# Acoustic Source Location in Vehicle Cabins and Free-field with Nearfield Acoustical Holography via Acoustic Arrays.

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## ABSTRACT

The technique of Nearfield Acoustical Holography (NAH) is used to identify sources in enclosed spaces with coupled structural and acoustical modes. Pressure measurements made on planes within an enclosure are expanded and projected onto the vibrating surfaces of interest, and active and reactive intensities are calculated. This procedure is applied to locate a known source of acoustic excitation in the interior of a small sport utility vehicle exhibiting strong modal characteristics. Acoustic modes somewhat obscure the source location in the measured pressure distributions, while the reactive acoustic intensity clearly indicates the location of the vibrational input.

The NAH technique is also applied to an idling engine with unknown sources radiating acoustic noise into a free-field. The active intensity on the engine surface is reconstructed and the located sources at particular frequencies correlated with rotating engine components.

## 1 INTRODUCTION

When evaluating the noise levels of machinery such as that found in the automotive industry, a major point of interest is to determine the location of noise sources. In the practical cases encountered in industrial measurements, this usually involves the analysis of both exterior and interior sound fields. In exterior sound fields, it is well known that direct measurements of the acoustic pressure in the farfield of the source can be employed to determine the sound power radiated by a source, but those measurements reveal little about the location of acoustic sources and the energy flow paths in the acoustic field. Direct measurements of the acoustic intensity, such as those made using a two-microphone probe, are capable of determining the energy flow pattern at a point, but those measurements can have difficulty in locating sources in complex acoustic nearfields which may contain many sources and sinks of acoustic energy. When the source is located in an interior space such as a vehicle cabin, more problems arise since little active intensity is generated and the acoustic pressure takes on the form of the interior acoustic modes, thereby further obscuring the locations of potential acoustic sources.

The technique of Nearfield Acoustical Holography (NAH) has been shown to be effective at locating acoustic sources and identifying acoustic energy flow paths in both interior and exterior acoustic fields. Originally developed for the analysis of exterior, or free-field, sound fields, the techniques of NAH may be extended to the analysis of interior acoustic fields as well. In NAH, pressure measurements made on surfaces in the nearfield of vibrating surfaces of interest may be used to calculate the spatial distribution of acoustic quantities such as pressure, velocity, intensity, etc., on the vibrating surface itself and on parallel surfaces in the region exterior to the vibrator. In free-fields, this includes the entire region exterior to the vibrator, while in interior spaces, this includes the entire region between the source surface and the ceiling on any surface that does not pass through the ceiling. Determining the velocities using the measured pressure also results in a more consistent set of data for calculating intensities and radiation efficiency.

Both normal active and reactive intensities may be calculated on the vibrating surface to give precise information about the location of sources of acoustic energy on that surface. In free field measurements, sources may often be located by observing the active intensity distribution on the source surface. However, for acoustic sources in enclosures, which excite strong acoustic modes in the interior but do not generate much active energy, active intensity does not pinpoint source location. Therefore, the calculation of the reactive normal intensity is particularly useful in determining source location in an acoustic space enclosed by walls and a ceiling. Typical intensity measurements made with two-microphone probes very often do not provide valid results in enclosed spaces with strong acoustic modes, unless some effort is made to prevent the standing waves of acoustic modes from developing. This is not a concern when applying NAH techniques, since the acoustic field is expanded into a sum of those modes in that technique.

Normally, the two-microphone probes used to make intensity measurements need to be accurately phase-matched and are expensive. Typical intensity measurements also require either a person to hold the probe or an elaborate and expensive robot. The NAH technique uses an array of single microphones which are phase-referenced to a selected set of microphones. The array of microphones are relatively inexpensive. The reduced cost allows a larger number of measurements to be taken simultaneously, minimizing test time and increasing consistency of the data. Also, the microphone array is assembled relatively quickly prior to testing, and does not require human involvement during the measurement stage, which eliminates safety concerns under certain conditions.

Some of the limitations of NAH include the following. The pressure measurements are assumed to be made in the nearfield of the radiating sources. Actually, there is nothing inherent in the technique that requires this, but if the measurements are made outside of the nearfield, then the projection of the acoustic quantities back onto the source surface will contain much larger errors and reduce the resolution of the reconstructed image. The microphones in the array must lie in a defined surface, such as a plane, and must be evenly spaced in order for the NAH algorithms to employ two-dimensional Fourier Transforms, which are computationally efficient. NAH also assumes that the sources originate in a defined surface. If this is not valid, the model of the system is in error, and the sources which are not in the assumed plane will appear as a "smearing" of the actual sources.

NAH was originally developed to locate acoustic sources of interest radiating into a completely free-field (ref. 1). Then, plane-wave reflection coefficients were measured by using the spatial transform techniques employed in NAH (ref. 2 and 3). This led to the development of a theory allowing for the presence of waves that reflect from a surface in the path of the normal component of an acoustic wave, such as the ceiling of an enclosure (ref. 4). NAH techniques were also developed to allow for the presence of reflections from the walls of a duct, provided that those walls were nearly perfectly reflecting (ref. 5). These procedures were combined to account for both ceiling and wall reflections, so that the acoustical field generated by a vibrating surface in a full enclosure was more accurately reconstructed by NAH (ref. 6). In this paper, NAH techniques are applied to locate sources in the interior of a cabin of a small sport utility vehicle, and to locate sources from an idling engine radiating into the free-field environment of a semi-anechoic chamber.

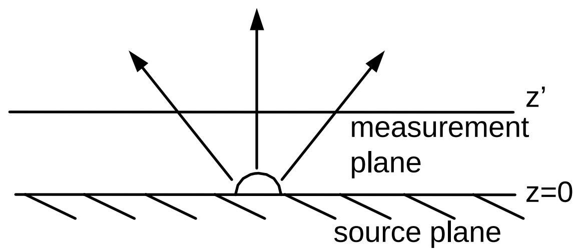


Figure 1: **Illustration of free-field NAH in a planar geometry.**

In the next section, the theory of NAH is outlined for free-field radiation and is expanded to include the effects of walls and ceiling encountered in enclosed spaces, such as the interior cabin of a vehicle. A more detailed description of the theory, including the underlying mathematics, is contained in (ref. 6).

# 2 THEORY OF NAH.

## 2.1 Free-Field NAH.

NAH can be used to predict the three-dimensional acoustical field generated by acoustic sources. This is based on measurements of the complex acoustic pressure made in the nearfield of the sources. Basically, the measured pressure is used as a boundary condition to solve the homogeneous acoustic wave equation in the region exterior to the sources. This assumes that the sources radiate into a free field, or that the region exterior to the source surface is both source and reflection free, as shown in Figure 1.

If this free-field assumption is valid, the solution to the acoustic wave equation for the pressure at any point exterior to the measurement surface can be expressed, in terms of the pressure on the measurement surface and a Green’s function which has a form particular to the geometry of the boundary surface, by using the first Rayleigh integral equation (ref. 1). Since this integral equation is in the form of a convolution, NAH uses computationally efficient wavenumber transform techniques to evaluate it, which is equivalent to performing a two-dimensional Fourier Transform. Once the integral has been evaluated, an inverse transform is performed to obtain the projected pressure distribution, at any plane above the source surface, in the space domain.

The acoustic particle velocity, which is needed to determine intensity or sound power, may also be calculated on arbitrary planes above the source surface. This is done by expressing the acoustic particle velocity vector in terms of the pressure gradient, the characteristic acoustic impedance of the fluid medium, and a Green’s function which has a form particular to the geometry of the boundary surface, by using Euler’s equation. Once the wavenumber domain velocity has been calculated, an inverse transform is performed to obtain the projected normal velocity distribution, at any plane above the source surface, in the space domain.

Once the projected pressure distributions and acoustic particle velocity have been calculated based on the measured pressures, the second order quantities of the acoustic field, such as intensity, may be determined.

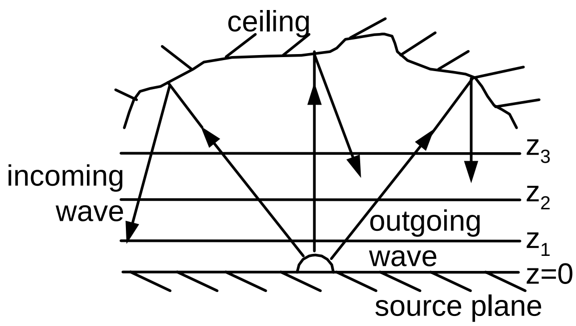


Figure 2: **Illustration of ceiling reflections.**

## 2.2 NAH in the Presence of Ceiling Reflections.

When a reflective ceiling exists, the outgoing acoustic waves generated in the source plane are reflected from the ceiling and travel back toward the source as incoming waves, as shown in Figure 2. If the previous free-field technique were applied, the incoming and outgoing waves would not be distinguished from one another. The incoming and outgoing waves are separated by measuring the acoustic pressure on two parallel planes near the source. The pressure distributions on a given plane are thus expressed as a sum of the incoming and outgoing waves. The incoming and outgoing components of the pressure on the measurement planes are coupled to those on a projected plane by applying appropriate propagation functions. A wavenumber transform is then performed and the total pressure on the projected plane calculated, and then inverse transformed back into the space domain.

The normal acoustic particle velocity, needed for intensity calculations, is related to the acoustic pressure, the characteristic acoustic impedance of the fluid medium, and a Green's function valid for a planar geometry, by the second Rayleigh integral equation (ref. 1). Again, this integral equation is in the form of a convolution, and the solution procedure for the acoustic velocity is the same as outlined previously for the free-field pressure. Once the pressure and acoustic velocities have been determined, it is possible to calculate the normal active and reactive intensities at any plane located between the source plane and the ceiling plane.

## 2.3 NAH in the Presence of Wall Reflections.

If walls are present, the pressure does not diminish at the aperture boundary as it did previously. This is because strong modal patterns develop in the measurement plane, which are due to the reflection of acoustic waves from the walls interfering with the direct waves generated by the source, as shown in Figure 3.

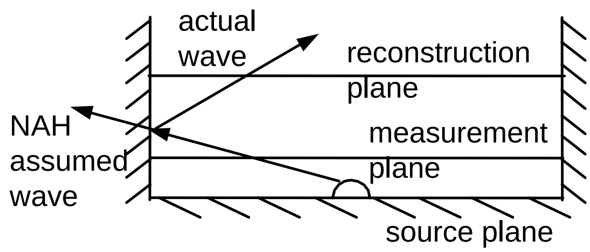


Figure 3: **Illustration of a wall reflection.**

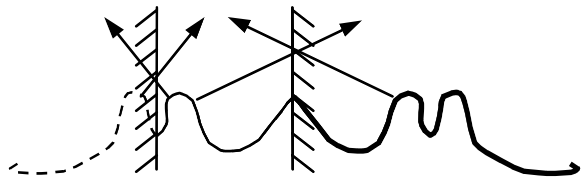

Figure 4: **Illustration of wall model created by extending the measured pressure distribution. Solid line – measured pressure. Dotted line – mirror image. Thick line – infinite periodic extension.**

If the walls are assumed to be perpendicular to the measurement plane, they can be replaced with an infinite series of images of the pressure distribution measured between the walls (ref. 5). This forces the velocity perpendicular to the walls to be zero, satisfying the wall boundary conditions needed. The measured pressure and its mirror-image extension are propagated with a form of the Green's function such that waves leaving the aperture at the wall boundary are replaced by waves contributed by the extended version of the pressure, as shown in Figure 4.

### 2.4 NAH in Full Enclosures.

The previous techniques are combined to apply NAH to a fully enclosed space. The assumptions are that the enclosed walls be hard and perpendicular to the measurement plane, and that reconstructions can be performed only on parallel planes which do not pass through the ceiling. Reconstructions of the acoustic properties of a sound field generated in a full enclosure can then be performed accurately in the regions shown in Figure 5.

## 3 APPLICATION OF NAH TO CABIN INTERIOR.

### 3.1 Test Setup.

To demonstrate the usefulness of NAH in determining vibrational excitation sources in the interior of a vehicle, the following test was performed. A shaker was attached to the floor pan of a sport utility vehicle and driven with random noise over the frequency range from DC to 400 Hz, in order to simulate the vibration of an exhaust mount point on the floor pan.

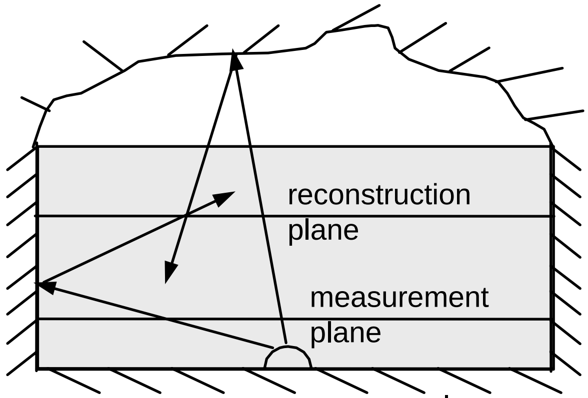


Figure 5: **Illustration of the valid regions of reconstructions for a full enclosure under the assumptions outlined in this section.**

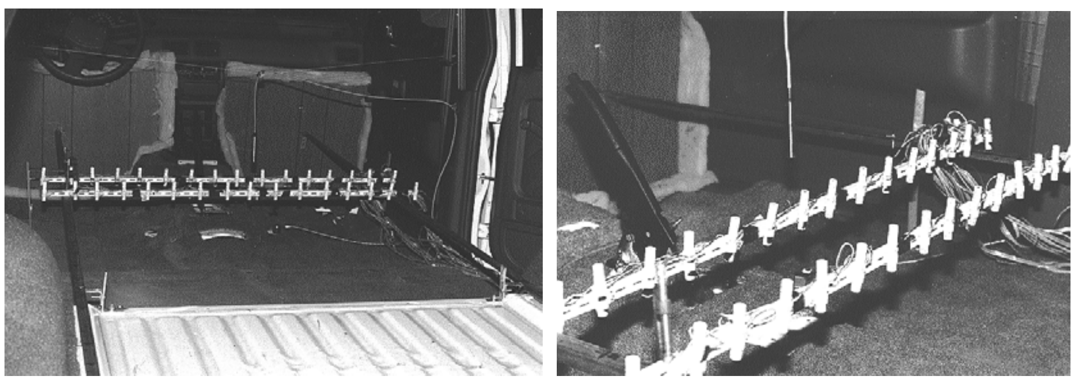

Figure 6: **Grid setup of microphone array for interior vehicle cabin test.**

The pressure was measured on two planes located at 22 mm and 72 mm above the floor pan on a 16 x 32 microphone measurement grid whose origin was located at the rear left corner of the vehicle. The x-axis of the measurement surface ran across the width of the vehicle between the two doors, while the y-axis of the measurement surface ran from the rear to the front of the vehicle interior. A microphone spacing of 86 mm in the y-direction and 67 mm in the x-direction was employed in order to cover the entire floor pan in the 16 x 32 grid.

The 16 x 32 microphone grid was scanned by a 16 x 2 subarray of Modal Shop model 130A Acousticel microphones. A total of 64 Acousticels were used. The subarray assembly, which was made quickly and inexpensively with two rods, is shown in Figure 6. The rods were clamped to the rails inside the vehicle for each scan, and were traversed over the measurement grid 16 times to cover the entire grid. The microphones at each measurement location on the rods were piggy-backed, as shown in Figure 6, so that measurements on both planes could be achieved simultaneously.

The phase of the sound field was referenced to a single B&K 4165 microphone placed directly over the excitation point at a height of 300 mm, with (x,y)=(0.6 m, 2.1 m). The seats were removed to facilitate the measurements. This lowered the front portion of floor pan an additional 150 mm, which was properly accounted for in the post-processing stage.

The data from the reference microphone and the grid microphones were collected with an HP 35650 data acquisition system controlled by the LMS Fourier

Monitor software package. The data was post-processed on a workstation using holography software written in Matlab script files.

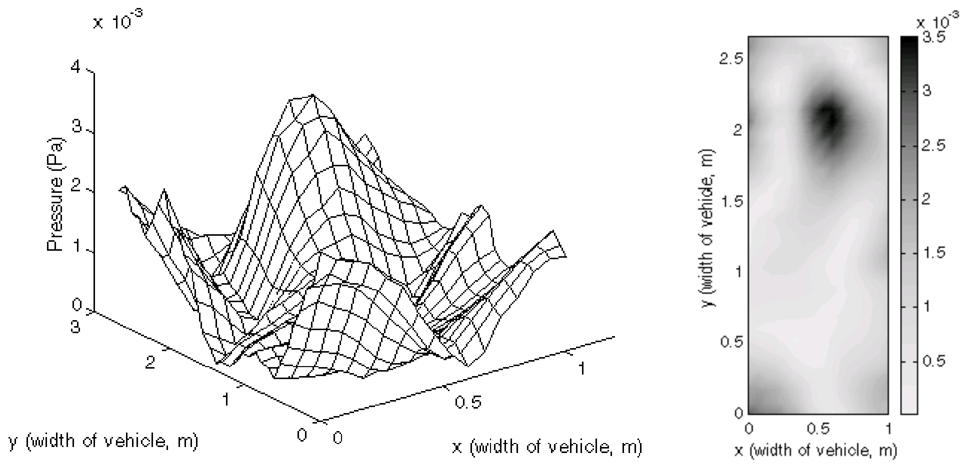


Figure 7: **3-d mesh and gray-scale map of the pressure magnitude measured at 22 mm above the floor pan.**

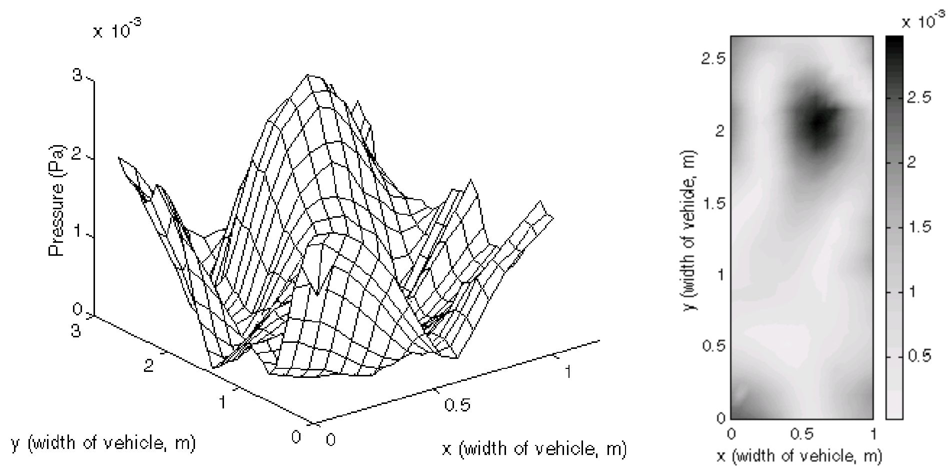


Figure 8: **3-d mesh and gray-scale map of the pressure magnitude measured at 72 mm above the floor pan.**

The entire test setup took approximately 6 man hours, while the data acquisition took about 1 hour.

## 3.2 Experimental Results.

Typical results for the two planes of measured pressure reconstructions at 260 Hz are shown in Figures 7 and 8. The left portion of each figure is a three-dimensional mesh plot with the pressure plotted along the z-axis, or the height dimension. The right portion of each figure is a gray-scale map with the pressure magnitude indicated by the shade – increasing darkness indicates increasing pressure magnitude. From these figures, a strong presence of a (1,3,0) acoustic mode is observed that somewhat obscures the source location. However, by reconstructing the reactive acoustic intensity at the floor pan, shown in Figure 9, the location of the vibrational input is clearly evident. Some excitation is apparent at the edges, where the floor pan radiates most efficiently, but those features are small compared to that over the excitation point. Thus, this NAH technique is able to locate the source of the excitation to a high degree of accuracy.

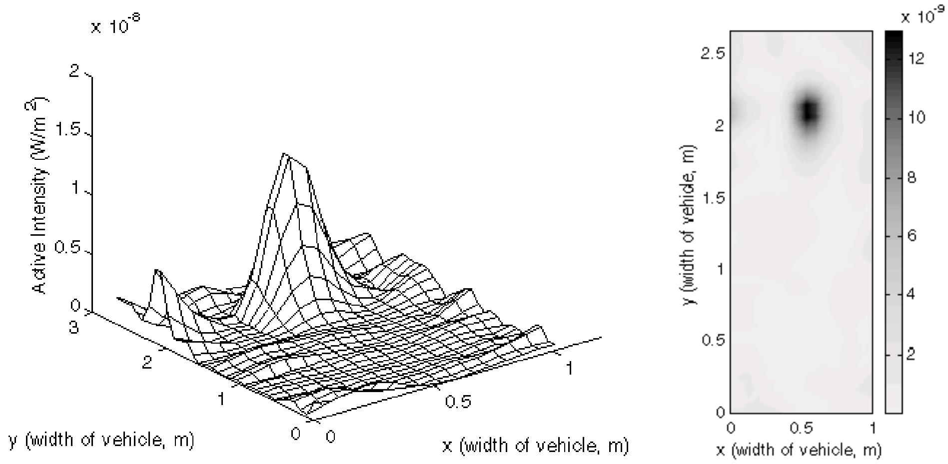


Figure 9: **3-d mesh and gray-scale map of the reactive intensity projected onto the floor pan.**

# 4 APPLICATION OF NAH TO IDLING ENGINE IN FREE-FIELD.

## 4.1 Test Setup.

The NAH technique was also applied to data from an engine operating at idle on a test stand in a semi-anechoic chamber. Since the room was not tremendously reverberant, free-field NAH was used, and only one measurement plane was needed. This experimental test was performed to demonstrate that intensity measurements could be made to accurately determine noise sources at the engine surface quickly, inexpensively, and without a person standing next to the operating engine.

A 16 x 16 microphone measurement grid of size 1.28 m x 1.28 m, shown in Figure 10, was constructed from chicken wire and wood to hold the five reference Acousticel microphones whose bases were hot-glued directly onto the chicken wire. This grid remained stationary for the duration of the test. The origin was defined to be the upper left corner of the grid shown in the left portion of Figure 10, with the x-axis of the measurement surface running along the width of the grid, and the y-axis of the measurement surface running vertically along the grid. The entire grid was supported vertically by tie-wrapping it to shaker stands, and was stationed 253 mm from the front surface of the engine, in the nearfield of the suspected sources. The five reference microphones were placed at various locations where the noise sources were suspected to be located.

A separate 4 x 16 microphone subarray grid of size .32 m x 1.28 m was constructed to hold the 64 Acousticel microphones spaced 80 mm apart in both the x- and y-directions. A total of four scans were made with the subarray to cover the entire grid area. The subarray grid was tie-wrapped to the stationary grid for each scan.

The entire grid assembly was performed prior to the test, which reduced the amount of time spent in the engine test stand chamber. The total setup time was approximately 6 man hours, and the data acquisition time was approximately 1 hour.

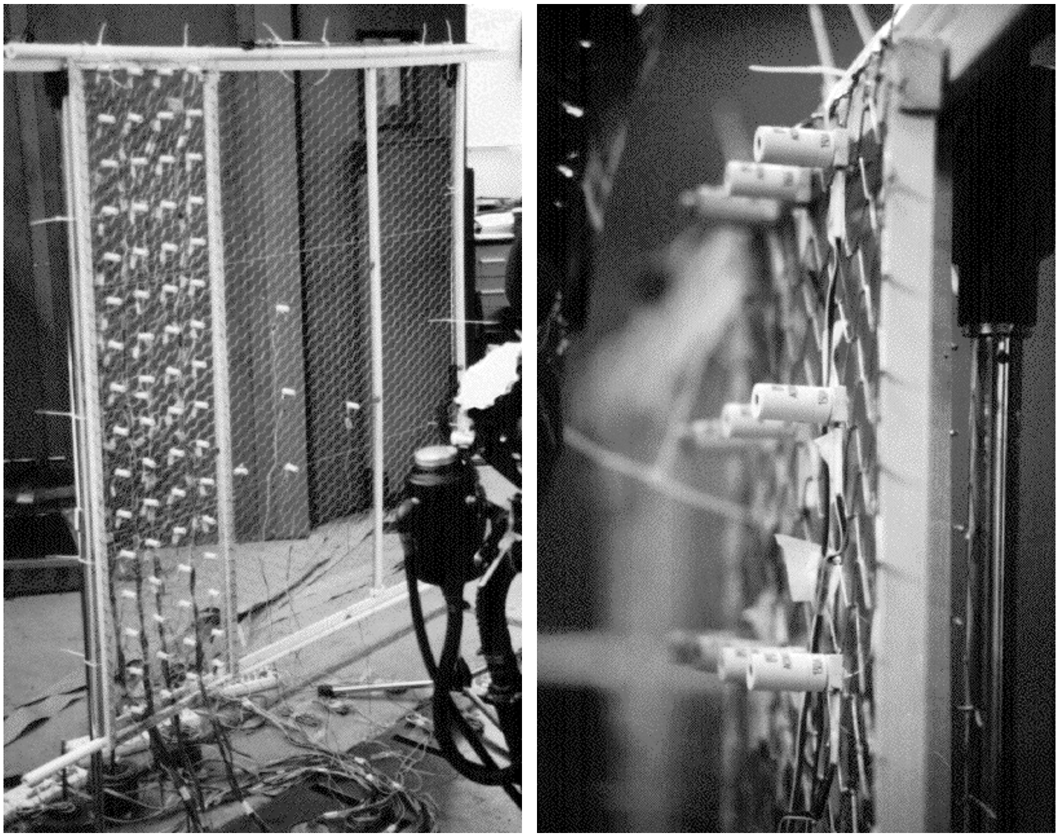

Figure 10: **Grid setup of microphone array for idling engine test.**

The data was acquired for a frequency range of DC to 1024 Hz, using the same acquisition equipment and software as that described in Section 3 for the sport utility vehicle test. Before the holography technique was applied, the data was first reduced using a singular value decomposition technique, written in Matlab script files, to obtain the partial pressure fields for each scan on the measurement plane. The data was then post-processed on a workstation using holography software written in Matlab script files.

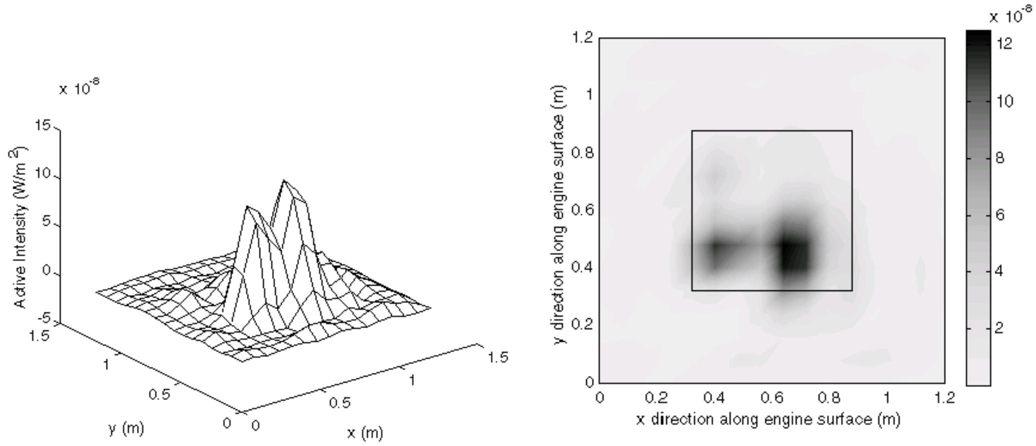


Figure 11: **3-d mesh and gray-scale map of the active intensity projected onto the engine surface.**

### 4.2 Experimental Results.

A typical result for the active intensity reconstruction at 680 Hz at the engine surface is shown in Figure 11. The left portion of the figure is a three-dimensional mesh plot with the intensity plotted along the z-axis, or the height dimension. The right portion of the figure is a gray-scale map with the intensity value indicated by the shade – increasing darkness indicates increasing intensity value. The black box on the gray-scale map indicates the location of the surface of the engine within the measurement area. The located sources using NAH correlate with the crank and air conditioner pulley locations on the engine surface, which are evidently rotating at this frequency. Various other sources on the engine surface may be located at different frequencies.

## 5 CONCLUSIONS.

NAH techniques were applied to experimental pressure measurements made on two planes in the cabin interior of a small sport utility vehicle. A source was simulated by driving the vehicle with random noise from a shaker attached to the floor pan. A relatively inexpensive and easy to assemble acoustic array of microphones was employed to obtain the pressure measurements. While acoustic modes obscured the source location in the measured pressure distributions, the reactive intensity distribution at the surface of the floor pan clearly indicated the location of the vibrational source. Although not addressed in this paper, the NAH technique may also be used to locate multiple sources in an enclosed space.

NAH techniques were also applied to experimental pressure measurements made on a single plane in the nearfield of an idling engine surface with sources radiating into the free-field of a semi-anechoic chamber. Using the acoustic array, the pressure distribution was measured, and the intensity at the engine surface calculated with NAH at selected frequencies. Sources were located which correlated to engine components rotating at those frequencies. The use of the grid array removed the need to measure intensities on an operating engine by hand or by robot, without being a costly alternative.

## 6 REFERENCES.


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