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ROOM ACOUSTICS CHARACTERIZATION FOLLOWING A PHONON TRANSITION THEORY

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ABSTRACT

A prediction technique is described for the calculation of the most relevant acoustic field parameters in enclosures with different wall materials and geometries, by considering three dimensional phonon random walks. A transition matrix is considered where the transition probabilities are based on the solid angle magnitudes of the enclosure walls, subtended at some particular wall centre. The wall phonon density transitions at every mean relaxation time and diffuse wall radiation allow the calculation of sound intensity, reverberation times and intelligibility indexes at a receiving point. Computer simulation results show good agreement with statistical theory for quasi-diffuse fields, whereas in other cases results are seen to depend on the particular location of the detection point.

INTRODUCTION

Assessment of room acoustical parameters is of major importance in room acoustics especially at the design stage. The classical statistical theories fail to give good results when compared with more elaborate simulation techniques, generally based on ray-tracing or sound images techniques, except for ideal situations, such as diffuse sound fields or homogenous geometrical and material arrangements

This paper describes a technique which can be used to yield the room acoustical parameters from an alternative theory that is seldom used and almost unknown, first implemented by Kruzins and Fricke [1], which makes use of phonons as sound energy particles. A computer program was written to calculate the relevant acoustical parameters of sound fields in enclosures with different wall materials and arbitrary geometrical arrangements. The steady-state sound pressure level distribution, reverberation time T_{60} and intelligibility indexes C_7, C_{70} and C_{80} were thus determined.

ACOUSTICAL PHONON TRANSITION AFTER A MARKOV PROCESS

Consider an enclosure limited by diffuse radiating plane walls and with an omni-directional sound source. The sound field will be considered to be constituted by a large number of sound energy packets, the acoustical phonons. The motion of a phonon, after it leaves the sound source and until it is detected, is regarded as random.

The various wall surfaces that a phonon can encounter can be noted W_1, W_2,..., W_n and it is first assumed that one phonon is emitted from the source and "collides" with W_i. Inside the enclosure, the phonon will be radiated, within a time interval ε, either from W_i to W_1 with probability $<1|P|i>$, or from W_i to W_2 with probability $<2|P|i>$, or in general from W_i to W_j with probability $<j|P|i>$. This process is repeated within the next time interval 2ε, but the phonon's probable position depends on the past history, that is, it depends on where the phonon decided to go earlier.

If the phonon is initially at W_i then an initial position vector can be defined as

$$E^0 = (0,0,0,0,\ldots,1,\ldots0) \qquad (1)$$

where the *i*th position represents the unitary probability of the phonon being initially over W_i. After a time interval ε, in which a reflexion has occurred,

$$E^1 = (<1|P|i>, <2|P|i>, \ldots, <n|P|i>) \qquad (2)$$

Since a wall can not radiate energy towards itself, $<K|P|K>=0$.

With a probability matrix P whose entries are $<j|P|i>$ with i, j = 1,2,...,n, and where the sum of every row must be unity, the position vector after k transitions within the time interval kε can be given by [1]

$$E^k = E^0 P^k \qquad (3)$$

where P^k represents the kth matrix power of P. The *i*th component of the position vector E^k represents the probability that a phonon is likely to be at W_i after k successive reflections. Note the probabilities product in (3), which implies that the successive steps are considered as independent and that the phonon evolution can be regarded as a "Markov Process".

For a phonon population, the initial vector E^0 is given by

$$E^0 = (e_1{}^0, e_2{}^0, \ldots, e_n{}^0) \qquad (4)$$

where e_i^0 is the initial phonon (energy) density, which is assumed to be constant over W_i. Therefore, the *i*th component of $E^k = E^0P^k$ defines the phonon density over W_i after k transitions.

For the initial phonon density over the wall surfaces, spherical waves are considered to be radiated by an omni-directional source

$$e_j^{\,0} = \frac{\Omega W}{4\pi A_j} \tag{5}$$

where Ω is the solid angle of W_j subtended at the source, A_j is the wall area and W is the sound power of the source.

The transition probabilities <j|P|i> must be defined by taking into account the area of each wall surface, as well as the "viewing angle" of the surfaces, as being viewed, for example, from the centre of W_i. The probability of a phonon being radiated from W_i to W_j, as given by <j|P|i>, can be estimated by the solid angle through which W_j is seen from the centre of the wall W_j. To obtain the correct normalisation, these solid angles must be divided by 2π.

The matrix P can be changed into the transition matrix T [1], by accounting for absorption phenomena. The absorption coefficients α_j of each surface and the air sound absorption coefficient m, both being frequency dependent, will be included

$$T_{ij} = (1-\alpha_i) < j|P|i > e^{-md_{ij}} \tag{6}$$

where d_{ij} is the mean distance from W_i to W_j.

If the initial density vector E^0 is multiplied by T, at discrete intervals, defined by the transition time $\tau = 4V/cS$ [2] (V=volume, S=total area, c=speed of sound), the sound energy can be computed in "real time".

The sound intensity at a particular point {x,y,z}, due to diffuse radiation from a finite surface W_j, with constant energy density e_j^i is [3]

$$I_j^i(x,y,z) = \frac{e_j^i \Omega_j (1-\alpha_j)}{\pi^2} \tag{7}$$

where Ω_j is the solid angle of W_j subtended at {x,y,z}.

The total steady-state radiated sound intensity is then [4]

$$I_r(x,y,z) = \sum_{j=1}^{n} \sum_{i=0}^{k} I_j^i(x,y,z) \tag{8}$$

where k is the last transition where the energy densities over the surfaces have become negligible.

The sound pressure level can be obtained from the total reflected sound intensity $I_r = p_r^2/3\rho c$, where the sound field inside the enclosure is assumed to be neither direct ($I = p^2/\rho c$) nor diffuse ($I = p^2/ 4\rho c$). The contribution of the direct sound emitted from the source should be added to obtain the total sound pressure level L_p [5]

$$Lp = 10\log\left[\frac{c\rho}{\left(2\times10^{-5}\right)^2}\left(\frac{W}{4\pi r^2} + 3I_r(x,y,z)\right)\right] \qquad (9)$$

where r is the distance between the receiving point {x,y,z} and the source.

The impulse response can be determined [4] by considering the various k transitions over a time interval kτ

$$I_r(k\tau) = \sum_{j=1}^{n} \frac{e_j^k \Omega_j \left(1-\alpha_j\right)}{\pi^2} \qquad (10)$$

The reverberation time T_{60} can be obtained by determining the transition k at which the intensity level has dropped 60 dB, from the impulse response.

The intelligibility indexes may be determined by the usual integration procedures.

PREDICTION TECHNIQUE

Simulation tests were applied to a simple test case: a cubic enclosure with dimensions 20m×20m×20m and with a 100 W omni-directional point source located at {2.0,10.0,1.5} referred to a co-ordinate system located at one vortex of the cube. The inside walls of the cubic enclosure were divided into a total of 54 squares, in order to guarantee a better constant energy density over each elementary surface and was "lined" with different materials: brick, wood panel and acoustic foam.

Values of reverberation times at various frequencies for a cube lined with wooden panels, calculated for a receiving point located at {10.0,10.0,10.0} are shown in Table 1, together with those obtained by using the Sabine and the Eyring formulae.

	SABINE	EYRING	PHONON
500 Hz	2.68	2.41	2.38
1000 Hz	3.15	2.88	2.85
2000 Hz	3.09	2.88	2.85
4000 Hz	3.02	2.94	2.91
8000 Hz	1.53	1.50	1.53

Table 1. Reverberation times

Figure 1 shows the sound decay curves as function of the distance to source obtained with this technique and with the classical Eyring theory and also the Barron-Lee [5] "revised theory".

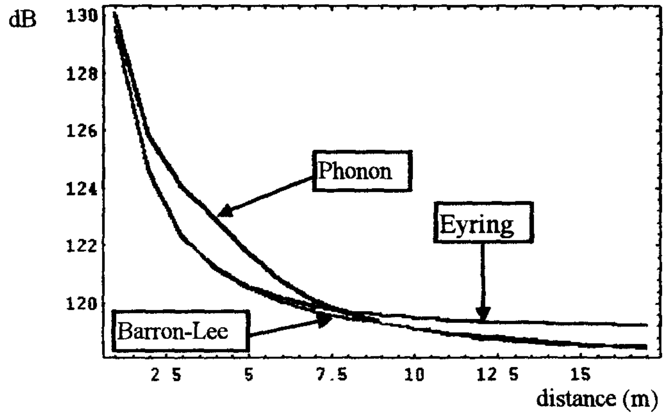

Figure 1. Sound decay as a function of distance to source

The results obtained from the different techniques compare very well in all situations tested.

The contourplot of the steady-state SPL, across a horizontal plane at height 1.5 m, for the wood panel lined cube is shown in figure 2. The brighter area corresponds to the source area. The maximum level contour is 129.4 dB, the minimum level contour is 119.2 dB and the difference between near-lying contours is 0.7 dB.

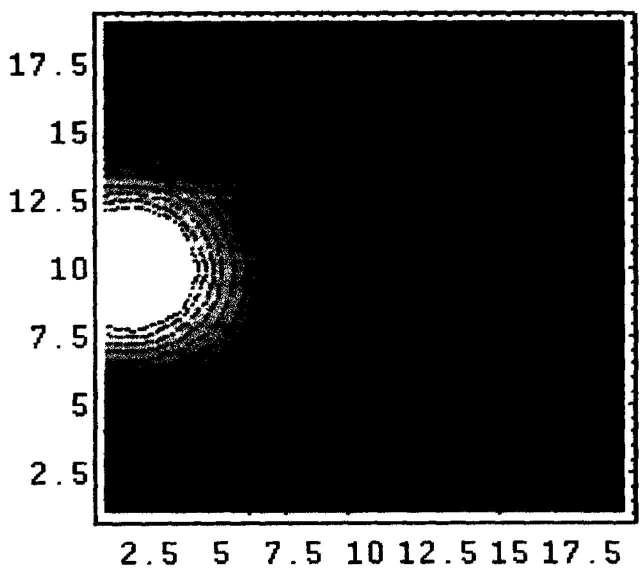

Figure 2. SPL contours for a cubic enclosure lined with wood panels

CONCLUSIONS

The phonon transition theory appears to be a valid prediction method for the calculation of room acoustic parameters as well as sound pressure distributions, thus making it a viable technique for room acoustics design. Computation is fairly fast being an interesting alternative to ray tracing procedures.

Measurements in auditoria of generic geometrical shapes are currently being conducted with the preliminary results showing a good agreement with simulations.

REFERENCES

1. H. Kuttruff, "Room Acoustics", London Applied Science (1973).
2. E. Kruzins and F. Fricke, "The prediction of sound fields in non-diffuse spaces by a random walk approach", Journal of Sound and Vibration 81 (4), 549-564 (1982).
3. H. Skudrzyk, "Über die Eigentöne von Räumen mit nichtebenen Wänden und die diffuse Schallreflexion", Akustische Zeitschrift 4, 172-186 (1939).
4. D. Alarcão, "Cálculo de parâmetros acústicos através da teoria da transição de fonões segundo um processo de Markov", CAPS/IST Report (1996) (in Portuguese).
5. M. Barron and L-J Lee, "Energy relations in concert auditoriums I", Journal of the Acoustical Society of America 84 (2), 618-628 (1988).