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Predicting the acoustic performance of concert Halls

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ABSTRACT: Predicting the acoustic outcome and acceptance of a concert performance hall by its users could be a difficult and onerous task even for an acoustician. This paper discusses a process of how previous research findings from expert authorities have been assembled into a method of evaluating acoustic hall performance. Several parameters of acoustic qualities and quantitative measures have been identified in the literature. These relate to Beranek’s acoustic variables of performance. Existing famous concert halls which have been previously evaluated and rated are now studies in terms of their results from a computer simulation. The research findings suggest that the use of a simulation program can be extremely accurate in the prediction of acoustic performance of new non-existing concert halls.

Conference theme: construction, computer simulation
Keywords: Acoustic, Concert Hall, Performance, Simulation

1. INTRODUCTION

Concert halls are usually large projects involving costly investment. Hence, proper evaluation on the acoustic quality of concert halls is essential to guarantee investment with value. Moreover, acoustic quality can be greatly improved for a concert hall during the design stage rather than after completion of the project. Computer based acoustic evaluation programs allow this to be done and allow a concert hall to be calculated with cost effective improvements.

This research aims to predict the acoustic outcome and acceptance of a concert performance hall, based on a set of criteria which can be identified in defining acoustic quality and performance. An investigation is performed to examine the validity of using a computer based acoustic evaluation program – BOSE Modeler (BOSE Corporation, 1994). It is intended that if successful, costly traditional subjective concert hall analysis methods can be replaced by simulation.

2. BACKGROUND

2.1 Acoustic attributes for concert halls

Various scientists and acousticians around the world have developed the selection of ‘acoustic attributes’ into an objective acoustic rating system. The major contributors involved in the development and discovery of these acoustic attributes development are summarized below:

*Development of Acoustic Attributes*

<table>
<thead>
<tr>
<th>Peoples Involved</th>
<th>Year</th>
<th>Findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beranek Studies</td>
<td>1962</td>
<td>18 subjective acoustic attributes</td>
</tr>
<tr>
<td>Hawkes and Douglas</td>
<td>1971</td>
<td>5 independent acoustic dimensions</td>
</tr>
<tr>
<td>Marshall and Barron Studies</td>
<td>1967-81</td>
<td>Inter-Aural Cross Correlation Coefficient (iACC)</td>
</tr>
<tr>
<td>Goettingen Studies</td>
<td>1970-74</td>
<td>Attributes: IACC, RT, Clarity (C50)</td>
</tr>
<tr>
<td>Berlin Studies</td>
<td>1970-76</td>
<td>Attributes: Strength value (G) &amp; Clarity (C80)</td>
</tr>
<tr>
<td>Yamamoto and Suzuki</td>
<td>1976</td>
<td>Relationship: Loudness with sound level (G)</td>
</tr>
<tr>
<td>Kimura and Sekiguchi</td>
<td>1976</td>
<td>Relationship: Attributes, width, room volume</td>
</tr>
<tr>
<td>Ando</td>
<td>1985</td>
<td>Attributes: IACC, Intimacy (l), RT, Loudness (G)</td>
</tr>
<tr>
<td>Barron</td>
<td>1988</td>
<td>Reverberance, envelopment, intimacy correlated</td>
</tr>
<tr>
<td>Gade</td>
<td>1985-91</td>
<td>Relationship: RT, Early Decay Time (EDT), (C90)</td>
</tr>
<tr>
<td>Vian and Perlorsen</td>
<td>1991</td>
<td>Possible unknown in attributes findings</td>
</tr>
<tr>
<td>Beranek</td>
<td>1996</td>
<td>Six dominated acoustic variables</td>
</tr>
</tbody>
</table>

Source: Beranek (1996)

Figure 1: Summary of the development of acoustic attributes
According to the literature, experts apply the Beranek (1996) study as the standard for acoustic attributes and concert hall ratings. Beranek concluded that there are six statistically dominated independent acoustic variables to be applied to rate acoustic quality. These are based on the findings from Ando’s previous study in 1962. The combined works of Beranek and Ando have established the following acoustic attributes:

- **Inter-aural Cross-correlation Coefficient (1-IACC<sub>E3</sub>)**
  
  IACC is a measure of the difference in the sound arriving at the two ears of a listener facing toward the stage. It is subjectively linked to perceptions of spaciousness in the hall.

- **Initial-time delay gap (t<sub>1</sub>)**
  
  t<sub>1</sub> is the difference in the time arrival between the direct sound and the first reflection arrival to the position at the centre of the main floor. It is correlated with the subjective feeling of intimacy. This is taken for a position at the centre of the main floor, about halfway between the stage and first balcony front. It is the scientific method of measuring the feeling of intimacy in concert halls.

- **Strength Factor (G)**
  
  G<sub>mid</sub> is a ratio expressed in decibels for mid-frequencies (500 and 1000Hz). It is the strength of sound pressure level at a point in the hall that comes from the omni-directional source to the sound pressure level from the same source operating in an anechoic chamber at a distance of 10m. This correlates to the subjective feeling of loudness.

- **Early Decay Time (EDT)**
  
  This variable is measured at a similar manner as Reverberation Time (RT). This variable indicates the reverberance level in halls. However, the result of EDT is taken as the mid-frequency (500 and 1000Hz) sound level decay in the hall from 0 to 10dB, then multiple the values with 6 to allow comparison.

- **Bass Ratio (BR)**
  
  Bass ratio is determined by the equation:

  \[
  \frac{RT_{125} + RT_{250}}{RT_{500} + RT_{1000}}
  \]

  It is calculated by the reverberation time (RT) ratio between low and middle frequencies. A value of the Bass Ratio is correlated to the subjective feeling of warmth in concert halls.

- **Surface diffusivity index (SDI)**
  
  This is the most inaccurate variable when compared with the rest of the five, as it requires personal judgment on the visual inspection of the irregularities of the ceiling and side walls in the concert hall. This method and procedure was developed by Haan and Fricke in (1993) and adopted for concert hall rating by Beranek. The irregularities of surfaces were weighted with a scale from high to low diffusivity.

Nevertheless, as Beranek and other experts declare, there are remaining unknown attributes that can affect acoustic quality. The proposed comprehensive, but not yet ideal Beranek analytical method, has yet to be improved to increase in its validity.

### 2.2 Rating concert halls

A rating system for concert halls is developed based on both subjective and objective evaluations of the acoustic attributes. The rating system documented in Beranek’s *Concert and Opera Halls, How they Sound* (1996), is the most recognized concert hall rating system produced. Based on the findings from literature, Fricke (1995) and Beranek (1996) have refined previous acoustic attributes and summarized them into a rating system that is typically used today. This rating system proposes a total of six categories of rating. Some concert halls analysed by Fricke and Beranek are getting a different rating due to their Acoustic Quality Index (AQI) and are located at marginal range in the categories.

These six categories rating for concert halls are used in Beranek’s study in 1996 for the 66 concert halls around the world. The data is provided by interviewing different musicians and consultants. Professor Fricke and his doctoral student Chan H. Haan in 1993 did another study comparing the concert hall ratings with Beranek’s results of 1962. They collected a series of surveys from musicians and music critics to evaluate the acoustics of halls using a self-administered questionnaire (Fricke, 1995). These results have queried the judgment of several concert halls ranked by Beranek.
3. METHODOLOGY

Given the assumption that Beranek’s acoustic attributes and system of evaluation has some merit, the foremost question in this paper asks: “Is there a tool or method which can be applied in the evaluation of a concert hall before it is built?” As stated previously, subjective acoustic attributes and their rating will be compared with the objective results from a computer simulation tool. To achieve this task, a research methodology has been developed and outlined towards testing the validity of the computer simulation tool. Figure 2 is a flow diagram illustrating the methods and processes of performing an acoustic quality analysis of concert halls.

**Figure 2: Methodology of performing acoustic analysis for concert halls**

It is hypothesized that subjective acoustical attributes and ratings can be converted into objective acoustic analysis through the use of a computer simulation program. There are three tasks to assess this hypothesis:

- Testing the accuracy of using a computer evaluation program as an acoustic evaluation tool
- Comparing existing concert halls rated by Beranek method with results of the tested program capabilities.
- Investigate the methodology and limitation of the tested program

The ‘validity study’ is performed by analysing four previously rated international concert halls by Beranek. Models of the four concert halls constructed in BOSE Modeler are based on plans and sections from the literature. Results from
BOSE Modeler will be extracted, calculated and converted into the Beranek acoustic variables to permit a comparison among the rating for a particular concert hall.

Based on the comparison between the results from BOSE Modeler and Beranek, the validity of the method will be assessed. The method developed will then be applied to investigating the acoustic quality of another concert hall, which has not been previously rated. Limitations of the computer simulation program are assessed. Discussion of the concert hall performance and their concert hall ratings will be examined through comparison.

As discussed previously Beranek’s studies have determined six statistically independent variables that are related to the acoustic quality in concert halls. These acoustic attributes from Beranek and their comparison to results from the simulation are illustrated below.

### Figure 3: Measurable variables by both analyse methods

#### 3.1 Choosing of Case Studies
The selection of case studies was based on their concert hall rating categories, significance of design, and availability of acoustic data from literature for comparison. Five concert halls have been chosen for study:

1. Boston, Symphony Hall
2. Berlin, Philharmonic Hall
3. Sydney, Opera House Concert Hall
4. London, Barbican Concert Hall
5. Geelong, the Great Hall

#### Figure 4: Case studies concert hall photos and simulation models

1. Boston, Symphony Hall - The symphony Hall is a category A+ concert hall by Beranek halls ranking system. It was a rectangular shape hall built in 1900. It is one of the best halls in the world, so the hall is vital for selecting as a case study in this research.

2. Berlin, Philharmonic Hall - This hall is categorized as “A” grade hall by Beranek. The seating layout in the hall is very different from the others. It was designed to breaking the audience into blocks, so that the first row in each block receives unimpeded direct sound. The orchestras are placing in the centre of hall to allow audience and musicians from communicating freely and intensely. Selecting of this hall for study is based on its ranking category and unique shape of the hall.
3. Sydney, Opera House Concert Hall - One of the world's landmarks built in 1973. Similar to the Berlin Philharmonic Hall, the performance stage for orchestras is not placed at one-end of the hall. It is in the 1/3 position of the hall. The hall receiving category B+ ranking from Beranek and is considered as above average performance concert hall.

4. London, Barbican Concert Hall - This concert hall was in category C+ from Beranek study. This hall is selected as a relatively poor performance concert hall among the case studies. The acoustic performance in the hall has received unsatisfactory reviews. Most of the acoustic deficiencies feedback are lack of bass and delayed reflection for walls. This is the only fan-shaped hall among the five selected case studies.

5. Geelong, the Great Hall - The Great Hall is the second largest concert hall in Victoria, Australia, behind the Victoria Arts Centre’s Melbourne Concert Hall. It sets the acoustical standard and quality for a campus concert hall. Since it is a relatively new hall among the five case studies, there is lack of acoustic data from the literature.

4. RESULTS

Between the four known case studies, Boston has the best ‘acoustic attributes’ which contribute to its superior performance. By comparing the two tables below, the objective results from BOSE Modeler are generally quite similar to the subjective data from Beranek. There are two ‘acoustic attributes’ results cannot be use for comparison: Inter-Aural Cross-Correlation Coefficient (1-IACCE3) and Surface Diffusivity Index (SDI). IACC cannot be precisely simulated in BOSE Modeler, as the acoustic attribute requires measuring the difference of sound arriving at the two ears of a listener. In BOSE Modeler, listener is simulated as a point receiver and cannot demonstrate the reception difference between two ears. SDI value is based on visual inspection of the irregularities of surfaces. Therefore, the SDI values of the case studies are the same in Beranek and BOSE Modeler.

<table>
<thead>
<tr>
<th>Acoustic Attributes Values from Literature</th>
<th>RT (sec)</th>
<th>1- IACCE3</th>
<th>t1 (sec)</th>
<th>Gmid</th>
<th>EDT (sec)</th>
<th>BR</th>
<th>SDI</th>
<th>Volume (m^3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boston, Symphony Hall</td>
<td>1.85</td>
<td>0.65</td>
<td>15</td>
<td>4.70</td>
<td>2.37</td>
<td>1.03</td>
<td>1.0</td>
<td>18750</td>
</tr>
<tr>
<td>Berlin, Philharmonic Hall</td>
<td>1.90</td>
<td>0.46</td>
<td>21</td>
<td>4.30</td>
<td>2.10</td>
<td>1.01</td>
<td>0.8</td>
<td>21000</td>
</tr>
<tr>
<td>Sydney, Opera House Concert Hall</td>
<td>2.20</td>
<td>0.55</td>
<td>36</td>
<td>3.75</td>
<td>2.20</td>
<td>0.98</td>
<td>1.0</td>
<td>24600</td>
</tr>
<tr>
<td>London, Barbican Concert Hall</td>
<td>1.60</td>
<td>0.46</td>
<td>27</td>
<td>3.40</td>
<td>1.90</td>
<td>1.07</td>
<td>0.2</td>
<td>17750</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Acoustic Attributes Values calculated by BOSE Modeler (developed method)</th>
<th>RT (sec)</th>
<th>1- IACCE3</th>
<th>t1 (sec)</th>
<th>Gmid</th>
<th>EDT (sec)</th>
<th>BR</th>
<th>SDI</th>
<th>Volume (m^3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boston, Symphony Hall</td>
<td>1.88</td>
<td>0.65</td>
<td>12</td>
<td>4.30</td>
<td>2.20</td>
<td>1.16</td>
<td>1.0</td>
<td>18613</td>
</tr>
<tr>
<td>Berlin, Philharmonic Hall</td>
<td>1.92</td>
<td>0.46</td>
<td>16</td>
<td>3.90</td>
<td>2.03</td>
<td>0.96</td>
<td>0.8</td>
<td>22446</td>
</tr>
<tr>
<td>Sydney, Opera House Concert Hall</td>
<td>1.63</td>
<td>0.55</td>
<td>25</td>
<td>2.80</td>
<td>1.81</td>
<td>1.09</td>
<td>1.0</td>
<td>23171</td>
</tr>
<tr>
<td>London, Barbican Concert Hall</td>
<td>1.71</td>
<td>0.46</td>
<td>50</td>
<td>3.80</td>
<td>2.20</td>
<td>1.07</td>
<td>0.2</td>
<td>19248</td>
</tr>
</tbody>
</table>

Table 2: The resulting six acoustic attributes of the case study halls by Beranek and BOSE Modeler

The results illustrated that the Sydney Opera House concert hall case study comparison has the largest error. Reverberation time of the hall by the simulation program is much lower than the reverberation time value in the literature. This is due to the limitation of the simulation program. Among the ‘acoustic attributes’, Initial Time Delay Gap (t1) is significantly different when comparing simulation with Beranek’s results. This is noticed in the London, Barbican Concert Hall study where the t1 value from simulation program is almost doubled the result documented in Beranek’s study.

Figure 5 illustrates the concert hall rating differences between simulation and literature. The Acoustic Quality Index (AQI) is used for categorizing performance of concert halls. The Great Hall, Geelong, due to lack of sufficient data from literature, was not used for comparison. Instead, it will be analysed by the developed method as a simulation prediction.
Comparing Concert Halls Rating:
Developed Method vs Beranek Results

<table>
<thead>
<tr>
<th>Concert Halls (case studies)</th>
<th>Acoustic Quality Index (AQI)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Documented in Beranek</td>
</tr>
<tr>
<td></td>
<td>Calculated by BOSE Modeler</td>
</tr>
<tr>
<td>Boston</td>
<td>-0.30</td>
</tr>
<tr>
<td>Berlin</td>
<td>-0.58</td>
</tr>
<tr>
<td>Sydney</td>
<td>-0.65</td>
</tr>
<tr>
<td>Geelong</td>
<td>-0.99</td>
</tr>
<tr>
<td>London</td>
<td>-1.28</td>
</tr>
</tbody>
</table>

Category A+, A      Category B+  Category B, C+, C

Figure 5: Comparing concert halls ratings between literature and developed method

The London Barbican Concert Hall has a poorer rating value when analysed by BOSE Modeler. The AQI value of the hall has significantly changed from -0.99 to -1.28. The difference on AQI value has not changed the concert hall rating, but it suggests that there is still room for improvement in the comparison between simulation and the Beranek findings.

Figure 5 has demonstrated the rating category differences undertaken by the two methods. Concern hall rating categories of the Berlin, Philharmonic Hall and Sydney, Opera House Concert Hall are different. Since the rating indices of both halls in literature are located near the category’s border, minor changes on the AQI index may influence the overall concert hall rating. Based on the simulation results, the AQI value of the Berlin case study has changed from -0.58 to -0.65, which changed its concert hall rating from category A to B+. The Sydney case study, on the other hand, has changed its rating from B+ to category A due to differences of AQI values. The concert hall rating of Boston Symphony Hall analysed by both methods are similar, and do not contribute to any rating category change.

4.1 Accuracy testing of the acoustic evaluation program

The accuracy of the program can be checked by analysing the error percentage on various acoustic attributes. No comparison is made between the Inter-Aural Cross-Correlated Coefficient (1-IACCE3) and Surface Diffusivity Index (SDI) attributes.

Figure 6: Accuracy testing of the acoustic evaluation program by comparing methods

Figure 6 illustrates that the Initial Time Delay Gap (t1) has the highest percentage of error among the evaluated attributes. The error has 39.91%, which is very questionable. Other than the above finding, the rest of evaluated acoustic attributes are showing a high degree of accuracy. The calculated volumes of the case study concert halls are very similar to the actual concert hall's volume. The errors on volume calculations are just 5.47% which is related...
to the complexity of modelling. EDT, BR, RT and \( G_{\text{red}} \) results are showing an average of 10% error which is satisfactory for concert hall acoustic performance prediction. These four acoustic variables are also closely related to the volume of concert halls, so high accuracy on volume calculation can enhance the precision of final results.

Using BOSE Modeler by the developed methodology to perform simulation analysis has an average of 14.93% error. It is lower than the expected 20% on acoustic performance prediction. Therefore, the developed method in this research can be classified as valid.

5. DISCUSSION

5.1 Validity of using simulation program for acoustic analysis

Based on the findings, applying the BOSE Modeler for concert hall acoustic performance prediction is reliable and legitimate. Average percentage errors among the tested acoustic attributes are within 15% deviated from Beranek's study. Concert hall rating of the case studies generally fall into the same category as in the literature. Exceptions such as the Berlin Philharmonic Hall and Sydney Opera House Concert Hall have changed their rating categories due to marginal difference in the Acoustic Quality Index (AQI) value.

Among the tested variables, the Inter-Aural Cross Correlation Coefficient (1-IACCE3) and Surface Diffusivity Index (SDI) do not contribute to the errors of the study. IACC, as stated previously, is impossible to measure through the simulation program. SDI value, on the other hand, is judged based on visual impression, and should be identical between literature and tested method. Initial Time Delay Gap (\( t_1 \)) has contributed to the largest percentage of error due to the limitation of the simulation program. Concert hall rating based on the developed method is at best 18.35% in error from the literature result. It is acceptable and better than the expectation of 20% in error from the literature result.

5.2 Limitations and errors of the developed method

There are certain limitations and errors inherent in this study. These limitations are categorized into two main aspects, based on the source of information and limitation of the simulation program.

**Source of information**

Although there is a comprehensive material library in the BOSE Modeler program for 100 common materials that can be selected for model construction, technical data such as absorption coefficient of the actual materials performance for concert halls are not abundant. Furthermore, walls and surfaces in concert halls are commonly use heterogeneous materials and multi-layer construction. Absorption coefficient of the default materials may differ from the real scenario. Drawing, section and specification of concert halls are inadequate for having a comprehensive analysis; however, availability of information can largely improve the accuracy of the simulation.

**Program limitation**

BOSE Modeler can be a difficult modelling tool. It is difficult to build complicated models with the program. During the modelling phase, walls, seating areas and ceilings are represented as a single layer of surfaces. Although the program allows choosing the surface to be either specular or scattering, thickness of the surface is neglected. This limitation contributed to differences on materials properties and the volume measured by the program.

From the experience of this research, complicated concert hall models are having less reliable results than simple geometric models. It is due to the difficulties to measure this acoustic variable in complicate models, such as Berlin Philharmonic Hall, and Sydney Opera House Concert Hall. The results are often shows incorrectly in the models.

The different between direct sound and first order of reflection is largely dependant on the ray tracing method. Complicated models may increase the possibility of errors during calculation.

Effects of ceiling reflectors are not significant in the case study models. This phenomenon especially happens on the Sydney Opera House Concert Hall. The 21 “Acoustic Rings” are specially design to suspending above the performance stage aims to reflect sound to a further distance without any distortion. However, this effect is neglected by the simulation program.

Most of the calculated results by the program are presented by graphical method instead of numeric values. Acoustic variables, such as Early Decay Time need to manually measure from the decay curve which may contribute to errors.

As stated earlier in the methodology paragraph, Inter-Aural Cross Correlation Coefficient (1-IACCE3) is impossible to measure by BOSE Modeler, and it contributed to the limitation of the program.

5.3 Benefits of using evaluation programs in replacing traditional analysis methods

Acoustic evaluation programs are often released as a universal analysis package. Once a virtual model has built for the evaluation, different analysis can be performed. The results are usually calculate automatically as user selected, and present graphically to the clients. Changes can be easily made by changing parameters of the model. Therefore, quick analysis and prediction is possible. It is an advantage of using simulation this with traditional analysis methods.

Traditional subjective analysis often requires long preparation. Design of questionnaires, contact subjects for interview are often time consuming and the feedbacks are often have no guarantee. Traditional objective methods,
although can perform analysis with high degree of accuracy, however, costly equipments and high level of techniques are required.

While comparing traditional methods with recent acoustic evaluation programs, simulation tools can always perform analysis in a cost-effective way. Mobility of using acoustic evaluation programs with handheld equipments allows measurement and simulations to be done anywhere in a short period of time. Different concepts and improvements can be tested with the tools by simply changing parameters in the virtual space. Some programs also allow auralisation for the clients to experience the virtual environment acoustically.

Some people may concern on the validity of using the new methodology and computer-based acoustic evolution tools. Based on the finding in this research, it is proved to be valid of using the simulation programs for concert hall acoustical design predictions. It is recommended that more acoustic evaluation programs should be tested to have a more comprehensive analysis on the validity of the methodology.

6. CONCLUSION

Based on the Beranek (Ando) study, the developed method by using BOSE Modeler for concert halls evaluation has tested to be valid. Although errors of using the developed method for acoustic evaluation are as little as 15% of average in this research, it should be reminded that, this methodology is good enough for acoustic quality prediction. It should be realised that this is the first effort in a continued study on acoustic simulation tools that predict 'acoustic attributes' of Beranek for concert hall performance. It is anticipated that in the future programs such as Odeon or EASE will be assessed for their capabilities of prediction.

The developed method with the studied tool is sufficient to produce constructive analysis prior to concert hall construction. Different concepts and improvements can be quickly tested and tuned for improving acoustic quality of a space. Acoustic evaluation tools and the developed method can be used to analyse proposed concert halls or to evaluate feasible concepts on designs.

There is room for improvement in the simulation tool in matching particular 'acoustic attributes' such as the Initial Time Delay Gap (t1). Other 'acoustic attributes' such as Inter-Aural Cross-correlation Coefficient (1-IACCCD) and Surface Diffusivity Index (SDI) require a more legitimate method of assessment through the simulation program of their approach is to be commonly applied. Nevertheless the above study provides a useful analysis of computer simulation in the prediction of ranking unknown concert halls with those of international standing.

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