Proceedings of the Institute of Acoustics

SOUND INTENSITY AND ITS USE IN ASSESSING THE SOUND QUALITY IN A SPACE.

R.W.Guy, A.Abdou

Centre for Building Studies, Concordia University
Montreal, H3G 1M8, Canada

1. INTRODUCTION

The primary purpose of an objective room-acoustic indicator is to provide the acoustician or engineer with an unambiguous measure of subjectively relevant quality at an auditor location. Over the past twenty years many indicators have been developed. Some relate to reverberance and musical clarity, others to spaciousness, spatial impression, speech intelligibility or conditions addressing the particular needs of the performer. Overall we can conclude that our primary purpose is quite well served.

A secondary desirable attribute for our indicators is to yield cause or if necessary, suggest engineering remedy. Contemporary indicators do not serve this purpose well and well reasoned treatments can be either ineffective or not cost effective. The main reason for this deficiency of function is that contemporary indicators pay sparse attention to directionality.

From a directional perspective indicators may be placed in one of three categories: Scalar, Directionally influenced, and Directional.

Scalar indicators include "Reverberation Time" (RT), "Early Decay Time" (EDT), "Definition" (D_{50}), "Clarity" (C_{50}, C_{80}), "Running Liveliness" (R), "Centre Time" (Ts), "Overall Sound Pressure Level" (SPL), "Relative Strength " (G), "Speech Transmission Index" (STI), "Rapid Speech Transmission Index" (RASTI),"Useful to Detrimental Sound Ratio" (SNR_{95}), "Support" (ST),"Temporal Diffusion" (Δ)[1]. Most of these indicators may be determined from the square of the "Impulse Response" (IR) by way of a single microphone measurement, thus energy in relation to temporal history is of sole concern. In passing we may note that the term energy as used above is not strictly correct since it is suggested by way of pressure squared; this matter will be explored in more detail during the talk.

Directionally influenced indicators include "Lateral Energy Fraction" (LEF) and "Inter Aural Cross Correlation" (IACC). Each of these measures involves the use of two transducers although IACC requires specialised signal processing by way of correlated measures between microphones arranged to mimic binaural sensing. These indicators whilst influenced by direction do not report it, for example LEF does not discriminate between left or right arriving energies in its assignment of energy in the lateral plane.

Directional indicators have been attempted, for example "Directional Diffusion Index" (θ)[1,2], or suggested, for example "Front to Back Energy Fraction" (F/B)[3]; a potential diagnostic parameter "Subjective Directional Preference" (SDP)[4] has also been proposed. θ requires a directionally sensitive microphone, usually in combination with a parabolic reflector, and under steady state conditions one senses the directional contribution through many solid angles; this technique has limited application. F/B and SDP have been deduced from laboratory measurements where directional fields can be established artificially, for example from speakers positioned as required but calibrated in isolation as to their energy contribution; thus the field can be created, defined and subjectively assessed, however the problem has been that the directional attributes of any other field could not be measured.

In the late seventies a new field of acoustic measurement was introduced, that of intensommetry. Intensity is an energy vector thus true energy and direction are measured, however the early measurement systems were confined to steady state conditions and also involved some limitations in both frequency and sound field, in particular highly reverberant spaces were to be avoided.

Very recent advances in personal computers, signal acquisition boards, related signal processing and reliable phase matched transducers, now support the development of transient intensity measurement systems capable of measurement over most frequencies and in most fields from free to highly reverberant. Thus a third parameter of temporal history can now be combined with the true energy and its direction to completely describe the response of a space. We may now refer to a new measurand, the "Intensity Impulse Response" (IIR).

This paper will describe the development of a 3-D measurement system based upon IIR assessment[5]. The attributes of IIR will be explored and examples of application for diagnostic purposes will be presented. The prospect of developing new directionally relevant indicators will also be addressed.

2. TRANSIENT SOUND INTENSITY MEASUREMENT.

The intensity of a wave may be described at any instant of time in a knowledge of the wave pressure, particle velocity and their respective phase. Whilst sound pressure is a straight forward measurement, particle velocity and phase are more difficult to achieve. In the present system, the particle velocity and its phase in relation to pressure are deduced from the measurements at two microphones located a short distance apart by way of a finite difference approximation. The operable equation in these circumstances is given by[6]:-

$$I_n(t) = \left(\frac{1}{2\rho_o d}\right)\left[P_1(t) + P_2(t)\right]\int_{-\infty}^{t}\left[P_1(\tau) - P_2(\tau)\right]d\tau \qquad (1)$$

where,
- p_1 = the sound pressure at microphone 1.
- p_2 = the sound pressure at microphone 2.
- ρ_o = air density.
- d = spacing between microphones.

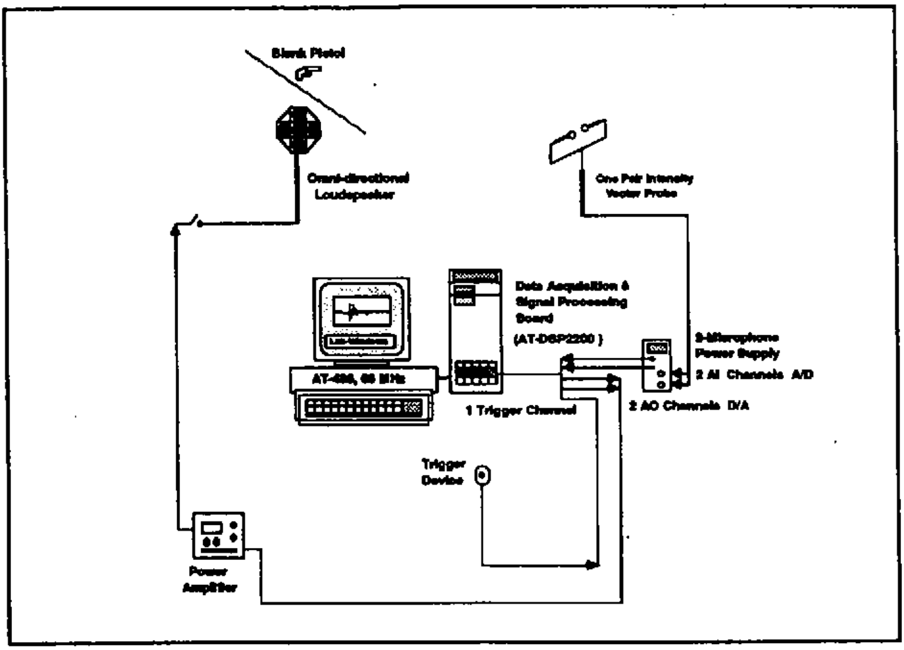

Figure 1. Transient Sound Measurement System

The equipment typically required to perform such a measurement is shown in Figure 1. A trigger initiates two synchronised processes, an output and an input, each very dependent upon a digital signal processing board, presently a National Instruments AT-DSP 2200. The output process retrieves a prepared m-sequence from memory, passes it to the DSP which performs an Digital to Analogue transform (D/A) which subsequently excites the space via an amplifier and omnidirectional speaker. The input process retrieves analogue signals from each microphone of an intensity probe pair, converts A/D and commits the resulting data stream to memory for subsequent processing. Figure 2 displays a flow diagram of the data processing. The data of a microphone pair are first processed to yield two IR and these are presently processed in two paths. Path 1 is in an immediate mode which presents the user with a table of contemporary objective indicators at the time of measurement; this is to provide an immediate guide as to the goodness of the space and/or goodness of the data so that on site decisions can be made concerning the need for further measurement at the point. Table 1 displays a typical output of path 1 processing. Path 2 is typically a later (off site) processing stage which primarily computes the IIR of a given microphone pair (axis), and combines three axis IIR to yield full directional information.

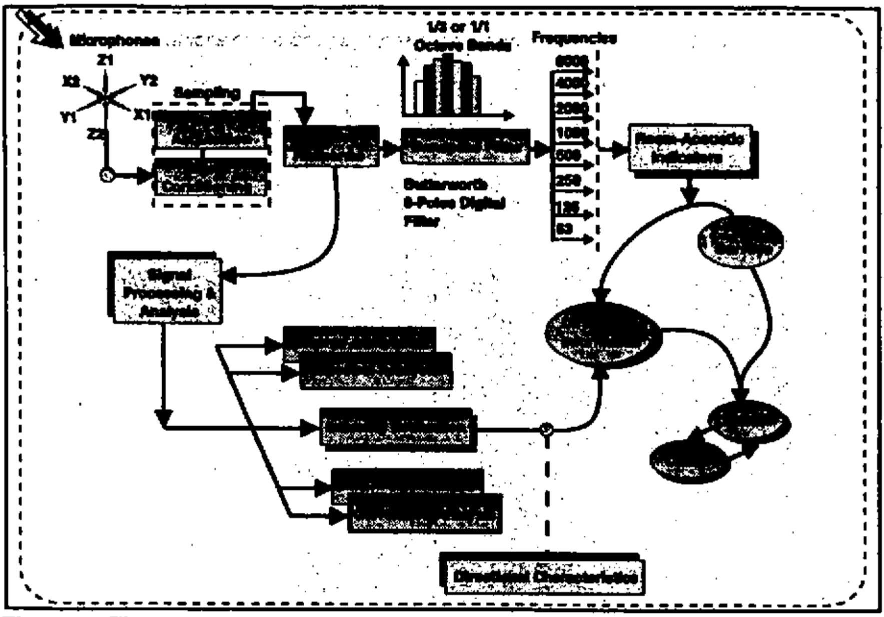

Figure 2. Flow Diagram of Room Impulse Response Processing

Table 2 depicts a typical numeric output for this stage. Path 2 also allows the opportunity to perform other forms of conventional signal processing, for example Cepstrum Analysis for echo detection or signal editing (what if analysis), and others.

Pictorial display of IIR may now be given as shown in Figure 3. An IIR can be directly displayed for a given axis, where +ve indicates one direction and -ve the reverse, eg Front/Back, Left/Right etc. An alternate presentation is the Envelope Intensity which confines attention to the temporal history of the total energy in the plane, much as the square of IR addresses the question of temporal history from all directions; viewing the envelope IIR as an in plane IR now suggests the possibility of subsequent processing in all ways currently undertaken on the IR except that the result can be assigned to a plane, Median, Lateral, or Horizontal. It will be shown during the presentation that this possibility can be exploited to determine the reverberation time (Intensity based) for each plane both as an indication of directional surface property and as an indicator of sound field diffuseness.

Combining the three mutual IIR now allows a complete time , energy, directional representation to be drawn, as shown in Figure 3. In practice, this depiction would be colour coded to distinguish directional components, however whilst of general use as an overview of events it is not likely to be used frequently. An alternative to the overall view is to consider either single axial views, or cumulative time period polar plots for a given plane. The polar plots can be dB scaled (typically 0 to -20 dB) as might be significant for subjective response, or linear (typically 1 to 0) ratios; a ratio of given vector within the time period to the maximum at any time is proving most useful.

TABLE 1. Contemporary Objective Indicators Presented in-situ

	Space Average	Room -Acoustic Indicators								
		EDT	RT	D_{50}	R	C_{80}	T_s	G	LEF_4	SNR_{sf}
	FREQ., Hz	Sec.	Sec.	Ratio	dB	dB	Sec.	dB	Ratio	dB
1	63	0.80	1.30	0.60	-1.8	6.90	0.060	2.20	0.10	
2	125	1.03	1.36	0.41	1.6	1.78	0.093	3.97	0.13	
3	250	1.24	1.43	0.29	3.9	-0.74	0.117	7.49	0.15	
LOW-FREQ. ●	Mean	1.02	1.36	0.43	1.2	2.65	0.090	4.55	0.13	
4	500	1.22	1.16	0.34	2.9	0.35	0.106	8.58	0.16	0.37
5	1000	1.14	1.16	0.39	1.9	1.43	0.098	6.97	0.20	1.27
MID-FREQ. ●	Mean	1.18	1.16	0.37	2.4	0.89	0.102	7.78	0.18	1.64
6	2000	1.19	1.07	0.44	1.0	1.80	0.091	6.46	0.24	2.03
7	4000	1.16	1.11	0.43	1.2	1.93	0.089	2.76	0.26	
8	8000	—	—	—	—	—	—	—	—	
HIGH-FREQ. ●	Mean	1.18	1.14	0.44	1.1	1.87	0.09	4.61	0.25	
			Value		%AL		Rating			% I . S.
●	STI		0.57		7.8		FAIR			95
●	RASTI		0.56		8.2		FAIR			

Tonal Colour	1.05	Bass Ratio	0.85	Treble Ratio	0.71

Note : % I . S. = % Intelligible Syllabus

TABLE 2. Directional Sound Energy Information Presented in Numeric Form

	Position Values S-T (Total Energy)	Directional Sound Energy Ratios (Direction/Total)								
		Front	Back	Right	Left	Up	Down	$(F/B)_t$	$(F/B)_s$	$(F/B)_{ss}$
	FREQ., Hz	Ratio						dB	dB	dB
1	63	0.14	0.54	0.09	0.05	0.09	0.08	-5.6	-5.8	-1.4
2	125	0.32	0.07	0.28	0.11	0.16	0.06	6.5	6.5	2.8
3	250	0.43	0.13	0.14	0.05	0.18	0.05	5.1	5.1	8.2
LOW-FREQ. ●	[illegible]	0.30	0.25	0.17	0.07	0.14	0.06	2.0	1.9	3.2
4	500	0.32	0.18	0.24	0.08	0.14	0.04	3.0	2.6	2.8
5	1000	0.25	0.29	0.14	0.07	0.19	0.05	0.3	-0.5	-0.1
MID-FREQ. ●	[illegible]	0.29	0.24	0.19	0.08	0.17	0.05	1.7	1.1	1.4
6	2000	0.37	0.20	0.16	0.09	0.08	0.09	3.3	2.7	4.6
7	4000	0.31	0.19	0.15	0.15	0.10	0.09	2.8	2.1	3.5
8	8000	—	—	—	—	—	—	—	—	—
HIGH-FREQ. ●	Mean	0.34	0.20	0.16	0.12	0.09	0.09	3.1	2.4	4.1

3. EXAMPLES OF APPLICATION

IIR measures may be processed for many purposes, for example:

1. The Determination of Cause and Effect, and Fault Resolution.
2. Spatial Field Categorization (Diffuseness, Balance, Envelopment).
3. Investigation of Contemporary Indicators (eg. LEF, C_{80})
4. The Development of New Objective Indicators.
5. In-situ Surface Property Assignment.

As an illustration of diagnostic assessment, the results of figure 4 apply to a particular position within a concert hall of 5000 cu.m, seating 620. The position in the theatre is roughly mid way but slightly off centre towards a left side wall within which is located a recessed lounge. The hall is managed by musicians and they report it to be acoustically irritating, however contemporary indicators were found to be within acceptable bounds, although LEF was slightly higher than optimal.

The two polar plots of Figure 4 detail the energies arriving in the lateral plane at 4 KHz.,and for the time periods 0-50 ms, and 50 to 100 ms. A particularly strong reflection is seen from the left in the early time period, and this may be identified as resulting from the recessed lounge; by comparison the later time period indicates a relatively diffuse field of low energy content. The characteristics of the later time period are typically desirable and explain why many conventional indicators would judge this position as acceptable. By comparing the angle of the strong reflection occurring in the first time period to the subjective preference angles suggested by Ando and Kurihara [4], we find that this reflection is outside of acceptable bounds. Similar reflections are detected at lower frequencies but at lower frequencies a wider band of angles are acceptable, thus we conclude that the problem is specific to 4KHz, and the lounge area can be treated accordingly.

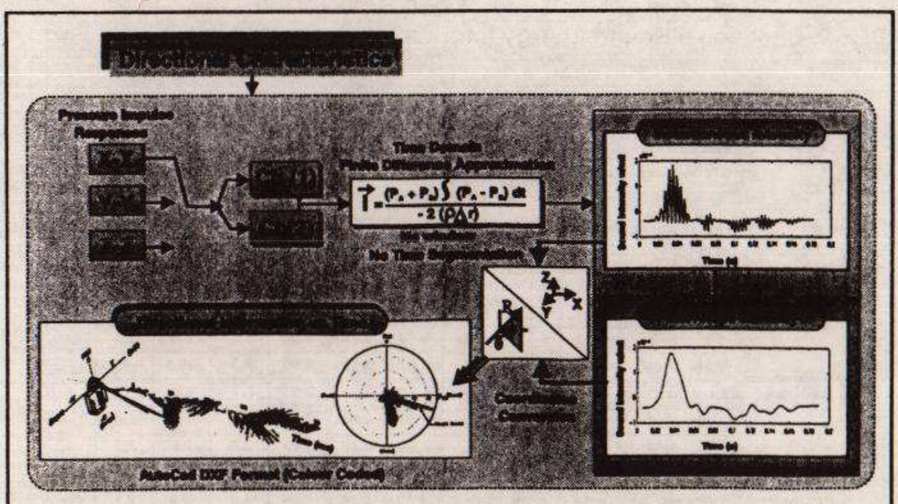

Figure 3. Typical IIR Graphical Representations

Other field applications will be presented during the talk to illustrate the measurement systems detection capability and use in investigating the question of diffuseness.

The ability to visualize an enclosures acoustic characteristic both in time, direction, and energy content presents experimenters, acousticians and engineers with a greatly improved investigative capability. Many of its uses have yet to be explored or detailed, for example apart from those mentioned above, possibly one could deduce and hence replace artificial head measures in a knowledge of laboratory established vector to IACC transfer functions.

The primary problem we have experienced in its use is the problem of data handling, there is so much and not necessarily all of interest. I will conclude my talk with a suggested measurement and analysis scheme [9].

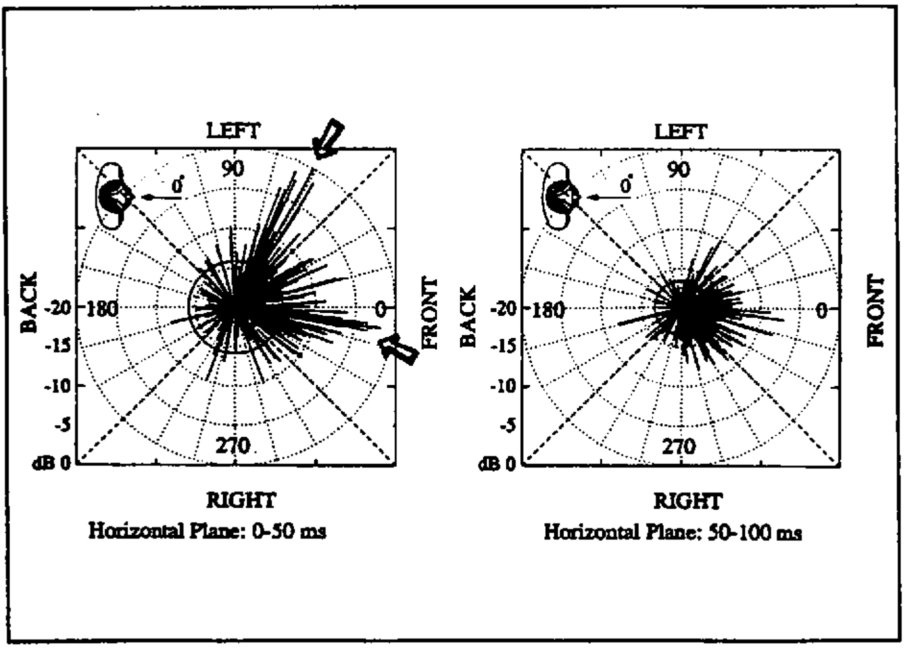

Figure 4. Directivity Patterns in the Horizontal Plane, at 4 kHz, (0-20 dB).

4. REFERENCES

[1] L. CREMER, H.A. MULLER, "Principles and Applications of Room Acoustics", Applied Science, London, Volume 1 (1982).

[2] V.S. MANKOVSKY, "Acoustics of Studios and Auditoria", Hastings House Publishers, London, (1971).

[3] M. MORIMOTO, " A New Physical Measure for Psychological Evaluation of a Sound field: Front/Back Energy Ratio as a Measure of Envelopment". J. Acoust. Soc. Am. Vol.93, N° 4 Pt. 2., p. 2282, (April 1993).

[4] Y. ANDO, Y. KURIHARA, " Nonlinear Response in Evaluating the Subjective Diffuseness of Sound Fields", J.Acoust. Soc. Am., Vol 80(3), pp. 833-836 (1986).

[5] R.W. GUY, A. ABDOU, "A Measurement System and Method to Investigate the Directional Characteristics of Sound Fields in an Enclosure" Noise Control Eng. 42(1), pp 8-18 (1944).

[6] F. FAHY, "Sound Intensity" Elseviere, Applied Science, New York, Ch. 5, p.92., Ch.7., pp. 171-173 (1989).

[7] A. ABDOU, "Transient Sound Intensity Measurement for Evaluating the Spatial Information of Sound Fields in Reverberant Enclosures", Ph.D.Thesis, Centre for Building Studies, Concordia University, Montreal, Canada, (Nov. 1994).