Acoustic Modelling: A Brief Review

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Non-refereed

Introduction

This presentation is largely based on a review on modelling from LMS, a Belgium company based in Leuven [1].

The New Zealand Acoustical Society aims to be a source of knowledge for the community and provide useful information regarding acoustic issues that influence our daily life. But this is not only about telling people what is acceptable according to which code, but also informing everyone about the tools that exist, not only in underlining danger, problems and annoyance, but also in providing alternative solutions.

This paper presents a brief overview of computer modelling methods to predict the acoustic and vibroacoustic behaviour of interior and exterior fluid regions and their interaction with structures, geometrical and energy based methods (acoustic ray-tracing, statistical energy analysis, etc) and wave-based methods (structural finite elements, acoustic finite elements, boundary elements, infinite elements, etc) with emphasis on the finite element and boundary element methods.

Background: The Computing Environment

Computer-based modelling methods are by definition dependent on the computer hardware and environment within which they operate. In considering where we are today in computer modelling of noise and vibration, it is worth remembering that the hardware environment has changed radically even within the last decade, during which computational acoustics has become common. I was not into acoustics “back then”, and my generation can only give respect and credit to those who dealt with low performance computing tools for so long. Now with more powerful computers, ‘local’ machines are capable of what was considered super-computing only a short while ago. This increase in performance will continue and allow increasingly large and complex problems to be solved numerically without excessive time or resource requirements. Likewise, more rapid solutions will allow more alternatives to be considered, a prerequisite for optimization processes.

Current Acoustic Modelling: a Review

The physics of sound and vibration

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 between 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.

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 is 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 used as a basic assumption in a simple modelling approach, is a key decision for the modeller.

Acoustic and vibroacoustic modelling approaches

Acoustic modelling methods can be broadly split into different approaches based on the assumptions about the acoustic behaviour:

- empirical methods, based on simple ‘rules’ or formulae, often derived from measurements; these may even be amenable to hand calculation in some 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 multiphysics models (finite elements, boundary elements, infinite elements).

The last two approaches are the more interesting, because they offer generalized methods that can be adapted and used for many different applications, as will be discussed below.

Key Features of Acoustic Modelling Techniques			
	Ray-tracing	**S.E.A.**	**F.E./B.E.**
Frequency range defined by:	Lower frequency limit.	Lower frequency limit.	Upper frequency limit.
Suitable for:	High frequency range.	High frequency range.	Low frequency range.
Modal assumption:	High modal density.	High modal density.	Not necessarily needed.
Domain of analysis:	Time and frequency.	Time and frequency.	Frequency only.
Uncertainty over input data:	Non-implicit.	Implicit	Non-implicit

Vibroacoustic Modelling Tools

Ray-tracing method

Geometrical acoustics uses a ray-tracing method to calculate the way sound is distributed [2]. The method can be used for completely closed interior spaces, partially open ones and fully open exterior environments.

Each source is located in space and given a defined power. It may radiate equally in all directions, preferentially in some (by a defined directivity, e.g. a directional loudspeaker) or wholly within a defined region (e.g. 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 like mirrors, losing energy at each reflection in accordance with the absorption properties of the surfaces. The rays 'capture' receiver points 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).

From the echograms (impulse responses) at each receiver point many sound parameters can be derived: steady-state sound pressure level, acoustic quality measures and Speech Transmission Index [3].

All of these can be frequency dependent, since absorption properties, source powers, and directivities can vary with frequency. By superimposing many different sources, varying their properties, 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 analysed.

Typically, the basic model data such as geometry is 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. Special techniques exist for modelling diffusion, diffraction (e.g. over barriers) and the transmission of sound through partitions from one region to another (e.g. from outside to inside of a vehicle, from one compartment to another). These techniques enable a complete model of the noise environment around as well as inside a vehicle or building to be built up.

Statistical Energy Analysis

Geometrical acoustics is more-or-less limited to purely acoustic calculations, such as building and environmental acoustics, and noise distribution in or around a vehicle. Where the noise is mainly structure-borne, it is necessary to consider the structural vibration behaviour, rather than the geometrical distribution of the sound.

At medium to high frequencies the standard approach for modelling has become Statistical Energy Analysis (SEA). In this approach, the structure is broken down into sub-systems, each of which has defined boundaries, geometry (curved shell, acoustic space) properties (thickness, honeycomb core, beam cross-section) and connections to other sub-systems (point, line, area) [4].

The geometry, properties and connections define the vibrational characteristics of the sub-systems and their interactions. An important input is also information about damping ('loss factors') within the sub-systems and in their connections. The model, consisting of the assembly of all the sub-systems, is driven by energy inputs related to the physical sources of vibration and noise, such as suspension mounts, motors, ancillary equipment, and so on, and an energy-balance (or flow) is derived. The results are then the energy levels (vibrational or acoustic) in the subsystems, and the flow of energy from the sources into the dissipating systems.

SEA provides an effective modelling tool for the global behaviour of structural vibrations and noise radiation to the exterior and interior spaces, with the benefit of being reasonably fast and therefore practical at the design stage.

By integrating experimental vibration measurements on prototypes, previous designs, or sub -systems of a new design, the data input to the models can be validated and improved.

Whilst a SEA model is essentially just a network of sub-systems and connections, it can also be visualized in a geometrical way, and geometrical data can be captured to provide the basis for the sub-system properties.

Finite Element and Boundary Element Methods

Finite element (FE) methods are well established for structural models, including dynamics as well as stress analysis and fluids [5]. FE acoustic models are effective, where discrete wave behaviour is to be modelled.

The basic concept of the FE method is that a body or structure may be divided into smaller elements of finite dimensions called "Finite Elements". The original body or structure is then considered as an assemblage of these elements connected at a finite number of joints called "Nodes" or "Nodal Points".

The properties of the elements are formulated and combined to obtain the properties of the entire body. Since the wave behaviour is also 'sampled' in space, a criterion for minimum element size versus wavelength is applied, typically six linear elements per wavelength [6].

By definition, FE 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.

Because each element has independent matrices, which build up the system matrices, each element can have unique properties: sound speed and density (e.g. Changing due to temperature) and volume absorbers.

Boundary element (BE) acoustic models implicitly have the Sommerfeld infinite-field radiation characteristic built-in, if they are exterior models, unlike FE methods which are conventionally limited to interiors [2].

BE methods can also be used for interior closed geometries, and the most-useful BE formulation (Indirect, Variational method) is generalised and can be used for interiors or exteriors or 'mixed' problems (cavities with openings...) and thin appendages like ribs, and complex topologies with 'junctions' (T- or X intersections of surfaces). Half-space conditions or symmetry can be used.

Both FE and BE acoustics models can be coupled to FE structural models in an effective way, 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. Most of the modelling done with FE and BE acoustics is currently in the frequency domain (i.e., Helmholtz form of the wave equation) but time domain methods are also possible.

For BE methods, time domain solutions have not proved reliable, but for FE methods it is robust and not too sensitive to input data or solution control parameters such as time step.

Infinite elements (IFE) 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 (volume) finite elements, which are used to model the near field. The base surface usually has to be a regular geometric shape (sphere, ellipsoid, etc).

IFE methods offer the benefits of FEM in the near field, and robust time domain solutions as well as frequency-domain.

Vibroacoustic panel and trim modelling

Special vibroacoustic models using FE methods can be applied to the design of panels and trim assemblies. These models use both structural and fluid elements for the appropriate parts, and special elements with properties related to both fluid (air) and structural 'phases' in the material. Typically, these elements use Biot's method [2] to define the interaction of acoustic waves and structural vibrations, in porous or fibrous material. Thus one can model the behaviour of a structural panel, where the vibrations are altered and the acoustic radiation or transmission is changed by the addition of multiple layers of damping and absorbent material. This can be especially useful in applications such as design for minimum acoustic transmission of floors, other vehicle panels or doors.

In the higher frequency range, multi-layer models can be developed based on transfer function models of the individual layers. Those models can either be used standalone (to optimise multi-layer configuration) or integrated within larger SEA system models, to evaluate their impact on vibroacoustic systems response.

Limitations of Modelling Techniques in Vibroacoustics

Frequency range

For the wave-based methods (acoustic BE methods, acoustic and structural FE methods) it is usual to require a minimum of 6 linear elements per wavelength for reasonable accuracy, thus setting a practical upper frequency limit. If the desired upper frequency is raised, the element size decreases and the model size increases, and the calculation time increases as a power of the model size, up to the limit of computer resources (or the time the user is prepared to wait).

A limit is also imposed by the assumption of discrete wave behaviour, with distinct modes of the acoustic cavity or the structure, which starts to break down at some frequency limit. Structural FE meshes used as the basis for an acoustic model may well be much too 'fine', but tools are available for re-meshing and even 'reverse-engineering' a geometry model from a mesh.

By contrast, the acoustic ray-tracing and SEA approaches have a lower limit to their useful frequency range, since they make the assumption of high modal density and acoustic or vibrational energy dispersion. In purely acoustic models the limit can be lowered or even removed, by using Phase Ray-tracing, in which a coherent wave-like behaviour is added back to the acoustic propagation.

Linearity

Most of the methods discussed here assume linear behaviour (small perturbations) which is also convenient for solutions in the frequency domain. However non-linear sources exist and have been implemented in several computing models, which allow acoustic wave input to depend on the computed acoustic pressure: this is characteristic of combustion noise in burners, boilers, etc.

However, high-energy acoustic behaviour (which may be of interest in acoustic fatigue, for example) becomes quickly non-linear. The structural behaviour may also include non-linearities: contact, non-linear or high-hysteretic materials... (For example, in tyre noise models), or kinematics motion (flexible, multi-body dynamics). Therefore, non-linear analysis has been implemented and is now available to general use. But such cases remain rare and confined to particular domains.

Most of these non-linear effects can be handled in a time-domain solution for multi-body dynamics of flexible bodies or submitted to high energetic excitations.

Uncertainty

In practical modelling, there is often an uncertainty over the input data for the model: values for acoustic sources or structural vibrations or forces may not be well quantified, materials data (especially damping) may be uncertain.

Ideally, the models should give indications of sensitivities or 'confidence limits' based on the uncertainties of the inputs. In some cases such as SEA (Statistical Energy Analysis) this is implicit, but most vibroacoustic methods are deterministic in nature. Examination of sensitivities then requires additional processing.

A key input in a deterministic model, such as the acoustic BE method, is the phase relationship of different sources or vibrations. This is often difficult to establish accurately, or it may be subject to 'drift' on the real-world product. Some input may be incoherent (within themselves, or in relation to others).

There is consequently no relative accuracy of each model but a given situation defines, in most cases, the appropriate model to be used.

Resources

Although the trend in computer speed and capacity is in the right direction, some of the methods described here place heavy demands on computer resources. This is especially true of BE method calculations, where the calculation time per frequency makes a complete solution with several scenarios quite expensive. As a result, the modeller has to use considerable judgement to reduce the numbers of runs to be performed [7].

Conclusions

The breadth of methods in acoustic and vibroacoustic modelling has been presented. The techniques available today are able to deliver tangible benefits in the product design process and in assessing acoustic performance in a wide range of applications. However, there is a significant lack of integration of these methods into the daily work of acousticians even though software utilising such tools already exists.

Transposing theses methods into user-friendly programmes, tailored to acoustic requirements, is indeed a complicated task. However, the performance of the tools, and the possibilities offered (and still to be discovered) seem to be worth the effort.

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