Comparison of Nearfield Acoustic Holography and Dual Microphone Intensity Measurements

Richard W. Bono **David L. Brown, Susan M. Dumbacher**

The Modal Shop, Inc. **University of Cincinnati, SDRL**

Abstract

The measurement accuracy of nearfield acoustic holography (NAH) and dual microphone intensity measurement techniques are examined in terms of source identification capabilities and sound intensity level estimates. Inherent differences in the data acquisition and post processing methodologies are investigated. The techniques are applied according to their individual limitation to best evaluate the test structure. The variance of their respective results and how those results aid in engineering solutions is thoroughly discussed.

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1. Introduction

Sound and vibration laboratories are commonly required to experimentally measure a test structure's acoustic properties and locate its sound sources. Since sound pressure is a scalar quantity which greatly depends upon the acoustic boundary conditions, additional acoustic properties are required to understand the structural and acoustic behavior of a given structure. Acoustic intensity is the rate of acoustic energy flow through an area in a given direction, typically in W/m^2. It is a vector quantity as it has both magnitude and direction associated with it. Additionally, acoustic intensity can be described in active and reactive components. Active intensity quantifies the net flow of energy caused by pressure gradients while reactive intensity quantifies the acoustic energy that is stored in the acoustic medium but does not cause energy to flow, such as in highly reflective environments.

The dual microphone intensity probe has been utilized over the last couple of decades to measure acoustic intensity levels. The cross-spectral method of determining sound intensity is well documented in its theory and applications. Standard grid intensity tests typically involve roving a pair of phase matched microphones separated by a known distance from grid location to grid location. The intensity probe scans a given grid area long enough to sufficiently average the acoustic data. A finite difference approach approximates the required acoustic properties. The sound pressure is estimated by averaging the microphone pair's output and the particle velocity is calculated from the pressure difference between the pair. For these estimates to remain accurate, high quality, phase-matched condenser microphones must be used. The accuracy of these estimates is also limited to a certain frequency range which is directly related to the spacing between the two microphones.

Intensity scans provide valuable information concerning the acoustic characteristics of a given test article; however, the procedure can be very costly and time consuming. A tremendous amount of test time is invested by scanning individual grid areas at a fine enough resolution to adequately illustrate the intensity pattern. Additionally, scanning involves either human or robotic interaction during measurement, which is potentially hazardous or cost prohibitive, respectively. Simultaneous acquisition of real-time intensity measurements at many points is generally considered not economically feasible. For many applications, newer acoustic array techniques have emerged as possible alternatives to intensity scanning.

Nearfield Acoustic Holography (NAH) is one such alternative. NAH uses a two dimensional surface of complex acoustic pressure measurements as the boundary conditions of the basic acoustic wave equation. A three dimensional acoustic field (sound pressure, particle velocity, and sound intensity) is computed using a two dimensional Fourier Transform and applying analytical wave propagation theory in the acoustic wavenumber domain. Since the particle velocity is computed in the wavenumber domain rather than using the finite difference approximation, the normally stringent constraints on the phase matching of the microphones can be relaxed and inexpensive acoustic array microphones can be used to acquire the data. The recent development of array microphone systems makes full instrumentation of a structure economically realizable. It also eliminates the need for human or robot involvement during data acquisition, effectively lowering test costs and increasing safety.

With any new technology, an understanding of its advantages and limitations is necessary. NAH is capable of completely describing the acoustic field generated by a structure. However, its limitations with respect to frequency range and test boundary conditions can be severe compared to traditional intensity measurement systems.

The purpose of this paper is to directly compare these two measurement techniques as applied to an engineering structure. The sound intensity radiated from an engine simulator constructed from wood and acoustic speakers was analyzed using both cross-spectral dual microphone intensity and nearfield acoustic holography. In the following sections, the basic theory and measurement process of each technique are discussed. Finally, the assumptions and constraints of and experimental variances between both procedures are summarized.

2. Basic Theory

Dual Microphone Intensity Probe

Scanning acoustic intensity measurements are fairly common place in today’s automotive, aerospace, and consumer product noise, vibration, and harshness (NVH) programs. Two different methods are used to evaluate the intensity radiated from a source. The first is a time domain technique using real time digital filtering techniques to calculate the acoustic intensity. This method was developed by O. Roth in the early 80's and has been well documented in [4,11,13]. The second method, used in this particular case study, employs the imaginary part of the cross spectrum between two microphones to calculate the intensity spectrum. The basis for this measurement is described in detail in [1,3,14,17]. A general description of the frequency domain measurement technique follows.

Sound intensity is defined as the product of acoustic pressure and particle velocity. Sound pressure is readily measured with a microphone, and for the case of an intensity probe, is generally determined by averaging the output of the two microphones.

$$\left(p_1(t) + p_2(t)\right)/2 = p(t) \qquad (1)$$

Particle velocity, however, poses some difficulties because no instrument exists which measures this quantity directly. Using a pair of microphones to estimate the pressure gradient, the finite difference approximation of particle velocity is based on Newton's' second law:

$$r\frac{\partial u}{\partial t} = \nabla p \qquad (2)$$

It follows that, in the measurement direction 'x' :

$$\frac{\partial u_x}{\partial t} = \frac{-1}{r}\frac{\partial p}{\partial x} \qquad (3)$$

$$u_x(t) = \frac{1}{r\ \Delta x}\int p_2(t) - p_1(t)\ \ dt \qquad (4)$$

Finally, from the estimations of pressure and velocity,

$$I = p(t)u(t) \qquad (5)$$

The true acoustic intensity vector may be pointed in any arbitrary direction which is generally unknown. With the dual microphone technique, it is only possible to measure a single component of the intensity vector at a time. Since only the normal acoustic intensity is of interest in most practical applications, this is usually not of significant concern.

In addition to signal processing errors associated with acquiring the cross spectrum [18], the measurement system has physical limitations which induce errors. High frequency limitations are the result of errors in measuring the pressure gradient, defined by the following relationship

$$\frac{I_{MEAS}}{I_{ACTUAL}} = \frac{\sin(k\Delta x)}{k\Delta x} \qquad (6)$$

where k is the wavenumber and Δx is the microphone spacing. Therefore, high end errors increase as microphone spacing increases. Practically, this means that closely spaced microphones are needed for accurate high frequency intensity measurements. Low frequency limitations are the result of phase measurement errors, which are a direct result of microphone phase mismatch, small phase shift due to wavelength, and narrow microphone spacing. Valid measurement frequency ranges dictated by the limitation of the finite difference approximation are well specified in [3,14,17] for a variety of spacer sizes. Measurement errors will also occur in the nearfield as a result of significantly differing intensity at the two microphone positions. This can happen in the case of higher order sources when large reactive intensity is present. Since an intensity probe is typically scanned over an area, significant errors may result if sound intensity gradient is not uniform over that area. Additionally, shadowing errors may occur associated with the intensity probe's presence in the sound field.

Nearfield Acoustic Holography (NAH)

The basis of NAH lies in the assumption that a two-dimensional surface of pressure measurements satisfies the homogeneous acoustic wave equation in the region exterior to the sources, given by

$$\nabla^2 P(r) + k^2 P(r) = 0 \qquad (7)$$

where k is the wavenumber and r is the desired point (x,y,z) of projection. The solution to equation (7) can be expressed as the convolution integral

$$P(r) = \iint_S P(r')G_D(z - z')dxdy \qquad (8)$$

where G_D is a Green's Function specific to the geometry of the two-dimensional surface and r'=(x',y',z') at the measurement position. The Green's Function describes the manner in which acoustic waves propagate from the sound source(s) and must be derived from analytical wave propagation theory. Since equation (8) is in the form of a convolution, a two-dimensional FFT can be utilized to evaluate it efficiently in the wavenumber domain. The complete theoretical development is presented in [8,10,15] for various geometries.

With P(r), one can determine the acoustic particle velocity, U, by considering Newton's law for fluids in terms of the pressure gradient

$$U = \frac{-j}{\rho_0 \omega}\nabla P \qquad (9)$$

where ρ_0 is the density of the acoustic medium and ω is the frequency of interest. This calculation is also performed in the wavenumber domain as a simple multiplication and inverse Fourier transformed into the spatial domain. Once both the sound pressure and particle velocity have been determined on a desired surface, the second order acoustic quantities such as sound intensity and sound power may be calculated.

Practically, to implement an NAH algorithm, one must measure the autopower and crosspower spectra of the reference and array microphones. Using either the virtual coherence method [5] or the partial coherence method [6], the data is processed so that the sound field is represented in terms of a set of fully coherent, mutually incoherent partial fields on the measurement surface. A two-dimensional FFT is employed to transform each partial pressure field into the wavenumber domain, where the partial pressure fields for each reference can be calculated on the desired plane from

$$p(k_x, k_y, z) = \frac{p(k_x, k_y, z')}{e^{jk_z(z-z')}} \qquad (10)$$

and the acoustic particle velocity from

$$u_\eta(k_x, k_y, z) = \frac{1}{\rho_0 c}\frac{p(k_x, k_y, z')\left[\frac{k_\eta}{k}\right]}{e^{jk_z(z-z')}} \qquad (11).$$

Applying a 2-D inverse FFT, the acoustic quantities are transformed back into the spatial domain at the desired plane exterior to the sources. It follows that sound intensity can be computed from

$$I(x,y,z) = \frac{1}{2}\left[p(x,y,z)u^{*}(x,y,z)\right] \qquad (12)$$

where the real part of I is the active intensity and the imaginary part is the reactive intensity.

As with dual microphone cross-spectral intensity measurements, signal processing errors associated with acquiring the frequency spectra for post processing are present and well documented [18]. The physical limitations of holography measurement systems, however, are not as well specified but are very important for accurate measurements.

The valid frequency range of the technique is defined from the physical dimensions of the measurement grid. This stems from NAH's ability to provide subwavelength resolution of sound sources. Information from the evanescent waves in the nearfield is required to accurately project holograms. If the measurement plane is more than a half wavelength from the source plane, the evanescent waves have potentially decayed too severely and are buried in the background noise. The error that results is somewhat analogous to a computational mode occurring in experimental modal analysis. Therefore, the upper frequency limit should be dictated by the dimension between array microphones and the source plane. Additionally, to avoid spatial aliasing when performing the two-dimensional FFT into the wavenumber domain, two points per wavelength must be sampled along the measurement planes x and y dimensions. All this considered, the upper frequency of the technique is defined by

$$x,y,z = \frac{\lambda}{2} \quad (13)$$

where z is the distance between measurement and source, x and y are the array microphone grid spacing, and λ is the wavelength of the highest valid frequency.

The lower frequency limit for NAH is defined by the overall dimensions of the array measurement plane, where the width and height should be greater than or equal to at least one wavelength of the lowest frequency of interest. Again, this error is the result of the two-dimensional FFT numerical problems. At lower frequencies, only the DC component of the FFT can be resolved by the given measurement grid. Practically, this rule of thumb only limits the capability to accurately project holograms into the far field. The overall grid dimensions should also be large enough so that the sound pressure at the boundaries of the measurement plane have decayed significantly (practically, at least twice as large as the source plane in near anechoic environments). This is to prevent leakage from occurring during the two-dimensional FFT into the wavenumber domain.

Other considerations include the proper placement of reference microphones. The number of reference microphones can be determined using standard principle component analysis. At least one reference per incoherent source is required. Also, the effects of incoherent background noise can be eliminated with proper placement of the reference microphones. Concerning boundary conditions, anechoic freefield or highly reflective environments support the technique. If the boundary conditions cause coherent reflections of moderate levels, significant errors result. Note that incoherent reflections are not a source of error.

3. Test Setup and Data Acquisition

An automotive engine simulator constructed from wood with four nominally 3 inch acoustic speakers flush mounted onto the ‘front cover’ was the test structure used in this evaluation. The test was carried out in an anechoic chamber located at the University of Cincinnati. The Modal Shop Model 130A Acousticel Array Microphone System acquired the raw data for the nearfield acoustic holography. The Modal Shop Model 150AI Acoustic Intensity Probe measured the raw data for the cross-spectral intensity calculations. The acquisition front end consisted of LMS Cada-X software and Hewlett-Packard 3565S hardware. All post processing calculations to reduce the data were programmed in MATLAB software.

The purpose of this test was to directly compare the sound intensity level estimates given by nearfield acoustic holography and dual microphone cross-spectral intensity. One fundamental difference between technique methodologies is that NAH provides acoustic information at discrete points in the form of projected holograms while traditional intensity measurements are scanned over small areas to estimate the time-averaged flow of acoustic energy. Therefore, the intensity probe was not scanned over an area but kept stationary at points which correlated to the NAH projections. The physical and acquisition parameters of the measurements were set with this comparison in mind. The NAH parameters were set according to the given structure, while the intensity probe measurements were made to correlate the results. The parameters are listed in Table 3.1 below.

Parameter	NAH	Intensity Probe
Node Configuration	16x16	8x8
Microphone Spacing, X Dir	38.1 mm	76.2 mm
Microphone Spacing, Y Dir	38.1 mm	76.2 mm
Overall Grid Dimension, X Dir	571.5 mm	533.4 mm
Overall Grid Dimension, Y Dir	571.5 mm	533.4 mm
Measurement Plane Location, Z Dir	50.8 mm	304.8 mm
Spacer Size	not applicable	25 mm
Number of Measurement Scans	8	64
Acquisition Frequency Range	0-2048 Hz	0-2048 Hz
Frequency Resolution	2 Hz	2 Hz
Source Type	Random Noise	Random Noise
Number of Averages	200	200
Window Type	Hanning	Hanning

Table 3.1 Physical and Data Acquisition Parameters

The test setup is illustrated in Figure 3.1 for both techniques. The 32 array microphones were supported by aluminum rods, 16 sensors per row. A 16x16 complex pressure map was acquired with 8 scans using a single reference microphone to provide the necessary cross-spectral phase information. The intensity probe was supported using a camera tripod. The aluminum rods used to support the array microphones were also used to locate the acoustic center of the intensity probe. The tripod was repositioned for each measurement point in the 8x8 intensity map. Additionally, the NAH measurement plane was positioned 50.8 mm (2 inches) from the source while the intensity measurement plane was positioned 304.8 mm (12 inches) from the source. This allowed for validation of the NAH projections while avoiding nearfield errors in the dual microphone cross-spectral intensity measurements.

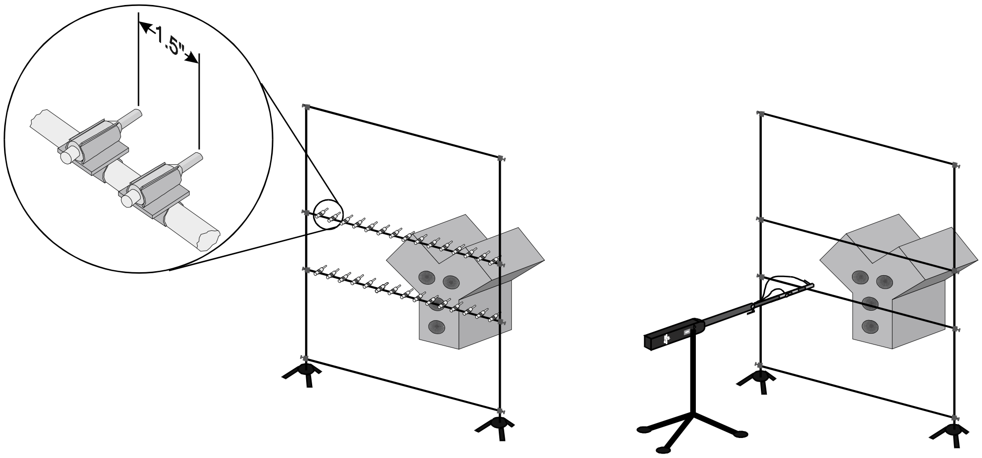

Figure 3.1 Schematic of Test Setup

4. Experimental Results and Discussion

The intensity maps measured by the probe correlated extremely well with the nearfield acoustic holography projections. Data was analyzed at 512, 600, 700, 800, 900, and 1024 Hz. NAH identified the correct location and intensity level on the source of the engine simulator, shown in Figure 4.1 for 512 Hz. Active intensity holograms were also projected to the probe's measurement plane. An 8x8 subset of those projections correlated well with the intensity probe's measurements. Slight variations along the boundaries of the intensity maps are the result of truncation errors of the two-dimensional FFT during NAH post-processing. This error was seen to be not greater than approximately 3 dBI. The interior grid locations exhibited far greater correlation, varying by less than ± 1 dBI at each of the analyzed frequencies. Figures 4.2 through 4.4 illustrate this correlation between the two techniques at various frequencies. Similar results were seen all other analyzed frequencies in the valid range of the measurement parameters.

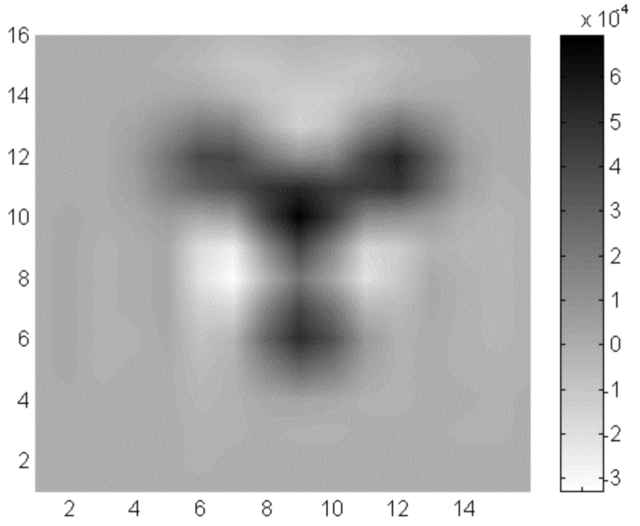

Figure 4.1 Active Intensity Projected onto Engine Simulator at 800 Hz.

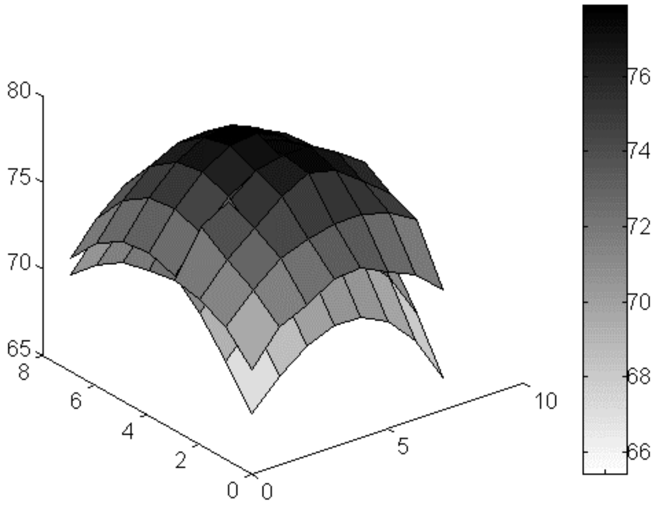

Figure 4.2 Overlay of Sound Intensity Level at 512 Hz, z=304.8 mm (1 ft)

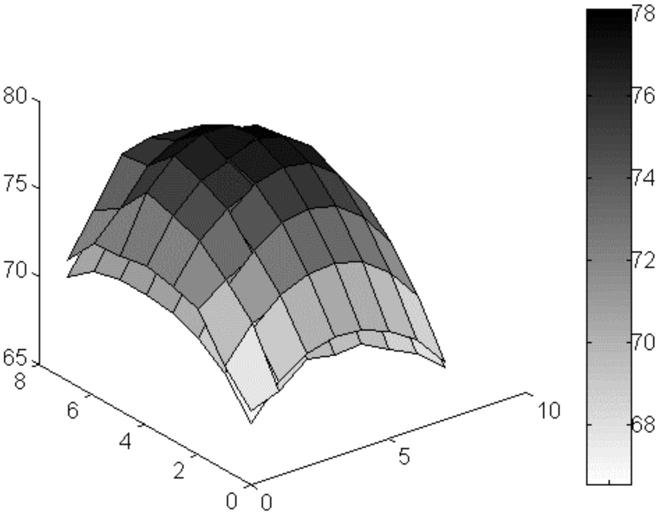

Figure 4.3 Overlay of Sound Intensity Level at 600 Hz, z=304.8 mm (1 ft)

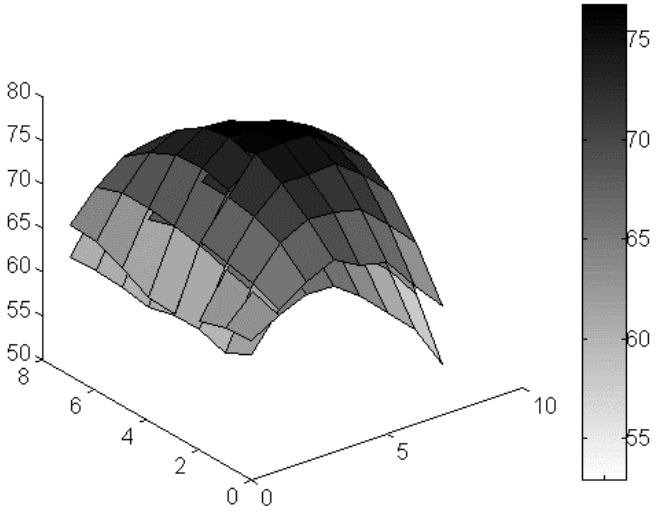

Figure 4.4 **Overlay of Sound Intensity Level at 1024 Hz, z=304.8 mm (1 ft)**

5. Conclusion

Nearfield acoustic holography has been shown to correlate with dual microphone cross-spectral intensity measurements. Both methods are viable measurement techniques when used properly. Currently, the dual microphone technique is widely used in the engineering community. NAH continues to expand in its use. Although NAH is not regulated by measurement standards, it is a powerful and practical engineering tool.

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