A Preliminary Numerical Model to Predict the Overall Acoustical Quality of a Concert Hall

BUMJUN KIM
University of Florida

INTRODUCTION

On the basis of physically measurable data, developing a numerical model to decide the acoustical quality of concert halls is the purpose of this paper. Developing a model to decide the acoustical quality of concert halls has been attempted by many researchers in the past using different methods. For example, Ando found that four orthogonal (statistically different) subjective parameters play an important role in judgments of acoustical quality: 1.loudness (G); 2.intimacy(t_I); 3.reveberance(RT); 4.the difference in the sound at the two ears (IACC). He devised a rating system that combined those four parameters in single rating figure (Ando, 1985). Beranek defined eight positive acoustical attributes (RT, EDT, C_{80}, (1-$IACC_{E3}$), t_I, G_{mid}, BR, and SDI) assuming that these attributes were independent and linearly additive. For each attribute he assigned points and added those points to compare with categorized rating points to decide the quality of the halls (Beranek, 1962 & Hawkes, R & Douglas, H., 1971). In the early 1970's two German universities (Goettingen & Berlin) performed test to determine acoustical parameters affecting subjective acoustical quality. In the Goettingen University study, music recorded in anechoic condition was used and for the Berlin study live orchestra music was used. From the response of listeners about qualities of the halls and physical acoustical attributes measurement data, acoustical attributes which most influencing subjective judgments was determined by a "factor analysis" (Beranek, 1996). Barron used subjective questionnaires to determine the quality of concert halls. He conducted listening experiments using expert listeners as subjects and analyzed relationships between overall hall qualities and acoustic parameters involving Clarity, Reverberance, Envelopment, Intimacy, Loudness, Balance, and Background Noise (Barron, 1988).

In this study, regression analysis was used to develop a preliminary numerical rating model. The model was devised through analyzing statistical relationships between existing physical measurement data made in 37 concert halls and overall judgments of the acoustical quality of the halls reported in Beranek (1996). This rating model can be used in the initial stages of the design of a concert hall and also in the value-engineering process in the quality improvement process of an existing hall. To architects, this rating model can be a guideline and an experimental tool in examining modifications of features and their effects on overall hall quality.

Need for This Study

Building a concert hall is quite different from making a musical instrument. Musical instrument craftsmen try to imitate a masterpiece and make similar sound. However, architects do not generally work this way. In architecture, every hall design is different, materials are different, and construction and design constraints are different (Beranek, 1996). For these reasons, to create exactly the same acoustic conditions and predict the acoustical quality of a hall has been difficult.

Recently, due to the development of modeling techniques, the characteristics of some acoustic phenomena such as reflection and absorption are understood and to some extent the prediction of acoustical quality is possible. For example, computer modeling techniques enable one to estimate physical acoustic parameters. However, it is hard to predict the actual acoustic quality of a hall as it is evaluated by human listeners on the basis of this information. Auralization methods offer the

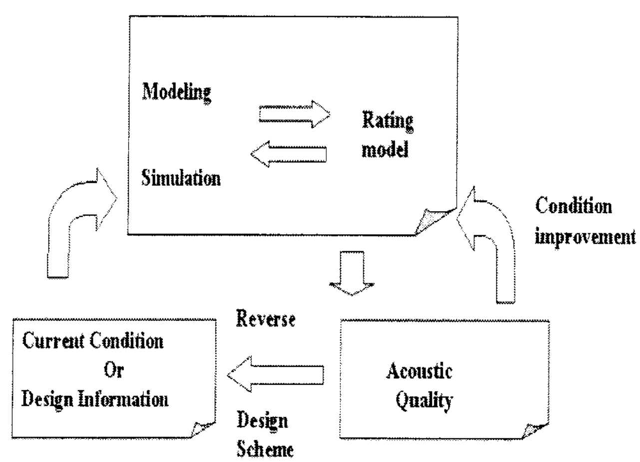


Fig 1. Diagram of the Acoustic Quality improvement process using a prediction model

In deciding the overall acoustic quality of an entire concert hall, a numerical rating model can be useful. By inputting acoustic parameters data obtained through modeling and simulation, the quality of a hall can be decided using an ordinal scale. This method is more useful in maximizing acoustic quality when designers are faced with the existence of material, financial or design constraints. Available parameters can be tested using simulation techniques and the effect on acoustic quality can be tested through the quality rating model. The overall acoustic quality of a hall and the effect of the constraints can be maximized at the same time through this method.

Objective Aoustic Quality Rating Model

The appreciation of music acoustics is multi-dimensional (Barron, 1993). On the basis of psycho-acoustic studies, several subjective acoustic qualities; Envelopment and source width, Clarity, Reverberance, Loudness, Intimacy, Warmth, Brilliance, Spaciousness, Localization of sound, Balance, Blend, Texture, and Ensemble play important roles in the judgment of acoustical quality (Siebein & Kinzey, 1998; Beranek, 1996). For example, in order to provide good acoustical quality, the clarity should be adequate to enable musical detail to be appreciated, the reverberance should be long enough to provide richness of sound, and the audience should feel themselves surrounded by sound and proper loudness (Barron, 1993). These acoustic qualities can be divided into 2 categories; physically measurable and qualitatively measurable. A summary of these qualities is provided in Table 1.

Table 1. Acoustical parameters and their measurement method

	Acoustic Quality	Acoustical Parameters that decide Acoustic Quality
Physically Measurable	Envelopment and source width	Lateral energy fraction (LEF)
	Clarity	Clarity index (C80)
	Reverberance	Reverberation time (RT)
	Loudness	Loudness (L) or Relative strength (G)
	Intimacy	Initial time delay gap (t_I)
	Warmth	Bass ratio (BR)
	Brilliance	Treble ratio (TR)
	Spaciousness	Interaural cross correlation (IACC)
	Localization of sound	Early loudness level

	Acoustic Quality	Acoustical Measurement that decide Acoustic Quality
Qualitatively Measurable	Balance	Listener's subjective impression
	Blend	Listener's subjective impression
	Texture	Listener's subjective impression
	Ensemble	Listener's subjective impression

This study is to develop a numerical measurement model that related only physically measurable acoustic qualities to the overall acoustic quality of the halls. Therefore only physically measurable acoustical qualities were considered.

Data Collection

Acoustical measurement data for 37 halls used for the model formation are listed in Table 2, with their acoustical parameters: $(1\text{-}IACC_{E3})$, t_I, G_{mid}, EDT, BR, and SDI. The data were all derived from Beranek (1996) and are defined below.

"The IACC (Interaural cross-correlation coefficient) is a measure of the difference in the sounds arriving at the two ears at any instant. If the sounds at the ears were to be completely different, the value of (1-IACC) will be 1.0, meaning that the correlation between the sounds at the two ears is zero. At the other extreme, a sound wave that arrives from straight ahead will engage the two ears alike (perfect correlation) and the value of (1-IACC) will take on the value of 0.0, meaning no spatial impression. In concert halls, the values lie in between. 'E' means early. This value is obtained when only the sounds arriving at a listener's position within 80msec after the direct sound are considered. It was found that four of the six frequency bands are equally important in determination for different concert-hall conditions, namely, the 500, 1000, 2000, and 4000 Hz bands. However, the loudness of symphonic music in the 4,000 Hz band is considerably less than in the other three bands, so that the most sensitive formulation of IACC is to eliminate that band. This leads to $IACC_{E3}$" (Beranek, 1996, p.463).

"t_I (the initial-time-delay gap), the time interval in msec between the arrival at a seat in the hall of the direct sound from a source on stage to the arrival of the first reflection" (Beranek, 1996, p.570).

"G_{mid} is a measure of the strength of the sound at seats in a hall from a loudspeaker source that has a known power output. It is the average of the measured values at 500 and 1,000 Hz and as the average of these values measured at 8 to 20 positions in a hall" (Beranek 1996, p.512).

"EDT (Early Decay Time) is a modified measure of Reverberation Time. Reverberation Time is the time required for a sound to decay 60dB whereas the Early Decay Time is the time required for the first 10dB of decay multiplied by 6 to extrapolate the result to a 60 dB decay" (Siebein & Gold, 1998, p.3-7).

"BR is the ratio of two reverberation times for an occupied hall. The denominator is the average of the RTs at 500 and 1,000Hz and the numerator is the average of the RTs at 125 and 250 Hz" (Beranek, 1996, p.513).

"SDI (Surface Diffusivity Index) is used to measure the relative amount of sound diffusing material in a room based on its visual appearance. SDI developed by Haan and Fricke (1993) is hard to determine with a desired degree of accuracy. It amounts to a visual inspection of the ceiling and sidewalls (neglecting end walls). The degrees of diffusivity are area weighted" (Beranek, 1996, p.513).

Acoustic quality was decided by professional musicians, who performed regularly in many auditoriums. Questionnaires were used in deciding the quality of the halls. A numerical value of "1" was assigned as "excellent", "0.5" as "good", and "0" as "mediocre." An acoustic quality index (AQI) for each hall quality was decided by normalizing all responding values by the number of responses. The study resulted in the following categories; "Superior," AQI:1.00 to 0.90, "Excellent," AQI:0.90 to 0.63, "Good to Excellent," AQI:10.63 to 0.40, "Good," AQI:0.40 to 0.25, and "Fair," AQI: less than 0.25 (Beranek, 1996). Due to possible inaccuracy of the rank orderings that resulted from the interviews and sequence that results from the computational method, 37 halls were classified into 3 categories of A, B, and C (Beranek, 1996). These rankings were translated to values of 3,2, and 1 in this study.

Deciding hall qualities are difficult. In deciding overall hall quality not only acoustical characteristics but also non-acoustical factors can affect the decision-making process. Preconceived notions regarding the hall that was evaluated from past experiences or anecdotes from other testers also could affect decisions on hall quality (Siebein &Gold, 1998).

Table 2. Acoustical parameter data for 37 halls (Beranek, 1996)

ANALYSIS AND RESULTS

Several components are very important in deciding the overall acoustic quality of a hall: Six physically measurable parameters; (1-IACC_{E3}), t_I, G_{mid}, EDT, BR, and SDI were

Name of Hall	(1-IACC_{E3})	t_I	G_{mid}	EDT	BR	SDI	Quality
Amsterdam, Concertgebouw	0.62	21	4.3	2.2	1.08	1	3
Baltimore, Meyerhoff Hall	0.54	13	4.1	2.3	1.1	0.8	2
Basel, Stadt-Casino	0.64	16	6.6	2	1.17	0.8	3
Berlin, Konzerthaus	0.66	25	5.5	2.2	1.23	1	3
Berlin, Philharmonie Hall	0.46	21	4.3	2.1	1.01	0.8	2
Boston, Symphony Hall	0.65	15	4.7	2.1	1.03	1	3
Bristol, Colston Hall	0.63	21	5.8	1.65	1.05	0.3	2
Buffalo, Kleinhans Music Hall	0.41	32	2.9	1.8	1.28	0.3	1
Cardiff, Walses, St. David's Hall	0.6	25	3.8	2.1	0.96	0.6	3
Christchurch, Town Hall	0.66	11	3.8	2	1.06	0.6	2
Cleveland, Severance Hall	0.59	20	3.9	1.7	1.14	0.5	2
Copenhagen, Radiohuset	0.58	29	6.4	2	1.07	0.5	2
Costa Mesa, Segerstrom Hall	0.62	31	4.4	2.2	1.32	0.9	2
Edmonton, Alberta Jubilee Aud.	0.49	31	0.4	1.4	0.99	0.3	1
Glasgow, Royal Concert Hall	0.77	20	2.2	1.7	1.12	0.8	2
Jerusalem, Binyanei Ha'Oomah	0.55	25	2.6	1.85	1.05	0.4	2
Lenox, Tanglewood Music Shed	0.46	19	4.9	2.1	1.45	0.3	2
Liverpool, Philharmonic Hall	0.6	25	3.9	1.6	1	0.4	2
London, Barbican Large Concert	0.46	27	3.4	1.9	1.07	0.3	1
London, Royal Albert Hall	0.52	15	-0.1	2.6	1.13	0.5	1
London, Royal Festival	0.63	34	2.6	1.7	1.17	0.6	2
Montreal, Salle Wilfrid-Pelletier	0.46	30	0.8	1.9	1.21	0.6	1
Munich, Philharmonie, Gasteig	0.49	29	2.2	2.1	1	0.8	2
New York, Avery Fisher Hall	0.54	30	3.8	1.95	0.93	0.7	2
Osaka, Symphony Hall	0.56	35	4.6	2.1	1	0.8	2
Paris, Salle Pleyel	0.54	35	4.5	1.8	1.23	0.5	1
Rotterdam, De Doelen Concert Hall	0.55	35	3.2	2.3	0.95	0.9	2
Salt Lake, Utah, Symphony Hall	0.59	30	2	2.1	1.06	0.6	2
Salzburg, Festspielhaus	0.64	27	4	1.85	1.1	0.9	2
San Francisco, Davies Hall	0.44	12	2.8	2.15	1.11	0.7	1
Stuttgart, Liederhalle	0.44	29	4.3	2.1	1	0.5	2
Tel Aviv, Fredric Mann Auditorium	0.41	30	2.9	1.7	0.93	0.5	1
Toronto, Roy Thompson Hall	0.54	35	3.8	1.9	1.1	0.5	2
Vienna, Musikvereinssaal	0.71	12	5.5	2.2	1.11	1	3
Washington, Kennedy Concert	0.61	25	3.3	1.75	1.06	0.6	2
Worcester, Mechanics Hall	0.57	28	5.6	2.15	1.16	0.8	2
Zurich, Grosser Tonhallesaal	0.71	14	6.7	2.2	1.23	0.9	3

considered in this study. Those parameters were regressed on the qualities of the halls. The qualities of 37 the halls were classified into 3 groups (A (3); B (2); and C(1)).

The statistical individuality (orthogonal) of each acoustic parameter was tested. Through correlation tests shown in Appendix 1, some parameters showed correlation-ship at levels of 0.01 and 0.05. SDI and (1-IACC_{E3}), SDI and EDT showed relationship at the 0.01 level, while at the 0.05 level, SDI and G_{mid}, EDT and TI, G_{mid}, and (1-IACC_{E3}) showed significance. Although some parameters were correlated, all parameters were considered in the statistical analysis. Reasons for this consideration were that many musicians and acousticians believe these parameters as independent variables and in some cases the use of these correlated parameters in the model can yield clearer results.

In determining the prediction model, a stepwise regression method was used. The procedure is shown in Appendix 2. The following equation is the result of the regression process.

$$\text{Overall Acoustic Quality} = 0.229 + 3.12\,(1\text{-IACC}_{E3}) + 0.151\,G_{mid} - 1.16\,BR + 1.04\,SDI$$

S=0.3314 R-Sq=76.5% R-Sq(adj)=73.6%

Appendix 3 contains the residual analysis for each of the parameters. There are no extremely large residuals and no trends indicating the regression model is not appropriate. A normal P-P plot of Regression Standardized Residuals (Appendix 4) with straight line also shows that this model is good.

CONCLUSIONS

The purpose of this study was to develop a numerical hall quality measurement model to predict the overall acoustical quality of a concert hall from physical acoustical measurements made in 37 concert halls and overall judgments of the acoustical quality of the halls reported in Beranek (1996). Through this study, 4 acoustic parameters ((1-IACC_{E3}), G_{mid}, BR, SDI) were important in deciding overall hall quality. The derived regression model from those 4 parameters can explain up to 73.6% of hall quality. This model can be used as a quality assessment tool. It can also be useful as a value-engineering tool during the quality improvement process. By improving acoustical parameters, which affect the overall quality of the hall, the total quality of the hall can be improved. However, there are problems in this model. Firstly, because only physically measurable acoustic qualities were considered in this model, the model can be different when all acoustic parameters are considered. Secondly, acoustic quality differences between hall groups, which were used as a dependent variable in the statistical model analysis, are not clear. Even though these problems exist, this numerical hall quality measurement model is potentially very useful in design and in quality improvement process. A possible next step is to make measurement of more acoustical parameters in more halls of varying acoustical quality and include those parameters and halls in the model formation.

REFERENCES

Ando. Yoichi. *Concert Hall Acoustics*. Berlin:Springer-Verlag. 1985.

Barron. Michael. *Auditorium acoustics and architectural design*. New York: Chapman & Hall Inc., 1993.

Barron. Michael. "Subjective Study of British Symphony Concert Halls." *Acustica* 66(1988):1-14.

Bernnek. Leo. *Concert and Opera Halls*. New York: Acoustic Society of America. 1996.

Bernnek. Leo. *Music. Acoustics & Architecture*. New York: John Wiley & Sons. Inc., 1962.

Egan. M. David. *Architectural Acoustics*. New York: McGraw-Hill. Inc., 1988.

Hawkes. R.J. & Douglas. H. "Subjective acoustic experience in concert auditoria." *Acustica* 24 (1971):236-250.

Siebein. Gary & Kinzey. B.Y. *THE EMERGING ART. SCIENCE AND TECHNOLOGY OF CONCERT HALL DESIGN*. 1998.

Siebein. Gary & Gold. Martin. *New methods to Integrate Acoustic Design Principals in Architectural Practice*. University of Florida. 1998. SPSS. SPSS Inc.

APPENDICES

Appendix 1. Correlations among acoustic parameters

		(1-IACCE3)	TI	GMID	EDT	BR	SDI
(1-IACCE3)	Pearson Correlation	1.000	-.248	.398*	.118	.069	.460**
	Sig. (2-tailed)		.139	.015	.485	.684	.004
TI	Pearson Correlation	-.248	1.000	-.153	-.365*	-.163	-.321
	Sig. (2-tailed)	.139		.367	.026	.336	.053
GMID	Pearson Correlation	.398*	-.153	1.000	.212	.198	.381*
	Sig. (2-tailed)	.015	.367		.208	.241	.020
EDT	Pearson Correlation	.118	-.365*	.212	1.000	.063	.526**
	Sig. (2-tailed)	.485	.026	.208	.	.712	.001
BR	Pearson Correlation	.069	-.163	.198	.063	1.000	.179
	Sig. (2-tailed)	.684	.336	.241	.712		.290
SDI	Pearson Correlation	.460**	-.321	.381*	.526**	.179	1.000
	Sig. (2-tailed)	.004	.053	.020	.001	.290	

* Correlation is significant at the 0.05 level (2-tailed)

** Correlation is significant at the 0.01 level (2-tailed).

Appendix 2. Regression Outputs (Stepwise method)

1.Model Summary[e]

Model	R	R^2	Adjusted R Square	Std. Error of the Estimate
1	.712[a]	.506	.492	.46
2	.806[b]	.650	.630	.39
3	.853[c]	.728	.703	.35
4	.875[d]	.765	.736	.33

2. ANOVA[e]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	7.581	1	7.581	35.891	.000[a]
	Residual	7.392	35	.211		
	Total	14.973	36			
2	Regression	9.737	2	4.869	31.618	.000[b]
	Residual	5.235	34	.154		
	Total	14.973	36			
3	Regression	10.894	3	3.631	29.380	.000[c]
	Residual	4.079	33	.124		
	Total	14.973	36			
4	Regression	11.459	4	2.865	26.084	.000[d]
	Residual	3.514	32	.110		
	Total	14.973	36			

a Predictors: (Constant), (1-IACCE3)

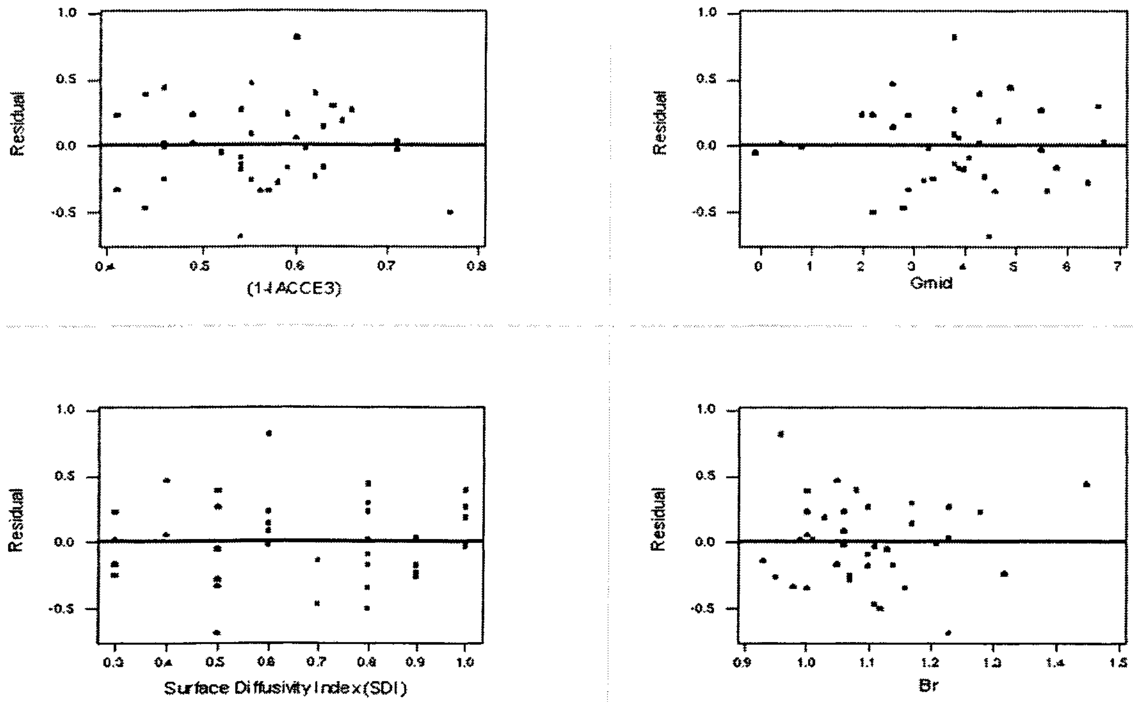
b Predictors: (Constant), (1-IACCE3), G_{MID}

c Predictors: (Constant), (1-IACCE3), G_{MID}, SDI

d Predictors: (Constant), (1-IACCE3), G_{MID}, SDI, BR

e Dependent Variable: QUALITY

Appendix 3. Quality Residual for parameters



Appendix 4. Normal P-P plot of Regression Standardized Residual