ON THE OBJECTIVE PARAMETER OF TEXTURE

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ABSTRACT The subjective impression called "texture," one index of the sound quality that a listener experiences in an opera house, has been attributed to the sequence of early sound reflections that reach a listener's ears (Hidaka and Beranek, JASA, **107**, 368, 2000). One of the possible physical measures is to count the number of the early reflections in the impulse response measured at the listener's position in a hall. For this purpose, the usual reflectograms scarcely aid in counting the significant reflections which is shown in this paper to aid in evaluating the acoustical quality of opera houses. This study proposes, as a means of counting the number of early reflections, an envelop-function based on the Hilbert Transform of a band-passed impulse response instead of the customary reflectograms. This method has an advantage of not only erasing the influence of phase in the impulse response but also is rigid mathematically. Only the amplitude information in the impulse response is extracted, and the number of reflections of any amplitude is countable. The correlation between this measure of "texture" is correlated with the previously published subjective rating of opera houses.

1. INTRODUCTION

Texture is defined by Beranek (p.25, 1996): "Texture is the subjective impression that listeners derive from the patterns in which the sequence of early sound reflections arrive at their ears. In an excellent hall those reflections that arrive soon after the direct sound follow in a more-or-less uniform sequence. In other halls there may be a considerable interval between the first and the following reflections. Good texture requires a large number of early reflections, uniformly but not precisely spaced apart, and with no single reflection dominating the others."

Counting the number of significant reflection peaks in the early part of a reflectogram is difficult and not accurate. A single reflection will often appear to be divided into two. Frequently, interference between two successive reflections and the tail of the transient impulse response (IR) of a band-pass filter often obscure the objective count. In the previous work of Hidaka/Beranek (2000) it was concluded, from using the count obtained by judging the peaks in a number of reflectograms for 22 opera houses, that in the "best" to "passable" houses the number of early reflections was 15 at most and 11 at least, so that direct use of the reflectograms to rank-order acoustical quality was not sufficiently accurate.

2. ENVELOPE FUNCTION AND SIGNAL PROCESSING

Visual inspection of a reflectogram is a very important index of sound quality in an opera house. In principle, rectifying and smoothing the reflectogram should facilitate this procedure, but the physical constant needed, the number of reflections in the early sound, is inaccurate. One way to eliminate the uncertainty in the count is to introduce a mathematically well-defined procedure to the reflectogram, namely to form its "Envelop Function" [Kuttruff, 2000 and Tygel/Hubral, 1987], as follows:

Denoting $x(t)$ as the reflectogram (or any physical signal), and $\tilde{x}(t)$ its Hilbert transform, the analytic signal $z(t)$ is defined by

$$z(t) = x(t) + i \cdot \tilde{x}(t) = A(t)\exp[i\boldsymbol{f}(t)]$$

$$A(t) = \sqrt{x^2(t) + i \cdot \tilde{x}^2(t)}$$

where $A(t)$ is the envelope function (EF), and $\tilde{x}(t)$ is obtained by the Fourier Transform, *FT*.

$$\tilde{x}(t) = FT^{-1}\left[-i\,\mathrm{sgn}(f)\cdot FT[x(t)]\right]$$

The flow chart of the analyzing system is shown in **Fig. 1**, in which a 3-octave-wide, band-pass filter, with a mid-frequency of 1kHz (f_L=353Hz and f_H=2.8kHz, **Fig. 2**) was connected in series. This bandwidth corresponds to the part of the spectrum of orchestral music that has the principal energy (Okano et. al, 1998). It also is consistent with the 3-band concept for the $IACC_{E3}$ definition (Hidaka et. al, 1995), and the length of the filter's IR. If a usual octave-wide band-pass filter with a mid-frequency of 500 Hz or lower is used, visual inspection becomes inaccurate because of the finite length of the filter's IR when one focuses on the first 80 ms of the room IR.

3. EVALUATION OF TEXTURE PARAMETER BY ENVELOPE FUNCTION

<u>Measuring Method</u>

The 3-octave band envelope function EF was obtained from the monaural IR measured near the center of the main floor (a position or positions near there are usually chosen as the lone number to be used for indicating the "intimacy" of a hall for music) for the 22 opera houses listed in **Table 1**. One expects that this position is not only one of the most important locations to choose for judging a hall's acoustical quality, but also at this position the IR is minimally affected by other local reflections.

A basic question is "How do we define meaningful and meaningless reflectograms in counting the reflection peaks as a measure of Texture?" Not only should the temporal integration and the binaural masking effect in human's auditory system be exactly taken into account (Marshall, 1967), but also an experimental result by Schubert (1961), namely, threshold of absolute perceptibility (aWs) of a single reflection vs. delay time for music, should be applied as a simplification. Other reasons for this approximation are (1) there are a significant number of reflection peaks in the range of 0 to –25 dB relative to the direct sound, (2) the aWs value does not substantially depend on the overall sound level, and (3) this count does not vary significantly even if the direction of the reflection changes (Schubert, 1961).

In this study, the "texture" parameter is defined as the number of reflection peaks higher than the aWs curve in the first 80 ms after the arrival of the direct sound as shown in **Fig. 3**. Using the same reasoning, one can count the reflection peaks higher than –15 dB relative to the direct sound in the EF as another approximation.

Results

A preferable result is obtained when the "texture" parameter is plotted against the conductors' subjective ratings (in the audience areas) of 13 opera houses as seen in **Fig. 4**. It is apparent that the method rank-orders the halls quite effectively. There is a discrepancy between measured value and subjective ratings for the La Scala house, Milan, MS. However this can be explained by similar reasoning for the contradiction between the [1-$IACC_{E3}$] and the ratings of this house (Hidaka/Beranek, 2000), i.e., there are inadequate surfaces near the proscenium to reflect sound to this part of the main floor, while for all the rings, there are an adequate number of reflecting surfaces. Also, even when the listener's position is moved 5 rows back on the main floor 22 reflections instead of six are measured. The most highly rated 6 houses have more than 17 reflection peaks, the middle group of ratings ranges from 10 to 16, and the 3 in lowest group have less than 10. These numbers would appear to be satisfactory as a means for classifying this index for opera houses into three categories.

Note that the "Schubert" curve is for 0 to -25 dB levels relative to the level of the direct sound. It is noted in Fig. 4 that almost the same results for 0 to –15 dB are found. Also, the "texture" parameter and [1-$IACC_{E3}$] (which Beranek has named the "Binaural Quality Index), averaged over a number of positions in each hall, are gently correlated, r=0.60, (**Fig. 5**).

Re-examination of Intimacy ITDG

It has been found that the best opera houses have ITDG of 20 ms or less and that the lesser quality halls have ITDG's in excess of 30 ms, measured at the near-center hall position (Beranek, 1996). Introducing the aWs curve again, one can examine whether the earliest reflection corresponding to the ITDG in **Table 1** is subjectively significant or not. As a supplementary quantity, one defines the aWs ITDG by the delay time of the reflection that initially exceeds the aWs curve.

Figure 6 shows the result of testing the usefulness of this re-examined ITDG in rank ordering halls shown in. It is seen that the first reflection at 21 ms, which is 10 dB lower than the aWs curve, of Milan should be modified to 59 ms, and this result does not conflict with the lesser evaluation of the acoustical quality on the main floor of this house (Hidaka/Beranek, 2000).

All halls rated high in quality have ITDGs in the region of 20 ms or less. This is consistent with the findings for concert halls and opera houses (Beranek, p.483). Three in four of the lowest ranked houses have ITDGs greater than 35 ms. As shown in Hidaka/Beranek (2000) the low ranking of the BK house is caused by its circular shape.

4. CONCLUSION

This exercise seems helpful in deriving a physical measure of "texture" that correlates reasonably well with the subjective rankings of opera houses by conductors. Of course, counting meaningful reflections by the proposed method leaves uncertainty in regard to what really goes on in the auditory system so that further research is indicated. This proposed method is very effective in seeking the following quantities:

- ITDG for each octave frequency band.
- Number of reflection peaks included in specific amplitude range.

- Relative amplitude in each octave band for a particular reflection.
- Evaluation of the effect of a diffusing surface for a particular reflection.

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Table 1 Opera houses for objective measurement.

	Hall Name	V, m^3	N	ITDG, ms	1-$IACC_{E3}$	Texture Parameter	aWs ITDG, ms
AM	Amsterdam, Music Theater	10000	1689	32	0.55	10	31.5
BA	Buenos Aires, Teatro Colón	20570	2487	18	0.65	24	24
BD	Berlin, Deutscheoper	10800	1900	33	0.39	6	61.5
BE	Budapest, Erkel Theater	17000	2340	17	0.45	15	23.5
BK	Berlin, Komischeoper	7000	1222	20	0.62	10	19
BS	Budapest, Staatsoper	8900	1450	15	0.65	17	21
CC	Chicago, Civic Opera House	23000	3563	41	0.53	6	40
DS	Dresden, Semperoper	12480	1300	20	0.72	24	19.5
EO	Essen, Opera House	8800	1125	16	0.54	10	25
HS	Hamburg, Staatsoper	11000	1679	34	0.46	13	36.5
MS	Milan, Teatro alla Scala	11252	2289	16	0.48	6	57.5
NM	N.Y., Metropolitan Opera	24724	3816	18	0.62	16	21.5
NT	Tokyo, Nissei Theater	7500	1340	17	0.58	11	16.5
PG	Paris, Opéra Garnier	10000	2131	15	0.50	17	13.5
PS	Prague, Staatsoper	8000	1554	16	0.64	18	21.5
RE	Rochester, Eastman Theater	23970	3347	22	0.54	6	29
SF	Salzburg, Festspielhaus	14020	2158	27	0.40	13	27
SO	Seattle, Opera House	22000	3099	25	0.48	6	26.5
TB	Tokyo, Bunka Kaikan	16250	2303	14	0.60	20	23
TN	Tokyo, New National Theater	14500	1810	20	0.65	18	22.5
VS	Vienna, Staatsoper	10665	1709	17	0.60	10	18.5
WJ	Washington, JFK Center	13027	2142	15	0.53	4	15

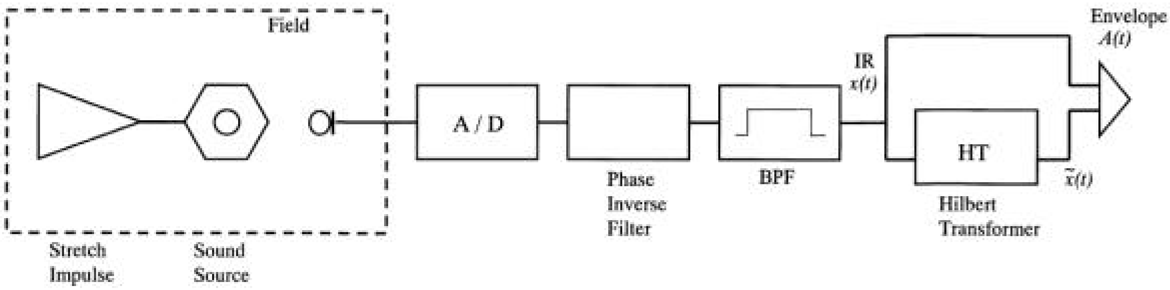

Fig.1 Block diagram of the measuring system for Envelop function.

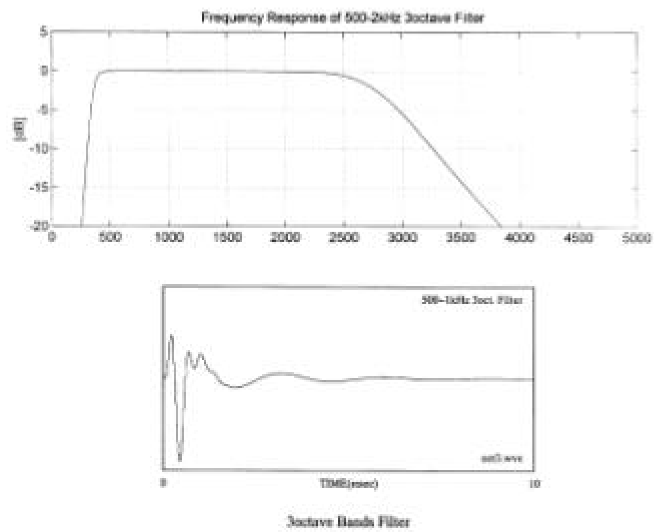

Fig.2 Frequency characteristics and impulse response of the 3-octave-wide band-pass filter with a mid-frequency of 1kHz.

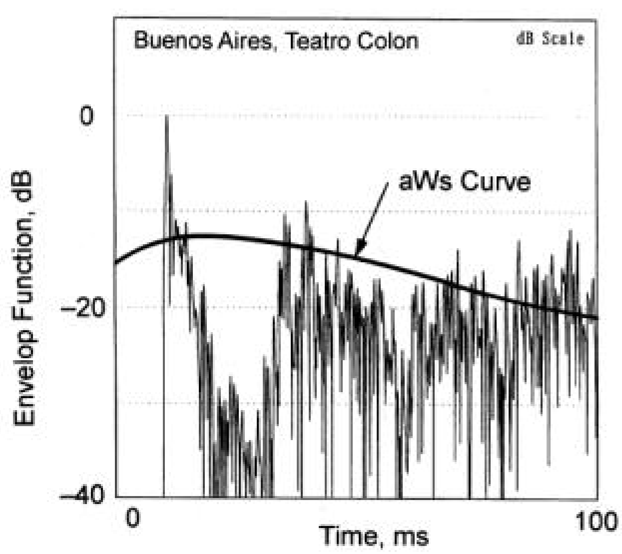

Fig.3 Example of Envelope function and aWs curve after Schubert (1961).

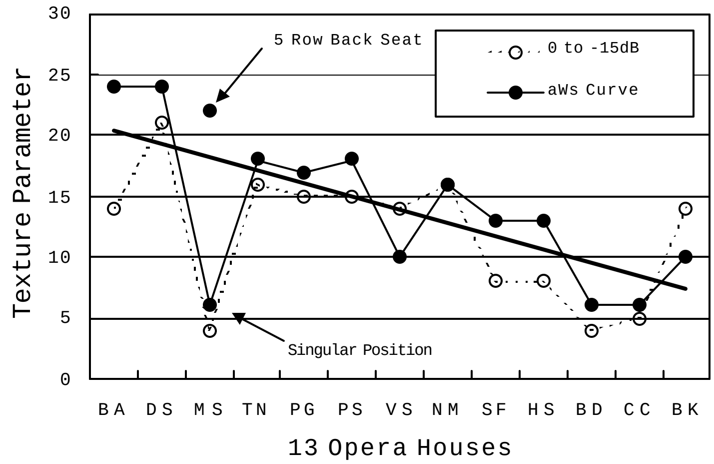

Fig.4 Plot of "Texture" parameter, number of significant reflection at center seat, vs. names of 13 opera houses. The rank ordering of the halls is from Hidaka/Beranek (2000).

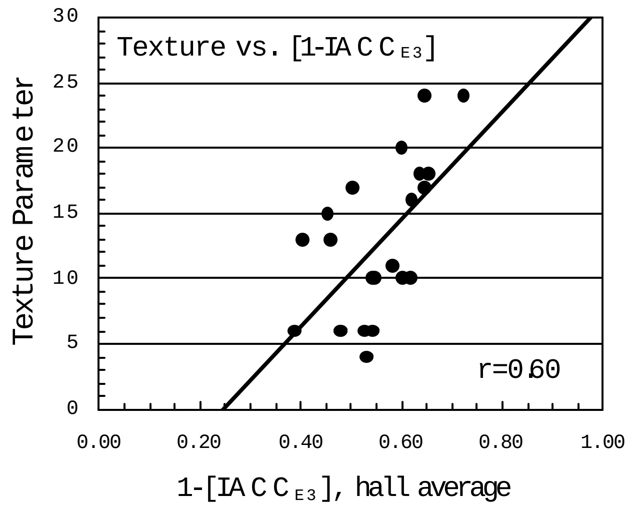

Fig.5 Plot of "Texture" parameter vs. [1-IACCE3] measured in unoccupied 22 Opera houses.

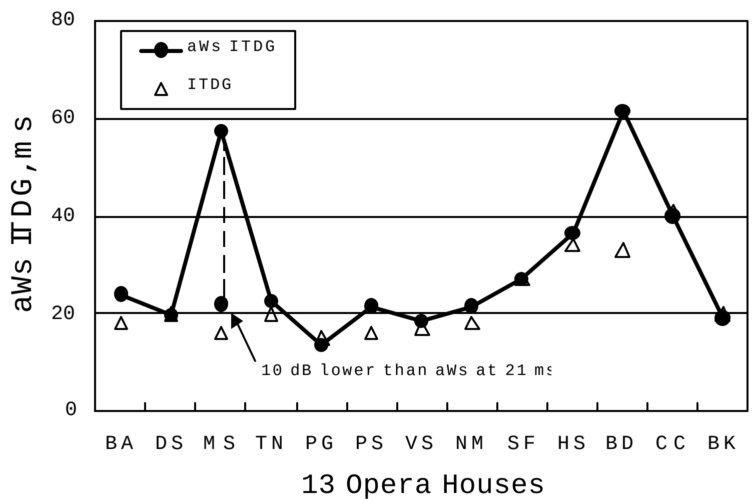

Fig.6 Plot of aWs ITDG vs. names of 13 opera houses.