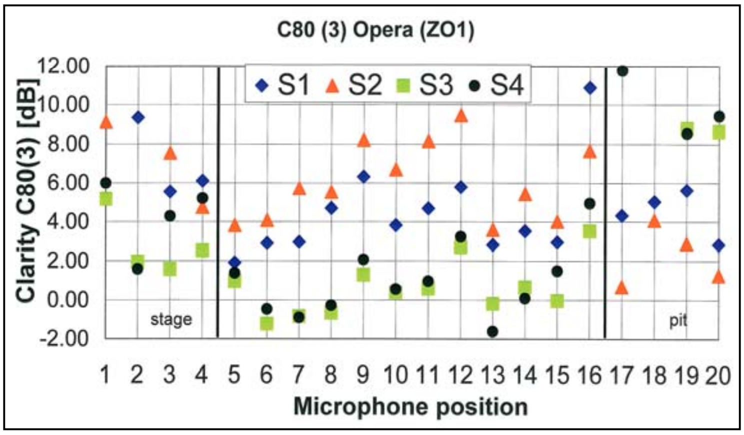

Figure 22- C80(3) values for opera for different source positions.

Some conclusions

A hall with interesting variable acoustic properties has been realized, worthwhile for further investigations and application.

With full occupation in symphonic concert situation (ZC2), an acoustic volume of about 11000 m^3 is realized with RT(3) values of 1.9 s. (avg. hall) up to 2.1 s (gallery level). With an orchestra slightly lower values will occur. Largest values for RT occur on the gallery level, which is in the middle of the large reverberant volume of the gallery with wider dimensions and relatively little absorption (audience). $C_{80}(3)$ values in concert mode with a source in the proscenium opening (1) fulfill the requirements set (-2;0 dB), with average $C_{80}(3)$ of 0 dB and values under the balconies (mic 9,12) limited to +2 dB; The strength G (@1K) measured is +6 dB for concert (ZC2). Stage conditions fulfil ST1>-14 dB.

When the ceilings are lowered while maintaining the orchestra shell on stage, RT values reduce to 1.5-1.6 s. and average $C_{80}(3)$ increases to +1 dB, while G increases to +7 dB. This situation with a reduced volume of about 7500 m^3 could be an interesting setting for chamber music.

When subsequently the orchestra shell is being removed and replaced with theatre drapes on stage, the stage opening is being reduced and the ceiling parts are lowered to their minimal height, the theatre situation has been realized. The acoustic volume reduces to 4100 m^3. Average (occupied) RT(3) values are 0.9 sec (variant ZT1) throughout the hall and balconies, indicating a sufficient acoustic homogeneity. Average $C_{80}(3)$ values increase to +7 dB, 7 dB higher than average concert values, and 3 dB higher than opera. AL-cons values measured are below 6%, indicating a good speech-intelligibility.
In the opera situation, an increased room volume of 8000 m^3 is realized when all ceilings are in their highest position (ZO1). Average RT(3) values increase from 0.9. to 1.5-1.9 s., with largest values up in the hall (fig. 15). On the lower balcony levels several double decays are measured, which are a combination of late reverberant sound from the gallery and the early sound of the relatively more absorbent lower part of the hall. This indicates a non-perfect diffusivity and somewhat limited coupling between both volumes. For the subjective opera experience this can be considered as beneficial, because it gives opera listeners an opportunity to choose their desired seat not only based on sightlines, but also on their own preference for more or less reverberance and clarity. Even with much late reverberance the intelligibility of the opera remains good due to the good sightlines and compact shape. An average decrease of $C_{80}(3)$ with -3 dB (from +7 dB to +4 dB) is realized between the theatre mode and the opera mode with a source on stage (1,2), mainly achieved by the additional volume above the hall. With a sound source in the pit, $C_{80}(3)$ values towards the hall are between -2 and +3 dB (Fig .22), as demanded.

Compared with the concert volume of 11000 m^3, the removal of the orchestra shell reduces the room volume in the opera situation with 3000 m^3 to 8000 m^3. This causes the RT(3) values on the (more distant) gallery level to be only slightly lowered (0.2s), whereas in the hall the reduction is larger (0.4s), as might be expected (Fig. 14-15). Average $C_{80}(3)$ values increase with +4.5 dB to +4.5 dB from concert mode to the opera mode with the sound source on stage (position 1,2).

Acknowledgement

Thanks to Rob, Dionne, Klaus, David and Carry for all their help and fruitful discussions.

References

1. M. Luykx, R. Metkemeijer, The new theatre in Zwolle (NL): Acoustical design and scale model study. Proceedings of the Institute of Acoustics **28**. Pt.2 (2006)
2. L. Beranek, Concert Halls and opera houses, Music, Acoustics and Architecture. 2nd Edition, 2004, Springer-Verlag New York Inc.
3. K.H.Lorenz, F. Breurer. Simulation des Publikums durch spezielle Polyester-Textilien bei der raumakustischen Messung von Konzertsalen in der Prakis. DAGA, Fortschritte der Akustik, Aachen, 2003.
4. T. Hikada, N. Nishihara, L. Beranek: Relation of acoustical parameters with and without audiences in concert halls and a simple method for simulating the occupied state. J. Acoust. Soc. Am. 109 (3), March 2001, 1028-1042.
5. Speech information and speech intelligibility, V. M. A. Peutz, AES Convention 1988.