ACOUSTIC DIAGNOSTIC ANALYSIS OF AUTOMOBILE PASSENGER COMPARTMENTS

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ABSTRACT

The automobile industry has long been fiercely competitive, with different vendors attempting to produce vehicles with better performance, handling and fuel efficiency. Now the industry is seeing the competition taking place in automobile acoustics, and a quiet ride has become an important attribute of modem vehicles.

In order to assess the noise levels inside a car, it is possible to analyze the acoustic field using a computer based model. Most recently this has been done predominantly using the Boundary Element Method (BEM). This predicts the acoustic pressures and sound intensities, etc. given a set of boundary conditions which describe the velocity of the body panels and the sound absorbency of the materials covering those panels.

A BEM analysis can be extended by performing an 'acoustic diagnostic analysis'. This considers the noise at any point (e.g. the driver's right ear), and breaks it down into the contributions from the individual body panels. Thus engineers can determine the panels which should be stiffened or otherwise modified to reduce the perceived acoustic pressures. This paper describes acoustic diagnostic analysis, and how the analysis may be formulated to consider the effect of multiple connected acoustic domains - e.g. the car acoustic cavity, the trunk and the foam material of the seats. The paper also describes how the acoustic diagnostic analysis may be reformulated to relate to the panel velocities rather than the more customary acoustic velocities at the panel surfaces. These extensions allow more accuracy in panel acoustic contribution analysis.

INTRODUCTION

It is becoming increasingly important in vehicle design to consider the Noise, Vibration and Harshness (NVH) which together define the quality of ride. A major factor in interior NVH is the vibrational and acoustic behavior of the vehicle body panels. Vibrations in these panels are excited by a number of sources, including wind, powertrain and road/tire effects. In turn the vibrating panels generate acoustic pressures in the acoustic cavity of the passenger compartment.

Panel acoustic contribution analysis (PACA) is a systematic approach which has been developed to determine the contributions of body panels to a vehicle interior sound pressure, pinpoint the local areas of the panel which need modification and provide the most effective solutions. It relies on the fact that the noise at any interior point, such as the driver's right ear, is a superposition of the contributions to that noise from the vibrations of the various body panels which surround the acoustic cavity.

The analysis which determines the contributions may be performed numerically using the technique known as the Boundary Element Method (BEM) [1,2]. A classical (or 'first generation') BEM prediction will provide information about the sound pressure levels at any point in the acoustic cavity which result from a prescribed profile of panel velocities at a given frequency. While this is a useful prediction in itself, it does not assist in pointing the way to improvements in the design. If a panel has a high velocity, for example, it does not follow that it will be making a high contribution to the noise at the driver's ear. Indeed, the panel may be acting to reduce the noise by cancellation effects.

This drawback has led to the development of 'second generation' BEM acoustic prediction techniques. Here, the contributions to the acoustic pressure at any point of each panel (or, further, of each part of the panel) may be computed, giving an immediate indication of the most effective modifications which can be made to the design to improve its NVH characteristics.

An essential part in the PACA process which is described in this paper is the accurate definition of the panel velocities which are used as the boundary conditions input to the BEM analysis. *The* velocities can be defined in three ways: firstly manual input to the program, which is highly time consuming and does not allow easily for anything but the simplest of variations in velocity over the panels. Manual input can be useful for simple tests with uniform velocities. Secondly, velocities may be taken from the output of a finite element structural vibration analysis. This has the advantage of simplicity in that it does not require a prototype vehicle, but suffers from the limited range of frequencies which may be considered. For vehicle structures, reliable velocities may be obtained in this way for frequencies up to around 80Hz. Thirdly, velocities may be found experimentally, and because of the drawbacks of the manual and finite element methods this is the only reliable method for the higher frequency noises. The PACA analysis presented in this paper is a combination of Computer Aided Engineering (CAE) with experimental methods using Computer Aided Holometry (CAH) [3], Scanning Laser Velocimeter (SLV) or an accelerometer net to measure experimentally the structural vibration velocities.

To demonstrate the PACA approach, a sheet metal box half the size of a 'typical' vehicle passenger compartment was tested [4]. The acoustic contribution of each panel was calculated and the positive, negative and neutral contribution areas were identified (figure 1). The experimental sound measurement showed a good correlation with the analytical results. To verify PACA's use in reducing sound pressure, a 0.9kg mass was attached to a positive contribution area to reduce vibration. The experimental results showed a maximum 12dB noise reduction (figure 2). When the same mass was moved to a negative contribution area, a 5dB noise increase was observed. There were virtually no changes in the sound pressure level when the mass was attached at the neutral areas.

THE BOUNDARY ELEMENT ACOUSTIC DIAGNOSTIC SOLUTION

The distribution of acoustic pressure p in a linear isotropic acoustic domain is governed by the Helmholtz *equation*

$$\nabla^2 p + k^2 p = 0 \tag{1}$$

where k is the wave number, equal to the angular frequency divided by the speed of sound. Using the concept of a free-field Green's function, or fundamental solution, a boundary integral equation can be written for each grid point on the boundary. Considering each grid point in turn one obtains

$$\mathbf{AP=BV} \tag{2}$$

where P and V are the acoustic pressure vector and the normal air particle velocity on the boundary. A and B are influence coefficient matrices of NxN dimensions where N is the number of degrees of freedom of the surface mesh.

At this stage there remains a total of 2N unknown terms (i.e. the complete contents of vectors P and V). To reduce this number to N, and thereby to obtain a solvable system of equations, a set of boundary conditions are applied. In practice, the boundary conditions consist of a velocity and/or impedance for each grid point. For vehicle acoustic applications, two types of interior boundary surfaces are considered; structures on Γ_1, such as bare sheet metals and glasses, and structures with acoustic absorbent materials on Γ_2, such as floor panels with carpet and roof panels with headliner. These two types of vehicle interior surfaces are represented by the boundary conditions below:

$$v = v_s \qquad \text{on } \Gamma_1 \tag{3a}$$

$$z(v - v_s) = p \qquad \text{on } \Gamma_2 \tag{3b}$$

where z is the acoustic impedance which is determined experimentally and v_S is the normal velocity of the structure. v is the acoustic normal particle velocity from vector V in equation (2). By considering equations (3a) and (3b) it is possible to rewrite the vector V in terms of the panel velocity vector V_s,

$$\mathbf{V} = \mathbf{V}_s + \mathbf{DP} \tag{4a}$$

where

$$\mathbf{D} = \begin{bmatrix} 0 & 0 \\ 0 & \mathbf{Z}^{-1} \end{bmatrix} \tag{4b}$$

and **Z** is a diagonal matrix that contains the normal impedance of discretized elements on the boundary Γ_2. Substituting equation (4a) into equation (2), the unknown acoustic pressure on the boundary is expressed in terms of known structure normal velocity. Once the particle velocity V and acoustic pressure P of boundary nodes are solved, the next step is to apply the boundary integral equation on the internal points of interest. Using this modified form of the velocity term in the boundary integral equation the sound pressure at any interior point can be calculated by

$$p = \mathbf{a}^T\mathbf{P} + \mathbf{b}^T\mathrm{V}_s \tag{5}$$

where **a** and **b** are Nx1 matrices obtained from integration of the free-field Green's function over the surface of the appropriate BE zone, using the same boundary discretization as for the boundary solution. Next, by using equations (3b) and (4a) to describe the pressure as a function of velocity, equation (5) can be rewritten to express the internal point pressure p as a function of the panel velocity, no longer including the pressure term.

$$p = \mathbf{T}\,\mathbf{V}_s \tag{6}$$

where T is a transfer function (or sensitivity) relating panel velocities to internal point pressures.

This is an important modification, since an analysis of contributions based on the acoustic particle velocity does not relate directly to the structural velocities which are measured more directly and which can be predicted more closely using numerical and experimental methods. Ideally, a non-vibrating surface should be calculated to have a zero contribution to the acoustic pressure at an internal point. With the original formulation based on acoustic velocities (equation (2)), elements modeling seats and surfaces with absorbing materials such as carpets and headliners will be found to have a non-zero contribution. This is because, although the surfaces themselves are not vibrating, the impedance of the materials causes a non-zero acoustic particle velocity as predicted by equation (3b). The new formulation gives these types of non-vibrating surface a zero contribution and thus redistributes the contributions to those panels which are the true source of the noise which is being reflected off the non-vibrating panels.

As a final extension of the method to be discussed here, the technique described above has been extended to predict panel contributions to internal points in multi-zone problems. This is an important extension for automobile acoustic applications, since it allows the body panels in the trunk to be considered in an acoustic contribution analysis. Zones are parts of a boundary element model which may be used to represent a part of the structure or acoustic cavity to be analyzed. In a PACA analysis, zones are most often used to represent the acoustically separate regions of the main cavity, the trunk and the foam material making up the seats. The zones may have different properties in terms of the speed of sound and density, and since these quantities are complex this formulation allows for panel acoustic contributions in the presence of some wave propagation through porous materials.

The modified boundary element formulations described in this paper have been implemented into the BEASY software [5], which has been selected as the analysis software for this work.

CONCLUSIONS

Several technological achievements have been accomplished in the PACA project. The multi-zone concept has been employed to model the seats, the acoustic transfer (sensitivity) function with respect to structural vibration has been considered, the acoustic pressures at interior points are traced to the panels making the largest contributions (including the effects of noise which may be reflected off other panels), and a complex velocity measurement of a full vehicle using laser technology has been developed. The example of the sheet metal box successfully proved the concept, and subsequent analysis of full vehicles has proved that the PACA technique is a powerful tool for vehicle NVH refinement.

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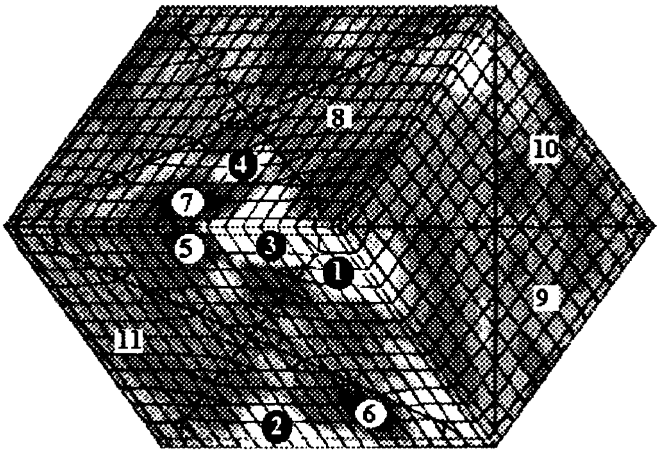

Figure 1. Boundary element model of the sheet metal box, showing acoustic contributions. Key: ● positive contribution area, O negative contribution area, ☐ neutral area.

Figure 2. *Noise* reduction when mass is applied to positive contribution area (o - original, x - modified)