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A STUDY ON THE ACOUSTICAL PERFORMANCE OF VARIABLE SYSTEMS IN BILKENT MUSIC HALL

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ABSTRACT[*]

Concert halls are mainly designed to accommodate a range of music performances since different performances require different room acoustics characteristics. There is an increase in demand for multi-use concert halls which requires flexibility in the design elements. Some previous studies prove that by implementing passive variable acoustic solutions, acoustical conditions can be modified to make the venues compatible with various performance types. This study investigates the potentials of passive variable acoustic methods in symphonic music halls with a focus on Bilkent Music Hall in Ankara, Turkey. The methodology includes acoustical field measurements to test the effects of the existing variable acoustic system, which is in the form of operable/retractable wooden doors with fabric backing. Later, questionnaire/online surveys by musicians and music conservatory students to assess the subjective parameters in relation to objective parameter outcomes. The results of field tests indicate that current indoor acoustic condition of the hall is not satisfactory. The problem is specifically in mid to low frequencies in retracted state of the doors and high bass absorption in closed state. Future work will further assess the causes of the absorption by field test tuned simulations to discuss possible acoustical treatments.

Keywords: *Room acoustics, music halls, variable absorption, reverberation time*

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1. INTRODUCTION

Concert halls are mostly designed with specific acoustic considerations which make them suitable for a range of music performances. Since different performance types require different acoustic conditions (see Table 1), a flexibility in design elements is required. Therefore, there is an increase in demand for multi-purpose halls that are compatible with various performance types such as orchestral music, chamber music, orchestral performance with choir and vocal accompaniment and as well as solo recitals. Many studies argue that by implementing passive variable acoustic systems, music halls can be tuned for a large range of performance types [1, 6, 8]. Therefore, this study focuses on the effects of variable absorption systems on the acoustic performance of concert halls by focusing on a specific case study, Bilkent Music Hall.

As a fundamental criterion in room acoustics, passive systems are used first to tune reverberation times. When reverberation is too long, one note can become inaudible by an earlier sound (or masked and blurred), when it is too short, the sound can lose its richness and the sound field can become dull. For piano recitals, a shorter reverberation can be acceptable since the pedals on the piano can lengthen the notes when necessary. However, for violins and pipe organs, a longer reverberation time is ideal since it allows the previous notes to continue to resonate which will create a rich and powerful transition in between notes [2]. Therefore, acousticians have to achieve a balanced and adaptable acoustic condition for various performances.

In order to increase or decrease the reverberation time, techniques such as reverberation chambers or variable absorption systems can be implemented. In smaller halls, retractable curtains might be sufficient enough to create a perceptible effect in reverberance. In other cases, operable panel systems are commonly used but this treatment requires a large area to be treated in order to have a noticeable impact on the auditory experience [3].

The success of the musical experience also depends on other parameters such as C80 and EDT. Hidaka and Nishihara conducted field measurements and subjective experiments with experts to determine the optimum reverberation time for piano and violin solos. It is found that the assessment of reverberance is highly correlated with C80 for piano and violin performances, especially at high frequencies. [10]. The ideal RT and C80 ranges for piano and violin solos, optimum objective acoustical criteria range for different musical periods and performance types are presented in Table 1. All the data gathered in the field tests regarding acoustical design parameters are analyzed accordingly.

According to interviews with members of Bilkent Symphony Orchestra, it is recorded that the proper use of the panel system is not acknowledged for different performance types. Therefore, the panels are constantly kept in the half-retracted state. In addition, the musicians were found unimpressed by the effects of the existing panel system since they need to retune their instruments when they switch venues. Thus, the main motivation of this study is first to test the effects of the existing variable system in Bilkent Music Hall and later evaluate according to the preference of musicians.

Table 1. Optimum objective acoustical criteria range for different performances

Acoustical design parameter	Criteria
Reverberation time, T30 (s)	1.4 s – 1.7 chamber music [3,7] 1.7 s – 2.3 s symphonic music [7,10] 1.2 s to 2.0 s (for piano) [10] 1.8 s to 2.4 s (for violin) [10]
Musical Periods, Classical Romantic Twentieth Century	 1.6 s – 1.8 s 1.9 s – 2.1 s 1.4 s (at mid-frequencies, occupied) [2]
Early Decay Time, EDT (s)	1.8 s – 2.2 s [4]
Clarity, C80 (dB)	-2 dB to 2 dB (for music) [3] 0 – +2.4 dB (for piano) [10] -1,6 – 0.7 dB (for violin) [10]
Bass Ratio	1.1 – 1.25, for halls with RT > 1.8 s 1.1 – 1.45, for halls with RT < 1.8 s

2. MATERIAL AND METHOD

2.1 Bilkent Music Hall

In this section, the detailed information regarding Bilkent Concert Hall's architectural characteristics and activity patterns are explained. Bilkent Music Hall was designed by Erkut Sahinbas for Bilkent Symphony Orchestra and Faculty of Music and Performing Arts in 1994 in Ankara, Turkey. It has a shoebox shape with the dimensions of (L x W x H) 34 m x 19 m x 17 m. It has 707 seating capacity with 447 seats on the ground floor and 212 and 48 on the two levels of balconies. Its total volume is 10,982 m^3. The stage platform is 0.9 m high from the main floor, and has a 127 m^2 surface area. The dominant material used on the interior is wood boards on battens on the walls and wooden parquet on the floor which is commonly used in order to provide a sense of warmth to the music (Fig. 1). The ceiling has a 6° angle (sourced from AutoCAD files provided by Bilkent University).

The interior views of the music hall during field tests are presented in Figure 1.

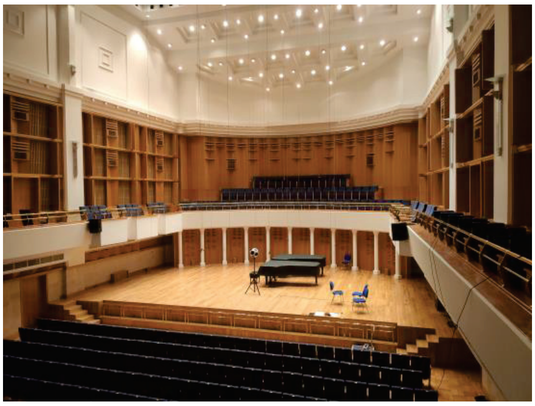

Figure 1. The experimental setup, view from balconies to the stage

The music hall is located within the Faculty of Music and Performing Arts of Bilkent University, and is mainly used for symphonic concerts, solo performances and rehearsals with additional speech events such as seminars and conferences time to time. The hall is also used by the music conservatory students. In order to provide a flexible acoustic environment, the initial design and implementation include three rows of operable/retractable wooden doors on the side walls with fabric backing. The wooden doors have a thickness of 2 cm. The retracted, half-retracted and closed states of the panel doors are presented in Fig. 2. The doors are generally used in their fully retracted (%100 sound absorbing) or half-retracted states (%50 sound absorbing). The panels are manually controlled, and there is no automated mechanical system for shut-off and on functions. So, it is not that practical to open and close the doors, thus they are mostly kept in a constant state.

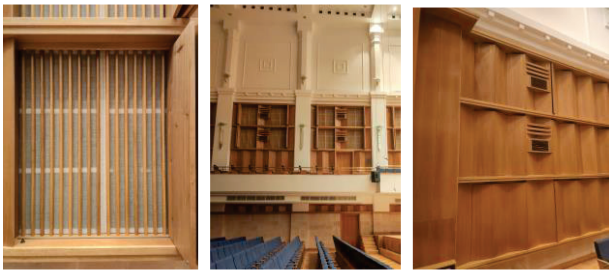

Figure 2. Retracted, half-retracted and closed states of the variable absorption system, respectively

2.2 Field Tests

In order to test the efficiency of the existing passive system in Bilkent Music Hall, acoustical field tests were held in the unoccupied hall in accordance with ISO 3382-1 on 3rd of August, 2022. Two different states of side doors were tested, which are retracted and closed states. As it is presented in Fig. 3, a series of room impulse responses (RIR) are collected for two different sound sources (S1 and S2 on stage), and 14 receiver positions (R) throughout the hall including on stage main parterre, and first balcony. The room impulse responses are collected by B&K-Type2250-A hand-held analyzer. Acoustic signal excitation is provided by B&K-Type4292-L standard dodecahedron omni-directional sound source and B&K-Type2734-A power amplifier. The collected impulse responses are analyzed by DIRAC room acoustics software v6.0.6470. The average indoor temperature during the field tests was 30°C and the humidity was 21% which was later converted to 22°C and 60% humidity using the DIRAC 1:1 scale model conversion. S1R2 is selected and compared with the typical environment when concert hall is in use and ± 0.01 s difference is calculated for T30 values. The difference was even smaller for EDT values however, when examining the average of C80 values at this position, a notable reduction of 33% was calculated.

After the post-processing of RIRs, reverberation time (RT), early decay time (EDT) and clarity (C80) are assessed in 1/1 octave bands for open and closed states of side doors. The results are discussed in the following section.

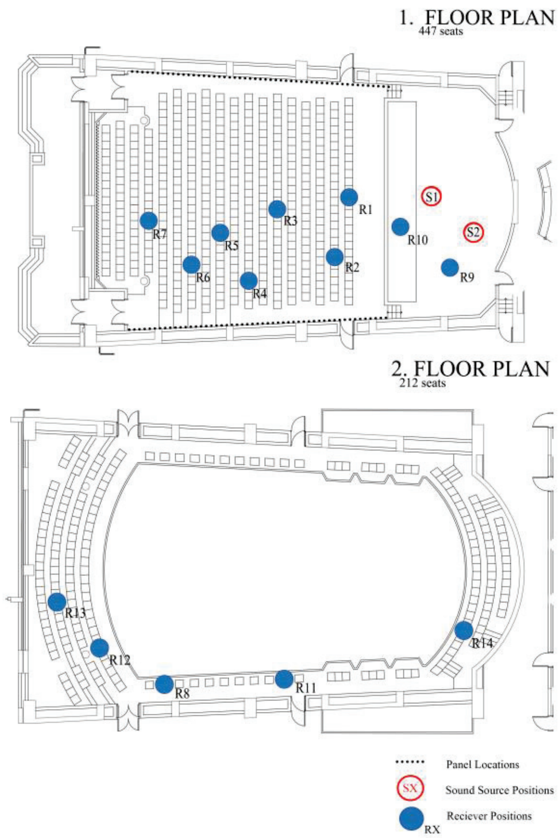

Figure 3. Sound source (S1-S2) and receiver positions (R1-R14) used at in-situ measurements

2.3. Questionnaire and Online Survey

Subjective acoustic evaluation of the Bilkent Music hall is investigated by conducting face-to-face questionnaires with 50 orchestra members and online surveys with 16 students and faculty members of Bilkent University Music Department. The aim of the questionnaire is to assess the acoustical preference of musicians and students with music background to measure the correlation between the subjective and objective acoustical variables. The scales are explained to participants prior and they are asked to answer questions according to their personal musical experiences in Bilkent Music Hall. The questionnaire comprises five major scales that test subjective 'Clarity', 'Reverberance', 'Envelopment', 'Intimacy' and 'Loudness' [5]. Three scales that judge acoustical balance between 'treble and mid-frequencies (B_TrebletoMid), 'bass and mid-frequencies (B_BasstoMid)' and 'singers/soloists and orchestra (B_SingertoOrch)' are used, in addition to one scale that judges 'background noise (Back_Noise)'. Overall impression is judged for 'chamber music (O_Chamber), 'orchestral music (O_Orchestra)' and 'orchestral music with choir and vocal accompaniment (O_OrchWithVocal)'. The responses were analyzed using SPSS (Statistical Package for Social Sciences) and are summarized in the following section. The internal consistency reliability of the scale is assessed using Cronbach's alpha coefficient (α=0.83), indicating high internal consistency among the items.

3. RESULTS

3.1. Field Test Results

In Fig. 4, Fig. 5 and Fig. 6, the average values of T30, C80 and EDT are presented with minimum and maximum values. The shortest T30 value measured is at 125 Hz with 1,29 s in the retracted state and 1,50 s in the closed state of the doors. The longest T30 value is measured at 1000 Hz with 1,97 s in the retracted state and 2,23 s in the closed state. At 500 Hz, the average T30 values are measured as 1,75 s in the retracted state and 2,01 s in the closed state of the doors.

According to the optimum ranges stated in Table 1, in the retracted state, T30 value at mid frequencies with an average of 1,86 s is too short for a music hall. Low frequency T30, with the average of 1,35 s, is even worse in that respect. Since the measurements are conducted in an unoccupied hall, these values are expected to become lower when the hall is occupied with musicians and audience. So, the major problem is the excessive bass absorption in the hall. When the doors are in the closed state, T30 values are still too short for symphonic music and, might be suitable for chamber music. According to Table 1, the reverberation in the closed state of doors at mid frequencies can be suitable for twentieth century pieces but still too short for romantic and classical period pieces. For piano, in the closed state, the reverberation at mid frequencies is in the suitable range, but might be too short for violin solos.

The bass ratio (BR), which is the ratio of reverberation times at low frequencies to mid frequencies, is calculated for both retracted and closed state of the doors. The BR for the retracted state is 0,72 while it is 0,74 for the closed state. In both states of the doors, it is lower than the ideal range stated in Table 1, therefore, not suitable for orchestral music. For musical performances, a longer reverberation in the low frequencies is desired so that the notes can reach their fullness when they are just generated by the instruments. In Bilkent Music Hall, at low frequencies (average of 125 Hz and 250 Hz), T30 value in the retracted state is 1,35 s which reveals the excessive absorption of low frequencies once again.

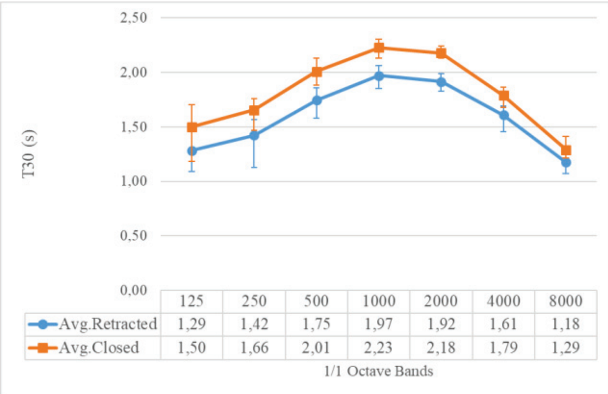

Figure 4. T30 values of Bilkent Music Hall for doors retracted and closed states

The Clarity (C80) values are presented in Fig. 5. for the retracted state of the doors. In that scenario, it is observed that C80 is in the range between -2 to +2, which is suitable for music performances. The proper values of clarity relate to both short reverberation times, but as well as the proper early reflections provided by the compact shape of the hall that is almost a shoe-box, in width-length-height proportions, but with a slight angle (2,69°) on the side walls towards the back of the hall. On the other hand, for the acoustic quality or overall impression in a music hall both clarity and reverberation time should be in the acceptable ranges. C80 value in 500 Hz for both states is in the optimum range for piano performances however, it is beyond the upper limit for violin performances with 1,69 dB in the retracted state and 1,13 dB in the closed state of the doors. The initial portion of the reverberant decay process relates more to the subjective assessment. Thus, early decay time (EDT) is highly correlated with the quality

of the perceived reverberance [11]. As it is presented in Fig. 6, the measurement results for EDT indicate that the average EDT at mid frequencies is 1,71 s in the retracted state and 2,0 s in the closed state. According to Beranek, the ideal EDT values for concert halls should be in the range of 1.8-2.2 [2]. Therefore, EDT values are in the acceptable range at mid frequencies in the closed state of doors.
In the closed state, the average T30 value at low frequencies is measured as 1,58 s in the unoccupied hall which is higher than the retracted state but still arguably too short for music performance spaces. This is resulted from the lack of thickness of the wood paneling material used on interior surfaces, both the variable doors and the hall in general, which absorbs low frequency sounds and acts as a bass trap. Therefore, it is observed that the existing variable sound absorption system also contributes to the unnecessary absorption at this state. In mid-frequencies, the avg. T30 value increases to 2.12 s which is suitable for symphonic music. In high frequencies, the T30 values are measured as 1,98 s in average, which is also suitable for orchestral music performances. When clarity (C80) at closed door state is compared to the retracted state, the values are lower but still in the acceptable range for music performances. For the closed state of doors, EDT is higher than the retracted state and measured almost the same as the T30 values. At low frequencies, the average EDT value is 1.50 s, which acts parallel with the T30 value in this frequency range. In mid and high frequencies in the closed state, the EDT value increases to 2,0 s and 1,81 s respectively which creates a suitable auditory environment for symphonic music. However, in this case, the difference between two states is only slightly perceivable therefore, the effectiveness of the system for different music types is found to be low.

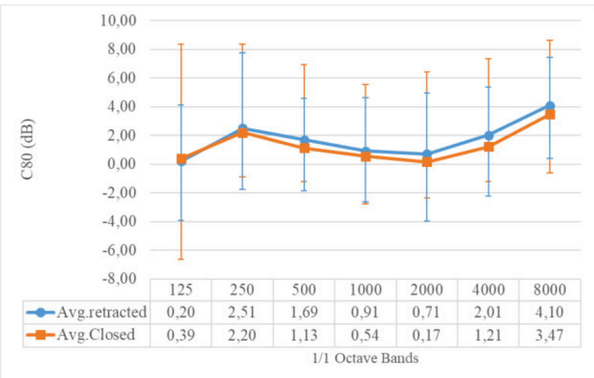

Figure 5. Clarity (C80) values of Bilkent Music Hall for retracted and closed states

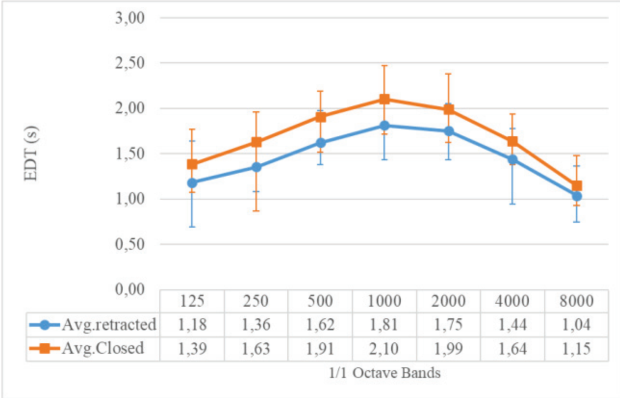

Figure 6. EDT values of Bilkent Music Hall for retracted and closed states

3.2. Questionnaire and Online Survey Results

In order to test whether there is a statistically significant mean difference between wind (n=22) and string (n=31) instruments for musicians' preferences of acoustic parameters, independent samples t-test is conducted and the results are presented in Table 2. According to the result of the independent samples t-test (p=0.05), no statistically significant difference for the major five scales ('Clarity', 'Reverberance', 'Intimacy', 'Loudness' and 'Envelopment') is found however for impressions of 'B_TrebletoMid', 'O_Orchestral' and 'O_OrchwithVocal', statistically significant results are recorded. This suggests that there are notable distinctions in the perceived acoustic characteristics between wind and string instruments in these specific areas. For the subjective evaluation of the concert hall's balance in terms of treble to mid frequencies, the ratings indicate that 6 musicians who play wind instruments and 16 musicians who play string instruments perceived the concert halls to be well-balanced. On the other hand, 9 musicians who play wind instruments and 4 musicians who play string instruments rated the same scale 'Slightly Weak' and 'Weak'.
In relation to the assessment of the concert hall for the scales 'O_Orchestral' and 'O_OrchwithVocal', it was found that 10 musicians who play wind instruments rated the concert hall as 'Good' and above for the 'O_Orchestral' scale, while 7 musicians who play wind instruments rated it as 'Good' and above for the 'O_OrchwithVocal' scale. Similarly, among musicians who play string instruments, 24 individuals rated the concert hall as 'Good' and above for the 'O_Orchestral' scale, while 19 individuals rated it as 'Good' and above for the 'O_OrchwithVocal' scale.

The overall acoustic quality for different performance types is evaluated by using a 7-point scale ranging from ‘Very Poor’ to 'Excellent. When assessing the acoustic quality, 39 participants rated it as ‘Good’ and above for chamber music, while 37 participants rated for orchestral music in the same range. Additionally, 20 participants rated the overall acoustic quality as ‘Mediocre’ and below for chamber music and 22 participants for rated the same for orchestral music performances. For orchestral music with vocal accompaniment, 28 participants rated it ‘Mediocre’ and below, 29 participants rated as ‘Good’ and above. Overall, while the majority of participants reported positive ratings for the acoustic quality of different performances, it is important to address the concerns raised by participants who rated the quality as 'Mediocre' or below. Also, it is concluded that musicians who play string instruments had higher ratings for scales that measure acoustical quality than musicians who play wind instruments.

Table 2. The results of Independent Sample Test conducted for wind and string instruments

Independent Samples Test		
	Levene’s Sig.	**Sig.(2-tailed)**
Clarity	0,018*	0,283 0,309
Reverberance	0,093	0,760 0,771
Envelopment	0,662	0,780 0,783
Intimacy	0,373	0,075 0,083
Loudness	0,832	0,078 0,077
B_TrebletoMid	0,028*	0,010 0,017*
B_BasstoMid	0,620	0,753 0,756
B_SingertoOrch	0,139	0,057 0,068
Back_Noise	0,753	0,046* 0,052
O_Chamber	0,480	0,233 0,248
O_Orchestral	0,040*	0,000 0,001*
O_OrchWithVocal	0,536	0,035* 0,035

The correlation analysis is conducted to examine the relationships between variables. The Pearson correlation coefficient is used to measure the strength and direction of these relationships. The variable ‘O_Orchestral’ showed the strongest positive correlation with ‘O_OrchWithVocal’ (r=0,719, p=0.01) which is as expected. On the other hand, the weakest correlation is between ‘O_Chamber’ and ‘Envelopment’ (r=0,282, p=0.05). The strongest positive correlation for ‘Envelopment’ is recorded with ‘Intimacy’ however, it is still moderate (r=0,483, p=0.01). On the other hand, ‘Intimacy’ has a stronger correlation with ‘Clarity’ (r=0,636, p=0.01), and three scales of overall impression (r>0.5, p=0.01) which means that positive overall impression for different performance types increases when ‘Intimacy’ increases. The ‘Intimacy’ also increases when ‘Clarity’ increases. ‘Intimacy’ also has a moderate correlation with the scales of acoustical balance. The impression of balance for treble to mid-frequencies, bass to mid-frequencies and for singer to orchestra increases when ‘Intimacy’ increases. Reverberance has only statistically significant correlations with ‘Clarity’ and ‘B_BasstoMid’ (r=0,344, p=0.01). ‘Loudness’ has a weak correlation with ‘O_Chamber’ and ‘O_OrchWithVocal’ but no significant correlation between ‘O_Orchestral’ which can be due to poor impression of acoustical quality for orchestral music.

When the data is grouped into musicians and faculty/students, all three scales representing the overall impression showed statistically significant differences (however, the unequal number of participants for each group also should be considered for this comparison). In the context of overall impression for chamber music, a rating of ‘Good' and below’ for the hall was given by 54% of musicians and 81% of faculty members and students. Similarly, for orchestral music, 54% of musicians and 90% of faculty members and students gave the same rating to the hall. In the case of vocal accompaniment, 56% of musicians rated the hall as ‘Good’ and below, while 90% of faculty members and students held the same opinion.

4. COMPARATIVE STUDIES

In this section, Bilkent Concert Hall’s acoustic conditions are investigated in comparison with other concert halls around the world. The primary source for this section is Beranek’s *Concert Hall and Opera Houses* since the detailed field measurement results of concert halls are available. Two different comparison studies are conducted which are according to volume and according to characteristics of variable absorption elements.

Reverberation time is used as main criterion since it is the only parameter that is available for all concert halls.

For the first comparison, concert halls with 500 - 1500 seating capacity and 5000 - 14000 m^3 volume are selected which are Hamarikyu Asahi Hall, Dai-ichi Seimei Hall, Stadt-Casino, Mechanics Hall, Kammermusiksaal der Philharmonie, Grosser Tonhallesaal, Seiji Ozawa Hall, Konserthus and Nielsen Hall. For the latter, in order to compare the variable absorption elements, Barbican Concert Hall, Dewan Filharmonik Petronas and Hong Kong Academy are selected.

In terms of volume/seat ratio, when compared to Dai-ichi Seimei Hall and Kammermusiksaal der Philharmonie, Bilkent Music Hall has a larger volume/seat for a concert hall with 707 seating capacity which can potentially contribute to better sound propagation and reverberation characteristics, however can also create a lack of intimacy and strength of the sound if sufficient early reflections are not provided. Compared to Hamarikyu Asahi Hall, which is the smallest hall in terms of volume and seating capacity, Bilkent Music Hall has a shorter reverberation time at low frequencies with 1,58 s in the closed state of doors while Hamarikyu Asahi Hall has 1,65 s.

In low frequencies, Bilkent Music Hall in the retracted state of doors has the shortest reverberation time with 1,36 s while Grosser Tonhallesaal has the longest with 2,45 s. Even Hamarikyu Asahi Hall and Dai-ichi Seimei Hall, which are the concert halls with the smallest volume, have higher reverberation times with 1,66 and 1,95, respectively. This indicates Bilkent Concert Hall's bass absorption is excessive even compared to other concert halls with smaller volume and seat capacity.

When mid-frequencies are considered, for highly rated concert halls, the reverberation time lies between 1,7 s and 2,0 s in occupied states. When compared, Nielsen Hall has the longest reverberation time of 2,2 s in occupied state while Bilkent Concert Hall is in the lower range even when unoccupied. In comparison with a concert hall with similar volume, Mechanics Hall has the reverberation time of 1,55 s occupied however it is also rated problematic for large orchestras and organ recitals.

Similar to Bilkent Music Hall, Konserthus is covered with 2,5 cm thick wood paneling on the interior that is prone to absorb bass sounds however, heavy materials such as 18 cm thick concrete is used to prevent the resonance while 19 cm thick brick wall is used in Bilkent Concert Hall. Konserthus and Bilkent Music Hall in retracted state has a reverberation time of 1,81 s and 1,86 s at mid frequencies respectively which make the halls suitable for classical and contemporary period pieces. In comparison with Bilkent Music Hall and Konserthus, Grosser Tonhallesaal has the reverberation time of 2,0 s at mid frequencies in occupied condition. However, the bass sounds in the main floor are rated unsatisfactory due to the thin wooden paneling used in the main floor.

In terms of EDT, Bilkent Music Hall in the retracted state also has the lowest EDT while Grosser Tonhallesaal has the highest. Except for Grosser Tonhallesaal, all C80 values are in the optimum range presented in Table 1. In terms of variable characteristics, similar to previous cases mentioned, a lack of strength in the bass sounds was observed in Barbican Concert Hall due to the thin wooden paneling which is similar to Bilkent Music Hall in the closed state of doors. In order to combat this issue, reflective panel system is installed that increases the reverberation time and enables to distribute the sound evenly to longer distances by adjusting the height and angle of the panels. In addition to wooden retractable doors, the wooden paneling on the interior of Bilkent Concert Hall can contribute to excessive absorption which will be analyzed in the further stages, through acoustical simulations.

Another concert hall with adjustable absorption, Dewan Filharmonik Petronas includes sound absorbing panels on the side walls in addition to a movable acoustic ceiling that modifies the volume for different purposes. When the concert hall is in half volume, which is sound absorbing state, the reverberation at mid-frequencies is similar to Bilkent Music Hall's retracted state with 1,65 s and when non-sound absorbing state, is similar with closed state with 1,96 s. However, at low frequencies, unlike Bilkent Music Hall, the reverberation time is over 2,0 s, which is ideal for orchestral music.

Hong Kong Academy for Performance Arts' rotating variable panel system on the side walls provides adjustability for reverberation time of 2,2 s for recording with a large orchestra and 1,7 s for rehearsals with a chamber orchestra [9]. When the volume/seat is compared to Bilkent Music Hall, the interior sound field is more suitable for symphonic music in the recording configuration.

5. CONCLUSION

According to field tests held in Bilkent Music Hall and the analysis conducted so far, the effectiveness of the existing variable absorption system is found to be inadequate. It is found that the system is decreasing the acoustical quality even further. When the reverberation times (T30) in 250 and 500 Hz are compared for two states of the variable system, it is 1.42 s and 1,75 s respectively in the retracted state while 1,66 s and 2,01 s in the closed state of the doors.

The 2 cm thick variable system doors act as a bass trap when they are closed, and in retracted state, the fabric backing is exposed to absorb more sound energy in the overall frequency spectrum. For that reason, bass ratio of the hall is 0,72 in the retracted and 0,74 in the closed state of the doors, which are much lower than in precedent cases.
According to Barron, for the variable absorption system to be perceivably effective, the differences between reverberation time in both states should be significant [3]. However, Bilkent Music Hall, approx. 0,2 s difference between open/closed stated of the doors is not much of a noticeable difference, moreover the system is not functioning for the sake of mostly dominant activity in the hall which is symphonic music.
The questionnaire results showed a significant difference between preferences of musicians' who play wind and string instruments for scales related with treble to mid balance, and overall impression for orchestral music. The musicians who played string instruments rated higher for acoustical quality for different performance types than musicians who play wind instruments.
In order to improve the acoustical performance in this hall, bass absorption problem should be fixed by proper door details as well as increased thickness of wooden surface finish is necessary to increase reflective properties of overall wooden wall surfaces. It should also be noted that in order to make accurate suggestions, further investigations should be conducted. Future work will include acoustical simulations to assess the existing situation and test alternative design solutions to improve acoustical quality for different music performances.

6. ACKNOWLEDGMENTS

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