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VISUALIZATION OF SOUND RADIATION FROM AN ENGINE BLOCK

S. Wu

Wayne State University, Department of Mechanical Engineering, 5050 Anthony Wayne Drive, 48202, Detroit, Michigan, United States Of America

Tel.: (313)577-3884 / Fax: (313)577-8789 / Email: swu@me1.eng.wayne.edu

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ABSTRACT
This paper presents the Helmholtz Equation Least Squares (HELS) method for visualizing the radiated acoustic pressure fields from a general three-dimensional complex vibrating structure in free space. The structure under consideration emulates a full-size four-cylinder engine. The radiated acoustic pressures are collected over several planar surfaces at certain distances from the source and taken as the input to the HELS formulation to reconstruct acoustic pressures in the entire field, including source surface. The reconstructed acoustic pressures thus obtained are then compared with the benchmark values. Numerical results demonstrate that good agreements can be obtained with relatively few measurements. The HELS method is shown to be very effective in the low-to-mid frequency regime, and can become potentially a powerful noise diagnostic tool.

1 - INTRODUCTION
It has been shown [1], [2], [3], that the radiated acoustic pressure fields in both exterior and interior regions can be reconstructed by using the Helmholtz equation least squares (HELS) method. This method expresses the radiated acoustic pressure field in terms of an expansion of spheroidal functions that satisfy the Helmholtz equation. Such an expansion is uniformly convergent because the basis functions consist of a uniformly convergent series of Legendre functions. The coefficients associated with these basis functions are determined by requiring the assumed-form solution to satisfy the pressure boundary condition at the measurement points. The errors incurred in this process are minimized by the least-squares method. The solutions thus obtained are unique. Further, the number of measurements is determined by the number of expansion terms, which is small when an appropriate coordinate system is selected for the particular source geometry under consideration. Consequently, the numerical computation efficiency is high.
The objective of the present investigation is to examine the effectiveness and robustness of the HELS method on reconstructing the radiated acoustic pressure fields from a general three-dimensional complex vibrating structure. In particular, the structure under consideration contains sharp edges, corners, and abrupt changes along the surface contour. The acoustic near field around these irregularities can be extremely complex because of local acoustic diffraction, scattering, and reflection effects.
The test object emulates that of an automotive engine running in a free field. In this paper numerical simulations are employed, namely, harmonic excitations on the engine block are assumed and the vibration responses of the engine block are calculated by using standard FEM codes. Once this is done, the surface acoustic pressures are determined by the BEM codes. The field acoustic pressures are calculated by the Helmholtz-Kirchhoff integral formulation and taken as the input to the HELS formulation to reconstruct the acoustic pressure distributions over the engine block surface as well as in the field. The reconstructed acoustic pressures are then compared with the benchmark results.

2 - THE HELS METHOD
The HELS method assumes that the radiated acoustic pressures can be represented by an expansion of the spheroidal functions that satisfy the Helmholtz equation 4

$$\hat{p}\left(\vec{x},\omega\right)=\rho_0 c\sum_{j=0}^{\infty}C_j\Psi_j\left(\vec{x},\omega\right) \tag{1}$$

where $\hat{p}\left(\vec{x},\omega\right)$ represents the complex amplitude of the acoustic pressure at any point $\vec{x}$ in the field with an angular frequency ω, ρ_0 and c are the density and speed of sound of the fluid medium, respectively, and $\Psi_j\left(\vec{x},\omega\right)$ are the basis functions that can be generated by using Gram-Schmidt orthonormalization with respect to the particular solutions to the Helmholtz equation 4. The coefficients C_j associated with the basis functions can be determined by requiring the assumed-form solution to satisfy the boundary condition at the measurement,

$$\rho_0 c\sum_{j=0}^{\infty}C_j\Psi_{m,j}\left(\vec{x}_m,\omega\right)=\hat{p}_m\left(\vec{x}_m,\omega\right) \tag{2}$$

Note that there is no restriction on the measurement location $\vec{x}_m$, so long as they do not overlap each other. If a J-term expansion in Eq. (2) is used, then M measurements in the field must be taken, where $M \geq J$. Theoretically, if the measured acoustic pressures $\hat{p}_m\left(\vec{x}_m,\omega\right)$ are exact, then the assumed-form solution (2) converges to the true value as $J \rightarrow \infty$ [5]. However, this never happens in reality because the measured quantities $\hat{p}_m\left(\vec{x}_m,\omega\right)$ always contain errors due either to measurement uncertainties or to rapid decay of the near-field effects. Hence the reconstructed acoustic pressure $\hat{p}_m\left(\vec{x}_m,\omega\right)$ will never converge to the true value.
To enhance the accuracy of reconstruction, the least-squares method is used to eliminate the first-order error imbedded in this process. Accordingly, Eq. (2) can be rewritten as

$$[T]_{J\times J}\left\{C\right\}_{J\times 1}=\left\{D\right\}_{J\times 1} \tag{3}$$

where $[T]_{J\times J}$ represents the transformation matrix that correlates the measured data to the reconstructed acoustic pressures, and $\left\{D\right\}_{J\times 1}$ contains the measured information [4].
For convenience sake, the basis functions in this paper are expressed in terms of the spherical coordinates. This is because the spherical Hankel functions and Legendre functions are readily available in many mathematical libraries, such as IMSL subroutines. Use of these functions can be extremely effective for spherical sources or chunky objects, whose aspect ratios are close to unity, $x:y:z \rightarrow 1$.

3 - TEST SETUP

The test object under consideration emulates a four-cylinder engine of a passenger vehicle. For the purpose of examining the effectiveness of the HELS method on reconstructing the radiated acoustic pressures from a general three-dimensional structure, it suffices to consider a simplified yet arbitrarily shaped object. Figure 1 shows such an engine block with an overall length of 0.435 m in the z-axis direction, an overall width of 0.460 m in the x-axis direction, and an overall height of 0.630 m in the y-axis direction.
To simulate sound radiation from this simplified engine block, harmonic forces are assumed to act uniformly on two arbitrarily selected surfaces. The amplitude of the pressure acting on the protruding part of the front surface (marked in red in Figure 1) is 2,000 N/m ^{2}, while that on the entire left surface is 800 N/m^2. The engine block is approximated by a solid piece of steel. The bottom the engine block is assumed clamped with zero displacement and slope, while the remaining surfaces are free to move. The dynamic responses of this engine block are solved numerically using the commercial FEM software I-DEAS [6] under various excitation frequencies. In carrying out numerical computations, the engine block is divided into 2,616 elements with a total of 4,228 nodes.
Once the normal component of the surface velocity distribution is determined, the surface acoustic pressures are solved by using the standard BEM codes. For simplicity, the numbers of segments and nodes discretized on the engine block surface are kept the same, at 368 and 1,106, respectively, for all frequencies considered. Having obtained the normal component of surface velocity and surface acoustic pressure, the radiated acoustic pressure at any field point is calculated by using the Helmholtz integral formulation.
To test the effectiveness of the HELS method, we take 36 measurements uniformly distributed over a planar surface at $x = +0.550$ m with respect to the center of the engine or equivalently, $d = 0.320$ m from the engine's front surface with a measurement interval of $\Delta = 0.220$ m. This measurement plane is parallel to one of the surfaces on which harmonic forces are applied. In addition, we take three measurements over the back, top, left, and right sides of the engine at the same distance and interval,

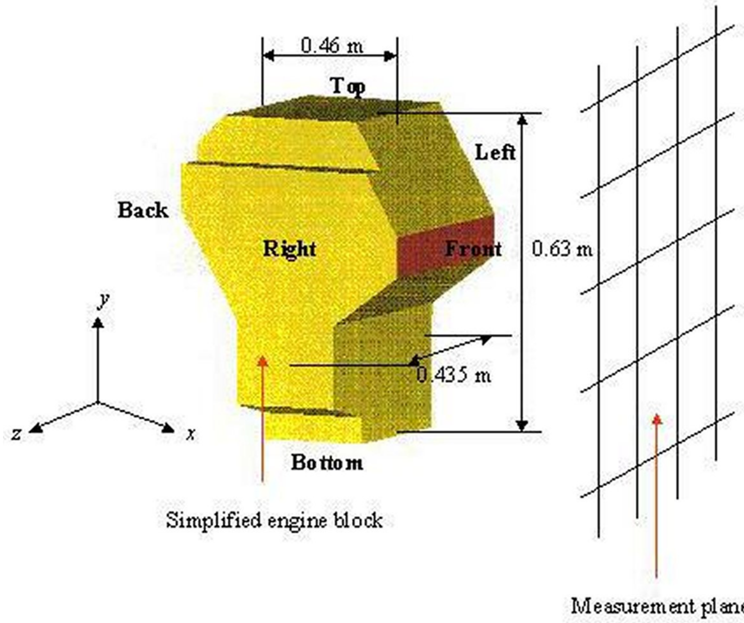

Figure 1: Schematic of a simplified engine block and measurement locations.

respectively, thus making a total of 48 measurements in the field. The reason for setting the measurement distance at $d = 0.320$ m is to ensure that all the input data fall outside the minimum sphere [7]. The measured acoustic pressures described in the preceding section are taken as the input to Eq. (3).

4 - NUMERICAL RESULTS

This section displays two-dimensional contour plots of the reconstructed acoustic pressures radiated from a simplified engine block based on 48 measurements with 18 expansion functions in Eq. (1). It is emphasized that in this example a somewhat unfavorable condition is assumed. This is because in reality the test environment may not allow for taking enough measurements at very close distances. Moreover, the vibrating structures often have complex shapes and the excitation forces are unspecified. These adverse circumstances may severely affect the accuracy of data acquisition.

Figure 2 shows the comparison of the reconstructed acoustic pressure distribution over a planar surface four times the size of the front surface of the simplified engine block at $x = 0.730$ m and 120 Hz with the benchmark values obtained using BEM codes. Results show that not only a large pressure peak in the center, but also two relatively small ones toward the right are captured. The difference between the reconstructed and benchmark acoustic pressure peak amplitudes is about 1 dB. Considering the fact that reconstruction is done by taking only 48 measurements, these results seem quite good. This is not surprising because reconstruction is done outside the minimum sphere where the acoustic pressure field can be adequately represented by a superposition of spherical harmonic functions.

Figure 3 shows the comparison of the reconstructed acoustic pressure distribution over the entire front surface of the engine block at 120 Hz with the benchmark values. Note that the front surface of the present engine block is non-planar, containing abrupt changes in surface contour, and the two-dimensional contour plots are projections of the surface acoustic pressures onto a planar surface. Obviously, the accuracy of reconstruction is not as high as that shown in Figure 2. The differences between the reconstructed and benchmark acoustic pressure peak values are about 3 dB. Further, the locations of the reconstructed acoustic pressure peaks seem shifted slightly from those of the benchmark results. These discrepancies are caused not only by the errors in the input data and truncations of the expansion functions, but also by the fact that the engine block surface falls inside the minimum sphere.

Comparisons of the reconstructed acoustic pressure amplitudes with the benchmark results over the entire top surface at 120 Hz, and that over the entire back surface of the simplified engine block at 361 Hz are displayed in Figures 4 and 5, respectively. While the accuracy in reconstruction using the HELS method is far from perfect, it nonetheless represents the only methodology known to the author that enables one to visualize the radiated acoustic pressure field around a complex vibrating structure based on a few measurements taken primarily on one side of the source.

It is emphasized that the accuracy of reconstruction on the source surface can be enhanced by taking

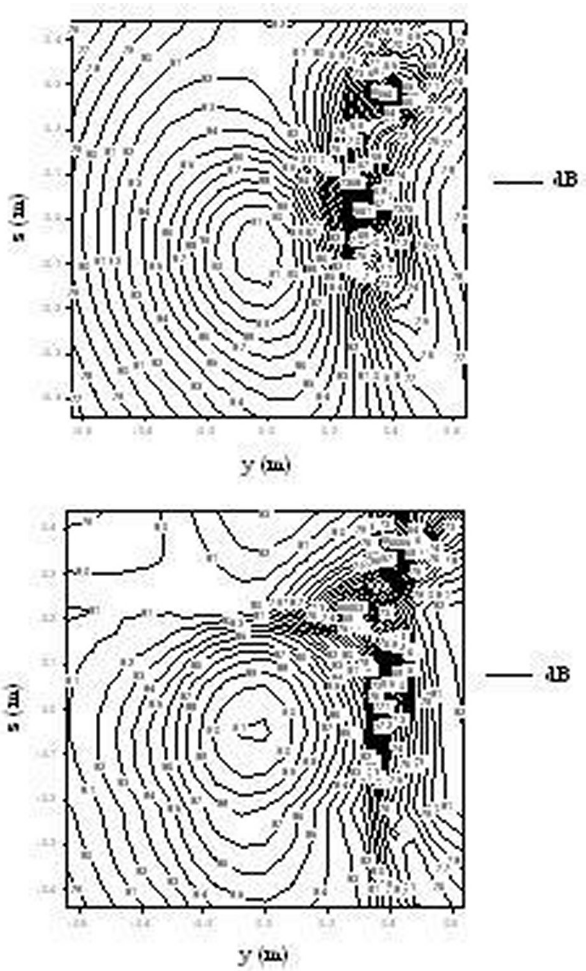

Figure 2: Comparison of pressure amplitudes on a planar surface at $x = 0.73$ m and 120 Hz.

more measurements over a conformal surface at very close range. The present example is designed to examine the robustness and effectiveness of the HELS method on a general, complex vibrating structure under relatively unfavorable conditions.

5 - CONCLUDING REMARKS

The HELS method is used to reconstruct the acoustic pressure fields radiated from an arbitrarily shaped vibrating structure, based on a finite number of measurements in the field. To examine the effectiveness of the HELS method, adverse conditions are designed, which include abrupt changes in surface contour and sharp edges and corners on source geometry, and a relatively small number of measurements taken primarily on a finite planar surface on one side of the source. These unfavorable conditions are of significance because in practice a vibrating structure is always of arbitrary shape, and location and number of measurements are always restricted. The HELS method seems to be able to work under these circumstances and produce reasonably good results at least in the low-to-mid frequency regime. The test results show that the reconstructed acoustic pressures agree satisfactorily with the benchmark values. Moreover, the accuracy of reconstruction increases significantly as the reconstruction surface moves to the far field.

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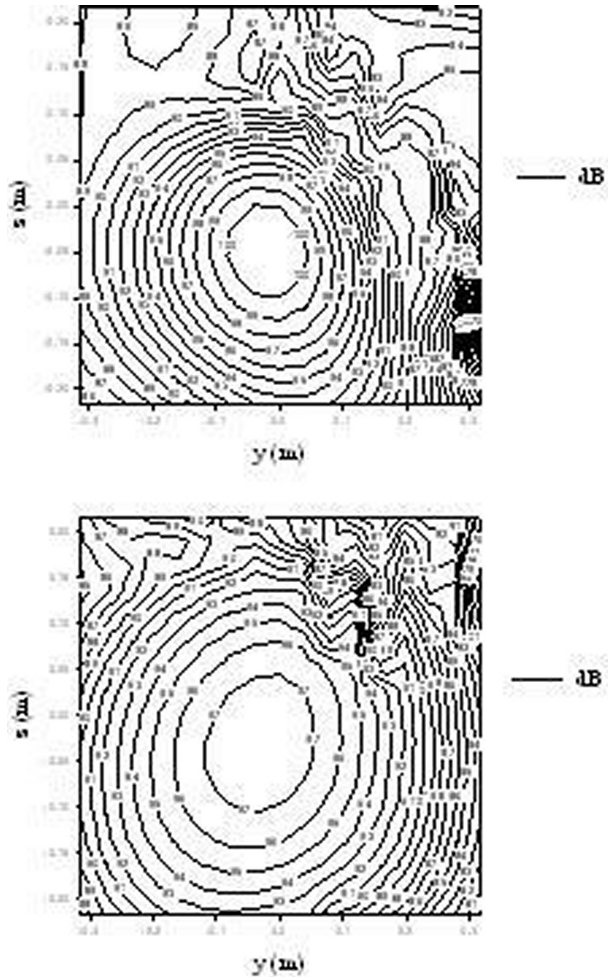

Figure 3: Comparison of pressure amplitudes over the entire engine front surface at 120 Hz.

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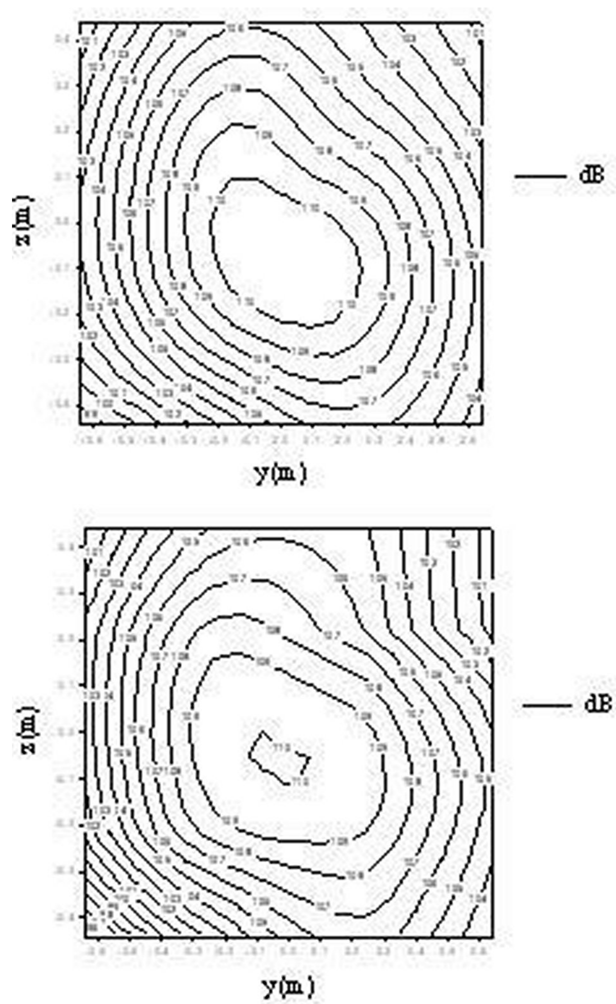

Figure 4: Comparison of pressure amplitudes over the entire engine top surface at 120 Hz.

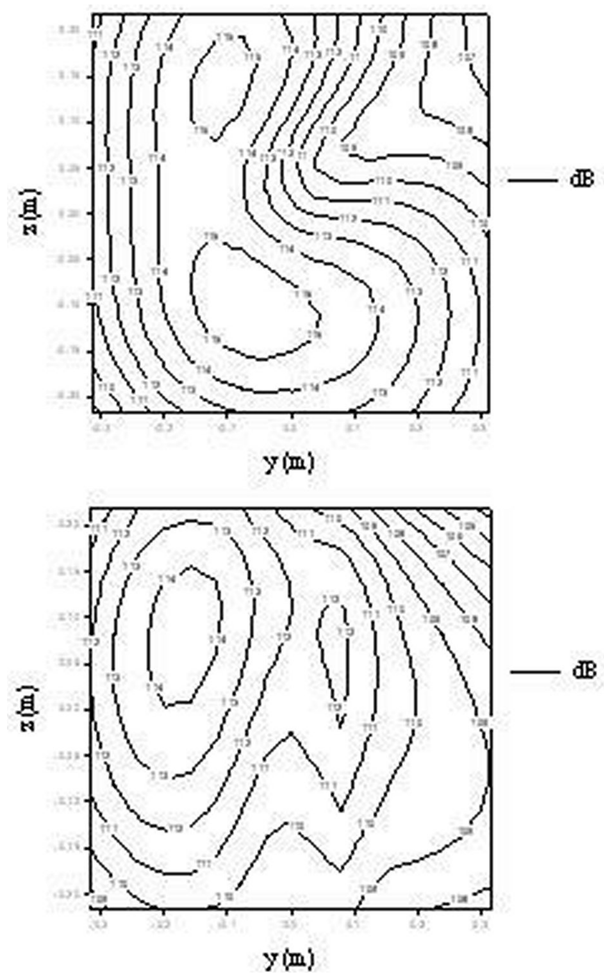

Figure 5: Comparison of pressure amplitudes over the entire engine back surface at 361 Hz.