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Acoustic Modelling of Enclosed Spaces

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This paper aims to review briefly the past, present and future of modelling acoustic radiation in enclosures. Whilst the illustrations and examples focus on domestic listening rooms the principles are general to other partly or wholly enclosed spaces.

1. Methods

There are four main methods:

1.1. Scale modelling

Historically scale models (typically 1:10) were an essential adjunct to numerical techniques, which were limited by pre-computer (i.e. human) processing capabilities. Barron [1] reviews the subject. Scale models are costly and time-consuming to implement and quite inflexible, although potentially very accurate. Likely to die out as computer methods become more prevalent.

1.2. Ray tracing

A mature and powerful technique, based upon tracing the paths of wavefront normals around the enclosure. Inherently limited by the assumption of specular reflections, although some improved algorithms have been developed [2,3]. Likely to remain popular.

1.3. Image model

The oldest [4] and most accessible method, both conceptually and mathematically. Treats enclosure boundaries as 'acoustic mirrors', generating image sources behind the boundaries. Similar in many ways to ray-tracing. Suffers from the need to generate an infinite number of image sources [5,6]. This is only ameliorated when boundaries have significant absorption. The author demonstrated the technique in 1986 [7] (as have many others before and since [8,9]) but this model used only 33 sources. It has been shown since that even 729 sources will not produce a convergent model without unrealistic amounts of (low-frequency) absorption [10].

1.4. Finite Element Analysis (FEA)

The author must admit to a preference for this method as the future of acoustic modelling. However, it is not without problems and limitations. At present FEA is very demanding of processing power and computer hardware in general. Accurate models of large and complex systems are therefore not always possible. Nevertheless, the technique is most accurate at low frequencies where the other numerical methods are weakest.

The principles of FEA are well documented [8,11,12]. To summarise, it is a numerical method whereby a macroscopic (in this case, mechano-acoustical) system is subdivided into many discrete (*finite*) elements. These elements are assigned degrees of freedom which are influenced by the other elements. The result is effectively a very large set of simultaneous equations which can be solved by a computer program. Although the FEA technique grew out of the need to model expensive life-supporting mechanical structures such as aircraft, dams and bridges, in recent years acoustics has been included and we can now model problems in acoustics which had previously been effectively insoluble.

2. Aspects of Enclosure Modelling

2.1. Three boundaries v. Six boundaries

Because of the complexity of modelling a fully enclosed space a common approach has been only to model the three boundaries 'closest to the source' [13, 14, 15]. Whilst this provides valuable insight into source/boundary interaction, it is also potentially very misleading. Figure 1 shows the predicted Sound Pressure Level (SPL) at two points (microphones) in an IEC standard room due to a point source radiator near one corner, assuming only the three boundaries nearest the source are present. The other three boundaries are 'anechoic' terminations, or total absorbers. One microphone is near the centre of the room, the other near the corner diagonally opposite the source. Figures 2 and 3 show the FEA predictions for the same microphone positions, allowing for the presence of all six boundaries. See Appendix for co-ordinate data.

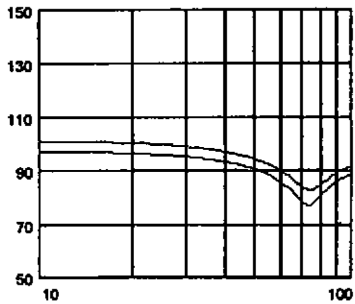

Figure 1. SPL (dB) v. frequency (Hz) at two points in a 'room' ignoring the 3 boundaries furthest from the source.

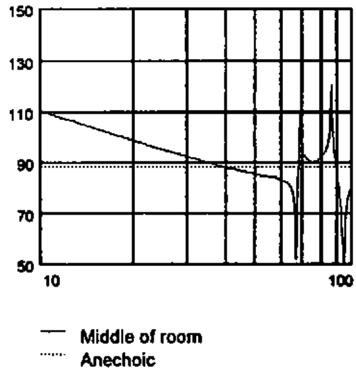

Figure 2. SPL (dB) v. frequency (Hz) in the middle of the room considering the effects of all 6 boundaries.

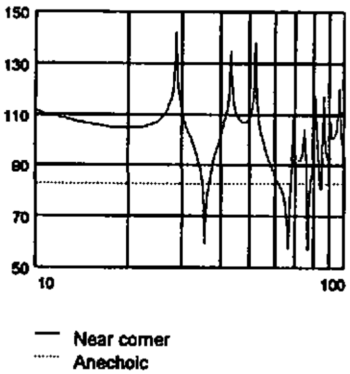

Figure 3. SPL (dB) v. frequency (Hz) near a corner of the room considering the effects of all 6 boundaries.

Some significant differences are apparent :-

a) the 'dip' around 75Hz predicted by the 3-boundary model becomes a general 'rise' in the 6-boundary case!

b) the asymptotic 'room gain' is 36dB for 6 boundaries, but only 18dB for 3 boundaries.

c) Modal behaviour is not supported at all by the 3-boundary model.

d) The 3-boundary model is in error by up to 50dB!

b) and c) are intuitively to be anticipated and d) is alarming but perhaps not surprising. a) is the most insidious, showing that the dip which the simpler model anticipates will not really exist!

2.2. 'Truncating' the impulse response

Many applications of the image source method try to circumvent the requirement for an infinite number of images by considering only the reflections arriving within a predetermined time. This raises the question of what that time should be. We would effectively be producing a 'truncated' impulse response of the room. Some of these methods then 'add on' an estimate of the reverberation tail, particularly those which are aiming to provide auralisation. Such approximations become more valid with increasing absorption (i.e. usually at higher frequencies).

We still do not fully understand the way the brain interfaces with sources in rooms. Is a steady-state model appropriate? How important are late reflections?

2.3. Complex structures

One of the primary practical requirements of acoustic modelling of enclosures must be the ability to study complex structures. Simple analytical techniques such as the image method are not at all suitable. The FEA approach is attractive to the practical acoustician, as the mathematical route to the solution allows for edge diffraction, reflection, mechanical motion (i.e. nonrigid surfaces), and absorption. Figure 4 shows a room with a mantelpiece and fireplace, and a closet in one corner. Two point sources are located either side of the fireplace, and the observation point set between the sources and near the back wall. Figure 5 shows the SPL v. frequency response at the observer when both sources are operating in-phase.

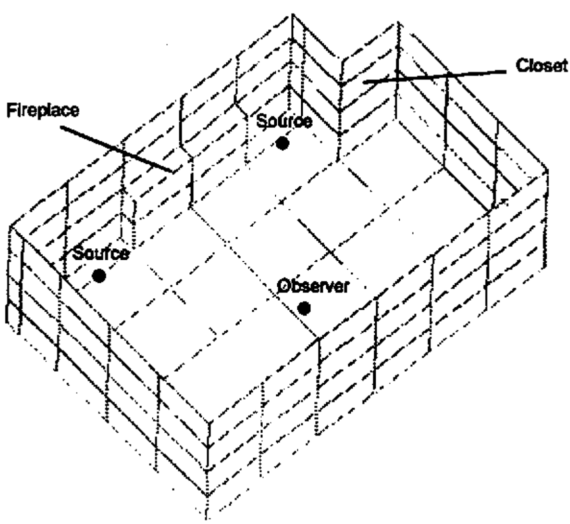

Figure 4. 'Real' room with fireplace, closet, two sources and a listening position (ceiling omitted for clarity).

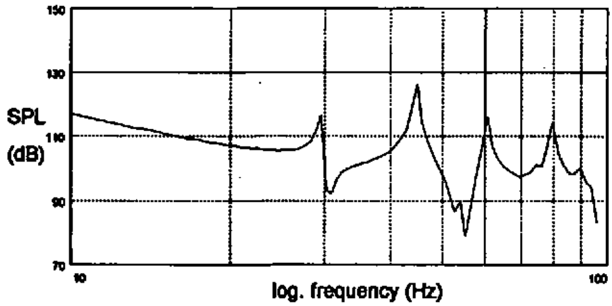

Figure 5. SPL v. frequency at the listening position.

3. Conclusions

The FEA technique is a potentially exact method for modelling acoustic radiation in enclosures, limited only (at present) by computer hardware, and there is little doubt that this method will become commonplace during the next decade as software runs faster and becomes easier to use. However, there is still a place for the established techniques, particularly ray-tracing which to some extent complements FEA. The image method should be used with extreme caution.

There is no longer any good reason to ignore boundaries when modelling enclosures. Such an approach may lead to flawed designs.

4. References

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Appendix

Co-ordinate data for the room models of figures 1-3 :

Room is 6m wide by 4m long by 2.5m high (x,y,z).

Source is at 1.5,0.75,1.0

Microphones at 3.0,2.0,1.0 and 4.5,3.25,1.0