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NO ROOM FOR LOUDSPEAKERS?

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ABSTRACT

A computer model is described whereby the in-room sound pressure response of a sound source of given directional characteristics can be predicted.

INTRODUCTION

The study of the effect of rooms or room boundaries upon the performance of sound sources has taken numerous forms over several decades.

In 1955 Waterhouse (1) produced an analysis of interference patterns of plane waves in reverberant conditions, and later extended his work to consider the effect of the directional characteristics of the source (2).

More recently, Allison published important work on the influence of boundaries on loudspeaker sound power output (3), observing that measurements of speakers in free-field (anechoic) conditions were of little use in predicting their performance in practical rooms.

Ballagh, in 1983, modelled the effect of the three nearest boundaries in an investigation of the optimum loudspeaker position for low-frequency extension of sound power output (4).

The major limitation of all these works is that only three of the six 'real-room' boundaries are considered. In order to gain a better understanding of the behaviour of sources in rooms it is essential to take account of the presence of all four walls, floor and ceiling, as Adams has observed (5). The output of a source in an enclosed space is a function of the radiation resistance associated with its environment. It is common knowledge that the output at a given point in 2π- or half-space is twice that at the same point in 4π- or free-space, and that for every 'halving' of solid angle of radiation there is a corresponding factor-of-2 increase in level, while there is no change in source efficiency. However, it is important to realise that room resonances (or 'modes') due to standing waves have the effect of modifying the radiation resistance. These influences cannot be modelled without considering all 6 boundaries.

Because of the existence of room modes and the absorptive nature of structures it is also impractical to assume diffuse sound fields, particularly in the case of steady-state narrow-band or transient inputs (or music, which is essentially a combination of the two).

Furthermore, in analysing sound power output we obtain little knowledge of the effect of boundaries on the sound pressure v frequency response of the source for given locations of observer (i.e. listener or microphone).

With these observations in mind a model has been developed, using a Hewlett-Packard 9816S computer, to predict the sound pressure level (SPL) at any frequency and at any point in a partially- or fully- enclosed space, from a specification of all relevant distances and of the directional characteristics of the source. Absorptive properties of the boundaries can be controlled, allowing investigation of the effects of different materials on the sound field.

THEORY

The sound pressure P due to a point source, at a given polar location (r,θ,ϕ) with respect to the source, may be expressed by

$$P = \frac{A(\theta,\phi)}{r} \exp j(\omega t - kr)$$

where $\omega = 2\pi f$ and f is the frequency of the source output
$A(\theta,\phi)$ is a function defining the directional characteristics of the source.

and $k = \frac{\omega}{c}$ where c is the velocity of sound in air.

By analogy with optical systems (or 'the method of images'(1,6,7,8)) it is possible to construct a (theoretically infinite) series of 'image sources' in the planes of the boundaries of a room. For a rectangular room, a 'second-order' approximation to this series has been generated whereby all single reflections and all double reflections are considered. This produces 32 image sources (fig.1.)

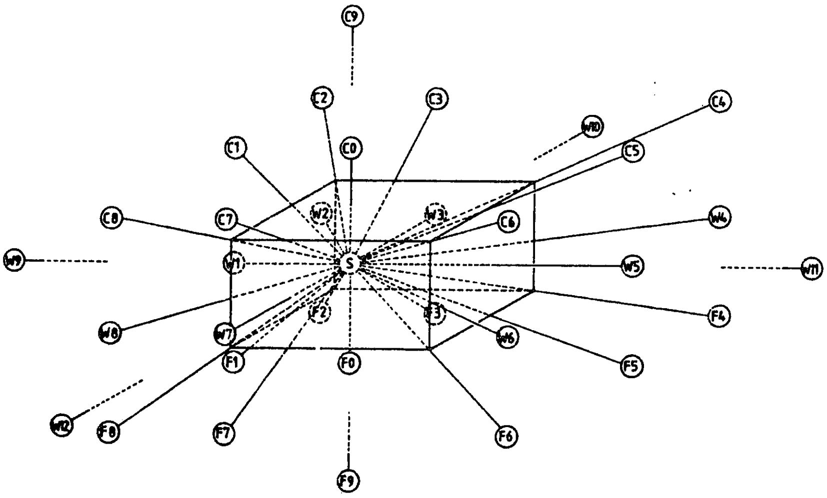

Figure 1. Second-Order Image Model of a Rectangular Room

Now, from above, if the direct sound wave from source to observer is given by

$$P_0 = \frac{A(\theta_0,\phi_0)}{r_0} \cdot \exp j(\omega t - k r_0)$$

then the sound pressure at the observer due to the nth image source is

$$P_n = \frac{A(\theta_n,\phi_n)}{r_n} \exp j(\omega t - k r_n)$$

Therefore the sum of all 33 pressure contributions will give the actual pressure P_t at the observer location;

$$P_t = \sum_{n=0}^{32} P_n = \sum_{n=0}^{32} \frac{A(\theta_n,\phi_n)}{r_n} \exp j(\omega t - k r_n)$$

and the magnitude of the total pressure at the observer is given by

$$|P_t|^2 = \left(\sum_{n=0}^{32} \frac{A(\theta_n,\phi_n)}{r_n} \operatorname{Cos} kr\right)^2 + \left(\sum_{n=0}^{32} \frac{A(\theta_n,\phi_n)}{r_n} \operatorname{Sin} kr\right)^2$$

- This equation applies if all boundaries are assumed to be perfect reflectors. If an 'effective' or 'average' absorption coefficient is assigned to each room surface, then the contribution of any first-order image source to the total sound pressure is modified as

$$P_n = (1 - \alpha_a) \frac{A(\theta_n,\phi_n)}{r_n} \exp j(\omega t - k r_n)$$

where α_a is the effective absorption coefficient of the relevant surface.

Similarly all second-order image contributions will be modified by a factor $(1-\alpha_a)(1-\alpha_b)$ when two surfaces are involved in producing a double reflection. -

ASSUMPTIONS, LIMITATIONS

At this stage, only rectangular (or cuboidal) rooms can be analysed: since most rooms are predominently cuboidal, this imposes no serious limitation. It should also be realised that the source is considered to act as a point source. In practice this may well be the case at low frequencies, but discrepancies will arise as the wavelength of radiated sound approaches the physical dimensions of the source.

For practical reasons the model is a second-order approximation to the theoretical infinite-image case. In a temporal sense the model has limitations for 'late' reflections. Because images are generated to second-order only, reflections in the room after a period dependent upon the dimensions of the source-room system are not catered for by a corresponding image. For example, for a 4m x 4m x 4m room the model will generate reflections within approximately 100mSec of the arrival of the direct sound wave, but not beyond this time.

For larger rooms this time-validity is extended, but the limitation is the same with respect to image generation. There will clearly be some deviation from reality, although the higher-order images will, in practice, be of progressively less consequence due to a) greater effective distances from source to observer (greater values of r_n); b) increasing absorption due to added reflection; c) air absorption may no longer be neglected for large distances.

THE COMPUTER MODEL

As previously noted, the model sums (vectorially) the contributions of 33 sources, one real and 32 images, at any point within a specified cuboidal space. The output from the model is available in three graphical forms; 1) the SPL v frequency curve for the frequency range 10-500 Hz, and the horizontal polar response for a given source-observer separation (radius), fig.2.; 3) a SOUNDFIELD plot, where the SPL is calculated for a 40 x 40-point matrix on a specified horizontal plane within the room, for a given single frequency. The soundfield is displayed in 3-D form whereby 'occulting', or 'hidden-point removal' is used to create a perspective effect. The soundfield plot has two guises; a) the 'reference' soundfield where only the radiation of the real source is considered, and the anechoic (or free-field) SPL is generated, fig.3.; and b) the 'in-room' soundfield where all 33 sources are used to generate the real-room SPL, fig.4.

All parameters, including room dimensions, source and observer locations, etc., are user-defined. There is also a facility to include boundary absorption for soundfield plots at the octave-band centre frequencies 63, 125, 250 and 500 Hz. In addition it is possible to specify the low-frequency response of a loudspeaker system and superimpose this on the SPL/frequency curve, to permit the study of more practical cases where the loudspeaker has a natural low-frequency roll-off, or conversely where a system is electronically equalised.

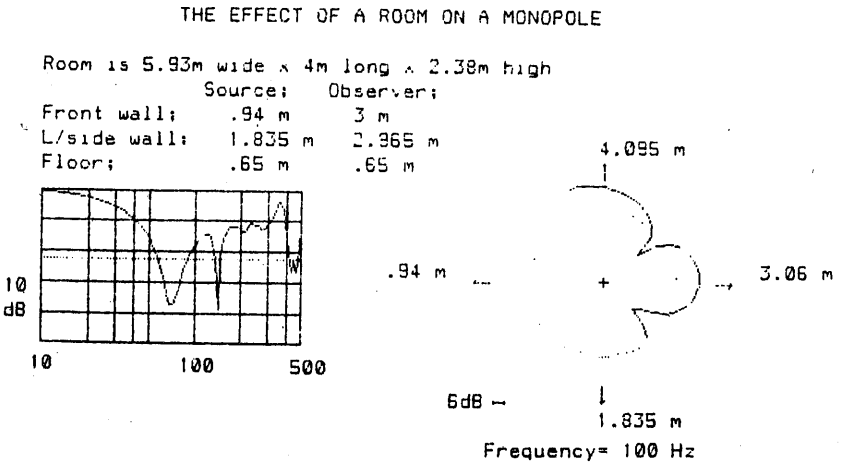

Figure 2.

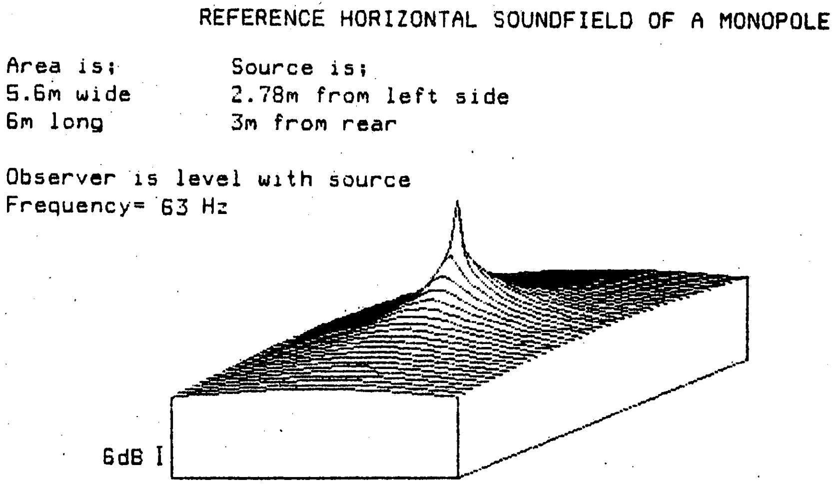

Figure 3.

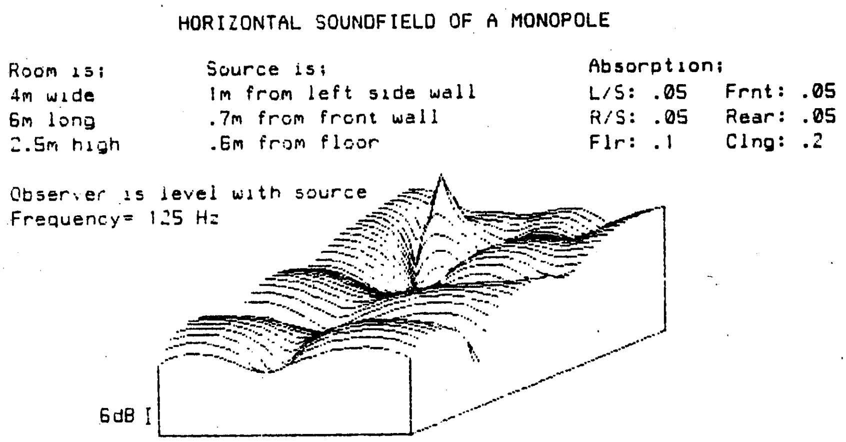

Figure 4.

The model can be used to examine trends in source-room interdependence. A soundfield plot will graphically demonstrate the well-known phenomenon that a room mode cannot be excited if the source is located at a pressure node for the mode frequency; similarly maximum excitation is revealed when the source is at a pressure antinode.

Of greater significance, however, is the ability to study changes in the SPL v frequency response as the source or observer is moved within the room. Pressure peaks and troughs can be predicted and detected in the soundfield and, perhaps of greater value in the domestic listening situation, variations in the in-room frequency response can be minimised by appropriate re-location of the source. This must of course be effected with regard to the practical equivalent, i.e. limitations on speaker placement in a domestic environment.

The model demonstrates the advantage of using 'directional' sources, and is particularly powerful in allowing the user to 'rotate' the polar pattern in order to find the optimum orientation of such a directional source.

The presentation will consist of a series of studies of the trends observed in the model's predictions.

ADDITIONAL CONSIDERATIONS

The model can be used to investigate changes in SPL at given frequencies. There are clearly numerous other parameters to consider for particular situations. For example, in domestic hi-fi listening a 'flat' frequency response down to 20Hz may be desirable, but would be useless if the required location of the sources resulted in a failure to generate an acceptable stereo image, or if the orientation of a diaphragm caused a degradation in the direct-sound reproduction. In addition the human observer (i.e. listener) normally listens to two sources with two ears located at two different points within the soundfield!

SUMMARY

A possible extension to this work is to generate the third-order images for increased accuracy. The absorption facility is at present somewhat limited, particularly in the use of a single absorption coefficient for each surface, and the assumption that the surfaces are local reactors.

It is important to realise that no practical acoustical situation can be simulated precisely by simple mathematical formulae and approximations to relatively long temporal processes. However, the purpose of this model is to facilitate the study of variation in the behaviour of sound sources in enclosed spaces, which it readily permits. Preliminary experimental work has shown good correlation within the accepted practical limitations of the theory.

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