# Using Probe Microphones For Nearfield Acoustic Holography Measurements of a Carbon Nanotube Speaker

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## Introduction

Carbon nanotube (CNT) thin-film speakers are a new kind of speaker that produce sound with thermoacoustic effect. Rapid heating and cooling of the air in the nearfield of the thin film produces a fluctuating temperature boundary condition and, therefore, creates pressure waves that are propagated into the surrounding medium as sound. This sound generation mechanism is completely different from commercial speakers that produce sound with a moving surface which creates a velocity boundary condition. Because the CNT thin film does not move, the source velocity of CNT thin film speakers is the particle velocity of the air particles in the plane of the thin film. Measuring the source velocity of the air surrounding the CNT film is important in understanding and modeling their fundamental behavior.

It is challenging to measure the surface velocity of the CNT speaker because the material is not moving, is very lightweight, and the surface temperature is very hot (on the order of hundreds of degrees Celsius). Because the surface isn't moving, we can't use common surface velocity sensors such as accelerometers or laser vibrometers. The high surface temperatures prevent the use of common microphones in the nearfield. The dual microphone intensity measurement method has inaccuracies due an exponential decay of ambient temperature as distance from the source plane increases.

Nearfield acoustic holography (NAH) is a non-contact method to calculate the velocity on the source surface using the set of acoustic pressure measurements on a holographic plane close and parallel to the source surface. The advantage of the NAH is that it reconstructs all acoustic quantities on the source surface, such as acoustic pressure, particle velocity and acoustic intensity, using a two dimensional spatial Fourier Transform and wave propagation theory. Because NAH must be conducted very close to the CNT film in a high temperature environment, selection of the right microphones is of critical importance.

PCB Piezotronics, Inc. model 377B26 probe microphone and preamplifier were selected for this project because it is designed to operate in a high temperature environment (up to and beyond 400 $^0$C). In addition, the probe tip provided us with the required standoff distance to run cables and mount preamplifiers without the risk of damage to our fragile source. Finally, the small diameter of the probe tip provided the opportunity for very high spatial resolution in our NAH measurements, if desired.

### Nearfield Acoustic Holography

In the NAH method, the complex pressure $(p)$ is measured over a holographic plane in the nearfield of a source. For a microphone located at $z = z_m$ (holographic plane), by using a spatial Fourier transform the pressure in the frequency domain can be described in wavenumber $(k)$ space:

$$P(k_x, k_y, z_m, \omega) = \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} P(x, y, z_m, \omega) e^{-i(k_x x + k_y y)} dx dy \equiv F_{k_x} F_{ky} \{P(x, y, z_m, \omega)\}$$

where *x* and *y* are the horizontal and vertical coordinates on the source surface plane, respectively, *P* is the frequency domain acoustic pressure as a function of radial frequency, $\omega$, and $k_x$ , $k_y$ and $k_z$ are the wavenumber components in the x, y and z directions such that

$$k^2 = k_x^2 + k_y^2 + k_z^2.$$

In this method, the green function, *G*, is used to reconstruct the velocity at the source plane, $z_s$, in wavenumber space:

$$G(k_x, k_y, z_m - z_s, \omega) = \frac{k_z}{\rho_0 c k} e^{i k_z (z_m - z_s)}$$

The source velocity in the spatial domain can be obtained using the inverse spatial Fourier transform and it can be used to reconstruct the acoustic properties, such as pressure or particle velocity, at any plane,

$$\dot{w}(x, y, z_s, \omega) = F_{k_x}^{-1} F_{k_y}^{-1} \{G(k_x, k_y, z_m - z_s, \omega) \times P(k_x, k_y, z_m, \omega)\}$$

It is not practical to measure a high spatial density of points on the measurement plane. This means that the exact acoustic waves on the source plane are not reconstructed exactly. A discretized array measurement is used and several parameters should be considered to reduce the error of finite measurements. Using the frequency range of interest and the dimensions of the measurement plane, the distance between the measurement plane and the source plane can be calculated using simple guidelines.

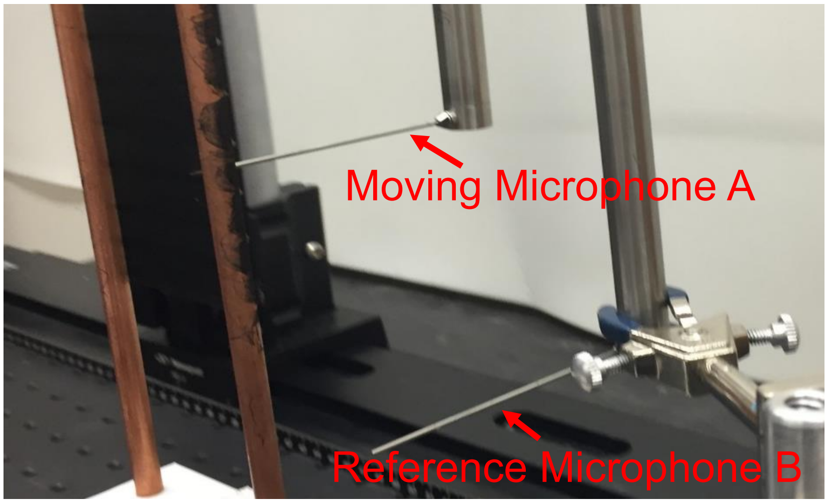
**Demonstration of NAH measurements using two probe microphones**

In this experiment, 195 points with 1 cm resolution in both x and y directions ($\Delta x = \Delta y = 0.01m$) were used to measure the pressure on the measurement hologram. The frequency range of interest was between 200 Hz and 4000 Hz, so a 5mm standoff distance was selected.

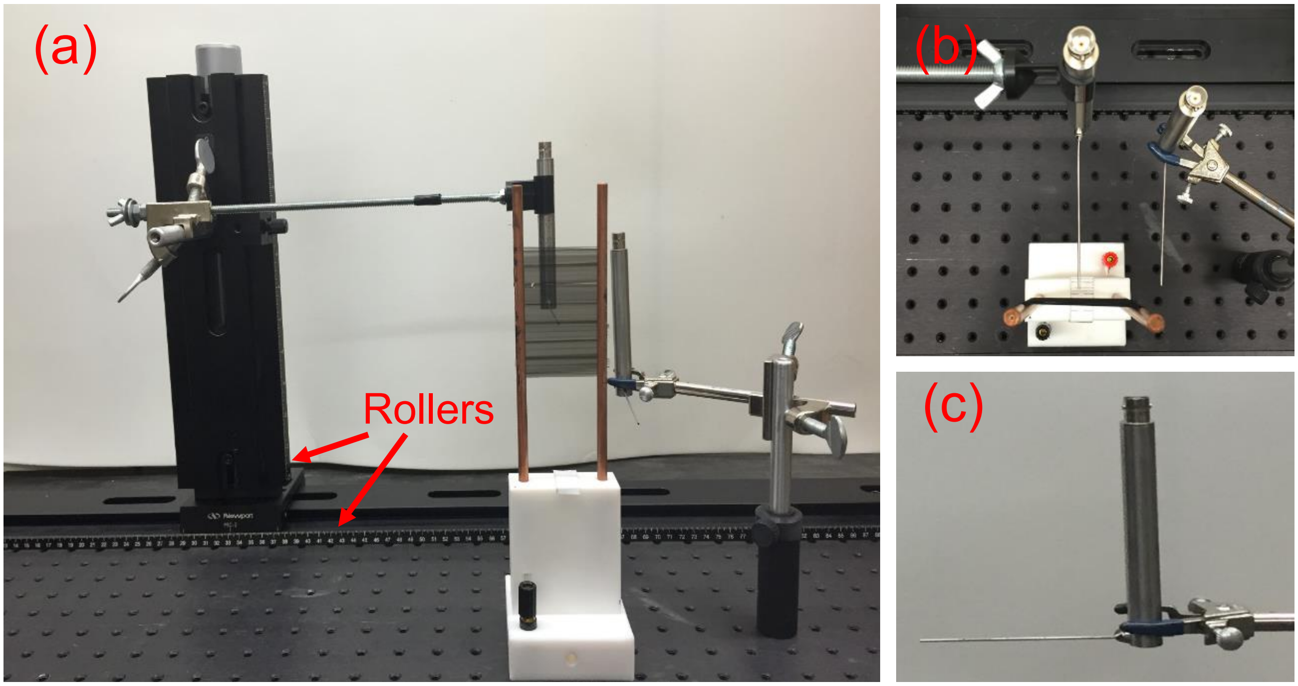
It would be difficult to physically fit 195 microphones in the defined test grid to measure the pressure on the hologram surface. Doing so would also potentially alter the acoustic field. Also, a data acquisition system with enough channels to record data from all microphones simultaneously would be required. In this experiment, instead of using an array of 195 microphones for the NAH method, only two probe microphones were used. Because the recordings take place at not only different spatial points, but also different temporal points, we must consider the phase of the acoustic waves. To do this, one probe microphone was used as an amplitude and phase reference microphone and was fixed to the base as shown below. If we denote the moving and reference microphones as *A* and *B*, respectively, the phase referenced sound pressure, *P*, for the moving microphone will be

$$P_A(\omega) = \sqrt{G_{AA}} e^{i * \angle(G_{AB})}$$

where $G_{AA}$ is the power-spectra of the moving microphone, *A*, and $\angle G_{AB}$ is the phase angle of the cross-spectra between the moving microphone, *A*, and reference microphone, *B*. This takes into account the temporally shifting phase reference of the moving microphone.

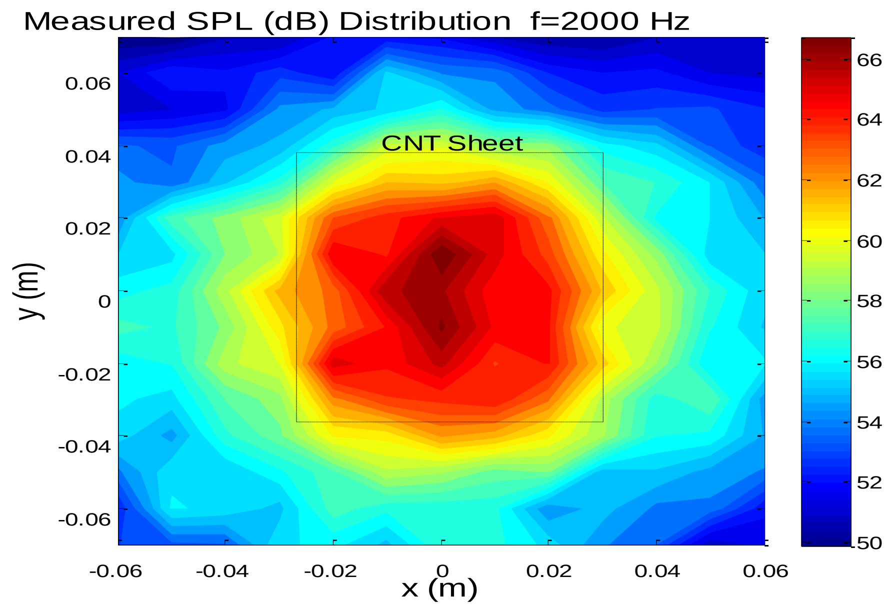



The test setup for the NAH method is shown below. To measure SPL data, two probe microphones, supported by rods, were used. One was used as a reference microphone and the other as a moving microphone. The moving microphone was attached to two translation stages in the x and y directions. The location of the moving microphone could be changed easily by using these stages. Also, a PCB 130A23 microphone was located 1m away from the center of CNT speaker and used to validate the results in far field and monitor for undesired temporal changes in the output sound pressure levels of the speaker.

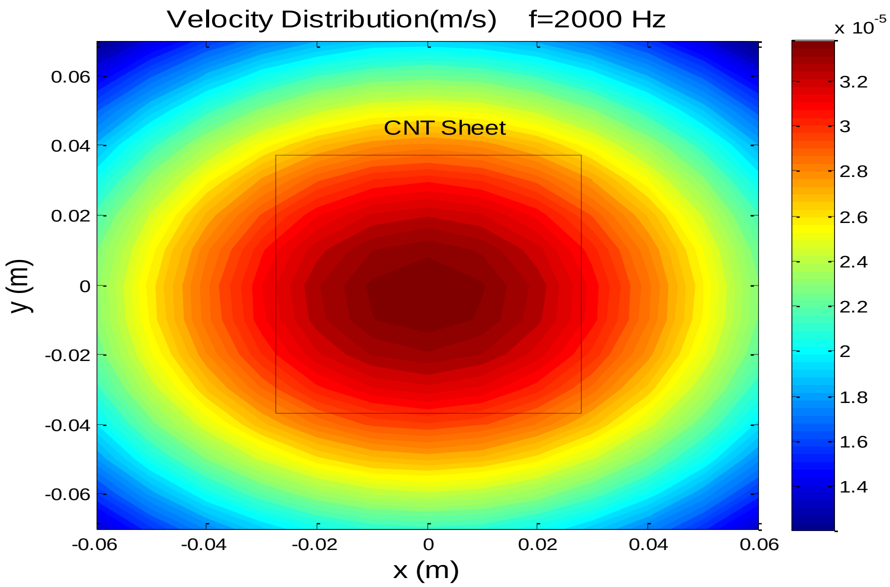



*Test setup shown on lab bench. Actual test took place in a fully anechoic chamber at Michigan Tech. a) Photograph of the NAH test setup showing the moving probe microphone mounted to the vertical and horizontal translation stage, the stationary probe microphone mounted to the base plate, the CNT speaker b) Top view showing the probe microphones and the distance from CNT sheet (5mm). c) PCB 377B26 probe microphone.*

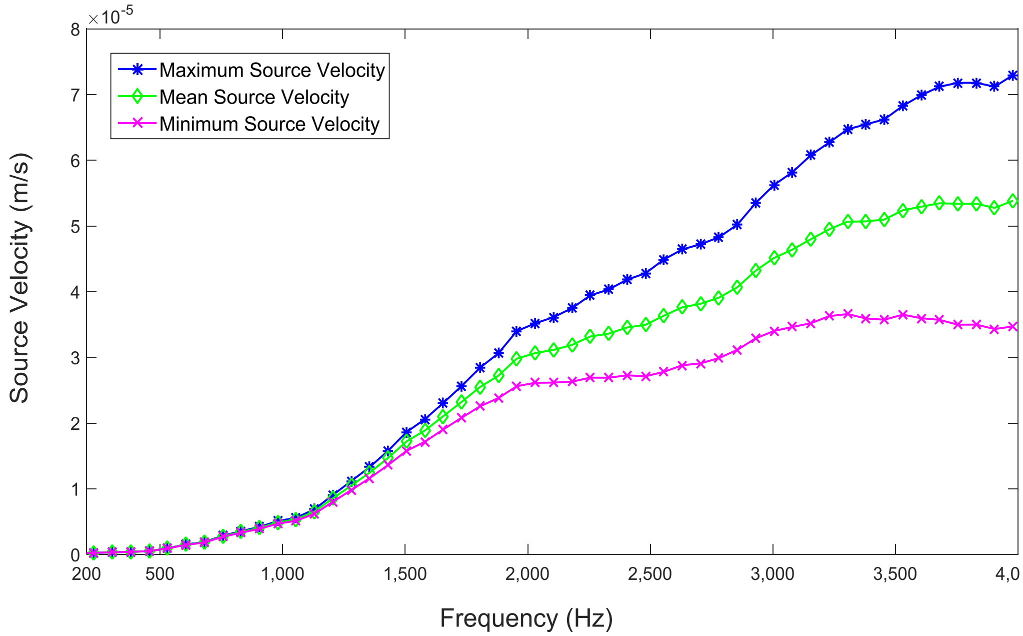
The SPL was measured at all 195 locations on the hologram plane (5 mm from the CNT source surface). The sound pressure distribution on the measurement plane is shown below. The dashed rectangle shows the dimensions of the CNT sheet. The maximum SPL is located approximately in front of the center line of the CNT sheet, as expected. The further a point is from the center of the CNT sheet, the lower its resulting SPL.




The measured SPL data was post-processed in MATLAB® to apply NAH theory. The source velocity distribution was obtained and is shown below. It is clear that the velocity is varying on the source surface and is maximum on the center of CNT sheet.



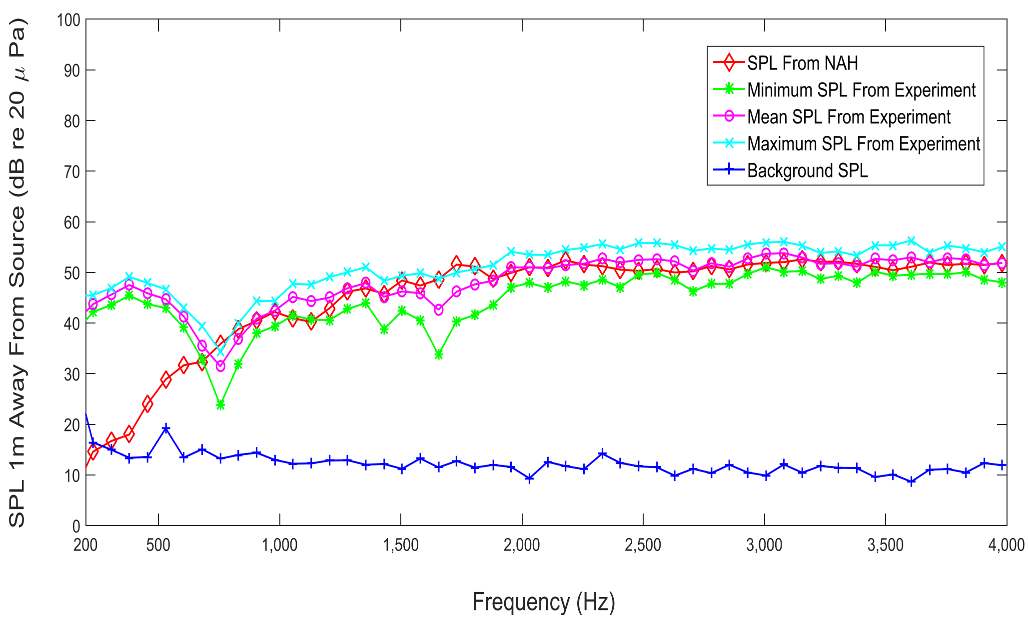

These velocity distributions were measured over a frequency range of 200 Hz to 4 kHz. The velocity variation over the source surface was calculated and is shown below. It was found that as frequency increases, the surface particle velocity variation also increases proportionally.



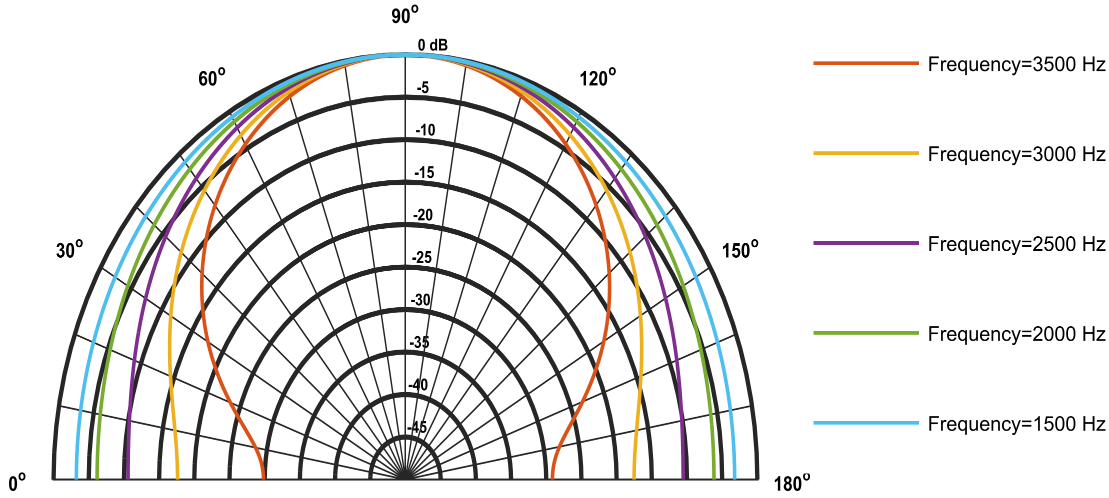

Source velocity versus frequency

The source velocity obtained through NAH can be used to reconstruct acoustic properties, like sound pressure, at any distance, or acoustic directivity. The following figure compares the measured SPL 1m away from the source (using the monitor microphone) with 1m pressure computed from the NAH measurement. There is good agreement between the measurement, the NAH computation, and the measured SPL at 1 m at frequencies greater than 750 Hz. It is believed that spurious reflections from the test apparatus are the cause of the unexpectedly high measured SPL at the 1m location at frequencies less than 750 Hz. Directivity of CNT speakers can also be obtained using the source velocity dis

below. As expected, the source becomes more directional with increasing frequency, as the source dimensions become a smaller fraction of the acoustic wavelength.




Comparison of experimental and analytical pressure distribution 1m away from source




Directivity patterns of the CNT speaker for frequencies from 1.5 kHz to 3.5 kHz.

**Conclusion**

Because of its small tip size and high temperature capability, the probe microphone enabled us to conduct a nearfield acoustic holography measurement of the surface velocity of a carbon nanotube loudspeaker. In addition, no new signal conditioning hardware was required, since the probe microphone is ICP® powered. The surface velocity of the ultralight, fragile structure was measured in a non-contact way. This, in turn, allowed us to compute realistic directivities and sound pressure levels of the CNT speaker on any far-field plane.

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