Three Dimensional Transient Sound Intensity Measurements for Comprehensive Room-Acoustic Evaluation

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INTRODUCTION

Contemporary objective room-acoustics indicators are based on the capture and subsequent analysis of room impulse response but subjective criteria are also influenced by the spatial distribution of sound energy. The spatial distribution of sound energy is usually not considered due to lack of an efficient, accurate and easy to perform measurement procedure. This study introduces a 3 dimensional sound intensity measurement for obtaining spatial information of the sound field in an enclosure. The measurement technique is described and its merits and potential are identified. Specular and diffuse sound field quantification is also introduced.

DIRECTIONAL DISTRIBUTION OF SOUND : STATE OF THE ART

Sound Directionality in rooms has been studied and assessed by a number of workers [1,2,3,4], however the measurement procedures do not allow ready or consistent evaluation. To resolve these difficulties a new measurement system is proposed. *CBS-RAIMS* is a new measuring system developed to fully evaluate sound quality in an enclosure by measuring a number of potential useful room-acoustic indicators and to provide directional information in a manner which allows ready interpretation for both sound quality assessment and diagnostic purposes. The description of the measurement system hardware and software components and data processing have been presented in Refs. [5,6]. In this study the measurement method and merits are elaborated.

THREE DIMENSIONAL TRANSIENT SOUND INTENSITY MEASUREMENT

The method utilizes sound intensity measurement from three microphone pairs arranged in cartesian coordinates or one pair in three successive orientations to establish 3-D intensity vectors. The sound field can then be visualized on an energy directional basis versus arrival time. The filtered sets of impulse responses X-X, Y-Y and Z-Z in each selective octave or third octave band allow three orthogonal intensity vectors components to be digitally processed in the time domain using a finite difference approximation approach given by the equation [7]:

$$I_n(t) = \left(\frac{1}{2\rho_o d}\right) [p_1(t) + p_2(t)] \int_{-\infty}^{t} [p_1(\tau) - p_2(\tau)]\, d\tau \quad (1)$$

where,

p_1 = sound pressure of channel 1, Pa.
p_2 = sound pressure of channel 2, Pa.
ρ_o = air density, kg/m^3
d = spacing between the microphone pair, m

When processing equation (1) the full transient record length for each set is used to avoid erroneous results from segmentation and time windowing procedures. The resulting instantaneous intensity vectors are then used to obtain specular sound reflection directions; however if one is only interested in sound energy direction the envelope intensity technique can be used; resulting in a smooth sound intensity components.

To yield a visually detailed 3-D image of incoming sound intensity vectors at the listener location on a time base, the 3-D intensity vectors are then calculated and a conversion from rectangular to spherical coordinates is also made. The directional information is identified in five principle directions with respect to the listener; these are front, back, right, left and up; the contribution of each can now be separately examined. The full directivity patterns can be displayed with time of arrival or viewed from different angles with respect to the listener as shown in Figure 1. The signal can be further processed to reveal left and right, up and down reflections in isolation. In practice the graphical output of vectors is color coded for ease of interpretation.

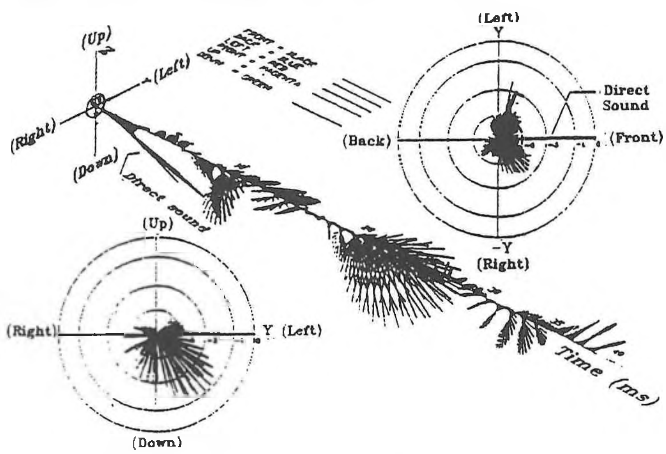

Figure 1. Example Directional Information (at 500 Hz).

It must be accepted that any instantaneous intensity vector is in fact an instantaneous resultant, thus directional components can be hidden for objective diagnostic purposes; this fact can be a problem, however by employing an instantaneous pressure intensity index, a measure of correct directional sensing can be established.

When using the intensity technique, the accuracy of direction sensing is influenced by the microphone pair channel phase mismatch; this causes a distortion of the probe directional characteristics. Further, directional characteristics vary with frequency and are usually problematic in the low frequency range. To validate the method and investigate its accuracy, known reflective surfaces and sound source positions in anechoic and reverberant environments have been examined. Measurements are found useful particularly for identifying specular reflections in the early reflections period.

SOUND DIFFUSENESS QUANTIFICATION

Measurements in existing halls show that the field is unlikely to be diffuse. To what extent the sound should be diffuse and how that could be judged or quantified is now of concern. Knowledge of directional distribution would identify the degree of sound diffuseness exhibited at a listener location.

The diffusion of a sound field can be defined and viewed from different perspectives. These can be examined utilizing the now available directional information obtained by *CBS-RAIMS*.

Sound Diffuseness : Visual Examination

Initially, with the current measurement system the sound directional distribution in a given solid angle of interest can be isolated and visually examined from different views for the uniformity of sound reflections. If the sound is fully diffuse, the envelope of the incoming intensity vectors tends to be smooth with no significant irregularities or sudden dips otherwise irregularities of their level and coherence of directional incidence dominates.

Sound Diffuseness : Net Sound Energy Flow

An ideal diffuse sound field is when the energy flow at a given position is the same in all directions for all arrival times, hence there is no acoustic net energy flow and the instantaneous sound intensity is zero.

To quantify the sound field diffusion with respect to acoustic net energy flow, a "Directional Diffusion", *DD* is proposed :

$$DD = \frac{1}{\Delta t}\int_{t}^{t+\Delta t} \vec{I}(t)\,dt \Big/ \int_{0}^{T} |\vec{I}(t)|\,dt \qquad (2)$$

where, the numerator is the mean energy flow, w/m^2 in a given direction, that is the magnitude of intensity which would result if all intensity vector components on a given directional axis, received within the time period t to Δt, were then divided by the time period over which the assessment is considered. The denominator involving $|I(t)|$ is a measure of the total energy passing through the measurement point over the total impulse response period T. The resulting sign of *DD* indicates the direction of the net energy flow. If DD_x, DD_y and DD_z are the cartesian component Directional Diffusion calculated from equation (2), the Spatial Diffusion (*SD*) will be given by:

$$SD = \sqrt{DD_x^2 + DD_y^2 + DD_z^2} \qquad (3)$$

DD and or *SD* if close to zero indicates that overall intensity vectors are evenly distributed directionally and in magnitude about the measuring point, suggesting that the sound field is diffuse. High *DD* or *SD* values imply a highly unidirectional sound field. The window Δt may be fixed for variable t, or Δt may be variable. The instantaneous sound intensity can be windowed by a successively sliding rectangular window of some interval to obtain successive values of *DD* and *SD* from the end of the direct sound; this would indicate the change of the mean energy flow with time. An example of DD_x is shown in *Figure 2* for measurement in a reverberation chamber at 500 Hz.

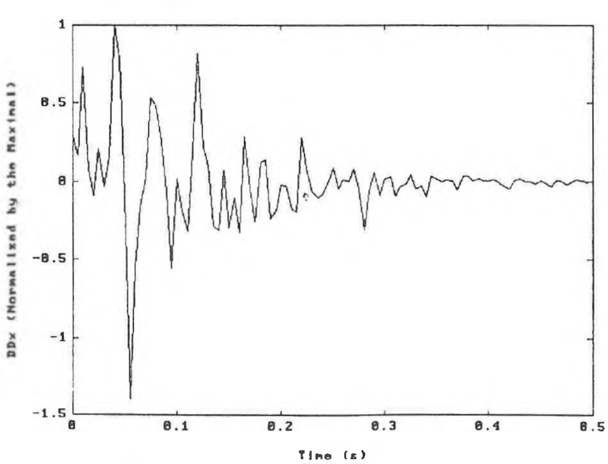

Figure 2. DD_x at 500 Hz in Reverberant Environment.

Sound Diffuseness : Balanced Spatial Sound Energy

A general indication of sound wave homogeneity may be inferred from examining received spatial sound energy ratios at frequencies of interest, excluding the direct sound, in six principle directions with respect to the listener (i.e. front , back, right, left, up and down). *Figure 3* shows a comparison of sound energy ratios (at lower frequency octave bands) received in six directions for measurements in reverberant field with the direct sound energy. Other measures of diffusivity will also be discussed.

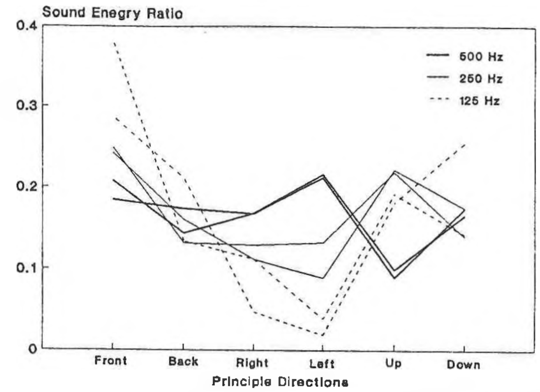

Figure 3. Comparison of Spatial Sound Energy Ratios at Low Frequency Octave Bands.

CONCLUSIONS

A 3-D transient sound intensity measurement method for obtaining directional information in enclosures is reported and shown to be effective. Contributions of particular boundary surfaces to early sound reflections can then be identified, isolated and examined for diagnostic purposes. Sound Diffuseness quantifiers are proposed; example results are given. Further work is necessary to directionally or diffusively qualify the newer room-acoustic indicators. Measurements are currently under way to investigate relationships between objective measures and spatial energy distribution.

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