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Physical measurements vs. auditory assessment of a concert hall by different groups of users: a case study

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ABSTRACT

The acoustical quality of a medium size (6200 m^3 volume, 880 seats) shoebox shaped symphonic concert hall, renowned for its acoustics and protected by the cultural heritage law, was evaluated by the measurement of acoustic parameters (EN-ISO 3382-1:2009) and by auditory assessment of sound with the use of survey questionnaires which required from the respondents to judge various attributes of sound and comment on their experience with the hall. The judgments were obtained from the conductor, the soloists, orchestra members, choir singers, recording engineers, and from the audience. The hall's acoustics received generally high ratings from the audience. Orchestral musicians highly estimated the audibility of one's own instrument and other instruments in the orchestra. Choir singers judged the audibility of other voices in the choir as satisfactory. The conductor assessed the overall sound quality as good, but also pointed at insufficient fusion of sound across the orchestral instrumental groups. Sound engineers judged the hall's acoustics as very good for recording of chamber music and small orchestras, but not for very large ensembles. An attempt is made in this paper to relate the results of auditory judgments of the hall's acoustics to its measured acoustic parameters.

Keywords: Room acoustics, Subjective assessment, Sound quality

1. INTRODUCTION

The building of the Ignacy Jan Paderewski Pomeranian Philharmonic in Bydgoszcz, Poland, was erected in 1950s and the orchestra began regular activity in the new venue in 1958. The concert hall of the Philharmonic is considered an exemplar of superior acoustics for symphonic music, chamber music and solo recitals, as well as for sound recording. Currently the philharmonic building needs comprehensive modernization after over 60 years of use. To keep a detailed documentation of the concert hall's acoustics for the future a comprehensive study was undertaken, including acoustic measurements, auditory sound quality assessment, and a survey questionnaire on the hall's acoustics conducted among musicians and recording engineers. The study also included an acoustical inventory and numerical modeling of the hall and documentary recording of symphony concerts. The purpose of the study was to create detailed, comprehensive documentation of the hall that would help in the renovation and serve as reference for the evaluation of the results of the renovation project. This paper presents the results of the study and discusses the relation of auditory judgments of the hall's acoustics to the measured room acoustic parameters.

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2. GENERAL CHARACTERISTICS OF THE CONCERT HALL

The building of the Ignacy Jan Paderewski Pomeranian Philharmonic houses a symphonic concert hall (6200 m^3 volume) and a chamber hall (890 m^3 volume). The concert hall is situated above the chamber hall in the building . A side view and a floorplan of the concert hall are shown in Figure 1.

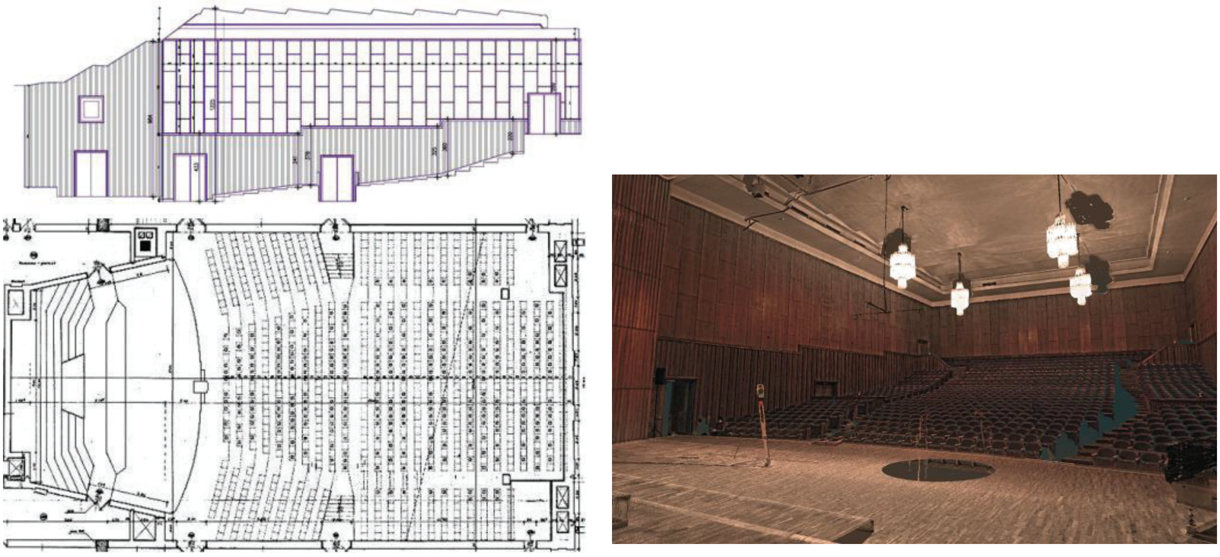

Figure 1 – A cross-section, a floorplan, and a scan image of the Pomeranian Philharmonic concert hall

The main specifications of the concert hall are as follows: capacity: 886 seats, volume: 6200 m^3, volume per seat: 7 m^3, floor area: 675 m^2, stage area: 163 m^2, hall length: 36 m, width: 21 m, maximum height: 12 m. The hall has a shoebox shape with the exception of a sloped floor in the audience area. The ceiling is tilted above the stage and lowered to about 7 m in the rear to reflect sound to the audience and provide good acoustic conditions for communication between musicians on the stage.

2.1 Materials

The hall's iterior (walls) is entirely covered with wood. The wall covering is made of deeply profiled wood panels (Figure 2, bottom part), wave-shaped profiled wood boards (Figure 2, wall on the left), and flat perforated panels.

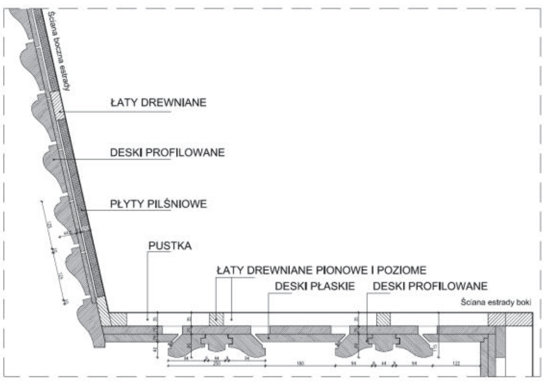

Figure 2 – A cross-section of profiled wood panels and wave-shaped panels covering the bottom part of the hall's side walls

Profiled panels, arranged at a distance of 35 mm from the layer of bricks, cover the lower parts of the side walls in the audience area and the bottom part of the back wall. The higher parts of the side walls are covered with flat panels. On the back wall, flat panels alternate with flat perforated panels arranged at a distance of 105 mm from the brick layer, some slightly tilted. The profiled wood panels (Figure 2, bottom) provide side-wall scattering of high-frequency sound in the audience area. Wave-shaped board panels (Figure 2, left) are predominant on the stage side walls. An important part of the stage back wall is the organ prospect strongly dumping the sound at mid frequencies (1 kHz).

Other acoustic elements include: (1) a reflecting ceiling covered with a 20-mm gypsum face set on a net attached to 20-mm slabs above the stage; (2) the ceiling above the audience area, 3 m wide, shaped in shallow contra tooth like surfaces, (3) wooden floor laid on a 50-mm concrete layer; (4) armrest chairs with medium thickness cushions in the seating area. An almost entirely wooden coverage of the interior surfaces results in relatively short reverberation time at 63- and 125-Hz frequencies and provides even sound decay throughout the audience area.

3. ACOUSTIC MEASUREMENTS AND NUMERICAL SIMULATIONS

3.1 Measurement setup and procedure

Most of the acoustic measurements were carried out in compliance with the EN-ISO 3382-1 standard [1] and consisted in recording of impulse responses from which the basic parameters and indexes were calculated. In addition to that, the Interaural Cross Correlation, IACC, was also assessed. The measurement setup included a Brüel & Kjaer 4292-L dodecahedron loudspeaker, a RME Fireface UC interface, two Microtech Gefell MK250 condenser microphones, a Dell XPS M1330 notebook with DIRAC Room Acoustic Software 7841, and a Brüel & Kjaer 2250 sound level meter. IACC was calculated from binaural recordings made with a Neumann KU100 dummy head.

The measurements were conducted both in an empty hall and during concerts, with 50 orchestra musicians and either 50 or over 80 choir singers on the stage, and fully occupied audience area. The measurements in an occupied hall were performed just before the concert with the consent of the conductor, the musicians, and the audience. The Brüel & Kjaer 4292-L sound source was placed among the musicians, close to the median of the stage, at a distance of about 1.5 m from the edge of the stage, approximately at the place intended for a concert soloist. The two measurement microphones were placed in two locations on the stage, among musicians, and moved from one place to another along the left and right aisles (see Figure 1) in the audience area. Eight placements in the audience area were used, with gradually increasing four distances from the stage, ranging from 1.5 m in the first seat row to 19.5 m in the 21st row. In an unoccupied hall 2–7 sound source placements were used, depending on the parameter measured. For IACC recordings the dummy head was placed in 10 locations, five along the room median axis and five on the right side of the hall.

3.2 Results

The main results of the measurements are shown in Figure 3 and Tables 1 and 2. It is apparent in Figure 3ab that the frequency characteristics of reverberation time, RT, and early decay time, EDT, have a bow-like shape with a maximum in a range of 500–1000 Hz. The average RT, measured in the audience area, is 2.1 s in an empty hall and 1.8 s in an occupied hall (Table 1) and the respective EDT values are 1.9 and 1.5 s. These data indicate that the room reverberation decreases by about 15% during concerts in a fully occupied hall. The difference in reverberation time between an empty and an occupied hall is not larger than typically encountered in concert halls but is still audible, as it exceeds the auditory discrimination threshold for reverberation time [2]. It also should be noted that the RT and EDT values are similar across the measurement points in the hall. The average sound strength parameter, G (Figure 3c, Table 2) is about 4 dB, except for an increase to 9 dB at 125 Hz. This increase in sound strength provides good bass support in the hall. In general, all basic acoustic parameters are within a range recommended for a concert hall of such a size: T_{30}=1.7 ÷ 2.2 s, EDT = 1.4 ÷ 2.0 s, C_{80}= –3 ÷ +3 dB, C_{50} = –1 ÷ +3 dB. The stage support parameters, ST_{Early} and ST_{Late} (Table 2), indicate good acoustical conditions for communication between musicians on the stage and for communication between the conductor and musicians.

Initial time delay gap, ITGD, shown in Figure 3d, was measured for six microphone distances from the stage in the audience area and seven placements of the sound source on the stage, covering the entire stage depth in 1.5 m steps. As expected, the largest ITDG values of 40 ms were obtained at a short distance with the sound source located close to the stage edge and the microphone placed in the first seat row (1.5 m from the stage) and the fifth row (4.5 m from the stage). The ITDG decreased to 10 ms either with sound source moved to the rear of the stage or the microphone placed at the end of the audience area (row 23). The ITDG, averaged over the microphone placements in the audience area, decreased from 27 to 12 ms when the sound source was moved from the front to the rear of the stage.

IACC (Table 2) indicates good sound quality in the hall as the average initial $IACC_{0\text{-}80}$ is about 0.4 and late $IACC_{80+}$ is below 0.2. The listener envelopment parameter, LEV, is 1.4 dB and the degree of source broadening parameter, DSB, is 27 dB. These values indicate good spatial perception in the hall.

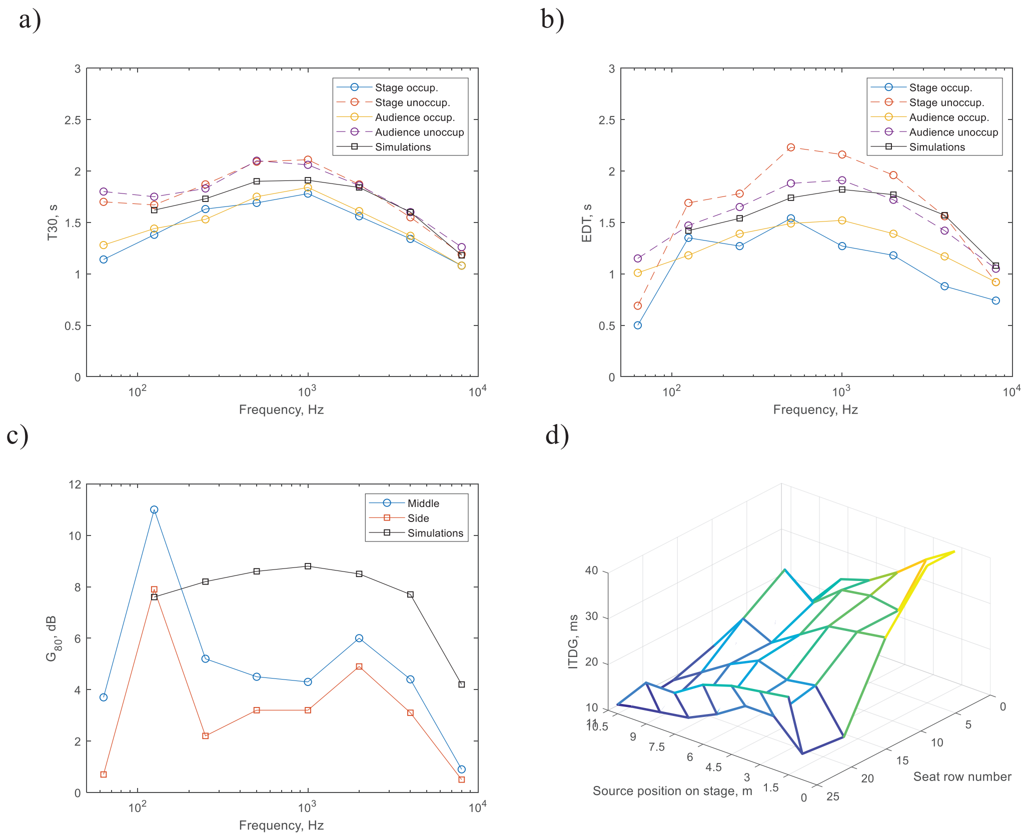

Figure 3 – a) Reverberation time T30, b) EDT on the stage and in the audience area in an occupied and in an empty hall, c) sound strength G_{80} in the middle and in the side (close to the side wall), d) ITDG determined for various placements of the sound source on the stage and various distances of the microphone in the audience area

Table 1 – Reverberation time (T_{30}), early decay time (EDT), clarity (C_{80}), speech clarity (C_{50})

	Average				Front-back change		Numerical model
	Stage		Audience area		Audience area		
Parameter	Unoccup.	Occup.	Unoccup.	Occup.	Unoccup.	Occup.	
T_{30}, s	2.1	1.7	2.1	1.8	2.0 ÷ 2.1	1.7 ÷ 1.8	1.9
EDT, s	2.2	1.5	1.9	1.5	2.2 ÷ 1.8	1.7 ÷ 1.4	1.8
C_{80}, dB	7.3	–	0.2	–	1.5 ÷ -1.5	1.5 ÷ -0.6	–0.8
C_{50}, dB	3.0	5.5	–2.8	–2.6	-0.8 ÷ –4	–1.2 ÷ –4.8	–4.3
STI	0.62	0.74	0.51	0.53	–	–	0.49

Table 2 – $IACC_{0\text{-}80}$ (Early) and $IACC_{80+}$ (Late), sound strength G, and stage support ST

Parameter	Average Middle	Average Side	Front-back change in audience area Middle	Front-back change in audience area Side	Numerical model
$IACC_{0\text{-}80}$, ms	0.50	0.33	0.70 ÷ 0.36	0.42 ÷ 0.26	–
$IACC_{80+}$, ms	0.18	0.12	0.20 ÷ 0.15	0.12 ÷ 0.11	–
G_{total}, dB	7.5	6.5	8 ÷ 6	8 ÷ 6	8.7
$G_{0\text{-}80}$, dB	4.4	3.2	6 ÷ 2	6 ÷ 1	–
G_{80+}, dB	5.5	3.8	7 ÷ 3	5 ÷ 3	–
ST_{Early}, dB	–12.9		–		–
ST_{Late}, dB	–14.3		–		–

3.3 Numerical simulations

A numerical model of the hall was created, based on laser scanning of the hall interior (Leica P20 scanner, tachimeter TS09 R1000). The raw data were exported to a CAD environment to create a computer model consisting of 795 planes subdivided into 16 groups with assigned absorption coefficients. The modeling was done with the use of AURA/EASE 4.4 software.

In the model's development a difficulty arose due to the lack of sufficient data on the absorption coefficients of certain surfaces in the hall. There was no proper documentation from the time when the hall was being built and the various wood panels were differently and deeply profiled (see Figure 3c), and differently separated from the brick walls. This prevented the use of catalogue absorption coefficient values in the model so it was decided to perform *in situ* measurements of absorption coefficients with the use of a *Microflown Technologies* sound absorption probe. Sound absorption coefficient, α, was measured for all surfaces included in the numerical model, i.e.*,* the profiled wood panels on the stage and on the audience area side walls, perforated and unperforated panels in the upper parts of the walls, the ceiling above the stage and the audience area, the floors, chairs, doors, and the organ prospect. The measurements were made at a given point or – in the case of profiled wood panels and the organ prospect – by scanning the surface during an assumed averaging time (15 s).

The sound absorption probe tends to overestimate the absorption coefficient if the probe is not placed close enough to the measured surface, which made the measurements of profiled panels difficult. A comparison of measured parameters (Table 1 and 2) and the outcome from the numerical model showed that the results of *in situ* measurement of sound absorption were overestimated by about 25%. Thus, the final modeling was performed with all absorption coefficients reduced to 80% of their measured values. Reduction of the coefficients also depended on the frequency band and ranged from 0.69 to 1.00, respectively, at 125 and 4000 Hz.

As an output of numerical modeling reverberation time T_{30}, EDT, clarity C_{50} and C_{80} indexes, STI, and sound strength G were calculated. These data are shown in Figure 3 and in Tables 1 and 2. Overall, it should be noted that the *in situ* measurement of sound absorption resulted in good agreement of the simulations with the measurements of room acoustic parameters.

4. AUDITORY ASSESSMENT

4.1 Questionnaires of orchestra and choir members

Subjective assessment of various aspects of the concert hall sound quality included questionnaires given to orchestra and choir members and interviews conducted with choir and orchestra conductors, soloists and sound engineers who had experience in music recording in the hall. The questionnaires were intended to collect opinions regarding the audibility and quality of sound during rehearsals and concerts and the comfort of performing music in the hall. Separate question categories were prepared in the questionnaires for orchestra and choir members, due to the specificity of their work.

The questionnaire survey was conducted during two concerts among 51 orchestra members and 58 choir members (concert 1), and 50 orchestra members and 82 choir members (concert 2). In total, 241 questionnaire forms were collected from the musicians. During those concerts acoustic measurements of the hall, described in section 3, were also conducted.

The questionnaire for orchestra members included questions concerned with various aspects of their work on the stage and general questions about the hall. Two questions given to orchestra members were about the sound of their own instrument: (1) audibility of the sound and (2) sound clarity. Further questions were about (3) the audibility of instruments of own section and (4) audibility and (5) clarity of other instrumental sections. There also was a question about (6) the sound projection range of the respondent's instrument and (7) the intelligibility of the conductor's voice.

The choir members were questioned about the sound of their own voice, its (1) audibility, (2) clarity, and (3) ease of voice emission. The remaining questions were about (4) audibility of other choir members from the same section and (5) audibility of other choir sections, (6) fusion of the choir sound, (7) audibility of the orchestra and (8) intelligibility of the conductor's voice.

The surveyed musicians responded by selecting one of three rating categories: poor, average, and good. Table 3 presents the percentage of responses assigned to each of the categories and a numerical index representing a weighted average, with weights of '0' for poor, '0.5' for average, and '1' for good category. The index shows the group result of rating on a scale from 0 to 1; an index value greater than 0.5 means that a given aspect of sound was positively evaluated by the respondents.

The questions about the hall quality were about (1) comfort of ensemble playing in the orchestra or comfort of singing with the orchestra (2) overall sound quality on the stage, (3) overall sound quality in the concert hall. In this group of questions a five-category rating scale was used, extending from very bad to very good. Table 4 presents the percentage of responses assigned to each category. Similarly as in Table 3, an index representing the weighted average was calculated, with weights '0' for 'very bad' and '1' for 'very good'. The index represents the average rating on a scale ranging from 0 to 1.

Table 3 – Percent distribution across rating categories obtained from orchestra members and choir members in the evaluation of sound in the concert hall. Rating categories: poor, satisfactory, good.

Orchestra members					Choir members				
Response category	Poor %	Satisf. %	Good %	Index* 0 ÷ 1	Response category	Poor %	Satisf. %	Good %	Index 0 ÷ 1
Sound of the respondent's own instrument					Sound of the respondent's own voice				
Audibility	3	25	72	.84	Audibility	2	29	69	.84
Clarity	5	22	73	.85	Clarity	3	29	68	.82
					Ease of voice emission	3	28	69	.84
Sounds of other instruments in the orchestra					Voices of other choir members				
Audibility of -own section	6	56	38	.66	Audibility of -own group	9	48	43	.67
-other sections	6	52	42	.68	-other voice groups	23	55	22	.49
Clarity - other sections	7	61	32	.63	Choir sound fusion	9	52	39	.65
Other									
Sound projection range	4	43	53	.75	Audibility of the orchestra	0	26	72	.87
Intelligibility of conductor's voice	6	60	34	.64	Intelligibility of conductor's voice	3	54	43	.70

*An index ranging from 0 (poor) to 1 (good), summarizing the responses, was calculated as a weighted average of ratings.

Table 4 – Percent distribution across rating categories obtained from orchestra members and choir members on the following scales: comfort of playing, quality of sound on the stage and overall concert hall quality.

Response category	Very bad (1)	(2)	(3)	(4)	Very good(5)	Index*
	%	%	%	%	%	0 ÷ 1
Comfort of ensemble playing						
Orchestra	1	6	15	46	32	0.76
Choir	-	1	9	49	41	0.83
All	-	3	11	48	38	0.80
Stage sound quality						
Orchestra	-	-	8	27	65	0.89
Choir	-	-	5	49	46	0.85
All	-	-	6	41	53	0.87
Hall sound quality						
Orchestra	-	1	7	28	64	0.88
Choir	-	1	6	50	43	0.84
All	-	1	7	41	51	0.86

*An index ranging from 0 (very bad) to 1 (very good), providing a summary of responses, was calculated as weighted average of ratings

The results compiled in Table 3 show that musicians generally approved the acoustics of the concert hall. Almost 75% of orchestra members rated the audibility and clarity of own instrument as "good". Audibility of instruments in the own and in other sections, as well as the clarity of sound of other instrument sections were judged as satisfactory or good. The corresponding weighted average index values were high: 0.69 for the sound of own instrument and 0.6÷0.7 for other instruments. The musicians were also satisfied with the sound projection range (index = 0.75) but less so with the intelligibility of conductor's voice, judged as only satisfactory. This result is in good agreement with the measured values of STI index on stage: 0.62 in an empty and 0.74 in an occupied hall.

The responses of choir members were similar to those of orchestra members and indicated high acceptance of the quality of own voice, neighboring singers' voices, and the overall sound of the choir (category 'choir sound fusion'). The lowest rating was given to the audibility of other voice groups in the choir (index = 0.49), but still at a satisfactory level. It should be noted, that the evaluated concert hall was the home hall of the orchestra therefore the musicians were very well familiar with its acoustics. Both choirs performed as guest ensembles in the hall and had much less experience with the hall's acoustics.

All musicians positively assessed the comfort of playing in the hall, and quality of sound on the stage as well as sound in the hall as a whole. The data in Table 4 show that over 90% of ratings of stage and hall sound quality fall into categories (4) and (5), labeled 'very good'. The comfort of ensemble playing was rated (4) and (5) in 78% cases, which is slightly less, but still very good. This could be related to relatively small stage area of this hall to accommodate over 130 musicians.

4.2 Comments of conductors, a soloist, and sound engineers

Comments were obtained from three orchestra conductors, two choir conductors and a soloist (a woman who sung in Mozart's Requiem). All those persons generally highly valued the hall, yet they had specific remarks regarding some deficiencies. The stage was judged as providing good sound quality at the place occupied by the conductor, however, with some complains about the lack of sufficient fusion of instrument sounds, especially in very large ensembles for which the hall is somewhat too small. A good feature of the acoustics in the stage area is easy communication of the conductor with the soloist and orchestral musicians. The hall provides good sound balance between the orchestra and the choir. However, some instrumental groups do not hear each other well enough which makes it difficult to synchronize the sounds of the instruments and this also applies to remotely located singers in large choirs. The hall is demanding for a solo singer who must, to a large extent, rely on his/her singing technique and receives moderate acoustical support from the room. The choir is well supported by the hall's acoustics when the ensemble is not too large and fits in the area close to the center of the stage.

Regardless of certain performance difficulties, the sound is precise in the concert hall. On the other hand, it is not easy to play in the hall as it does not mask performance imperfections. The timbre of reverberant sound is correct. An important feature of the hall is that the difference between the acoustics of an empty and a filled hall is very small. Regardless of the detailed, somewhat criticizing comments, the overall sound quality was judged high and comparable to major concert halls in Europe.

Comments were also gathered from 11 sound engineers who used to work in the concert hall, at present or in the past. They emphasized that the hall is very well suited to the needs of music recording. For instance, the hall acoustics allows to use omnidirectional microphones placed at large distances from the sound source and microphone placement is easy in the hall. The hall is best for chamber and other relatively small ensembles and also very good for recording of works for piano and an orchestra. The intimacy of the hall's sound is audible in the recordings. The hall has a good ratio of direct to reverberated sound and the reverberation time is proper for music recording. Despite of several specific critical remarks, the hall is unique in many aspects and very friendly for music recording.

5. FINAL REMARKS

Measurements done in the Pomeranian Philharmonic concert hall showed that it was possible to expect good acoustical conditions of the hall. Basic parameters such as reverberation time T_{30}, EDT, clarity $C_{50/80}$, stage support ST and strength G assumed values correct for music performances in the hall of this volume. Binaural parameters (IACC and derived from it LEV and DSB) also predicted good hall quality. Results of measurements were at large confirmed by subjective quality assessment done by performers, conductors, sound engineers, and persons from the audience.

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