

A computational approach for evaluating the probability of acoustic detection of a military vehicle

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ABSTRACT

ADRPM (Acoustic Detection Range Prediction Model) is a software program that models the propagation of acoustic energy through the atmosphere and evaluates detectability. ADRPM predicts the distance of detection for a noise source based on the acoustic signature of the source. In this paper the assessment of the acoustic signature which characterizes a vehicle is performed by the conventional Boundary Element Analysis (BEA), and by the Energy Boundary Element Analysis (EBEA). BEA is used for computing the radiated noise for the 1/3 octave bands up to 500Hz, and the EBEA is used for the remaining frequency range. By combining the conventional BEA (for low frequency) with the EBEA (for high frequency), it is possible to perform noise radiation computations over the entire frequency range in a seamless manner. Once the initial detection range is predicted, the main contributors to the acoustic detection are identified and their location on the vehicle is modified in order to assess the corresponding effect to the detectability.

Keywords: boundary element analysis, acoustic detection, energy methods, acoustic radiation

1. INTRODUCTION

The ADRPM software model has been developed over the last 25 years under sponsorship by the U.S. Army Research, Development and Engineering Command (RDECOM) Tank Automotive Research Development and Engineering Center (TARDEC). Given the acoustic signature of a vehicle (i.e. the SPL at a distance of 30m from the vehicle for each one-third-octave band from 10Hz to 2 kHz), the environmental conditions, and the detector parameters, the acoustic detection range of the vehicle is evaluated. ADRPM simulations can identify the most important environmental parameters for detecting a vehicle. Up to this point, the acoustic signature of a vehicle must be measured in the field. In this paper an alternative approach is presented where the acoustic signature is evaluated numerically. The BEA [1-3] is used for computations in the 1/3 octave bands below 500Hz and the EBEA is used for the remaining frequencies. The BEA is using the acoustic pressure and the acoustic velocity as primary variables for the computations. A conventional BEA model requires at least six elements per acoustic wavelength in order to capture correctly the radiated noise. Thus, as the frequency of analysis increases the number of elements required in the model also increases. In addition, the BEA method requires a specialized computational approach in order to eliminate the singularity effects created by irregular frequencies when solving acoustic radiation problems [4]. The treatment of the irregular frequencies becomes more difficult as the frequency of analysis increases and the irregular frequencies become closer spaced and with more complex mode shapes. The EBEA method was specifically developed for high frequencies [5,6]. The acoustic energy and the acoustic intensity constitute the primary variables of the formulations. The EBEA does not require an increasing number of elements as the frequency of analysis increases and the solution does not experience numerical singularities from irregular frequencies. By combining the BEA and the EBEA methods it is possible to compute the acoustic signature of a vehicle over the entire frequency range of interest. The same boundary element numerical model is employed by both methods (Figure 1), thus making the computational process seamless. In this paper a generic analysis for a military vehicle (Figure 2) is presented in order to demonstrate how the new process works.

The acoustic signature of the vehicle is computed by following a methodology developed in the past for pass-by noise simulations [7]. The acoustic spectrum for each source is used for computing appropriate velocity or intensity boundary conditions (in the BEA or EBEA method, respectively) which recreate the prescribed acoustic spectrum from each source in the nearfield. Once the appropriate boundary conditions have been developed for defining all the sources, the noise radiated from the entire vehicle is computed and the acoustic signature at 30m distance is evaluated. Based on the spectrum of the acoustic signature the maximum detection distance from the

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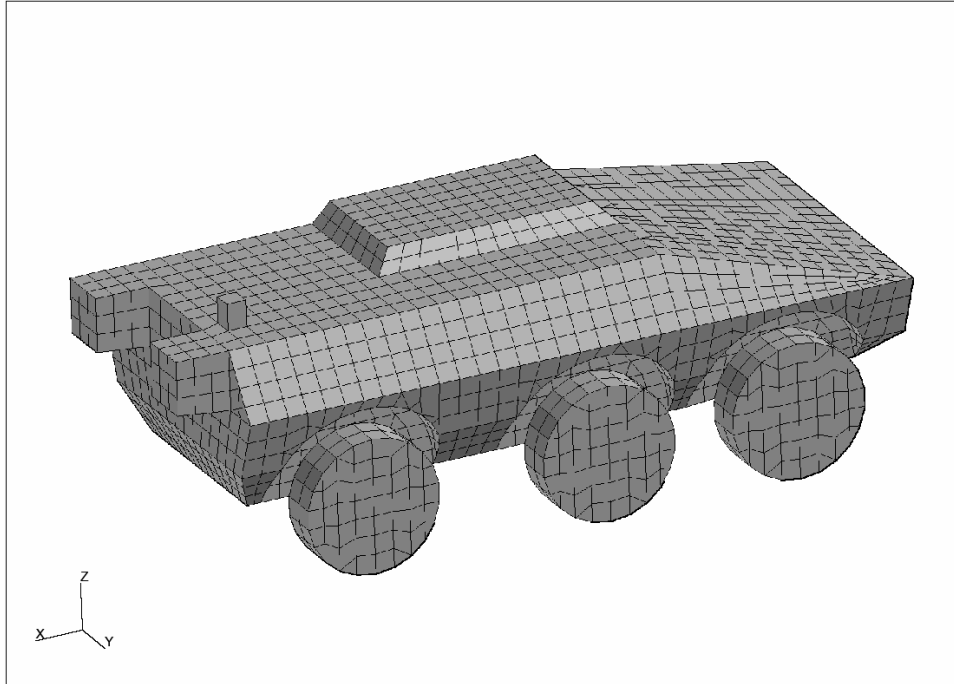


Figure 1. Boundary Element Model and in both BEA and EBEA computations

vehicle is computed from ADRPM. Since the acoustic signature is evaluated through simulation, the contribution from each one of the sources to the acoustic detection is computed separately. In the generic analysis presented in this paper the exhaust constitutes the most significant source. The location of the exhaust is modified and the acoustic detection analyses are repeated in order to demonstrate the impact from the placement of the source to the detection of the vehicle.

Technical background on the BEA and the EBEA methods is presented first. The process of computing appropriate boundary conditions for the BEA and EBEA models from the nearfield spectra of the individual sources is discussed. The functionality of ADRPM for determining the acoustic detection from the acoustic signature of a vehicle is presented. Finally the new process which combines BEA and EBEA computations with ADRPM for acoustic detection is demonstrated through generic analysis for a wheeled military vehicle.



Figure 2. Military vehicle analyzed in this paper

2. REVIEW OF BEA AND EBEA

The conventional BEA method is based on the Helmholtz integral equation [1-3] (Figure 3).

$$\int_{S+\Sigma} \left(G(r, r_s) \frac{\partial p(r_s)}{\partial n} - \frac{\partial G(r, r_s)}{\partial n} p(r_s) \right) dS = \begin{cases} p(r) & \text{if inside the acoustic domain} \\ 0 & \text{if outside the acoustic domain} \\ \frac{1}{2} p(r) & \text{if on a smooth boundary} \end{cases} \quad (1)$$

where the Green's function is

$$G(r, r_s) = \frac{\exp(-ik|r - r_s|)}{4\pi|r - r_s|} \quad (2)$$

Since the integral vanishes naturally on the surface Σ as $r_s \rightarrow \infty$ due to the Sommerfeld radiation condition, the integration in Equation (1) needs to be performed only on the surface S which is done using boundary elements. The advantage of boundary element method is that only the exterior elements are needed rather than modeling the entire acoustic domain. The non-uniqueness frequencies were specially treated with the super CHIEF method.

Figure 1 shows the boundary-element acoustic model of the vehicle's exterior geometry. The model includes 4-node quadrilateral and 3-node triangular boundary elements. As a rule of thumb, the model should have a minimum of 6 elements per wave length, so it is valid up to the 500Hz 1/3 octave band. The ground modeled as a rigid half plane at $z=0$ by modifying the Green's function using an image source.

The primary variables of the BEA formulation are the acoustic pressure and the acoustic velocity on the surface of the BEA model. Once both of them have been evaluated, Equation (1) can be used for computing the acoustic response anywhere in the field. The primary variables on the surface of the model are evaluated from the prescribed velocity boundary conditions. Appropriate velocity boundary conditions are defined at the location of each noise source on the surface of the BEA model from the nearfield spectra and based on the procedure outlined in Section 3.

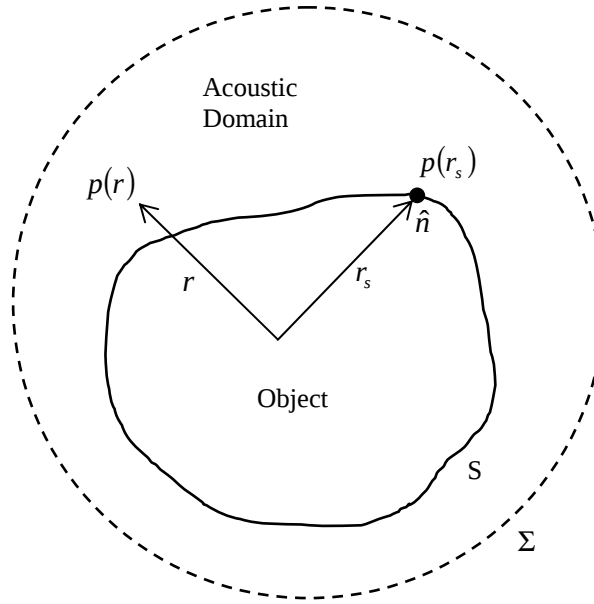


Figure 3. Notations for Helmholtz Integral Equation

The EBEA method was developed for computing noise radiation at high frequencies. It uses as boundary conditions the acoustic intensity on the surface of the source and computes the acoustic propagation in the field. The acoustic pressure at any field point Y exterior to the structure is expressed as:

$$\hat{p}_Y = \int_S A(P)g(P,Y)dS \quad (3)$$

where S is the surface of the structure, P denotes the point located on the surface S , $A(P)$ is the complex source strength amplitude at P , and $g(P,Y) = \frac{e^{-ikr}}{4\pi r}$ is the Green's function for three dimensional infinite system, r is the between points P and Y , and k is the wavenumber. The acoustical velocity vector is obtained from the acoustic pressure

$$\hat{v}_Y = -\frac{1}{i\omega\rho}\nabla\hat{p}_Y = -\frac{1}{i\omega\rho}\int_S A\nabla g(P,Y)dS \quad (4)$$

Equations (3) and (4) are employed for developing expressions for the ensemble averaged quantities $E[\hat{p}_Y \cdot \hat{p}_Y^*]$, $E[\hat{v}_Y \cdot \hat{v}_Y^*]$, and $E[\hat{p}_Y \hat{v}_Y^*]$. The latter expressions are introduced in the equations for the frequency averaged acoustic energy density and intensity:

$$\tilde{e}_Y = E[\langle e_Y \rangle] = \frac{1}{4} \left[\rho E[\hat{v}_Y \cdot \hat{v}_Y^*] + \frac{1}{\rho c^2} E[p_Y \cdot p_Y^*] \right] \quad \text{and} \quad \tilde{I}_Y = E[\langle I_Y \rangle] = \frac{1}{2} \text{Re} \left(E[\hat{p}_Y \hat{v}_Y^*] \right) \quad (5)$$

Then the equations for the primary variables of the EBEA formulation are developed:

$$\tilde{e}_Y = \int_S \sigma(P) \left(\frac{\rho}{64\pi^2 r^4} + \frac{k^2 \rho}{32\pi^2 r^2} \right) dS \quad \text{and} \quad \tilde{I}_Y = \int_S \sigma(P) \frac{k^2 \rho c}{32\pi^2 r^2} E_r dS \quad (6)$$

where $\sigma(P)$ is the strength density of the energy source placed at point P of the surface of the model. The acoustic power radiated from each element of the structure in contact with the fluid comprises the corresponding acoustic intensity boundary condition for each element. By placing the field point Y on each one of the elements of the model and by requiring for the acoustic intensity to be equal to the prescribed intensity a square system of equations is generated and the source strengths $\sigma(P)$ for all the distributed acoustic sources are computed. Then, the acoustic energy and the acoustic intensity in the field can be computed from Equation (6).

3. CHARACTERIZATION OF SOURCES FROM NEARFIELD MEASUREMENTS

In order to perform the acoustic signature computations and create numerically the information necessary for ADRPM, the different noise sources on a vehicle (tires, exhaust, hull, grille) must be first characterized from nearfield data. A procedure was developed in the past for characterizing noise sources on a boundary element model from near field data and then using them for performing a pass-by noise simulation [7]. The same procedure is employed in this paper for developing appropriate boundary conditions for the BEA or EBEA analyses.

Acoustic measurements taken in the field around an actual source are utilized for defining appropriate boundary conditions. The boundary element equations (BEA or EBEA) are employed for deriving transfer functions between the elements of the generic source and the field points where the acoustic measurements are collected. The transfer functions and the measured acoustic field allow computing proper velocity or intensity boundary conditions on each source. Thus, the originally measured acoustic field is expected to be recreated numerically from each source. The individual sources are combined with the vehicle model in order to compute the acoustic signature and thus the input to

ADRP. By taking into account the numerical discretization of the BEA or EBFA equations, computations associated with recovering the acoustic pressure at several field points can be written in matrix form:

$$\overbrace{\{p_0\}}^{M \times 1} = \overbrace{[DR]}^{M \times N} \overbrace{\{q\}}^{N \times 1} \quad (7)$$

where $\{p_0\}$ is the vector of acoustic pressure at “ M ” number of field points, $[DR]$ is the matrix with entries derived from the boundary element integrals, and “ N ” is the number of nodal primary variables present in the boundary element formulation. The vector $\{q\}$ of the primary acoustic variables on the surface of the model can be expressed in terms of the primary acoustic matrix $[A]$ and the vector of the boundary conditions $\{f\}$. Then,

$$\overbrace{\{p_0\}}^{M \times 1} = \overbrace{[DR]}^{M \times N} \overbrace{[A]^{-1}}^{N \times N} \overbrace{\{f\}}^{N \times 1} \quad (8)$$

The terms of vector $\{f\}$ are linear functions of the boundary conditions (velocity for BEA and intensity for EBFA). Thus, the vector $\{f\}$ can be expressed as a product between a matrix and the vector of the boundary conditions.

$$\overbrace{\{f\}}^{N \times 1} = \overbrace{[FV]}^{N \times K} \overbrace{\{\bar{v}\}}^{K \times 1} \quad (9)$$

where $\{\bar{v}\}$ is the vector of the appropriate boundary conditions applied on the elements of the boundary element model, and “ K ” is the number of elements in the boundary element model. The entries of $[FV]$ are derived from the boundary element integrals. Introducing Equation (9) into Equation (8) results in:

$$\overbrace{\{p_0\}}^{M \times 1} = \overbrace{[DR]}^{M \times N} \overbrace{[A]^{-1}}^{N \times N} \overbrace{[FV]}^{N \times K} \overbrace{\{\bar{v}\}}^{K \times 1} \Rightarrow \overbrace{\{p_0\}}^{M \times 1} = \overbrace{[B]}^{M \times K} \overbrace{\{\bar{v}\}}^{K \times 1} \quad (10)$$

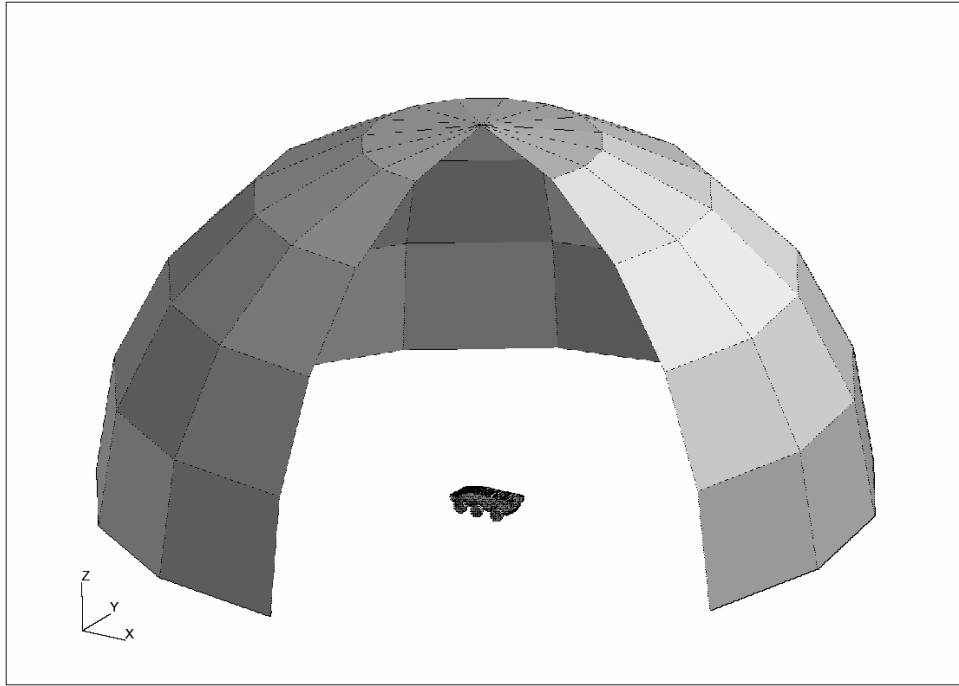


Figure 4. Field point surface for computing acoustic signature by BEA and EBFA methods

The transformation matrix $[B]$ establishes a direct relationship between the boundary conditions on the surface of the source and the acoustic pressure at the field points. The transformation matrix is employed for determining proper boundary conditions $\{\bar{v}\}$ on each source that can recreate the measured acoustic pressure $\{p_0\}$. Once the appropriate boundary conditions have been computed the acoustic signature of the vehicle is evaluated at a hemisphere of 30m radius around the vehicle (Figure 4).

4. APPLICATION

The boundary element model presented in Figure 1 is employed in the analysis. The noise sources which are considered in the computations are: tires, exhaust, hull, and grille. The same numerical model is used for both BEA and EBEA computations. Thus, the acoustic analysis is seamless over the entire frequency range of interest. Appropriate velocity boundary conditions are computed for the BEA and appropriate intensity boundary conditions are computed from the EBEA based on the method presented in Section 3. The acoustic signature is computed on field points residing over a semi-spherical field point surface (Figure 4). Typical results from the BEA analysis are presented in Figures 5 and 6 for the 1/3 octave bands of 160Hz and 1,250Hz. The former are computed by the BEA and the latter by the EBEA. The SPL spectrum for a typical point at 30m distance from the vehicle used as input to the ADRPM computations is presented in Figure 7.

The corresponding detectable distance is evaluated from ADRPM using a variety of parameters. The surface roughness and the air temperature were identified as the most important ones. The detectable distance as a function of these two parameters is presented in Figure 8. In the numerical prediction of the acoustic signature it is possible to make only one source at a time active and compute the acoustic signature from each individual source. In this manner it is possible to identify the importance of each source. Results from the four sources considered in this analysis are presented in Figure 9.

It is evident that the noise from the exhaust is the most important contributor. Based on this contribution analysis the location of the exhaust is chosen as a target variable for decreasing detectable distance. In the numerical model the position of the exhaust is changed from the top position to the lower part of vehicle. The computations are repeated again for the acoustic signature and new SPL results are provided as input to ADRPM. The difference in the detectable distance is presented in Figure 10. It can be observed that an overall decrease is achieved by changing the location of the exhaust. The change in the detectable distance appears to be dependent primarily upon the surface roughness and to a much lesser extend upon the temperature variation.

5. CONCLUSIONS

In this paper a new approach of combining the BEA and the EBEA methods for computing the acoustic signature of a vehicle is presented. Combining the two methods allows to use the same numerical model for radiation prediction over a complete frequency range. The predicted acoustic signature comprises the input for ADRPM for evaluating the corresponding detectable distance. The ADRPM analyses allow to identify the most important environmental parameters on the acoustic propagation. Using a numerical prediction for the acoustic signature allows to identify the contribution of individual sources to the overall signature. Then, it is possible to evaluate the effect of design modifications on the acoustic signature and the detectable distance of a vehicle.

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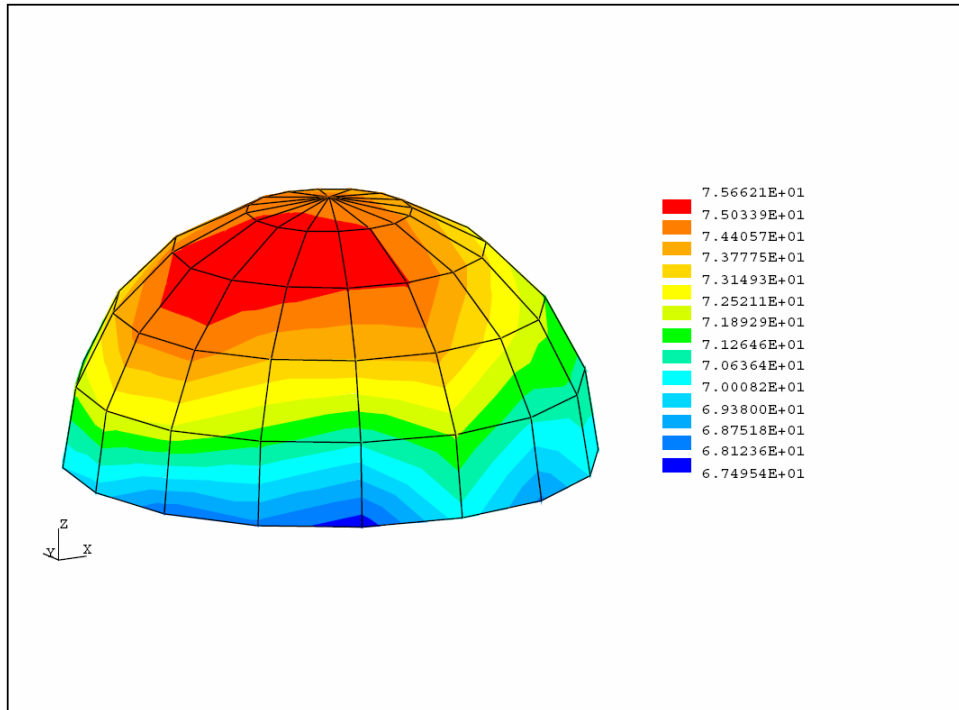


Figure 5 Acoustic SPL for 160Hz 1/3 octave band

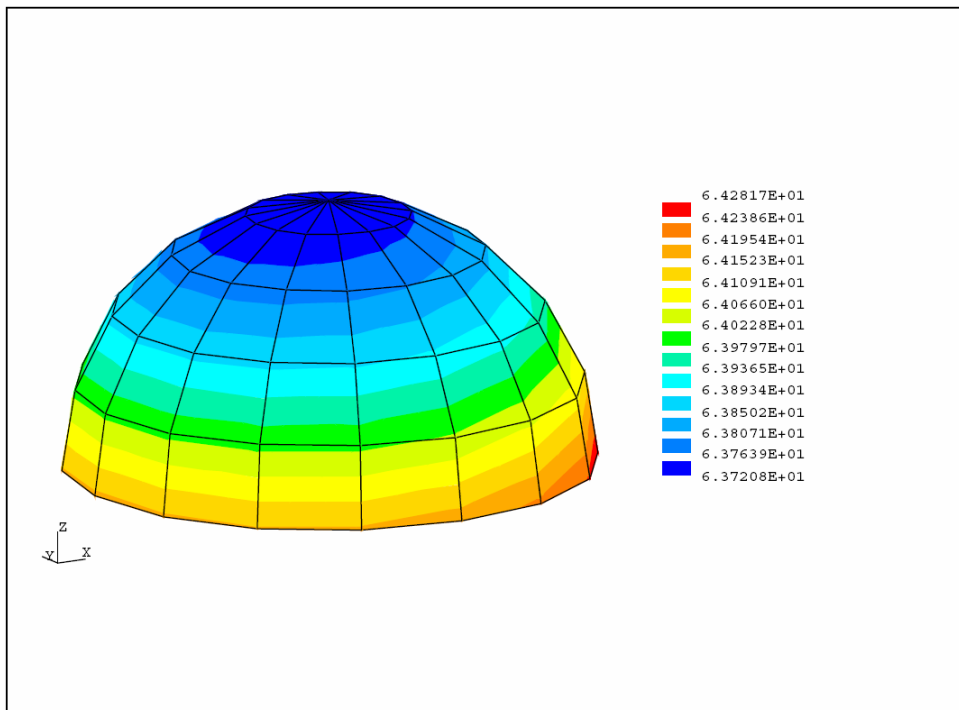


Figure 6. Acoustic SPL for 1,250Hz 1/3 octave band

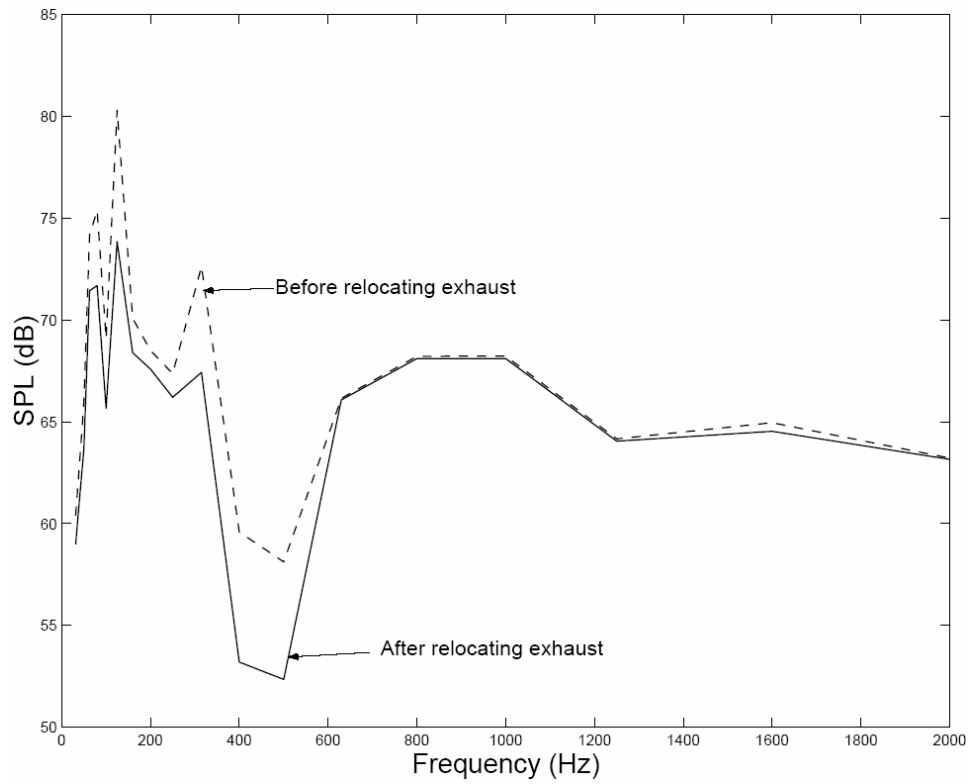


Figure 7. Acoustic signature used as input to ADRPM

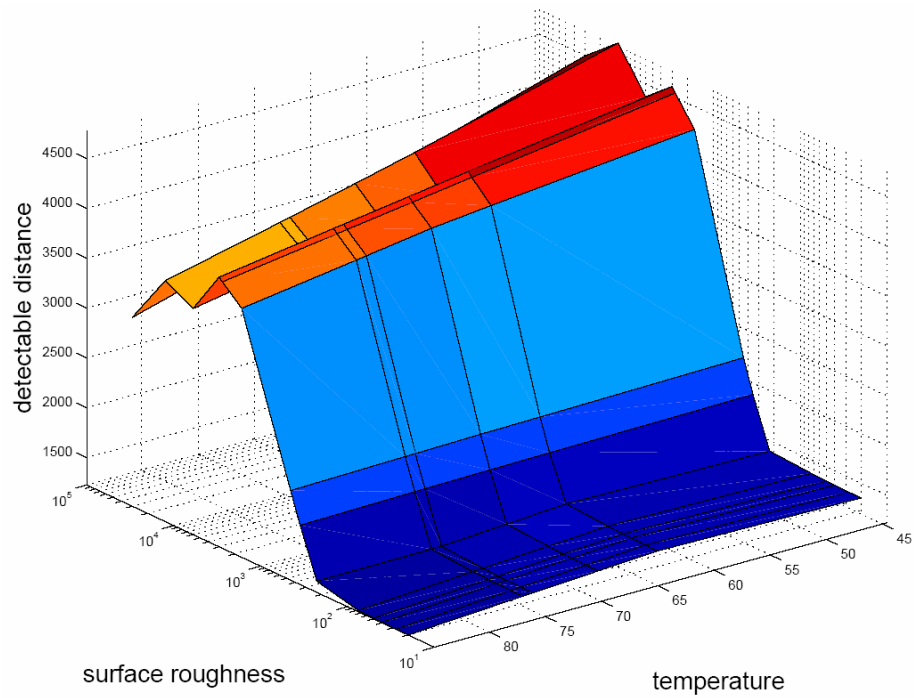


Figure 8. Detectable distance for original vehicle configuration

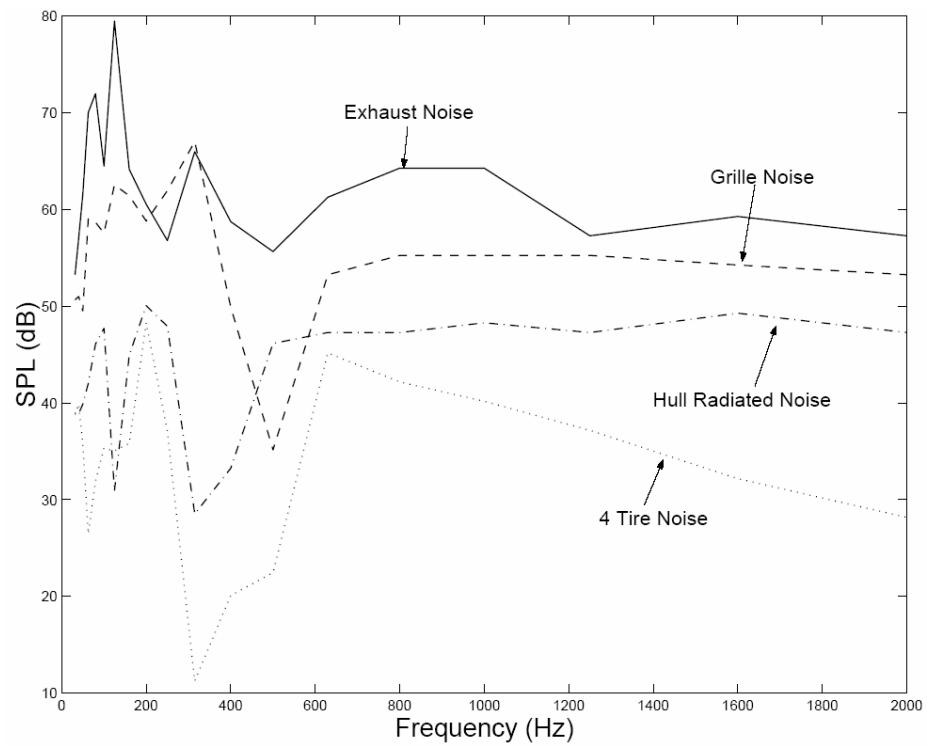


Figure 9. Contributions from each source to the acoustic signature

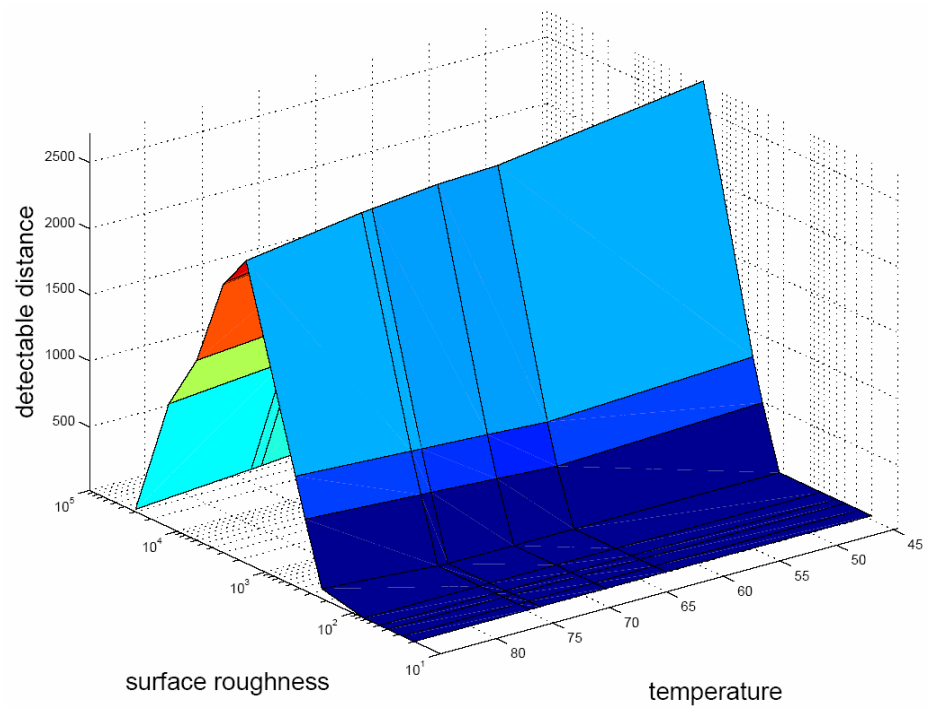


Figure 10. Decrease in detectable distance between the original configuration and with modified location for the exhaust