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NOISE PREDICTION: WHAT SOME COMPUTER MODELS CAN DO

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1 INTRODUCTION

Until recently, the question of noise from private motor vehicles was addressed mainly with regard to interior noise and the comfort of driver and passengers. Only for commercial vehicles and public-service vehicles was exterior (ie, pass-by) noise treated as a major problem - which is understandable, given their higher basic noise levels (the only exception being motor-cycles - a perennial problem). The current desire for generally lower environmental noise levels, combined with the increased traffic densities and urbanisation of developed countries, has caused attention to be focussed increasingly on the exterior noise from private cars.

Computer modelling has also followed the changing emphasis in noise reduction: initially, methods were developed for the analysis of interior cabin noise - resonances (boom) and forced response, including the influence of different panels, location and effectiveness of absorption and damping treatments and interaction between different volumes and intervening structures. Now, analysis software and modelling methods are being developed and used for exterior noise problems. In some cases, they require new or refined technologies and application techniques, and it is the aim of this paper to highlight these.

2 MODELLING VERSUS EXPERIMENTS

It is possible to address exterior vehicle noise solely by experimental methods: test track and semi-anechoic chamber tests on prototype vehicles and/or sub-systems. However, this has several disadvantages:

- time delays before problems are clearly identified (and solved)
- costs of facilities and prototypes
- cost and time consequences of repeated modifications and tests.

Computer modelling allows potential problems to be identified, quantified and their causes assessed, at an early stage whilst the design is still only 'on paper'. The reasons for particular phenomena can be identified (large volumes of data are often generated, compared to tests) and many re-analyses can be carried out rapidly, on relatively low-cost facilities, allowing sensitivity studies and optimal solutions. However, many of the input data to computer modelling of vibro-acoustic behaviour are poorly known and assumptions have to be made: these can be based on past experience (as expertise builds up in the modelling techniques) or in some cases derived from tests - for example, body or engine-block vibrations or modal tests, or experiments to determine specific acoustic properties such as absorption (as a frequency-dependent complex number). Partly because of these input assumptions, computer models do not give absolute noise levels, but do indicate trends and the relative importance of different effects or design changes.

We conclude that modelling and experiments are complementary rather than competitive, although it is likely that the proportion of project time and cost devoted to modelling will increase and testing will decrease in future. In some cases the two will be linked, for instance some 'models' are used to carry out further analysis on experimental data. Models will allow a most-likely optimum design to be achieved earlier, but testing will still be needed for verification and to provide reliable input data.

3 BASIC THEORY

3.1 Linear, Steady-State Phenomena

The noise phenomena considered are essentially steady-state and can be analysed as frequency spectra, hence the models are calculated in the frequency domain and Helmholtz' form of the wave equation can be used. The results are the behaviour of the whole system at each selected frequency, or at selected points at all frequencies (FRFs). The behaviour is assumed linear (eg, absorbers have the same characteristics whatever the sound pressure level (SPL) although it may be frequency-dependent). Hence the results of various analyses may be superposed or factored - including rotation in the complex plane, ie changing phase relationships, which is often of interest and not least in the design of anti-noise effects.

For closed volumes, finite element (FE) discretization is favoured, mainly because of the straightforward understanding of the results. For exterior fields, a boundary element (BE) approach is superior, since the radiation to zero SPL at infinity is automatically taken into account. A special form, the variational BE method, is of particular use in many real-life cases, because it allows the fluid to be on both sides of a structure at the same time and can account for open structures with 'free edges' without the numerical difficulties of the conventional BE formulation.

At high frequencies, an 'asymptotic approximation' can be used in the BE method, for considerable savings in computation time of sound radiation. Likewise, where deterministic effects (eg, discrete modes) are not significant, mainly at higher frequencies, ray- or beam-tracing techniques may be used: a development will be reported at another time.

3.2 Coupled or Uncoupled Analyses

Whether or not the structural behaviour must be included in the acoustic analysis is a question that can only be answered based on experience with the specific application. If the structure is included, it may be represented as a conventional structural finite element model, either in physical terms (mass and stiffness matrices) or as a modal model. We call this fully-coupled or two-way interaction. Otherwise, structural vibrations just form the boundary conditions for an acoustic radiation calculation and the structural behaviour is not modified by the presence of the mass and stiffness of the fluid. We call this uncoupled or one-way interaction.

The mathematics of the FE and BE acoustics and fully-coupled calculations have been described in detail elsewhere [1,2].

4 TYPES OF MODEL

4.1 General Classification

We can identify three general types of model, based on their extent:

- components
- sub-systems
  (assemblies of components and their installation location)
- whole vehicle

4.2 Components

The modelling of individual components is usually oriented towards finding the local sources or causes of noise on those components and reducing their noise output in order to reduce the noise output of the total vehicle. The models are frequently very detailed, but different modelling approaches are needed, depending on the item considered.

4.2.1 Engine

Boundary element models enable noise radiation prediction into a free field. Half-space (ground) effects may be included. The response in terms of SPLs and intensities at selected locations or on cross-sections or other surfaces in the field can be presented as FRFs and as spatial contour or vector plots (see Figure 1). Since surface intensities are known, total sound power and the contribution from selected surfaces can be found directly, as can the sound power radiated in different directions (directivity). Conventionally, the collocation BEM has been used, but the variational BEM is needed to handle structures with free edges, such as ribs, skirts or shields. Our experience is that variational BEM is in any case faster for solving problems of realistic size. The fluid influence is negligible, so a one-way coupling analysis is used. the boundary conditions of the BEM acoustic solution are usually the surface vibrations of the engine block (with oilpan, covers, &c as required) which may be automatically transferred from a structural FE analysis, either as modes or forced response (based in turn on defined mechanical and combustion forces).

4.2.2 Exhaust systems - mufflers

An exhaust system can be modelled in its entirety or individual sections can be considered. In the first case, 'system' models are often used, based on relatively simple 'elements' (tube, muffler, branch, end, ...) which have complex behaviour defined as transfer functions, derived analytically or more often from test data. The result is an overall transmission (or insertion) loss for the complete system. This is most useful at the feasibility/design stage.

In the second case, individual elements can be considered to optimise their details. Acoustic FEM allows detailed internal modelling, including volume absorber elements with properties representing the behaviour of basalt wool, E-glass and similar packings, at the densities and properties found in practice. Transfer impedances can also be used, for example to represent the perforated tubes and wire wool sleeves used inside reverberant/absorbent boxes. Figure 2 shows a typical detailed FE model of the internals of a muffler.

Some current work uses special test rigs to derive materials or micro-component data for use in such FE models: the test measurements can be used directly, or in some cases the tests themselves are modelled and the model parameters updated to match the test results. Special modelling techniques are also developed to cater for the internal characteristics of catalytic converter units.

The overall result of the interior (FE) model of a muffler is a transmission loss, derived from models with appropriate boundary conditions at input and output and the 'four-pole parameter formula'.

If local effects on exterior noise need to be investigated (eg, tail-pipe directivity) a BEM acoustics model must be used instead of or as well as FEM. If fluid-structure interaction is significant (shell ringing) a fully-coupled FEM structure/BEM acoustics model may be needed.

4.2.3 Intakes

Although not as serious as exhaust noise, intake system noise can be a significant part of the total powertrain noise. Intakes may be modelled by acoustic FEM, but since they are often light, thin structures (eg from plastic/composite materials) fully-coupled fluid-structure interaction analysis can be essential to get correct results (see Figure 3 and [3]). Since intakes are often short, open structures, acoustic BEM (variational formulation) is more often the approach chosen.

4.2.4 Tyres

Noise due to the contact patch itself is due to a combination of tread and road surface and the speed and load. Modelling this as a noise source (a series of sources around the periphery of the contact patch) in acoustic BEM is under evaluation, and results in a semi-empirical approach. Modelling noise radiation due to the vibration of the sidewalls is more straightforward and uses the same BEM techniques as engine block radiation.

4.2.5 Other Components

As the engine, exhaust and intake noise levels are reduced, the influence of other, previously-secondary sources becomes more apparent, such as alternators, gearboxes and auxiliary under-bonnet equipment. These can often be modelled with acoustic BEM, similarly to the engine (Figure 4).

4.2.6 Design of Absorbers

Under-bonnet acoustic performance can often be improved by adding absorbent panels or linings, as well as component re-design such as reducing engine block and cover vibration based on acoustic sensitivities. The design of special absorbent materials such as the 'damped foil' absorber has benefitted from fluid-structure interaction analysis and special modelling techniques.

4.3 Sub-systems

Sub-systems are essentially assemblies of individual components and as such can be modelled by assembling individual component models. Of particular interest at the design stage is the geometric placement of different items - for example, placing shields around an engine or lining appropriate parts of an engine bay with absorbent material, or the influence of tail-pipe location on exterior noise distribution. In many cases, free-field (or partly free) conditions exist, so acoustic BEM is used. However, in some cases (where the model has a large number of elements or high frequencies are to be calculated, for which classical BEM requires numerically very large models) specially-adapted ray- or beam-tracing techniques may be used.

4.4 Whole vehicle

In theory, a whole vehicle model is just another step up in assembling sub-system and component models in acoustic BEM, including the vehicle structure envelope and other significant geometric parts which are not direct noise sources. In practice, this does not seem to be used as a regular design tool, in a deterministic manner. Specific models may be used for trouble-shooting, but most often where the major sources have already been quantified as individual components (often verified by tests) and the main aim is geometric re-organisation and eliminating specific problems.

At present, effective approaches seem to be based on experimental data, so are used in trouble-shooting and verification work. Some numerical techniques, based on simplified relationships for wave propagation, permit the transformation of a sound field from one location to another in space (eg, towards or away from the vehicle side). Acoustic BEM adds a more powerful capability: no restriction on the geometry (eg, transformation onto irregularly-shaped 3-dimensional surfaces) and, by solving an inverse problem, source identification: deriving sources from known pressures and phases and/or intensities in the field.

5 CONCLUSIONS

- Acoustic modelling allows problems to be identified and solved at the design stage, before any prototyping.
- Many design options can be studied cost-effectively and sensitivity studies performed, to arrive at designs nearer to optimum.
- Special modelling techniques enable very powerful analyses of specific components to be carried out.
- Whole vehicle behaviour is not so easily assessed solely by deterministic models: test/empirical data are also likely to be needed, but acoustic models can be very useful in trouble-shooting.
- Experimental work will continue to be needed for verification and to derive specific materials data and other modelling inputs.
- Variational acoustic BEM is a powerful technique for many cases.

6 REFERENCES

[1] J-P Coyette, K Fyfe, C F McCulloch 'Modelling interior and exterior acoustics ...' IMechE Autotech Conference C399/21, 1989

[2] SYSNOISE Theoretical Manual, Version 4.4, Numerical Integration Technologies, Leuven, Belgium, 1992

[3] G Schellino, C Vipiana, P Guisset 'Study of a Structural Acoustic Interaction in an Air Intake System for Commercial Vehicles' Conference on Vehicle Comfort, Bologna, Italy, October 1992

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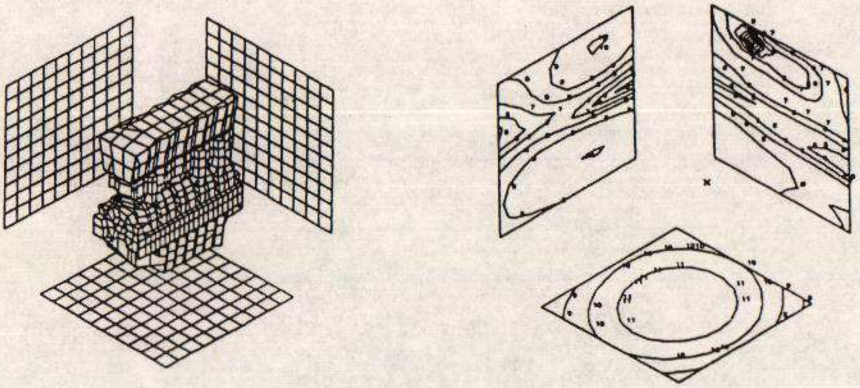

Figure 1: Engine block radiation model and SPL on visualisation surfaces

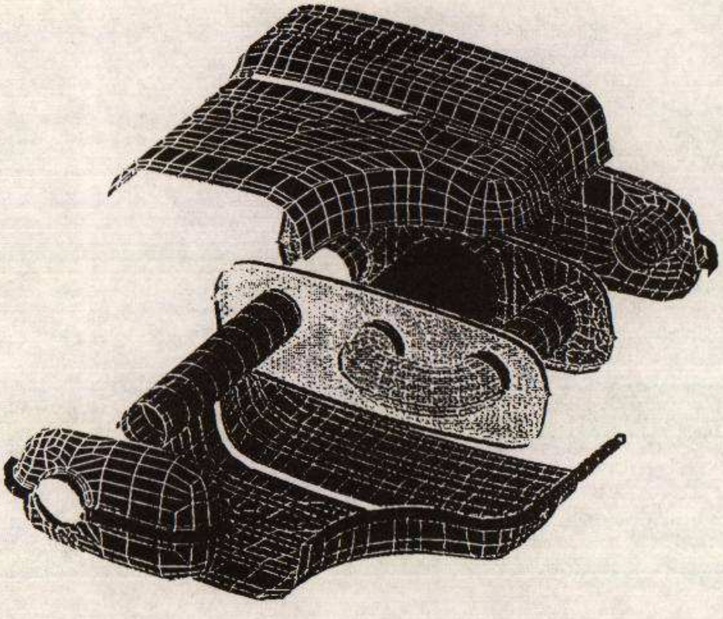

Figure 2: FE model of clamshell muffler (mesh surfaces)

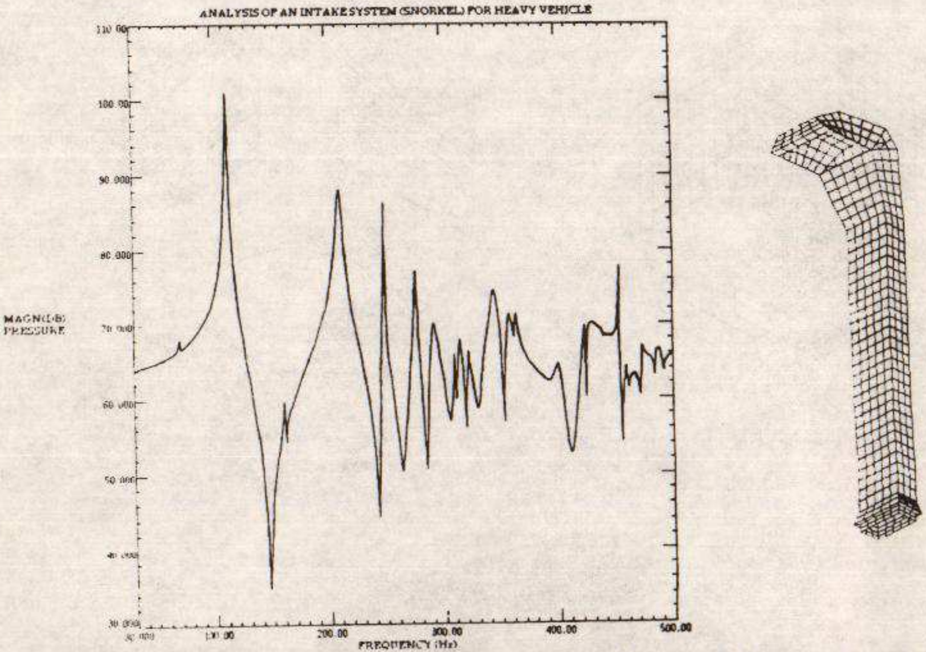

Figure 3: Air intake frequency response (correlated with test): BE model

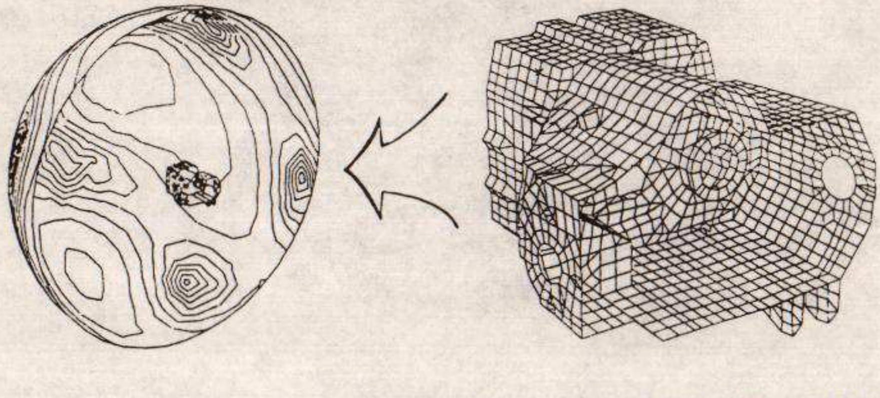

Figure 4: Drive-train noise radiation BE model, with directional effects