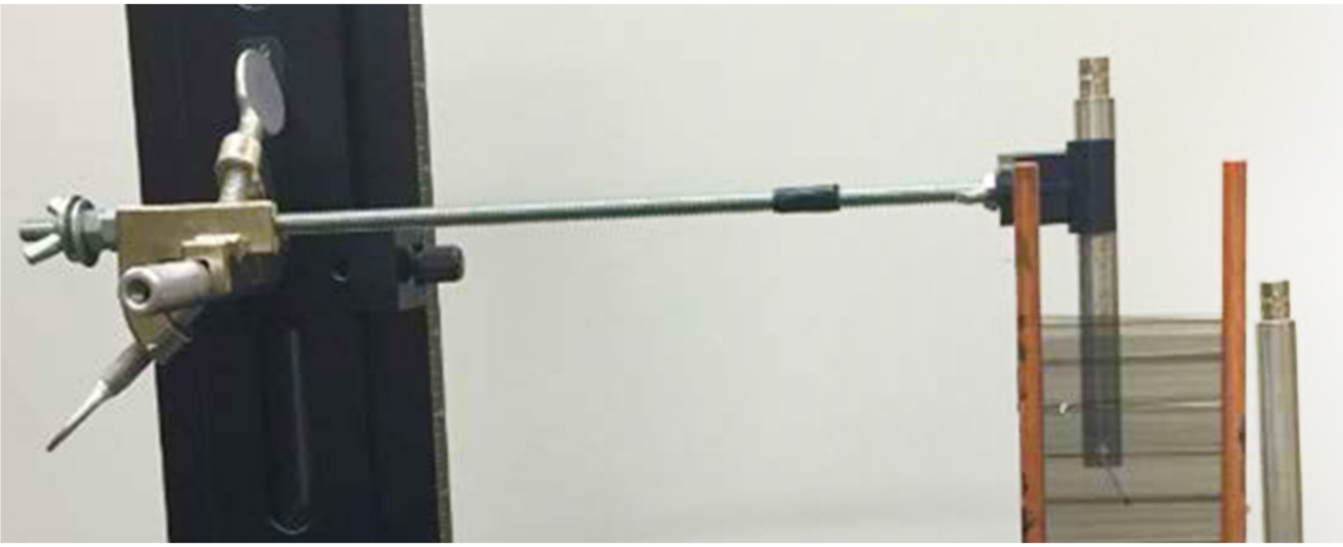

Using Probe Microphones for Nearfield Acoustic Holography Measurements of a Carbon Nanotube Speaker

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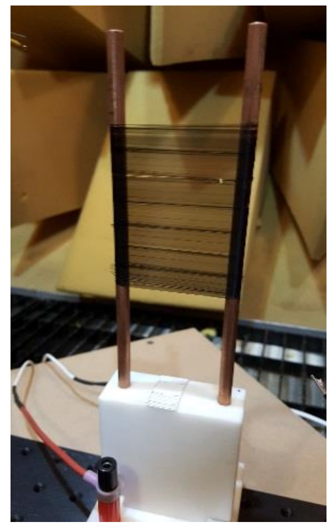
Introduction



Carbon nanotube (CNT) thin-film speakers are a new kind of speaker that produce sound with the 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 and is open on both sides, the source velocity of CNT thin film speakers is the particle velocity of the air particles in the plane of the thin film and is theoretically zero. Measuring the sound pressure and particle velocity of the air surrounding the CNT film is important in understanding and modeling their fundamental behavior.

It is challenging to measure the acoustic properties on the CNT sheet 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 velocity sensors such as accelerometers or laser vibrometers to measure the source characteristics. Also, the high surface temperatures prevent the use of common microphones in the nearfield. The dual microphone intensity measurement method has inaccuracies due to an exponential decay of ambient temperature as the distance from the source plane increases.

Nearfield acoustic holography (NAH) is a non-contact method to calculate the acoustic properties 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 method 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.

Model 377B26 probe microphone and preamplifier from PCB Piezotronics was 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 the needed 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; ω, 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

$$G(k_x, k_y, z_m - z_s, \omega) = \frac{k_z}{\rho_0 ck} e^{ik_z(z_m - z_s)}.$$

The source velocity in spatial domain can be obtained using inverse spatial Fourier transform and it can be used to construct the acoustic properties like pressure at any plane

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

Also, by knowing the pressure on the holographic plane, the pressure on any plane is given as

$$p(x, y, z, \omega) = F_{k_x}^{-1} F_{k_y}^{-1}\{e^{ik_z(z - z_m)} \times P(k_x, k_y, z_m, \omega)\}.$$

In practice, it is not possible to measure all points on the measurement plane to obtain the exact reconstructed waves on the surface plane. Therefore, 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 it and the source plane can be calculated using simple guidelines.

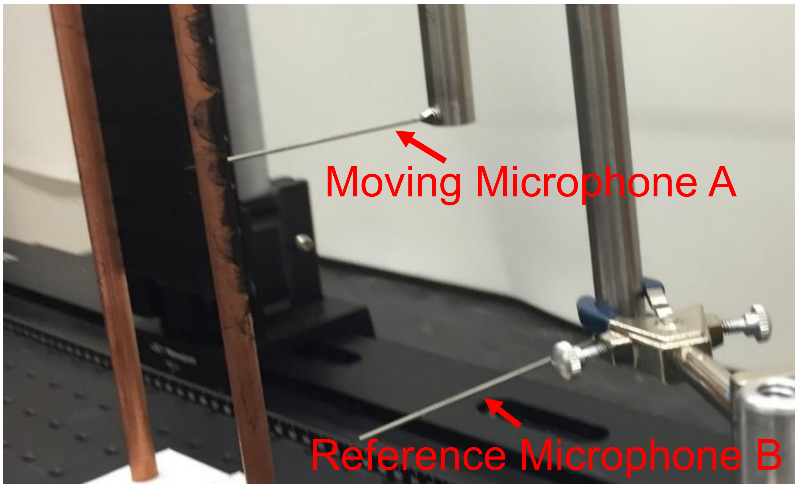
Demonstration of NAH measurements using two probe microphones

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 in this experiment 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 without significantly altering the sound field. This would also need a data acquisition system with enough channels to record data from all microphones simultaneously. Instead of using an array of 195 microphones for the NAH measurement, only two probe microphones were used. Because the recordings take place at not only different spatial points, but also different temporal points, the phase of the acoustic waves must be considered. To do this, one probe microphone was used as an amplitude and phase reference microphone. It 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

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

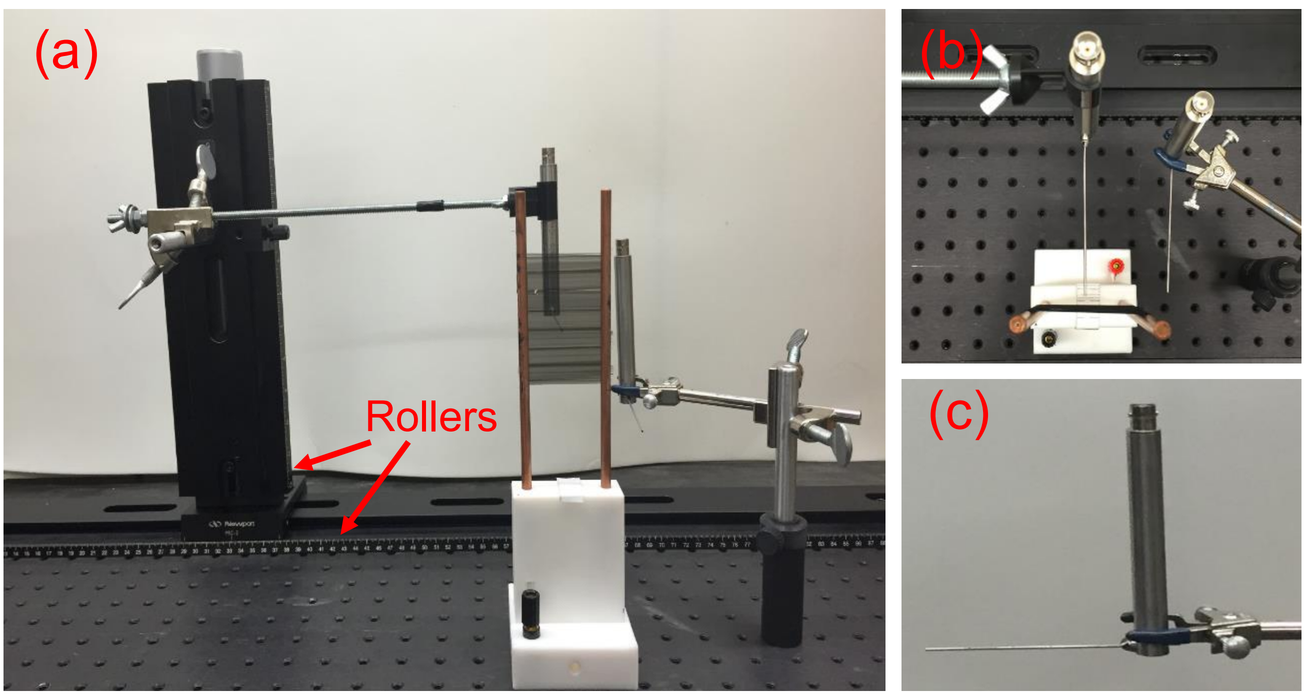
where G_{AA} is the power-spectra of the moving microphone, *A*, and $\angle G_{AB}$ is the phase angle of the cross-spectra between the moving microphone, *A*, and reference microphone, *B*. This takes into account the temporally shifting phase reference of the moving microphone.



Photograph of the reference and moving probe microphone

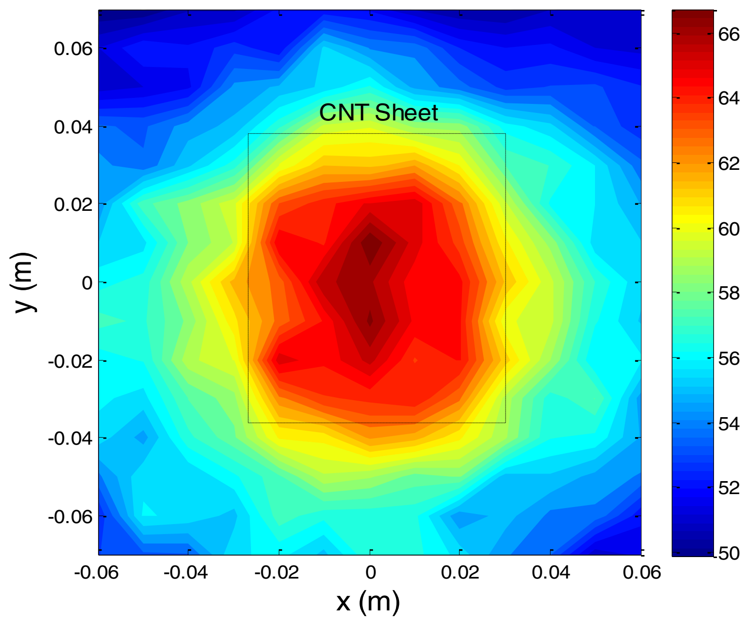
The test setup for the NAH method is shown below. To measure SPL data, two probe microphones were supported by rods. One was used as a reference microphone and the other as a moving microphone.

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. In addition, one PCB model 130A23 microphone was located 1 m away from the center of CNT speaker. It was used to validate the results in far field and to monitor for undesired temporal changes in the output sound pressure levels of the speaker.



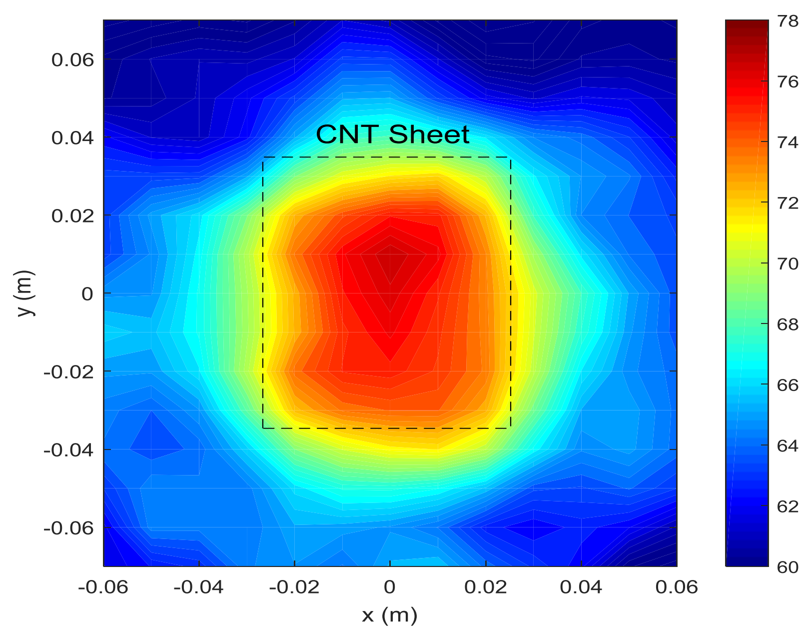
Test setup shown on lab bench. Actual test took place in a fully anechoic chamber at Michigan Tech. a) Photograph of the NAH test setup showing the moving probe microphone mounted to the vertical and horizontal translation stage, the stationary probe microphone mounted to the base plate, the CNT speaker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

The SPL was measured at all 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.



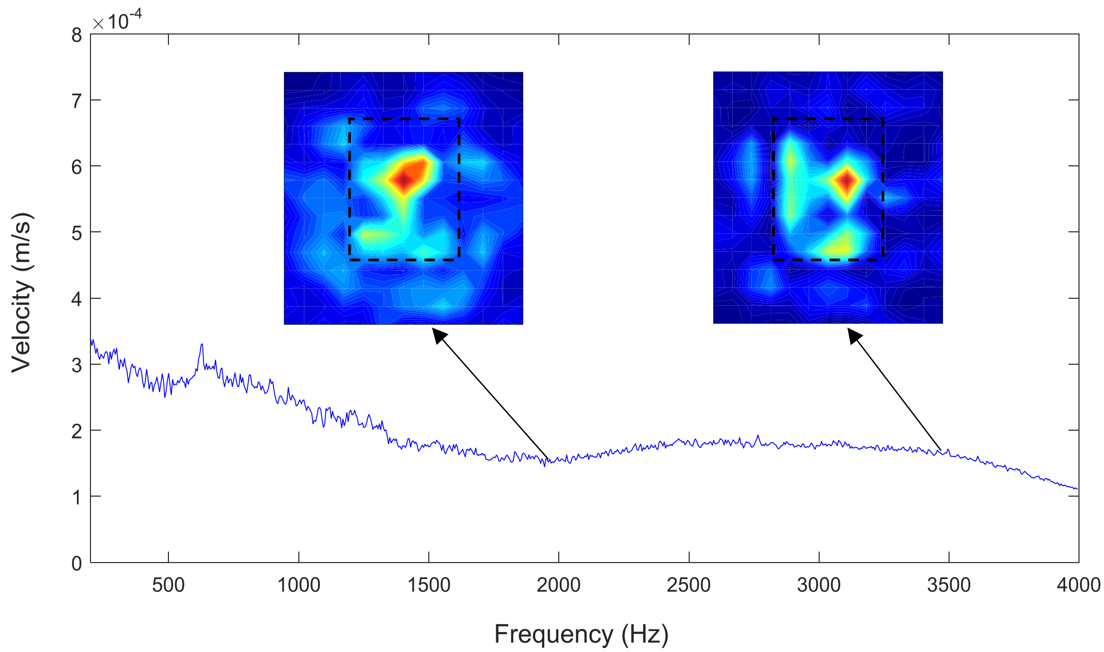
Measured SPL (dB) distribution   Frequency=2000 Hz

The measured SPL data was post-processed in MATLAB® to apply NAH theory. The source sound pressure level distribution was obtained and is shown below. It is clear that the sound pressure level is varying across the source surface and is maximum on the center of CNT sheet. The sound pressure level at the center of sheet at 2kHz is on the order of 8-to-10 dB higher than the corners.



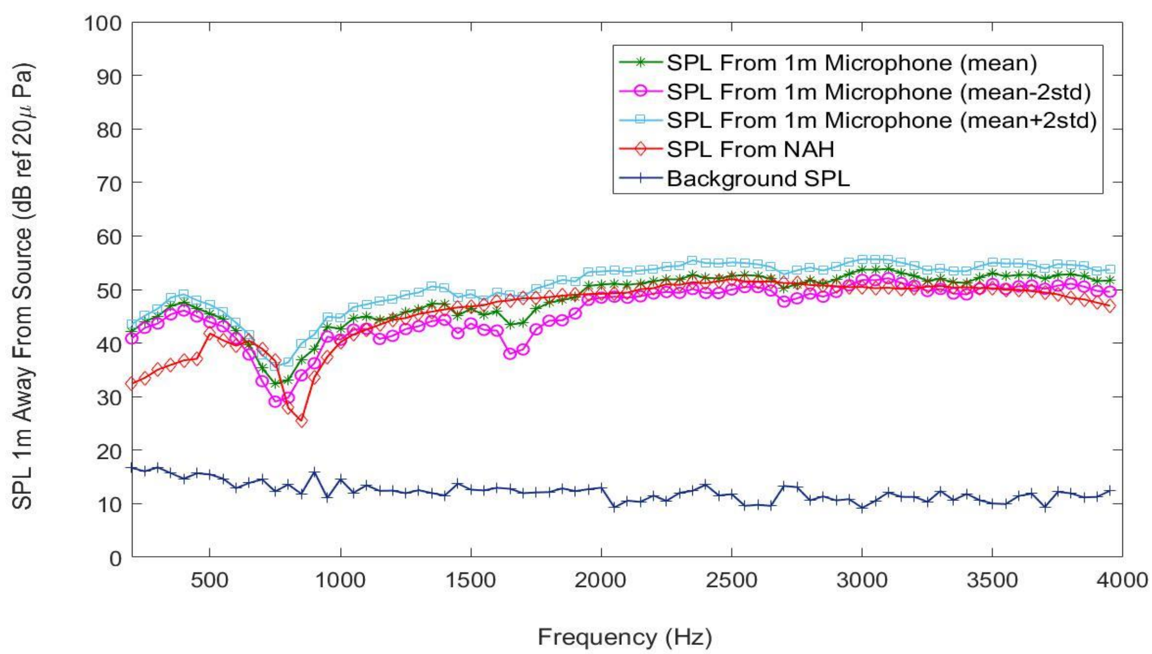
SPL (dB) distribution on Source   Frequency=2000 Hz

The median of velocity variation over the source surface as a function of frequency is shown below. Because the CNT source is open to air on both sides, it is expected that the surface velocity would be uniformly zero. It is shown that the measured surface velocity is non-zero, but small in magnitude with a sound velocity level in the range of 40-48 dB (re 1µm/s).



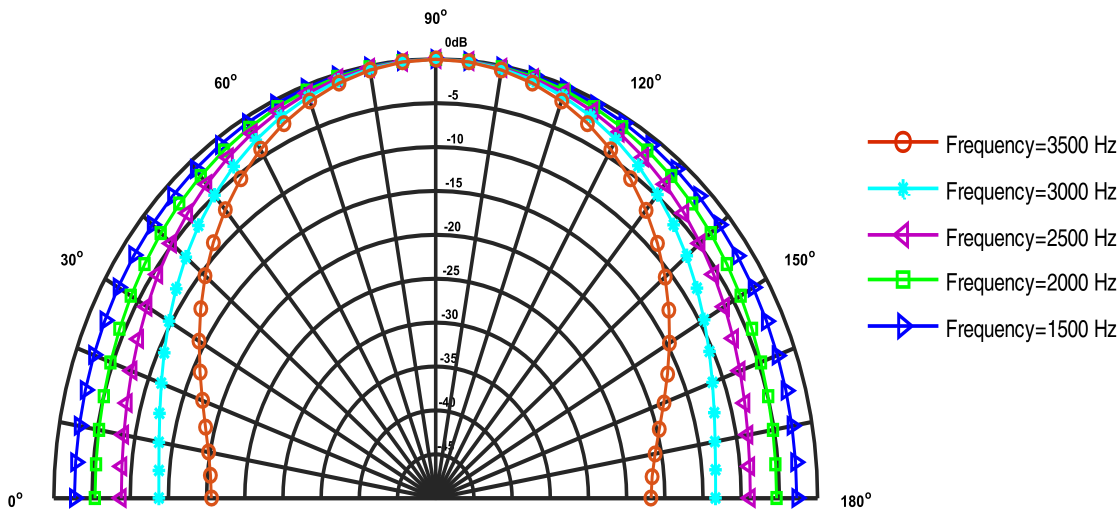
Source velocity versus frequency

The source pressure obtained through NAH can be used to reconstruct the pressure at any distance or acoustic directivity. The following figure compares the measured SPL 1 m away from the source (using one PCB 130A23 monitor microphone) with 1 m 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 500 Hz.



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

Directivity of CNT speakers can also be obtained using the source pressure distribution. Directivity for several different frequencies is shown below. As expected, the source becomes more directional with increasing frequency, as the source dimensions become a smaller fraction of the acoustic wavelength.



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 acoustic properties on the surface of a carbon nanotube loudspeaker. In addition, no new signal conditioning hardware was required, since this probe microphone is ICP® powered. The surface acoustic properties of the ultralight, fragile structure were 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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