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SYSNOISE and RAYNOISE : MODELLING SOURCES, INTERIOR AND EXTERIOR SOUND

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SYNOPSIS

This paper gives an overview of numerical modelling methods for acoustic and vibro-acoustic applications, with particular reference to audio devices and room acoustics. The features of SYSNOISE (finite element and boundary element acoustics and vibro-acoustics) and RAYNOISE (beam-tracing for interior and exterior sound) are described, together with some application examples.

1 INTRODUCTION - A SHORT REVIEW OF ACOUSTIC MODELS

Sound is essentially a wave phenomenon of compressions and rarefactions in the fluid. Vibrations in structures can consist of combinations of compressive waves and (more often) bending and shear. The interaction of a vibrating structure and an adjoining fluid, with kinematic and material continuity considerations at the interface, defines vibration-generated noise radiation or noise-induced vibration, in principle always with a two-way interaction, but in practice the 'feedback' element may be so small as to be negligible: whether to ignore it or include it an a model is a key decision for the modeller.

At higher frequencies, or if there are many combinations of waves interacting with each other, for example with a high modal density, it may be reasonable to assume that the sound or vibration are behaving more as 'energy' which is stored or propagated through the structure and the fluid. Whether this behaviour is derived from a detailed analysis of the wave behaviour, summed in a 'random' or incoherent manner, or is used as a basic assumption in a simpler modelling approach, is a key decision for the modeller.

Thus, a simple division of acoustic modelling methodologies can be made, into different approaches based on the assumptions about the acoustic (and vibro-acoustic) behaviour:

- empirical methods, based on simple 'rules' or formulae, often derived from measurements; these may even be amenable to hand calculation in simple cases
- special analytical methods, usually only relevant to particular cases (transmission loss in ducts, one-dimensional propagation, flow noise sources...)
- general, three-dimensional, sound dispersion and structural energy flow models (ray- or beam-tracing, statistical energy analysis, ...)

- general, three-dimensional, wave-based and multi-physics models (finite elements, boundary elements, infinite elements, ...).

The last two approaches are the more interesting, because they offer generalised methods that can be adapted and used for many different applications, as will be discussed below. They are also embodied in general-purpose, commercial, supported, software: in this paper, the LMS SYSNOISE program for finite element, boundary element and infinite element acoustic and vibro-acoustic models, and the LMS RAYNOISE program for beam-tracing models for interior and exterior room/architectural/environmental acoustics, will be presented.

2 FINITE ELEMENT AND BOUNDARY ELEMENT MODELS

2.1 Principles

In both the finite element (FE) and boundary element (BE) approaches, the fluid domain is discretised into an array of elements, from which a matrix equation system is built, which defines the acoustic or vibro-acoustic behaviour. The solution of the equation system requires significant numerical computation. Typically, the solution is in the frequency domain - thus the equation system embodies the Helmholtz form of the wave equation for the fluid behaviour.

FE methods are well-established for structural models, including dynamics as well as stress analysis. FE acoustics models are effective, where discrete wave behaviour is to be modelled. Since the wave behaviour is 'sampled' in space, a criterion for minimum element size versus wavelength is applied, typically six linear elements per wavelength. By definition, FEM models are closed (finite) so cavity modes can be extracted, and forced response to structural vibration or other boundary conditions can be solved using modal superposition as well as direct methods. A FEM equation system is characteristically sparse, so is also amenable to some efficient solvers. Because each element has independent matrices, which build up the system matrices, each element can have unique properties: sound speed and density (*eg*, changing due to temperature) and even volumic absorption.

BE acoustics models implicitly have the Somerfeld infinite-field radiation characteristic build-in, if they are exterior models, unlike FEM which is conventionally limited to interiors. BEM can also be used for interior closed geometries, and the most-useful BEM formulation (Indirect, Variational method) is generalized and can be used for interiors or exteriors or 'mixed' problems (cavities with openings...) and can handle thin appendages like ribs, and complex topologies with 'junctions' (T- or X-intersections of surfaces). Half-space conditions or symmetry can be used. The Indirect BE method is generally the most-useful approach for vibro-acoustic models of audio devices.

Both FE and BE acoustics models can be coupled to FE structural models, for full, two-way, fluid-structure interaction. A 'modal coordinates' description of the structure is efficient in this context. Boundary conditions can then include: known structural vibrations; known forces on the structure; and known incident wave fields.

Infinite elements (IFEM) provide an extension of finite elements into exterior, free field, modelling. Both radiation and scattering (incident wave) problems can be handled. The infinite elements have terms representing the wave propagation, built into their element functions: geometrically, they are seen as infinitely-long elements, which begin on bases which are the outside faces of (volumic) finite elements, which are used to model the near field. The base surface usually has to be a regular geometric shape (sphere, ellipsoid...). The benefits of FEM (non-uniform fluid properties, volume absorption, ...) can be used in the near field. IFEM also offers robust time-domain solutions as well as frequency-domain solutions.

2.2 SYSNOISE Features

SYSNOISE enables detailed models of vibro-acoustic behaviour to be created and solved in an interactive user environment, on PCs or Unix workstations.

User Interface
Graphical display of model and results with pull-down menus and dialogs, interactive viewing, rotation, panning, zooming, results enquiry, etc. Modelling actions create corresponding commands, which are saved and can be re-used in a 'batch' or interactive way, also providing an 'audit trail' for QA. The complete model, solution parameters and results are stored in one binary database file.

Model geometry
The mesh definition of the model can be imported using a interfaces with many standard CAD/mesh-generator/structural-FE systems. Sets of elements in SYSNOISE can be created automatically, based on groups with identical properties or other attributes.
The finite element method requires a closed mesh of 'volume' elements, but this can be extended to open geometries by using infinite elements – for which SYSNOISE offers a choice of formulations.
The boundary element method requires a 'shell-like' surface mesh: in SYSNOISE, this can be quite general in form, with t- or x-junctions and free edges (around holes) – when using the generalized or Indirect boundary element method. (This is a key advantage of SYSNOISE for 'open' geometries, such as enclosures with holes, since the interior and exterior regions are modelled by one single mesh, without the need for interior and exterior domains which are then interfaced in some way. The benefit is that the equation system is compact and is solved reliably).
Symmetry or anti-symmetry conditions can be defined in SYSNOISE when required.
SYSNOISE also has a tool-box of geometry generators, particularly for creating the field point grids ('microphone positions').

Materials data
In a BE model, the fluid is homogeneous, unless the SYSNOISE multi-domain BE method is used, whereas an FE model can have heterogeneous fluid properties, including volumic absorption in selected elements.
Selected surfaces can have specified admittance representing surface treatments.

Vibration data and structural properties
If the acoustic model has 'one-way' coupling – that is, given structural velocities as boundary conditions – these velocities are usually imported from a separate structural analysis, using interfaces to standard FE codes (Nastran, Ansys, ...).
If the model has 'two-way' coupling – that is, unknown structural behaviour, the structural part also being solved at the same time as the acoustic part – then SYSNOISE enables the structure to be modelled with finite elements, either using a library of elements within SYSNOISE or importing data from an external code. The latter can be especially effective when a modal representation of the structure is used, leading to an efficient solution of the coupled equation system due to the big reduction in the total number of unknowns.

Solvers
The SYSNOISE solvers are adapted to make efficient use of available hardware: in-core and out-of-core methods are selected automatically, to optimize the solution process.
Parallel solutions are also possible, on both Unix and PC systems: typically, a multi-frequency solution is divided between several machines at the frequency level, although matrix-level parallelism is also possible for very-large problems.

A unique solution scheme, based on Acoustic Transfer Vectors, provides super-fast solutions of some acoustic radiation calculations, such as multi-loadcase, multi-rpm radiation from machines.

Results

All acoustic parameters can be displayed interactively, as contour plots (eg, sound pressure distribution in the field) as deformed-shape plots (eg, deflected shapes of flexible components like speaker membranes) and as vector (arrow) plots (useful for acoustic intensity and other values). Surface results on the boundary elements can also be displayed, for example to identify the regions which are radiated sound. Because the wave equation is solved, the results at any point are complex values, for example of pressure and velocity, and other parameters such as intensity (real and imaginary parts) can be derived. Total radiated sound power is also derived.

Directivity diagrams and frequency-function plots are also available, interactively.

Using a built-in 'frequency-function toolbox', many different results can be derived, results can be combined and further processed, and values can be exported in tables and other formats.

Special techniques

Using a unique formulation, *Inverse Numerical Acoustics* problems can be solved, in which a set of known pressures in the field (ie, measured) can be used to determine the vibration characteristics of a radiating object. This enables the vibrating surfaces to be identified, even when conventional vibration measurement techniques are impractical (because they load the surface, or the surface is hot, wet, moving, etc).

Panel Acoustic Contribution Analysis is a special tool, used interactively, that enables the relative importance of the contribution of different vibrating surfaces to the overall acoustic response to be determined. This can be useful in deciding where to give attention to design changes to optimize the acoustic behaviour.

Panel Transmission Loss can be computed for a flexible structure set into an infinite rigid baffle, representing a typical transmission loss test set-up. The shape of the structure can be quite general, including multiple-leaved panels, holes, ribs, etc.

2.3 Application Examples

Loudspeakers are usually modelled with fully-coupled BEM-FEM fluid-structure models. The effects of holes in the enclosure can be handled efficiently using the Indirect boundary element method with its 'double-sided' elements, modelling interior and exterior region at the same time. Some parts of the BE model can be effectively rigid, others are coupled to a structural FE model. The results are contour plots of pressure distribution, as shown in Figure 1, frequency functions of pressure and total radiated power (and hence radiation efficiency) and directivity diagrams.

The modelling of the response of the space in which the speakers are placed is better done with ray-tracing, which will be discussed in the next section.

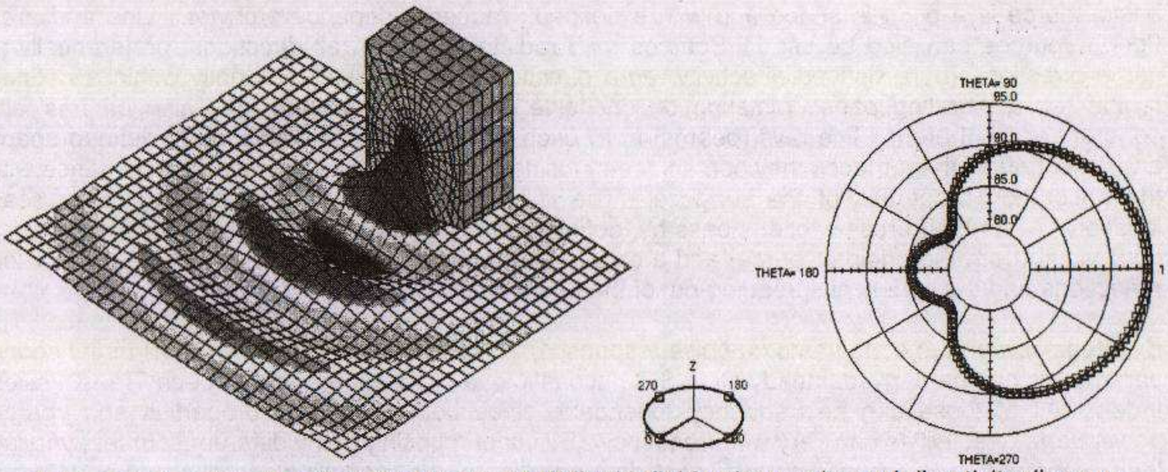

Figure 1: Loudspeaker (coupled Indirect BEM) with field point results and directivity diagram

Some acoustic transducers do not require fully-coupled vibro-acoustic models, since the structural behaviour is not significantly altered by the fluid coupled to it. Examples include horn speakers and many sonar devices. These are suitable for BEM modelling of their radiation characteristics (eg, directivity, beam-forming, cross-impedances...) as for example the multi-transducer stack in Figure 2. The interaction of multiple transducers in an array, with FEM models of structural and local acoustic behaviour (mounting windows, ...) can also be assessed, using fully coupled FEM/BEM models if necessary.

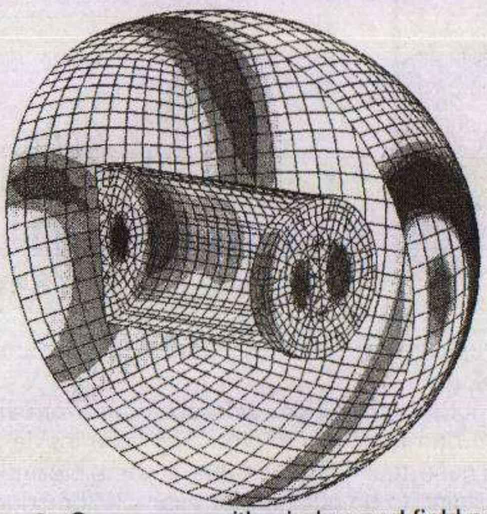

Figure 2: Sonar array with window and field points

3 RAY-TRACING (BEAM-TRACING) MODELS

3.1 Principles

Ray-tracing uses a geometrical acoustics method (in its basic form, specular reflections). LMS RAYNOISE in fact uses beam-tracing, which gives improved results compared to ray-tracing in terms of temporal accuracy of the echo arrival data (precise arrival times and less deviation from the expected statistical reverberation behaviour at higher orders of reflection). The method can be used for completely-closed interior spaces, partially-open ones and fully-open exterior environments. The basic source is a point in space and with a defined, frequency-dependent power. Line and area ('grid') sources can also be used. Sources may radiate equally in all directions, preferentially in some directions (by a defined directivity, *eg* a directional loudspeaker) or wholly within a defined region (*eg* a vibrating panel, radiating on one side only). Each source may also be basically coherent or incoherent. The rays (beams) from each source are traced around the defined space and reflect off all the surfaces they contact (see) losing energy at each reflection in accordance with the absorption properties of the surfaces. The rays 'capture' receiver points (occupants head location, ...) as their cross-sections pass by, defining an echo with a certain arrival time (due to its path length from the original source) and a certain energy level (due to the energy absorbed at the reflections and the spherical spreading-out of the beam cross-section).

By integration on the echograms (impulse responses) at each receiver point (Figure 4) many sound parameters can be derived: steady-state SPL, acoustic quality measures and Speech Transmission Index. All of these can be frequency-dependent, since both absorption properties and source powers and directivities can vary with frequency. By superimposing many different sources, varying their properties, and so on, with intelligent data-handling in the modelling process, many different possible scenarios can be assessed and the effects of different combinations of sources (wanted or unwanted) can be rapidly analyzed. Typically, the basic model data such as geometry are loaded more-or-less automatically from a general-purpose CAD system, but the more-specialized acoustic data such as loudspeaker properties are usually derived elsewhere and saved in dedicated databases.

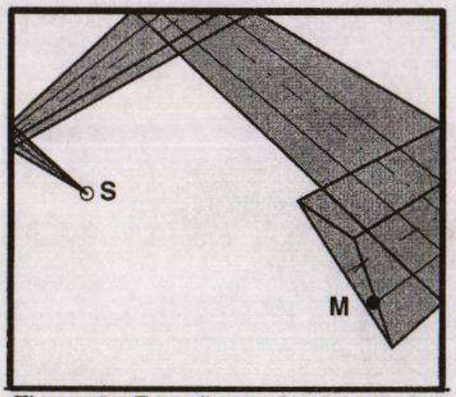

Figure 3: Ray- (beam-) tracing scheme

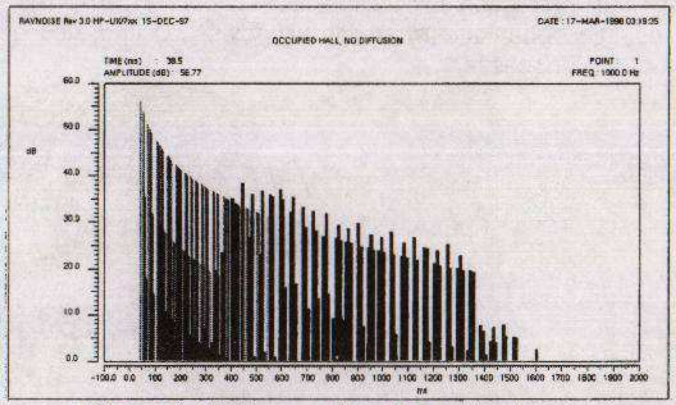

Figure 4: Echogram from beam-tracing

Special techniques exist for modelling diffusion, diffraction (*eg* over barriers) and the transmission of sound through partitions from one region to another (*eg* from inside to outside of a building, from one room to another, ...). These techniques enable a complete model of the noise environment around as well as inside a building to be built up, for example the sound outside a stadium during a concert, due to reflections inside, diffraction over the edges of the stadium roof and transmission through the (lightweight) stadium walls.

3.2 RAYNOISE Features

RAYNOISE enables simple and complex models of acoustic spaces, interior and exterior, to be created and solved in an interactive user environment, on PCs or Unix workstations.

User Interface
Graphical display of model and results with pull-down menus and dialogs, interactive viewing, rotation, panning, zooming, results enquiry, etc. Modelling actions create corresponding commands,

which are saved and can be re-used in a 'batch' or interactive way, also providing an 'audit trail' for QA. The complete model, solution parameters and results are stored in one binary database file.

Model geometry

The definition of surfaces can be done within RAYNOISE, but more-commonly is imported using an interface with CAD systems, typically using the AutoCAD DXF format. The AutaCAD Layers can also be imported, to create Sets of elements in RAYNOISE, which can be useful for reducing the model size (removing unwanted geometry) and applying materials data in an efficient way (Layers can consist of one material type).

Materials data

The fluid (usually, but not exclusively, air!) can be given user-defined properties (sound speed and density) and the effect of air absorption can be included by defining the temperature and relative humidity, in which case the absorption/metre is found by looking up standard tables.

Surface absorption data can be input manually, but is usually retrieved from a materials database, which can be altered and extended by the user with permanent changes. The standard Sabine absorption coefficients are offered, by default, in eight octave bands, but it is also possible to give these data (and any other frequency-dependent data) in narrow-band form, as tables, with any desired frequency intervals.

Surface data can also be extended with diffusion coefficients (see later) and transmission loss (for transmitting panels).

Diffraction

Additional energy can be applied to receiver points in the shadow zone of a barrier (or building or other object) by an extra computation process that uses an inversion of the 'barrier insertion' formulae (eg, after Maekawa). Diffraction edges are identified and the path with minimum length from a source (or image source) to the receiver is computed. The path length difference between this path and the direct source-receiver path is then found and the diffracted energy from that (image) source is computed. In the case of a coherent source, the 'minimum phase path' is used. All diffraction calculations are of course frequency-dependent. Diffracted energy from more than one path may be added to the same receiver, for example if there is diffraction around the ends as well as over the top of an object. If there are several objects in between the source and the receiver, an 'equivalent screen' approach can also be used. All the path-searching necessary to compute diffraction in this way is handled automatically, in a fully three-dimensional sense: thus, it is possible to have diffraction as an additional phenomenon in a complex model in which there are, for example, multiple reflections between parallel-sided objects, followed by diffraction over a barrier.

Source data

Basic sources can be *points, lines* or *areas* (grids). Source power can be given in octave band or narrow-band forms, or sources can be looked-up from a data file – which can be altered and extended by the user. There is no limit on the numbers of sources of any type.

Directional sources are defined by directivity diagrams in 'horizontal' and 'vertical' planes, with elliptical interpolation for intermediate angles. These directivities can also be frequency-dependent. The actual source orientation in space is arbitrary. Directivity data are often imported from other calculations or measurements. Sources can also be limited to specified emission angles, ie a complete cut-off of sound radiation outside a certain zone, which has the advantage of reducing the number of rays to be computed.

Panel sources can be defined, where the source location is the centroid of a specified element and the source is hemispherical (with additional directivity if required) on one side of the element.

Transmitting sources are also panel sources, but have the special property that their sound powers are not given by the user, but are derived during the calculation by taking the sound pressure on one side of the panel, computing from it the incident acoustic intensity, factored by the proportions of direct and diffuse incident energy, and deducting the transmission loss of the panel.

Solution processes and parameters

The initial ray-tracing (beam-tracing) is computed on a source-by-source basis. For each source, a certain number of beams 'per full sphere' can be defined, which sets the solid angle between each beam centre-line (or 'ray'). Each ray is traced in turn with specular reflections off each surface that it intersects, at which the necessary energy is deducted according to the surface properties. The tracing of each ray continues until it is lost to infinity, reaches the maximum Order of reflections, its intensity level falls a given amount (eg, 90dB) from the initial level, or the path length reaches a given maximum (maximum 'time of flight'). All these cut-off parameters are user-controlled as well as the total number of rays per source.

The 'capture' of a receiver point by each ray is logged in an accumulating results array during the process. Various user-defined parameters also control the storage (level of complexity, compression of data into 'time windows' in the echogram/histogram...). Thus both the overall calculation time and the volume of results storage can be fully controlled, to give the user the choices of trading solution time for accuracy and file size for results detail.

The result arrays for each source are stored as separate 'cases': thus, in order to get actual results at any receiver point, these 'raw' results are combined in a post-processing. Before doing this, the source data can be changed (coherent/incoherent switch, source power versus frequency, relative time delay...). This enables rapid re-analysis of multiple real-life cases.

Diffusion

If a ray strikes a surface which has a diffusion coefficient defined, and a Diffusion calculation is called-for as well as a specular ray-trace, the arriving ray can be reflected not in a specular direction but possibly in a random direction (within the relevant half-space defined by the reflecting surface). The random or specular nature of the reflection of any specific ray is determined by a check in which a random-number between 0 and 1 is compared with the diffusion coefficient: if it is less, the ray is reflected in the diffuse way. Thus, at diffusing surfaces, rays can switch between specular and 'diffuse', or the reverse. The effect is that a statistically-consistent but geometrically-localised diffusion effect is produced across the diffuser surfaces and within the whole model.

Speech Intelligibility

Speech Transmission Index can be determined, either by a simplified formula assuming an exponential decay, or using the echogram at each receiver point in a precise manner, generating modulation transfer functions. The procedure takes into account the self-destructive reverberant effects, the interference from other coherent sources (where a time delay or phase shift may be necessary or may be destructive) and the interference (masking) from incoherent sources. Due to the separate storage of the results of each source and their combination in a second step, the effects of changing source powers, relative phases and indeed turning them on or off to simulate different scenarios, can be assessed with minimal extra computation. Thus performance targets for intelligibility can be assessed in multiple operating conditions and re-design can be achieved, rapidly.

Receivers and results

The 'microphone positions' or field points can be imported as grids from external geometry definition, but are often defined within RAYNOISE using a set of geometry-modelling tools. There are no limits on the number of receiver points.

The basic acoustic results can become very voluminous, leading to large data-storage requirements if all 'raw' data (eg, all echoes) are stored, so typically they are compressed at most field points and only stored in detail at a few selected points, where detailed echogram plots are required. The basic results then become the sound pressure levels (frequency dependent and broadband, with/out weighting) NR and NC, and many acoustic quality parameters (Echo criteria, EDT, RT30, Lateral Efficiency, TDSR, STI...).

Many graphical results-presentation tools are available – contour plots of SPL and the other acoustic parameters, echograms, three-dimensional views of ray paths – and these can be exported for incorporation into reports (eg, as GIFs) and also tabulated.

Auralization
Using detailed echogram results at a specific receiver point, the impulse response can be produced and then converted to a Binaural Impulse Response (BIR) using head-related transfer functions (HRTFs) which come from published data and are provided in the program. The orientation of the 'virtual head' at the receiver position can be controlled by the user. Using the BIR, a Convolution process is computed (within RAYNOISE) in which a 'driver' signal (typically an anechoic speech or music recording) is used to create a stereo replay signal simulating the sound that will be heard at the receiver location. This can take into account the effects of multiple sources driven by the same original signal but with different relative phases (time delays) and powers (and indeed frequency responses, which will 'shape' the received sound).
It is also possible to export the basic impulse response data (including ray-arrival directions) and use these in an external Convolution and auralization process.

3.3 Application Examples

Velodrome public address system
The velodrome shown below in Figure 5 suffered from poor acoustics, specifically as regards the intelligibility of announcements on the PA system. It was unclear what treatments would be effective, and there were limited choices. If possible, large areas of expensive treatment should be avoided and the PA system itself improved, or some local treatments only could be used. As is often the case in sports venues, very little area was available for treatment, due to operating constraints and the purpose of the building (the track itself in particular is very reflective!).

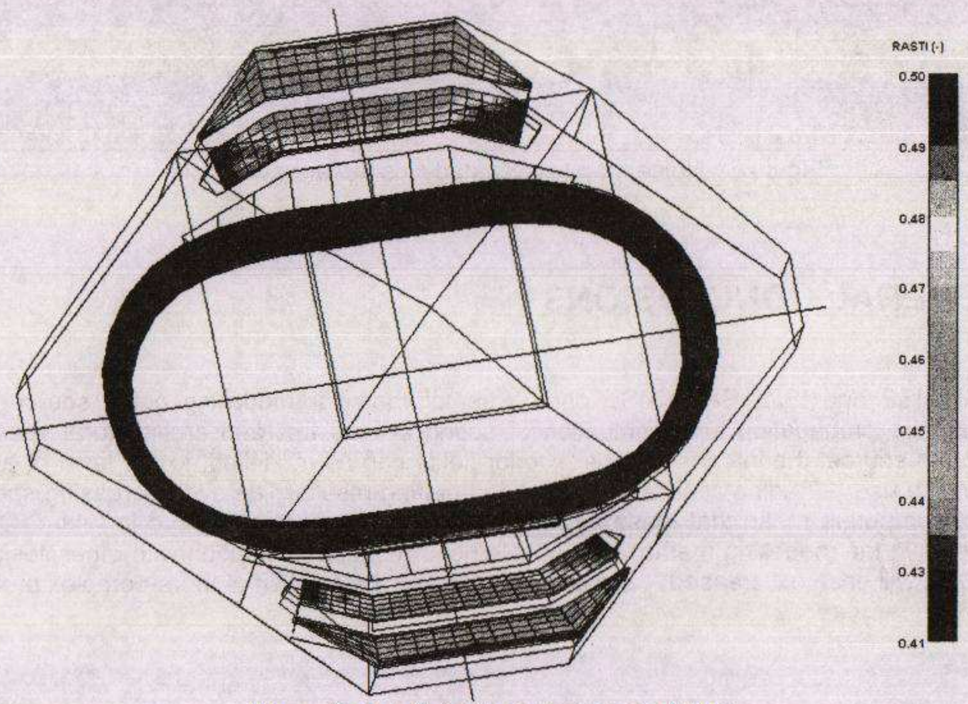

Figure 5: Intelligibility study on velodrome

The RAYNOISE model enabled the problem to be diagnosed and a solution was proposed, based mostly on applying some surface treatments to the facings of the balconies opposite the loudspeaker arrays, and some modifications to the directional characteristics of the arrays. An auralization of the 'before' situation provided a qualitative verification of the model as well as checks on quantitative measures, and the measures and auralization on the model 'after proposed modifications' convinced the client to go ahead with the proposed changes. They proved to be effective in practice.

In-vehicle noise and sound systems
RAYNOISE can also be applied in vehicle design, for example to check noise levels and distribution and particularly in the design of audio systems for in-car entertainment or for public information purposes. For example, the following Figure 6 shows a model used to verify the speech intelligibility in a railway car, using an array of ceiling-mounted loudspeakers (coherent sources, which lose intelligibility because of mutual interference and their own reverberant sound from interior surfaces) and incoherent sources and general background noise (providing masking).

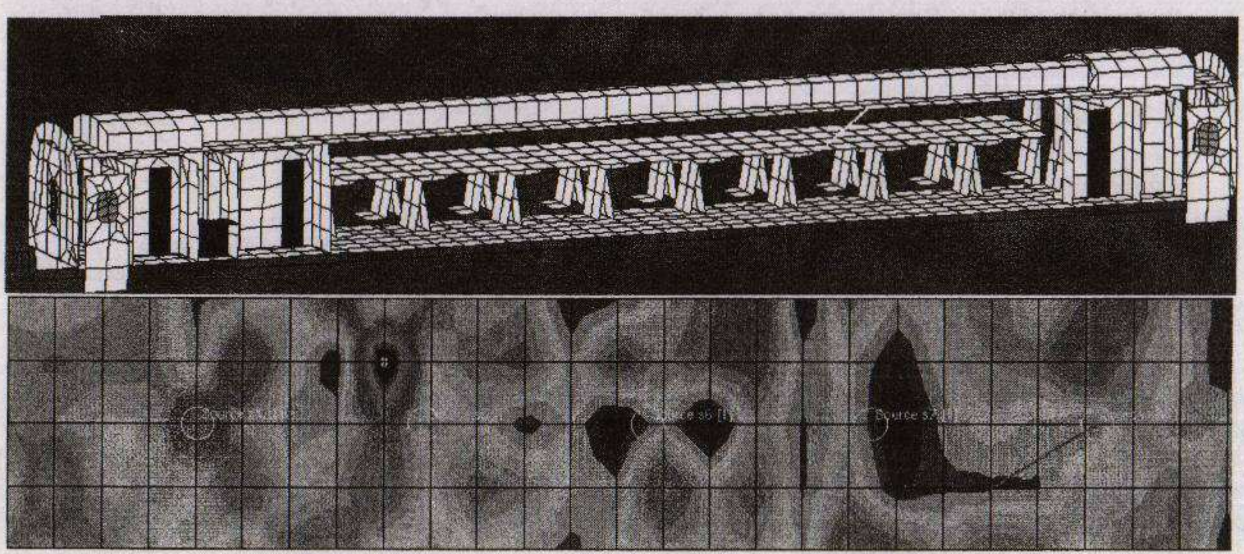

Figure 6: Noise map for STI study inside railway vehicle

4 GENERAL CONCLUSIONS

LMS SYSNOISE and LMS RAYNOISE offer a set of tools for modelling noise sources, audio devices and the propagation and distribution of sound in industrial and architectural spaces and vehicles. The source, the interior and the exterior fields can be modelled, to the level of accuracy required by the user – trading accuracy for speed of getting results. The ever-increasing speed and capacity of computers mean that these methods can be used more and more in future. On-going developments in the modelling methods, solution algorithms, and integration with other design tools such as CAD, will enable increased – and easier – use and the solution of more-complex problems.