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NUMERICAL MODELLING IN GEOMETRICAL ACOUSTICS USING THE CONICAL BEAM METHOD, WITH APPLICATIONS IN ARCHITECTURE, INDUSTRY AND THE ENVIRONMENT

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1 INTRODUCTION

Experimental simulation techniques for acoustics, such as light-ray models or water wave models, are usually time-consuming and expensive, whereas in recent years the power of even modestly-sized computers has increased dramatically. Computer simulation is thus an attractive alternative for predicting the acoustics of enclosed and open spaces.

An important factor, however, is the choice of the method to be used. This paper discusses various methods and shows why the Conical Beam Method was selected for implementation in a practical computer program. Examples of its application are also discussed.

2 NUMERICAL MODELLING IN GEOMETRICAL ACOUSTICS

2.1 Geometri .1 Acoustics

All numerical models derived from geometrical acoustics are subject to restrictions - namely, the results are only valid for high frequencies and wave effects are not taken into account. In essence, sound waves are treated as rays following the same reflection laws as light rays in geometrical optics. Thus, concave surfaces concentrate rays and convex surfaces disperse them.

Despite the simplicity of this general approach, it turns out to be quite useful in predicting room, industrial and environmental acoustics. The Mirror Image Source Method (MISM) and the Ray Tracing Method (RTM) are two well-known algorithms and indeed have been applied for several decades. We will firstly review the features of these methods and then detail an improved approach and its application.

2.2 The Mirror Image Source Method

The basic principle of the MISM is that sound ray paths from a source to a receiver can be calculated by constructing virtual image sources. The impulse response at a receiver point, caused by a pulse originating from a sound source within some physical boundaries, is reduced to a free-field condition (ie, no boundaries) with several mirror-image sources, each radiating spherical waves synchronised with the original source.

Every mirror-image source has a certain order, hence a source of i-th order represents a sound ray which has undergone i wall reflections. When applied to a rectangular room, a regular lattice of mirror-image sources results, and every element is visible from any position in the room (see Figure 1). In irregular rooms this is not the case, and visibility tests have to be made (see Figure 2).

Borish [1] has described the generalisation of the MISM to reflections of higher orders and rooms of general shape.

2.3 The Ray Tracing Method

In the Ray Tracing Method (RTM) one assumes that the energy emitted by the sound source is discretised into sound rays. Each ray has an initial energy equal to the total energy of the source divided by the number of rays. Each travels at the speed of sound and collides with the walls, floor, ceiling, &c, in accordance with the law of specular reflection. The energy level of each ray decreases only by absorption at walls &c and absorption in the air. When the energy level falls below a user-defined threshold, the ray is abandoned and the next one is traced.

In order to calculate the sound energy at different points in a room, receiver cells with finite volumes are defined. Each ray is checked to see whether or not it crosses the receiver volume. The number of rays crossing a receiver volume and the energy contributions of those rays gives a measure of the sound pressure level. Losses due to spherical divergence are included as a result of the increasing separation between the rays as they spread out from the source with increasing time.

2.4 Acoustical Differences Between MISM and RTM

The acoustic character of an enclosed region can be shown graphically by a reflectogram. It shows the decay with time of the sound energy at a certain point, due to the propagation of wave fronts originating from an impulse at some other point of the room (see Figure 3). This shows that an impulse response starts with strong early reflections, which are spaced-out in time, and ends with many weak reflections, which are close together in time. The time decay is nearly exponential (an exact exponential decay is only found in an 'ergodic' room).

It can readily be shown that the time density of reflections arriving at a given time t increases quadratically with time:

$$\frac{dn}{dt} = \frac{4\pi c^3}{V} t^2$$

where dn = number of reflections between t and t+dt
c = velocity of sound
V = volume of room

The reflectograms calculated with MISM have a very high time-resolution: the accuracy of the calculated energies and arrival times is limited, in fact, only by the accuracy of the floating-point variables used in the computer program. Hence, within the limits of the general assumptions of geometrical acoustics, the MISM is exact.

For the RTM, each ray arriving at the fictional, finite receiver volume has a current energy level and an arrival time, so similar reflectograms can be produced, but they are anything but acoustically exact: whereas the time density of arrivals should increase with time, the reverse is obtained. The only information of value in such a 'reflectogram' is that its envelope is a Schroeder reverberation curve (obtained by reverse integration of the energy impulse response) and the summation of the energy levels of the contributions to the 'reflectogram' is a measure of the sound pressure level (SPL). Using the RTM it is not possible to calculate any of the quality parameters which are based on a ratio of time windows, such as definition or clarity.

A second drawback of the RTM is that it gives rather unreliable values for SPL in a 'free' field. Such errors are due to the finite size of the receiver volume, whereas in a free field SPL decreases spherically by 6dB per doubling of the source-receiver distance.

Thirdly, the RTM is a statistical method and suffers from uncertainties about how many rays to emit, what volume to use for receivers and energy threshold values. None of these issues occur in the MISM, which is very deterministic: any program embodying the MISM should give identical reflectograms for the same geometry and maximum order of reflection.

We conclude that, from an acoustical viewpoint, the MISM is preferred over the RTM. The only reason for choosing the RTM would be its potential to account for wave effects, diffusion, diffraction, refraction, &c.

2.5 Computational Differences Between MISM and RTM

Stephenson [3] has drawn up some formulae for calculation times for the MISM and the RTM. He concluded that the MISM can suffer from absurdly long calculation times, because it is necessary to have a large number of reflections to give an accurate result, especially when a large number of surfaces is involved. However, the mean absorption has a significant effect: if it is large, higher-order reflections have low energy contents and calculation time for reliable results is shortened.

2.6 Conclusions on Differences Between MISM and RTM

From an acoustical point of view, the MISM is to be preferred to the

RTM, but the calculation times are only acceptable if there is a low number of surfaces and/or high absorption. This explains why many MISM programs have been developed to simulate outdoor acoustics, although screen effects (diffraction) and meteorological effects (refraction) tend to be important out of doors, and are not easy to take into account in a MISM model.

3 NEW APPROACHES

In recent years some new approaches have been introduced, all prompted by the basic question: 'How can the great inefficiency of the MISM algorithm be avoided?' The answers to this question vary from patched-up solutions to new MISM/RTM mixtures.

3.1 It has been proposed to replace the calculation of higher-order reflections by adding-on a statistical reverberation 'tail', based on an exponential decay. This approach gives inconsistent results, because of the unknown, user-defined, parameters. Moreover, the assumption that the time decay is exponential is very untrue at receiver points near to the source.

3.2 Lee and Lee [2] suggest using a coordinate transformation method to reduce the size of core memory required, as well as doing some visibility tests whilst constructing mirror sources in order to reduce the calculation time.

3.3 Vorlander [4] applies a RTM, retaining a history path of the ray paths, and when a receiver volume is hit, this history path is used to calculate very rapidly the subsequent mirror sources.

3.4 Vian and Van Maercke [8] introduced a cone tracing method, whereby receiver points are touched by cones, travelling with rays at their centres. This approach is the basis of the Conical Beam Method (CBM). We will describe the method and show how it has been embodied in practical software (the RAYNOISE program) and used on different examples.

4 THE CONICAL BEAM METHOD

4.1 Cone Tracing

In essence, the cone tracing method is a MISM which finds the visible image sources efficiently, by emitting a large number of cones with their vertices at the source. The propagation of the cones through the room is handled by applying a ray tracing algorithm to the axes of the cones (see Figure 4). When a receiver point lies inside a truncated cone, between two successive reflections, a visible image source has been found. Its contribution is easily calculated, using spherical divergence in the cone.

Two problems must be considered:

1) To avoid gaps between the cones, they must be overlapping (see Figure 5). This means that an image source can be detected two, three or four times. This is resolved by keeping track of the path histories of each arrival at the receiver point and reducing identical image sources to only one contribution.

2) When a large solid angle is used, the chances of hitting a corner are increased. What then occurs may be described as 'cone narrowing' (see Figure 6 and Ref [9]) with the effect that some of the visible image sources will not be found. This anomaly will always occur but can be reduced by applying a smaller solid angle.

4.2 The Conical Beam Method

The Conical Beam Method (CBM) applies a weighting function to the cross-section of each cone, in such a way that the superposition of the cones reconstructs the original spherical wave source (see Figure 7). This has the advantage of not requiring additional data storage.

The problem of cone narrowing is dealt with as follows: Each time a cone touches a receiver point, there is a chance that this reception does not correspond to a visible image source, due to edge effects. However, if we relax the rigid idea of using the MISM, we can accept 'invisible' image sources on the basis that no arithmetic absorption of energy takes place, and 'false' image sources compensate for 'missing' ones.

The CBM thus 'trades' some of its deterministic nature, derived from the MISM, for some statistical character, from the RTM. This adds the advantage that diffusion, diffraction and refraction models can be added to the CBM with the same effectiveness as in the RTM.

4.3 Comparison of the Conical Beam Method with the Ray Tracing Method

As shown above, the RTM only provides sound pressure levels (SPL) and reverberation times (RT). When comparing SPL and RT results from RTM and CBM for various numbers of rays and cones, it is found that the RTM converges faster then the CBM [9]. This is to be expected, since the RTM can afford to leave out many higher-order reflections: if one is detected, spherical divergence is not taken into account and its energy contribution is much higher than one obtains with the CBM, which compensates for all the reflections which are missed in the RTM.

Moreover, as indicated in section 2.4 above, the RTM does not give the full set of results which may be needed to assess acoustic quality, whereas the CBM (like the MISM) does.

5 APPLICATIONS OF SOFTWARE BASED ON THE CONICAL BEAM METHOD

5.1 Architectural Acoustics: Fan-shaped Auditoria

It is well known that fan-shaped auditoria are attractive for combining large audiences with good sight-lines, but are not ideal acoustically. The problem is a lack of early reflections in the centre of the main floor. It is known that this can be handled by using side walls with a saw-tooth shape, where the surfaces are parallel to the longitudinal axis of the room. Figure 8 shows the lateral efficiency of an auditorium with and without appropriately-corrugated walls.

5.2 Industrial and Environmental Acoustics

The CBM is also applied to industrial interior acoustics such as power-station halls and exterior, environmental models, such as noise from factories and railways. Topography, ground absorption, barrier effects and meteorological effects can be included. Figure 9 shows an example of an outdoor problem, mapping noise contours around an industrial building with several sources related to noise escaping through walls, vents, doors, &c as well as discrete sources due to plant adjacent to the building.

6 CONCLUSIONS

The Conical Beam Method allows the calculation of a complete set of results for the acoustical behaviour and quality of an interior or exterior region.

Extensions to the method can allow wave effects such as diffraction and refraction also to be taken into account.

The method has acceptable calculation times, especially considering the ever-increasing power of computers, and has been embodied in robust, practical software, which has been used to solve many problems in architectural, industrial, transportation and environmental acoustics.

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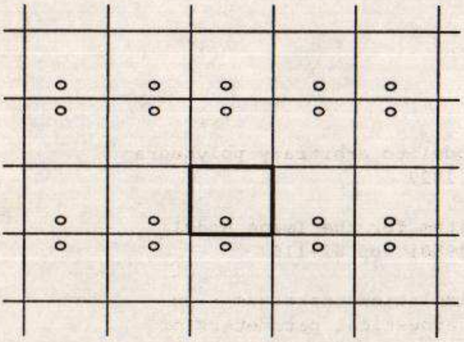

Figure 1: Mirror image sources

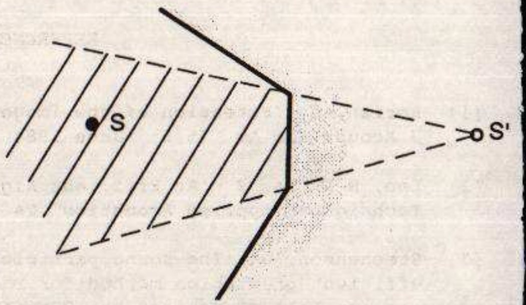

Figure 2: Visibility test

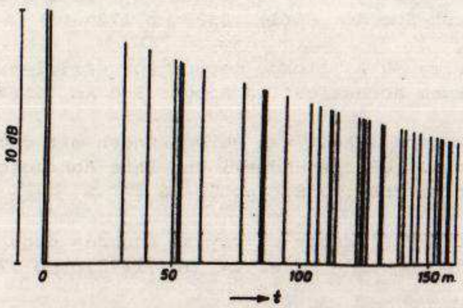

Figure 3: Typical reflectogram

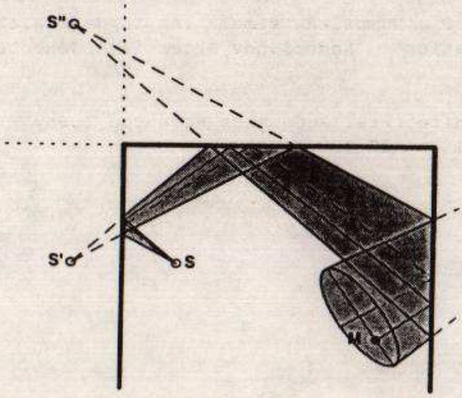

Figure 4: Cone tracing within an enclosed space

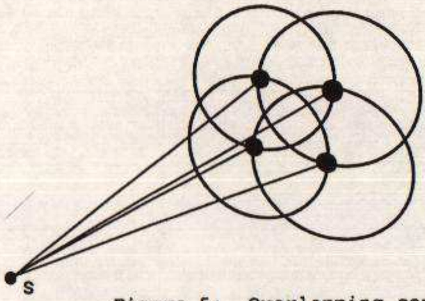

Figure 5: Overlapping cones

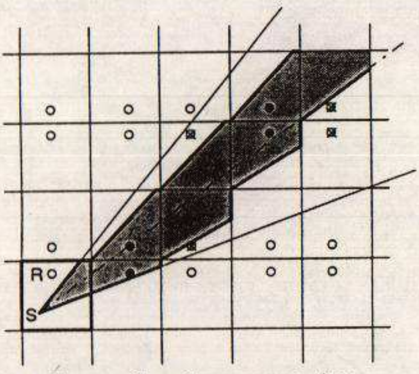

Figure 6: Cone narrowing

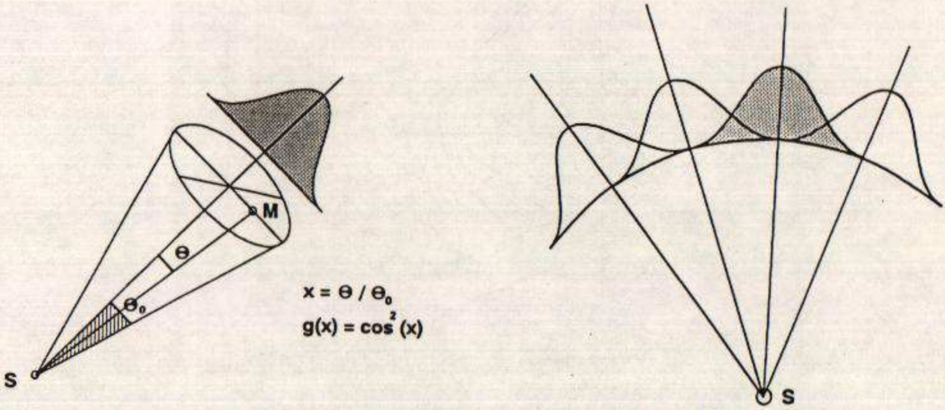

Figure 7: Weighting function on cone cross-section

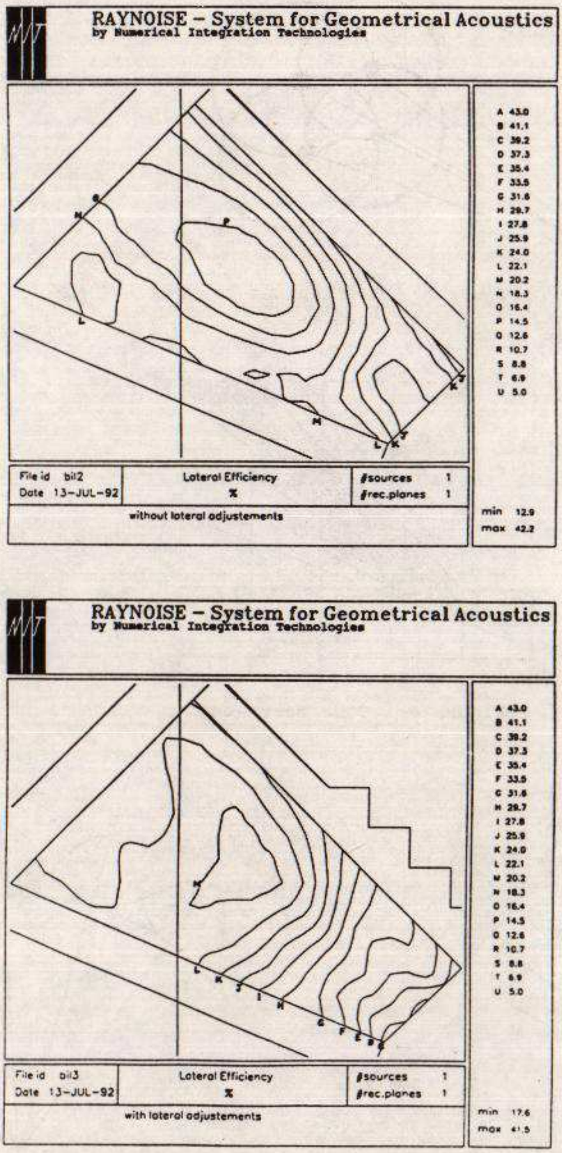

Figure 8: Typical program output - lateral efficiency contours

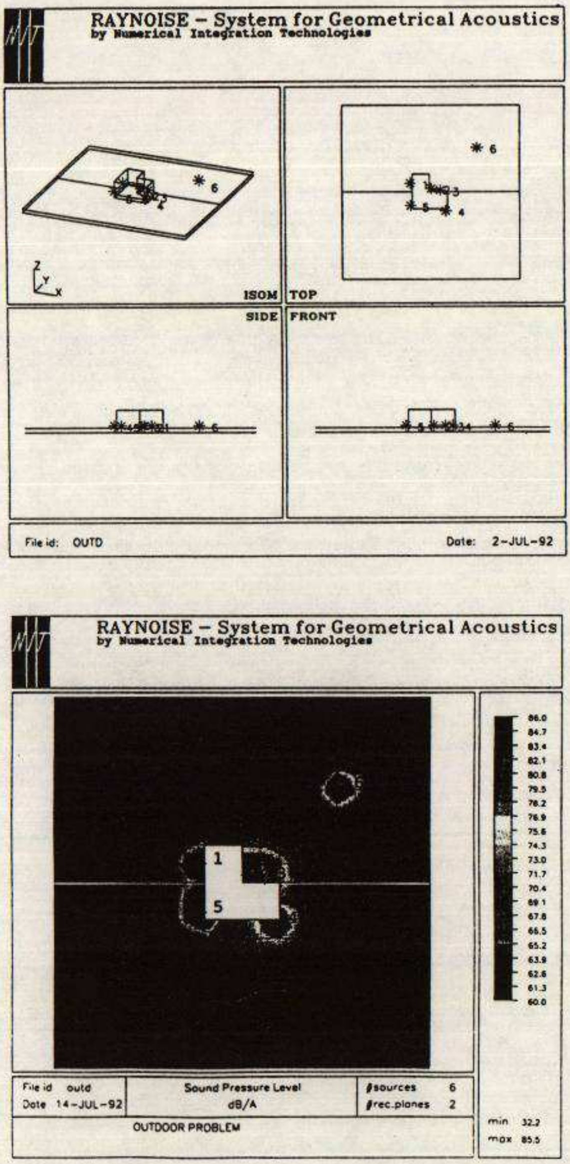

Figure 9: Outdoor industrial/environmental application