Nearfield Acoustic Holography Experiments on Variously Correlated Compound Sources

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Abstract: Experiments were performed to determine guidelines for the placement of multiple reference microphones for NAH measurements on weakly correlated source regions. It was found that multiple references are not required to image the same source, and thus the number of references should approximate the expected number of source regions. It was also found that reference microphones should be placed as close to the source as possible, but should be sufficiently separated from each other that they provide independent information. Characteristics of measured data also suggest that it may be possible under certain conditions to carry out NAH-type reconstructions without using reference microphones at all, by sampling a pressure field in blocks and shifting phases to minimize discontinuity.

Introduction: Nearfield Acoustic Holography (NAH) is an analysis procedure used to reconstruct and map sound and pressure fields. It allows the acoustic properties of a sound field to be determined at one location based on sound measurements taken at another location.

NAH makes use of a microphone array and a separate reference microphone to obtain information about the spatial nature of the pressure field and the relative phases or arrival times of pressure events at the microphone array. By correct correlation of the array microphone signals and the reference signal, it is possible to determine how the entire pressure field is changing in time.

A potential use of NAH is to study the characteristics of noise sources and pressure fields within the exhaust plume of a rocket or jet engine. Direct measurement within the plume is impractical; High temperatures and pressures would damage sensitive equipment.

NAH would provide information about the nature of the field within the plume based on measurements taken in a safe zone at the edge of the plume. It is hoped that these measurements will give insights into rocket engine performance and the effects of modifications to rocket engines. NAH information could also potentially be used to reduce ground crew hearing loss.

A significant challenge in applying NAH to the study of jets and rockets is that exhaust plumes are so large and turbulent that the sound field has poor spatial coherence. In other words, use of a traditional single reference microphone does not provide sufficient information about the relative phases of pressure events to allow for time reconstruction of the entire pressure field. Correct reconstruction of the pressure field requires the use of multiple references.

By using multiple references, the virtual coherence algorithm can be used to break the measured field up into a number of partial sound fields, each individually coherent. These partial fields can be reconstructed with NAH individually, and the results added together on a magnitude basis. A number of papers on the topic have been published by Lee and Bolton[1].
Although mathematical formulations exist for virtual coherence, little information is available with regard to applying it to real-life measurements. The purpose of this research was to investigate the use of multiple references in virtual coherence.

**Design of Experimental Setup:** For experiments on multiple-reference NAH, it was necessary to simulate sound fields that somewhat mimicked the characteristics of a jet or rocket exhaust plume. The sound field associated with a plume has a varying frequency spectrum as a function of distance, and at least locally, is somewhat coherent.

To create this type of source, a row of loudspeakers was used, each with its own input signal. Figure 1 shows a row of two dual-cone Mackie speakers in the BYU anechoic chamber with six reference microphones placed nearby. Sets of four speakers were also used in experiments.

$$\begin{bmatrix}
L_1 \\
L_2 \\
L_3 \\
L_4
\end{bmatrix} = \begin{bmatrix}
m_{11} & m_{12} & m_{13} & m_{14} \\
m_{21} & m_{22} & m_{23} & m_{24} \\
m_{31} & m_{32} & m_{33} & m_{34} \\
m_{41} & m_{42} & m_{43} & m_{44}
\end{bmatrix} \begin{bmatrix}
S_1 \\
S_2 \\
S_3 \\
S_4
\end{bmatrix}$$

$L_i$ represents the output signal of the $i^{th}$ loudspeaker, $S_i$ represents the $i^{th}$ independent random signal, and $m_{ij}$ represents the amount of random signal $i$ sent to speaker $j$. This setup allowed for zero to four sources with any desired degree of correlation.

To mimic the spatial development of frequency, the frequency band of each source $S_i$ was chosen to have some overlap with the other sources. A sample spectrum of this type is shown in Figure 2. This set of source spectrums was designed to have frequency sub-bands with zero to four contributing sources.

In order to measure the sound field as efficiently as possible, an 8x8 array of quarter-inch microphones was used. It was attached to a computer-controlled trolley system that moved it around to generate a plane of measurement points. Measurements were taken on at least two planes in each experiment, the idea being that measurements taken on one plane could be used as a check on a reconstruction based on data taken at the other plane.
**Experimental process:** This section is intended to describe the experimental process used for the special case of a two speaker setup. Experiments with four speakers followed a similar pattern. Subsequent sections describe observations and guidelines developed from these experiments as a whole.

For the two speaker case, only two independent white noise sources were needed. The frequency band for the first source was 200-800 Hz. The frequency band for the second was 500-1700 Hz. Although the frequency bands of the sources had some overlap, the source signals were not mixed before being sent to the loudspeakers. In other words, any off-diagonal m-terms were zero.

Six reference microphones were placed at distances of 1-3 ft. from the speakers. Measurements were made at 3200 points on two planes at 18 and 33 cm above the speakers. Figure 3 shows the resulting measured pressure field for the third block at 600 Hz and 33cm.

![Figure 3](image)

*Figure 3.* Two-speaker measured field, 600 Hz.

The virtual coherence algorithm was applied to the measured data to obtain partial fields. Figure 4 shows the sum of the partial fields, indicating that the virtual coherence algorithm can be used to clarify field information in real life. The amplitude is much more uniform, and a source region is better defined. It should be noted that the “spots” in Figures 3 and 4 are the result of a malfunctioning microphone in the array, and not a mathematical or computational anomaly.

![Figure 4](image)

*Figure 4.* Sum of coherent partial fields obtained by applying virtual coherence.

After partial fields were created, they were reconstructed individually. Figure 5 shows the sum of the reconstructed partial fields at 600 Hz and 18 cm. Note that the source regions are even more clearly defined, and that two distinct sources are apparent, one at y = -1.3m, and a weaker one at y = -0.7m. This indicates that virtual coherence does indeed produce partial fields suitable for NAH analysis, and that the two techniques can be applied together to the study of source identification in complicated sound fields.

![Figure 5](image)

*Figure 5.* Sound field reconstructed from partial fields.
General Guidelines on the Number and Placement of Reference Microphones:
Theoretically, only one reference per incoherent source is required in virtual coherence. However, it was not known if the coupling and interaction between the different sources would make it necessary to use more.

It order to answer this question, the number of reference microphones placed was always much greater than the number of loudspeakers. The virtual coherence algorithm was used to determine how many of the placed microphones were actually necessary for a reconstruction. The algorithm is able to sort available reference data, and discard those signals that do not provide sufficient new information about the sound field.

It was observed that only slightly more reference microphones than sources are needed. For the two speaker case, in particular, only two references were typically selected by the virtual coherence algorithm, and occasionally three. For four-speaker measurements, only four were typically selected.

Reference microphone placement was found to affect the quality of the partial fields. It is also important to maximizing the effective utilization of available equipment.

Placement of reference microphones very close to the source improves partial fields almost to the point that NAH reconstruction may be unnecessary. Figure 6 shows the sum of the partial fields generated from a 4-speaker test with reference microphones mostly placed 4-6 inches from the speaker instead of 1-3 ft as with the two speaker case shown above. Although this plot shows pre-reconstruction data, the four sources are already very well defined.

With regard to jet and rocket plume measurements, this behavior indicates that reference microphones should be placed as close to the plume as possible without compromising their safety.

It was also found that if two reference microphones were very correlated with each other, only one of them would be utilized by the virtual coherence algorithm. To use equipment efficiently, references should be separated far enough that they capture independent information. Achieving this in actual measurements is somewhat of an iterative process.

Numerical experiments performed by another student indicated that the required density of reference microphone placement is affected by the degree of spatial correlation. A four-speaker, two-reference field was simulated, with and without correlation between the sources.

Figure 7 shows the simulated reconstruction for the case with no correlation. Although four source regions are identified, their relative amplitudes are incorrect. Figure 8 shows the simulated reconstruction for the case with partially correlated sources. The four sources are more clearly identified, and their relative amplitudes are more accurate.

For application to real-life measurement, this indicates that reference spacing should be varied to match the degree of local spatial coherence. This will maximize utilization of data acquisition capability.
Observations on Data Processing: Before virtual coherence can be applied, waveform data must be converted to a complex representation through the Fourier transform. During this process, decisions are made with regard to the number of blocks of data used. The process of selecting the number of blocks depends on how many partial fields are needed to accurately represent the entire field. The formation of each partial field requires one block of data and one reference microphone. Thus, the duration of time sampling should be long enough to produce a sufficient quantity of meaningful blocks.

If after applying virtual coherence, it is found that there were fewer partial fields created than available references, the number of blocks should be decreased, and their lengths increased. This will help to smooth amplitude variance in the measured field.

Once the optimal set of partial fields has been produced, NAH reconstruction can proceed. Initially, both Fourier NAH [2] and Statistically Optimized NAH (SONAH) [3] were used to reconstruct the partial fields. It was quickly discovered that the SONAH method was far superior for this application.

While Fourier NAH is much faster computationally and produces good results for simple sources, when applied to the partial fields, it was extremely sensitive to the selection of regularization parameters. Regularization is used to prevent reconstructed noise from grossly exaggerating the predicted source amplitude. Too much regularization however, obscures the spatial characteristics of the field.

Figure 8 shows a Fourier NAH reconstruction for the two-speaker case, comparable to Figure 5, a SONAH reconstruction. The regularization used was strong enough to maintain a reasonable amplitude, but practically eliminated information about the true location and shape of the source. When regularization was loosened, unrealistic source amplitudes, such as 600 dB, were predicted.
It was nearly impossible to set regularization strength such that both amplitude and spatial information were preserved. It was thus decided that Fourier NAH should be set aside in favor of SONAH for this application.

**Phase Relationships:** During analysis of experimental data, interesting trends in phase and amplitude were noticed. First, although measurements were taken on a somewhat incoherent field, phase and amplitude of the complex pressure varied smoothly across each 8x8 block of data.

More importantly, it was noted that common edges of adjacent blocks displayed the same trends. Figure 9 shows half of two adjacent blocks and their common boundary. Although there is a jump in phase across the boundary, the spatial derivatives of the phase are practically the same on either side. This relationship of phase trends held fairly well for the boundary between most adjacent blocks of data.

![Figure 9: Common boundary of two blocks of data.](image)

Although phase continuity was first seen in laboratory experiments, previous data from field measurements of a fighter jet was checked and found to have similar trends.

It was hypothesized that the entire pressure field could be assembled into a cohesive whole without use of reference information, simply by shifting the phase of each block of data to minimize discontinuity with adjacent blocks. This would be extremely advantageous in the study of jet and rocket plumes, which are so long that covering the entire field with reference microphones would be impossible.

Phase shifting was implemented on laboratory data, and a pressure field was produced that had fairly a continuous phase throughout. NAH reconstruction of this field failed, however, due to the large variations in amplitude between the blocks.

This failure led to another important idea. Since an incoherent field is not really a well defined source, but rather a source region in space, it would make more sense to represent it as a statistical distribution of point sources. Each 8x8 block could be considered separately, and associated with a few representative point sources in space. Amplitude discontinuity would become unimportant, since each block would contribute independently to the overall statistical description of the field. Such a description could look something like Figure 10.

![Figure 10: Hypothetical appearance of a statistical point source distribution](image)

Possibly the most important benefit of this type of relationship is that phase differences between blocks could be converted to time differences. By associating the time difference of each block with an appearance time of its associated point sources, it may be
possible to show not only where a sound field originates from in space, but how it simultaneously develops in time.

Initial work in locating a characteristic point source for each block of data attempted to use equipressure contours and a phase gradient to locate an apparent point source in space. While this technique worked well for simulated data with low noise, it failed when tested on experimental data. Nevertheless, the concept of phase shifting is valid, and deserves more investigation in the coming year.

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References:
