Sound Radiation Analysis of Automobile Engine Covers

Summary

A methodology to study the sound radiation of engine valve covers is presented. The analysis process uses a nonlinear static simulation followed by a steady state dynamics simulation to determine the sound pressure field due to the vibration of the engine cover. The effects of assembly loads are included. The methodology is demonstrated with two representative engine valve covers using acoustic finite and/or infinite element methods. Good correlation between the analysis results and available experimental data is achieved.

Introduction

In a typical automobile engine, a high percentage of the radiated acoustic energy is due to vibrations of various covers attached to the engine block. Among them, the valve cover has been consistently implicated as being a major noise contributor due to its large surface area and relatively small thickness. Thus, in conjunction with the structural analysis, acoustic analysis of the valve cover has become one of the key steps in the design process.

Analysis of the noise radiation from the valve cover involves modeling the adjacent air, which is of infinite extent. Directly modeling the infinite air domain with acoustic finite elements is not practical. However, the effect of the infinite extent can be simulated in two ways; through the use of acoustic infinite elements, or impedance treatments on the boundary of a truncated mesh of acoustic finite elements.

The infinite element method has been gaining popularity in the simulation of exterior noise radiation problems (Refs 2-4). Infinite elements possess surface topology; i.e. "shell-like" in three dimensions and "beam-like" in two dimensions. The elements can be applied directly to a structure or on the terminating surface of a region of acoustic finite elements. Infinite elements may lower modeling expense by minimizing or completely eliminating the need for finite element discretization of the surrounding air.

The boundary impedance technique is essentially a non-reflecting boundary condition (NRBC) that prevents acoustic energy from reflecting back into the domain. The impedance-based radiating boundary conditions, while approximate, do in practice yield acceptable results; however, the distance between the structure and the radiating surface must be sufficiently large (typically a third to one acoustic wavelength)

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Key Abaqus Features and Benefits

- Ability to use a single model for the entire analysis sequence of mechanical and acoustic simulations

- The inclusion of non-linear effects and frequency-dependent viscous damping of the elastomeric components in the prediction of sound radiation

- Ability to create surrounding air domains in Abaqus/CAE using the underlying geometry of the structure

- Ability to model near-field acoustics with acoustic finite elements

- Ability to model the infinite domain via acoustic infinite elements or impedance boundary conditions

- Ability to visualize the far-field acoustic pressures

This technology brief illustrates some practical aspects of using acoustic infinite elements in modeling the noise radiation from automobile valve covers. The methodology is presented using two different models that differ primarily in their geometric complexity.

Acoustic Infinite Elements in Abaqus

The acoustic infinite element formulation differs from the radiation boundary condition formulation in several key aspects. The infinite elements use higher order interpolating functions, so the per-element cost of this approach is higher than that of a simple first-order radiation boundary condition. However, as the accuracy of the infinite elements is typically much greater than that of the impedance condition, the required size of the acoustic finite element region may be considerably reduced, thereby reducing the total cost in many applications.

In addition, the infinite elements in Abaqus retain their locality, in that each element is coupled only to its immediate neighbors (akin to regular finite elements). This offers significant performance gains over the boundary element method (BEM) where each element is coupled to all others. This advantage becomes increasingly important as the number of infinite elements is increased. Moreover, as opposed to the BEM, the infinite element matrices do not need to be re-evaluated at each frequency of interest. This fact is advantageous when a dense frequency sweep is required.

When using infinite elements, the nodal normal vectors must point into the infinite domain. For geometrically complicated surfaces, it may be difficult to satisfy this requirement. Hence a combination of finite and infinite elements may be required. In this approach, the finite elements serve as "fillers" for any concavities, such that when the infinite elements are placed upon the finite elements, they are certain to point in the infinite direction, and there is no overlap between any two infinite element normal vectors.

Analysis Approach

In the first model, a cover with a geometrically simple shape (henceforth referred to as the 'prototype' cover) is analyzed. The surrounding air was modeled in two ways, using infinite and finite elements. Due to the simplicity of the shape, the acoustic infinite elements may be coupled directly to the cover structural finite element model, without the need for an intermediate acoustic finite element domain. The results from this model are consistent with those obtained using acoustic finite elements and an impedance condition. However, the use of acoustic infinite elements has proven to be significantly more efficient, both in terms of meshing effort and computational cost.

In the second model, a more complicated cover assembly (henceforth referred to as the 'production' cover) is simulated using a combination of acoustic finite and infinite elements. Due to the complex features of the cover, a small volume of acoustic finite elements is constructed so as to encompass the cover, and the infinite element mesh is constructed on the terminating surface of this finite element region. The results from this model have been compared with experimental measurements conducted at various engine operating conditions, and satisfactory correlations have been observed.

Prototype Cover

Structural Model

The first engine valve cover under consideration is shown in Figures 1a and 1b.
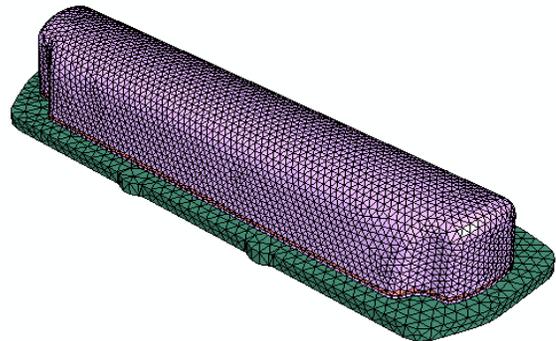

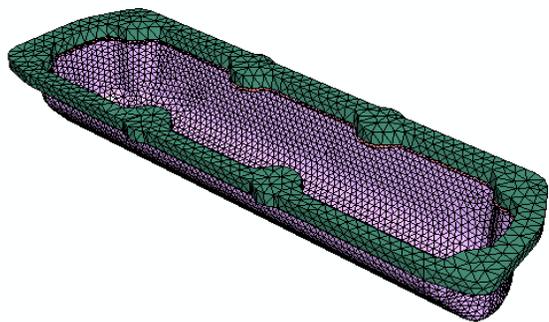Figure 1a: Prototype engine valve cover model - top view

Figure 1b: Prototype engine valve cover model - bottom view

Acoustic Model and Structural Coupling

The exterior air adjacent to the cover was first modeled with acoustic infinite elements. The infinite element mesh is applied as 'skin' on the surface of the structural mesh (Figure 2). Thus the surface nodes on the shell are also shared with the acoustic infinite elements. This node sharing is purely a matter of convenience; there is no need for the structural and acoustic meshes to conform at their interface; one could create a separate infinite element part and couple it to the structure using a surface-based tie constraint – in that case, the structural and acoustic infinite meshes could be arbitrary and non-conforming.

The valve cover structure was also directly coupled with an acoustic finite element mesh of the surrounding air in a single model. The exterior and interior air domains were created in Abaqus/CAE using the "Merge/Cut" or "Boolean" feature, and meshed with first-order tetrahedral elements. On the exterior surface of the air mesh,
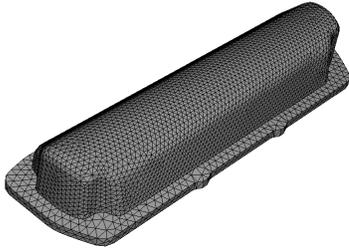
Figure 2: Acoustic infinite element model for the geometrically simple engine valve cover

Figure 3a: A production engine valve cover model

an impedance-based terminating boundary condition is applied which prevents acoustic energy from reflecting back into the domain (also called non-reflecting, absorbing, or anechoic). The coupling between the structure and the air does not require compatible meshes at the common boundary and uses a surface-based tie constraint to enforce the coupling.

The fully-coupled structural acoustics capability was used to obtain maximum possible accuracy. The analysis may also be carried out in a sequential manner—the structure-only displacement analys is carried out first, and its results used to drive the subsequent air-only acoustic analysis.

Analysis

The simulation consists of two steps: a static cover assembly step to simulate bolt tightening followed by a dynamic harmonic vibration step.

In the dynamic step, a fully coupled structural-acoustic analysis is carried out in the frequency domain using the steady state dynamics procedure, wherein the structural displacements and acoustic pressure are solved simultaneously.

To simulate the vibration of the engine, the accelerations at the engine cylinder-head are measured near each fastening bolt at idle driving condition. The data are recorded as acceleration in *g* as a function of frequency in Hz, and subsequently used to drive the finite element model to simulate the engine excitation.

Production Cover

Structural Model

The complete cover assembly (cover, rubber gasket, rubber isolators and necessary mating components) is shown in Figure 3a. The cover is modeled with 10-node tetrahedral elements, while the gasket/grommet is modeled with special-purpose gasket elements that possess frequency-dependent viscoelastic properties.

Acoustic Model and Structural Coupling

For the acoustic domain, an interior air mesh and a small hemispherical exterior air mesh (r = 300mm) are created adjacent to the cover and meshed with tetrahedral acoustic finite elements (Figure 3b). A layer of acoustic infinite
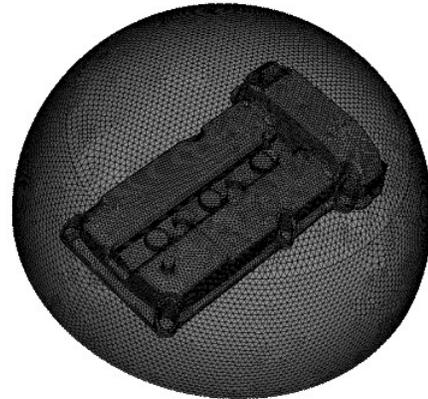

Figure 3b: Combined acoustic infinite/finite element model for the production engine valve cover

elements is then applied on the terminating surface of the finite element mesh.

Analysis

Similar to the prototype cover case, the simulation consists of two major steps: cover assembly and harmonic vibration. Once assembled, the cover model is excited through the bolts around the bottom flange. The excitation profiles are generated by measuring the vibrations from a running engine at various driving conditions – idle, light drive, 2400 RPM, and 3600 RPM. The data are used in the finite element model as acceleration amplitudes. In addition, the sound pressures at a plane 20cm above the cover top surface are measured with microphones. The detailed experimental procedure can be found in reference (5).

Results and Conclusions

Infinite Elements vs. Impedance Approach, Prototype Cover

As both the acoustic finite and infinite elements use identical formulations, similar results are expected. The comparison between the valve cover surface displacements obtained from the two methods is shown in Figure 4.

It is observed that the results are identical. The acoustic pressures at the cover surface from the two methods are shown in Figure 5; little difference is observed.
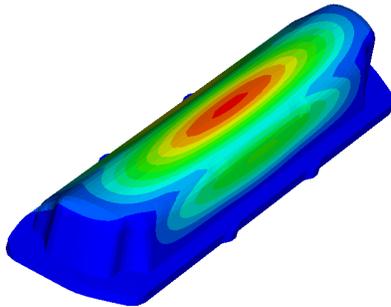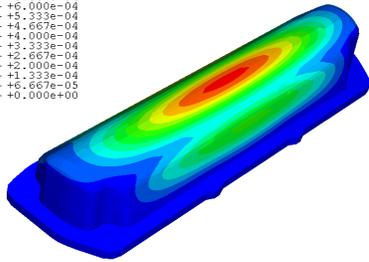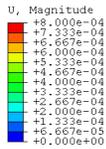
Figure 4: Comparison of surface displacements obtained from acoustic infinite element model (top) and the imped-ance model (bottom) for the prototype cover
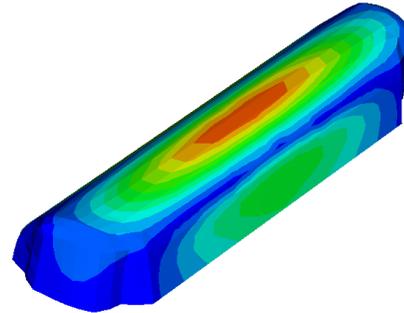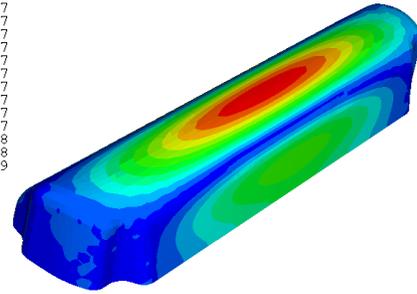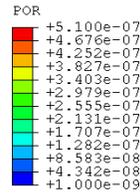
Figure 5: Comparison of acoustic pressures obtained from acoustic infinite element model (top) and the imped-ance model (bottom) for the prototype cover

Compared to the finite-element-only approach, the infinite element approach significantly reduces the modeling and computational expense. The number of elements drops from 391,644 to 18,474, the required memory drops by a factor of 7, and the total computational time of the infinite element model is less than one-tenth that of the imped-ance model.

Far-Field Sound Pressure Extraction in the Infinite Element Method

Figure 5 shows the acoustic pressure at the structural surface of the prototype cover. In practice, the sound in the far field is of greater interest. For large structures such as automobile engine components, this means that a fairly large acoustic domain needs to be modeled. The conventional finite element method faces severe problems modeling such a large domain due to computa-tional limitations. In contrast, the infinite element tech-nique enables the analyst to access the acoustic quanti-ties in both the near and far fields. Figure 6 shows the sound pressure on a spherical surface at a distance of 250 mm, 500 mm, and 1000 mm from the cover.

This functionality is obtained using a Python script (included in the Abaqus Scripting User's Manual) that uses the polynomial coefficients from the infinite ele-ments, available after the analysis is complete, to interpo-late the pressures into the far-field. The acoustic pressure may thus be obtained at any point in space. This obviates the need to create a large mesh solely in order to obtain results at a desired location; one may simply use a mesh

that is sufficiently large to provide accurate results, and then with the script, project the results to the desired locations.

Infinite Elements vs. Experimental Measurements

For the production valve cover model, the cover surface vibrations and radiated sound are computed and com-pared to the experimental measurements obtained from a running vehicle equipped with these covers.

Figure 7 compares the surface vibration of the production cover from testing and analysis at light-drive condition. The vibration is an average of the accelerations meas-ured at four locations on the cover surface. It is observed that the analytical result has good qualitative agreement with the experimental measurement within the specified frequency range.

The average sound pressures at a plane 20 cm above the cover top surface are shown in Figure 8. At all conditions, the predictions follow the trends of experimental micro-phone measurements. The analytical tests were performed at specific frequencies with much larger intervals between adjacent frequencies than those used for the experimental tests. This may account for the fact that all the experimen-tally-observed peaks are not captured in the analytical study. In addition, the experimental data are unfiltered, and thus the signal-to-noise ratio in these data may also be influencing the accuracy of the experimental tests.
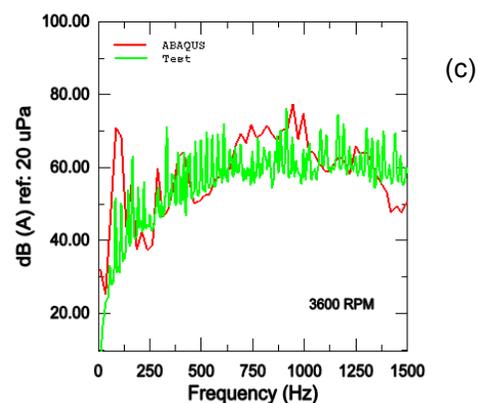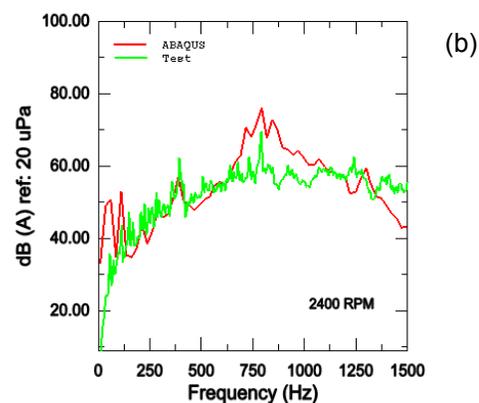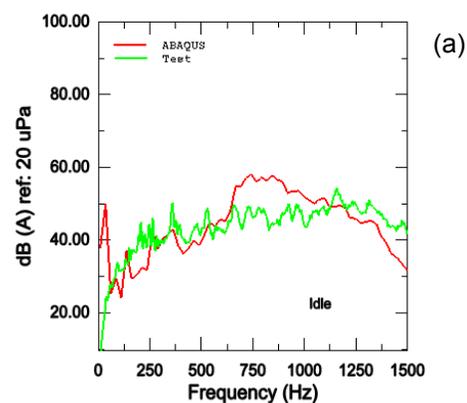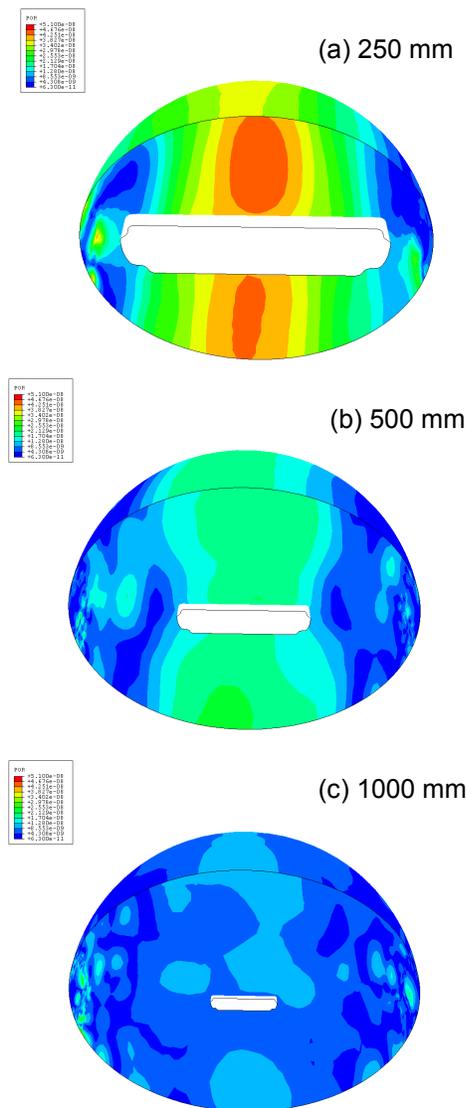
Figure 6: Far-field sound pressure from the infinite ele-
ments: sound field at a distance of (a) 250 mm, b) 500 mm,
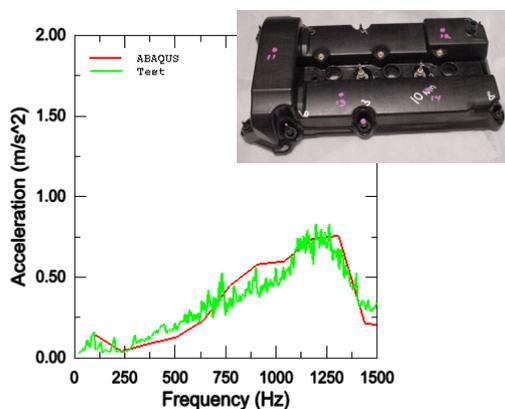and (c) 1000 mm, from the surface of the prototype cover

Figure 7: Comparison of computed and measured surface
vibration of the production cover at light-drive condition

Figure 8: Comparison of computed and measured radi-
ated sound from the production cover:
(a) IDLE, (b) 2400 RPM, and (c) 3600 RPM

Conclusions

The acoustic infinite element approach has been used to predict the exterior sound radiation of automobile engine valve covers. The solutions from the infinite element approach have been found to be consistent with those from the impedance technique and actual experimental measurements.

The infinite element approach allows the prediction of acoustic quantities in both in the near field, directly from the analysis results, as well as in the far field, using a post-processing script. Overall, the infinite element approach has proved to be an accurate and efficient technique for modeling the sound radiation of realistic structures.

Acknowledgements

Dassault Systèmes SIMULIA Corp. would like to thank the DANA Corporation for providing the materials discussed in this article.

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- Lu, Y. C., Periyathamby, H., Krishna, M. M. R., and Nash, D., "Spatial Transmissibility of Plastic Cylinder-Head Covers," SAE Paper 2005-01-1515, 2005.

For additional information on the Abaqus capabilities referred to in this brief please see the following Abaqus 6.12 documentation references:

- Analysis User's Manual
  - "Static stress analysis," Section 6.2.2
  - "Direct-solution steady-state dynamic analysis," Section 6.3.4
  - "Acoustic, shock, and coupled acoustic-structural analysis," Section 6.10.1
  - "Submodeling: overview," Section 10.2.1
- Example Problems Manual
  - "Acoustic and shock analyses," Section 9.1
- Scripting User's Manual
  - "Using infinite elements to compute and view the results of an acoustic far-field analysis," Section 9.10.11

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