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Near-field acoustical holography of military jets: Experiments on partially correlated noise sources

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ABSTRACT

The desire to better characterize the jet noise source region for high-performance military aircraft has resulted in an effort to apply near-field acoustical holography (NAH). The extended and partially correlated nature of the source poses challenges. To overcome these challenges, scan-based patch NAH, coupled with partial field decomposition, is being investigated. Partial field decomposition uses multiple stationary reference microphones, but specific guidelines for determining proper reference microphone number and placement relative to the jet are needed. To help determine appropriate reference microphone configurations, numerical and physical laboratory experiments have been performed. The numerical and physical sources consist of series of partially correlated point sources and loudspeakers, respectively. Statistically optimized NAH is employed as the reconstruction method. Reference microphone placement is not found to be as significant of a factor as number of reference microphones for reconstruction error. Partially correlated sources decrease the required number of reference microphones from the uncorrelated case.

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1. INTRODUCTION

Near-field acoustical holography (NAH) has been widely used for localizing and characterizing sound sources ever since the general theory was developed in 1985 by Maynard, Williams, and Lee[1] It was originally used for measuring complex vibrating structures, typically very coherent sources. Sometimes the desired number of measurement positions exceeds the number of available microphones for measuring a large, extended source. This necessitates a scan-based form of NAH which relies on one reference signal (e.g. microphone) for one coherent source. In 1988, Hald published a technical review[2] which detailed a method of using NAH without restrictions on coherence. This opened the door for the use of NAH on aeroacoustic sources which have limited turbulence coherence lengths. The method, now called the virtual coherence technique or partial field decomposition (referred to throughout this paper as the virtual coherence technique) allows one to decompose an incoherent field into coherent partial fields by using multiple stationary reference microphones. These partial fields are then sent individually to NAH to be processed and then they are added back together on an intensity basis since the partial fields themselves are mutually incoherent. As many reference microphones are required as there are independent sources. Several have performed NAH using this new method on aeroacoustic sources such as fans and jets (a subsonic model-scale jet)[3-4] while we will ultimately apply this method to a supersonic, full-scale jet.

We know that jet noise is partially correlated, meaning that there is some finite distance over which the source is coherent.[5] However, guidelines in the literature for reference microphone number and placement for such a source are limited. Fully correlated sources would have a fixed phase relationship between all the sources; uncorrelated sources would have no predictable phase relationship between sources. Partially correlated noise is in between these two extremes. There is some phase relationship across the jet noise region, though not a deterministic one. In the literature thus far on the virtual coherence technique, the guidelines for reference microphones have been to sense all the sources in order to properly decompose the complex pressure field into an appropriate set of partial fields. Because we want to give guidelines for a full-scale test of a military aircraft jet, we have investigated reference microphone placement in controlled physical and numerical experiments

2. METHODS

Experiments were designed to investigate partially correlated fields and their effect on reference microphone number and placement. Four loudspeakers were sent signals with varying degrees of correlation: uncorrelated, moderately correlated, highly correlated, and fully correlated. We control the degree of correlation across the sources. The correlation coefficient between the sources as measured by the reference microphones in the physical experiment for the different cases is shown in Fig. 1. The correlations for the numerical experiment matched those of the physical experiment. Notice that for the fully correlated case, the coefficient is not exactly one. We attribute this to the fact that all 4 microphones sense 3 time shifted versions of the signal (from the other 3 loudspeakers) in addition to the signal they sense from the source directly below them. The correlation coefficient in the highly correlated case drops to about 0.8 for the last microphone but in the moderately correlated case, it drops all the way to 0.2.

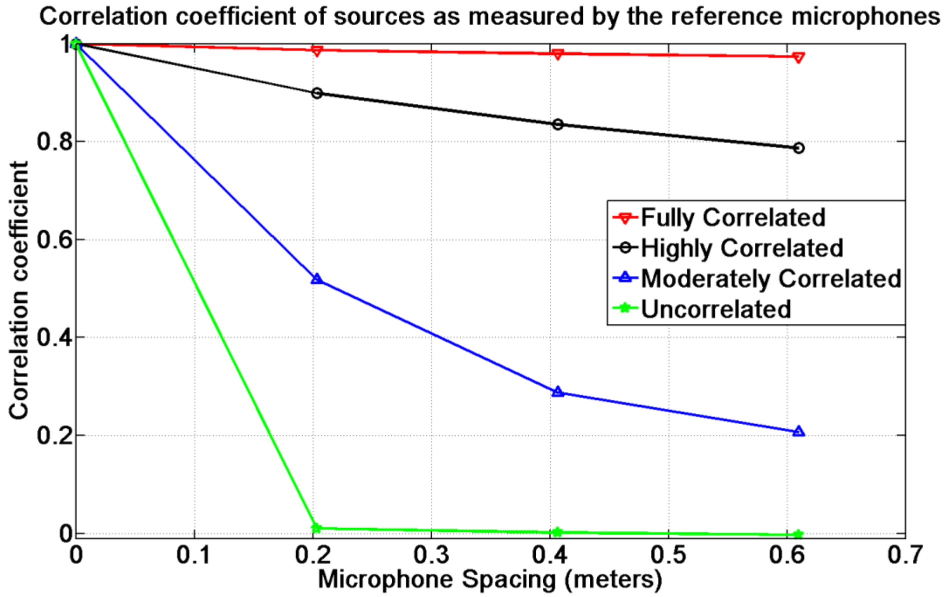

Figure 1: Correlation coefficient between each of the four reference microphones directly over the sources (loudspeakers) and the first reference microphone for the four different degrees of correlation.

In the numerical experiment, scan-based NAH was then simulated on the sources. For the scan, 11 microphones were used in a linear array. These 11 microphones were then scanned in 43 positions extending beyond the four sources in both directions. They were scanned at a distance of 47.5 cm away from the source. A planar version of statistically optimized NAH (SONAH) was then used to reconstruct the sound field in a plane 7.5 cm from the face of the loudspeakers.[6-7] Figure 2 shows the geometry of the setup with different markers showing the respective measurement, reconstruction, reference microphone, and source locations from two different angles.

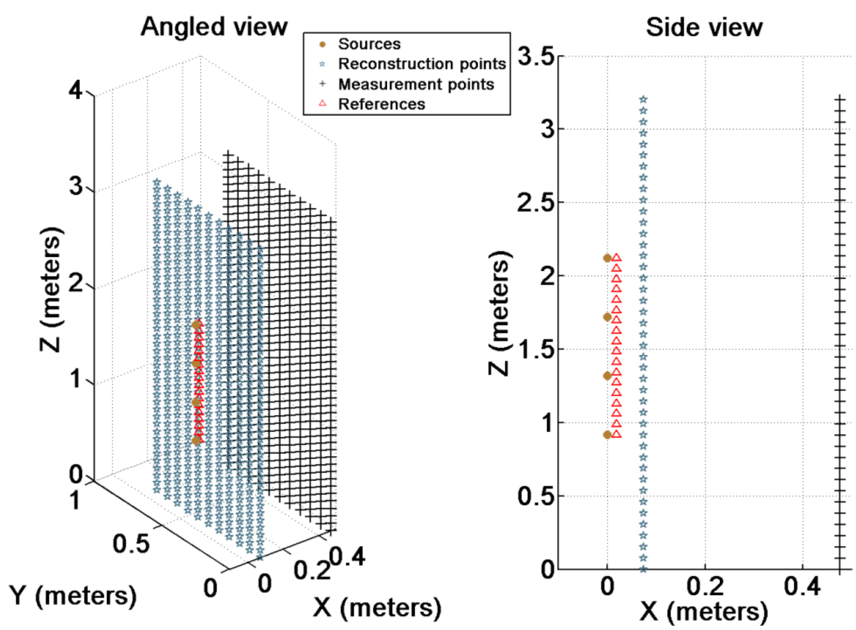

Figure 2: Geometry of the sources, references, reconstruction and measurement points from two different angles.

Parallel to this numerical experiment was the physical experiment, which involved four loudspeakers in a fully anechoic chamber (see Fig. 3) with the same varying degrees of correlation across the sources: uncorrelated, moderately correlated, highly correlated, and fully correlated.

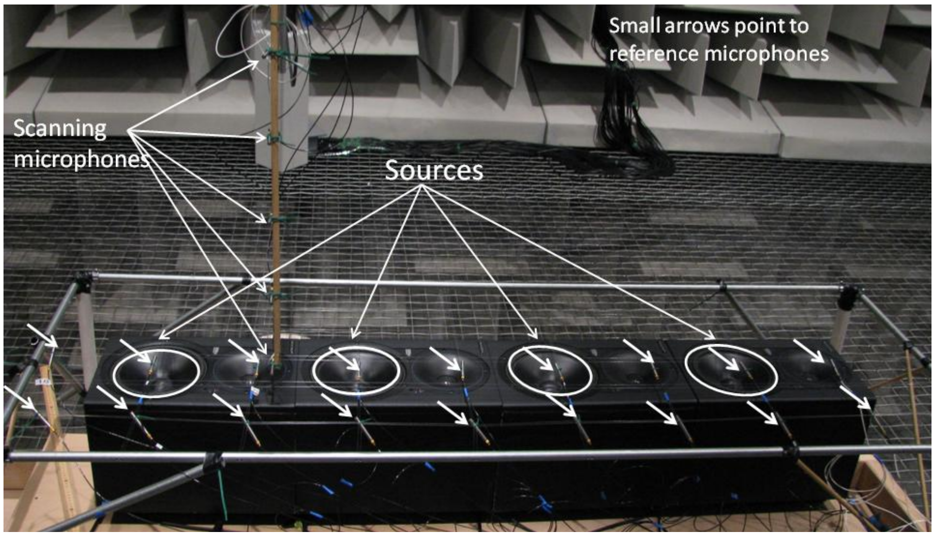

Figure 3: Setup with the loudspeaker sources and the scanning (measurement) and reference microphones.

Because only frequencies below the cutoff of the tweeter are of interest, the woofers were considered to be the four discrete sources. Reference microphones were located directly above the woofers, in between the woofers, and in the same locations off-center of the loudspeakers. Five microphones in a vertical array were scanned 473 times to match the grid of the numerical experiment (11 x 43). Even though grid was not broken into the same number of scans (43 for the numerical, and 473 for the physical), the results are similar. The scan planes were at distances of 7.5, 17.5, 27.5, 37.5, and 47.5 cm vertically from the loudspeakers. The 7.5 cm microphone was used as a benchmark for reconstructions of the higher microphones. Results from the 47.5 cm measurement plane propagated down to the 7.5 cm plane will be shown. This will be compared with the result for the same reconstruction performed numerically.

First, pressure measurements are made in the time domain for all time blocks at all scan positions in the hologram plane and at all the reference microphone locations. The time waveforms are converted into the frequency domain to get complex pressures via the Fast-Fourier Transform (FFT). Using methods set forth in the virtual coherence technique[3-4], the total sound field is decomposed into partial fields. Source non-stationarity is also accounted for.[8] The partial fields are then sent to SONAH to be processed individually and reconstructed at the reconstruction plane, which was 7.5 cm from the sources. These are then added on an intensity basis to get the total pressure field at the reconstruction plane. This is then compared to the measured benchmark. The root-mean-square error in decibles between reconstruction and benchmark gauges the quality of reconstruction. To determine if the reference set was sufficient, the virtual coherence function (which is the coherence between the virtual references and the measurement points) is summed across all partial fields. If the virtual coherence function approaches one for all the measurement points, then the reference microphones adequately capture the source. The coherence criterion chosen for these experiments was 0.99. If a coherence of 0.99 was not reached, then we used all available partial fields. For example, with

3. RESULTS

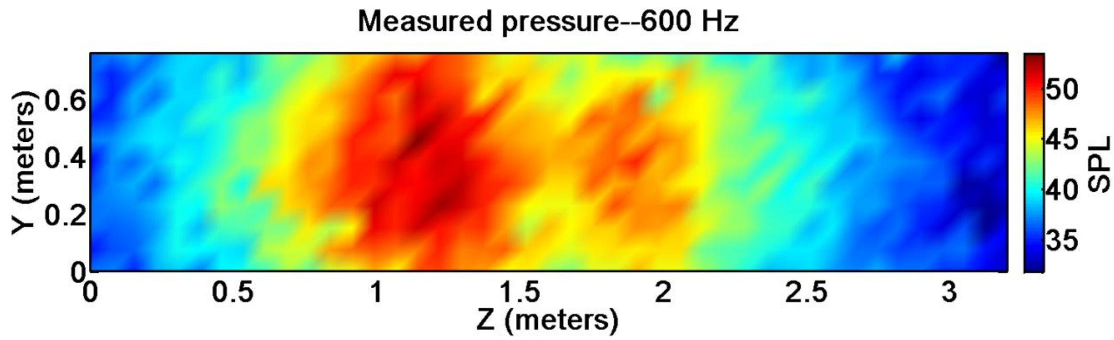

Figure 4: Averaged measured pressure (SPL) at 600 Hz before virtual coherence at 47.5 cm from the speakers (moderately correlated).

only two reference microphones for the uncorrelated case, the coherence did not reach 0.99, thus we use all two available partial fields. The measured pressure at 47.5 cm for a frequency of 600 Hz is shown in Fig. 4 for the highly correlated case. As seen in Fig. 4, the measured pressure averaged over blocks is coarse and discontinuous due to its incoherent and the non-stationary nature of the random noise source. The partial field decomposition accounts for this and the reconstruction shows the distinct source locations. The first case shown uses the four reference microphones that are directly above the loudspeakers. The reconstructed sound pressure level is shown in Fig. 5 at 7.5 cm and is compared with the benchmark in Fig. 6.

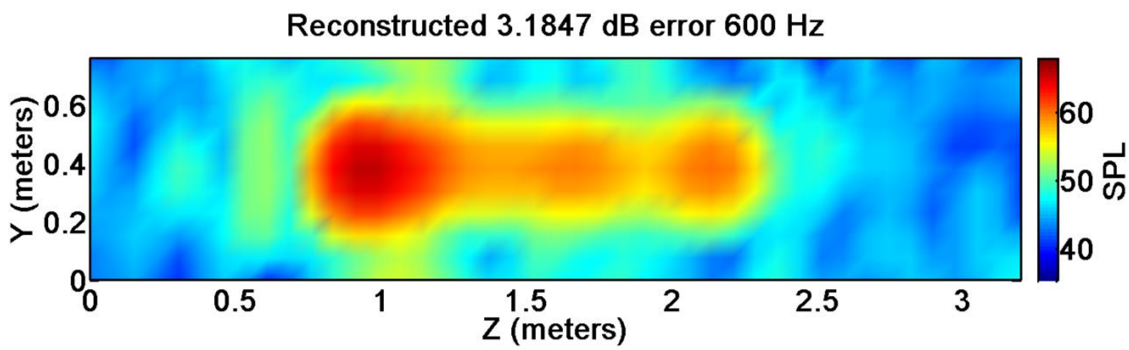

Figure 5: Reconstructed pressure (SPL) at 7.5 cm above the speakers (moderately correlated) using the 4 reference microphones directly above the sources for a frequency of 600 Hz. Also showing 3.18 dB error (RMS)

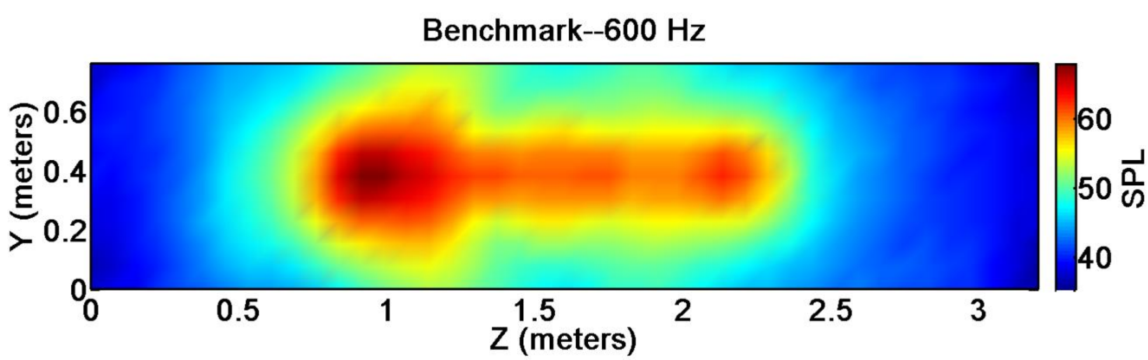

Figure 6: Actual pressure (SPL) at 7.5 cm above the speakers (moderately correlated) as computed from the quadratic sum of the partial fields in that plane for a frequency of 600 Hz.

The decibel root-mean-square (RMS dB) error is 3.18 dB and Fig. 7 shows that most of this error occurs on the edges of the reconstruction, not where the sources are. The RMS dB error weights errors in both the quiet and loud regions equally. We expect and get good results because we are using four reference microphones directly over the speakers and there are only four independent sources.

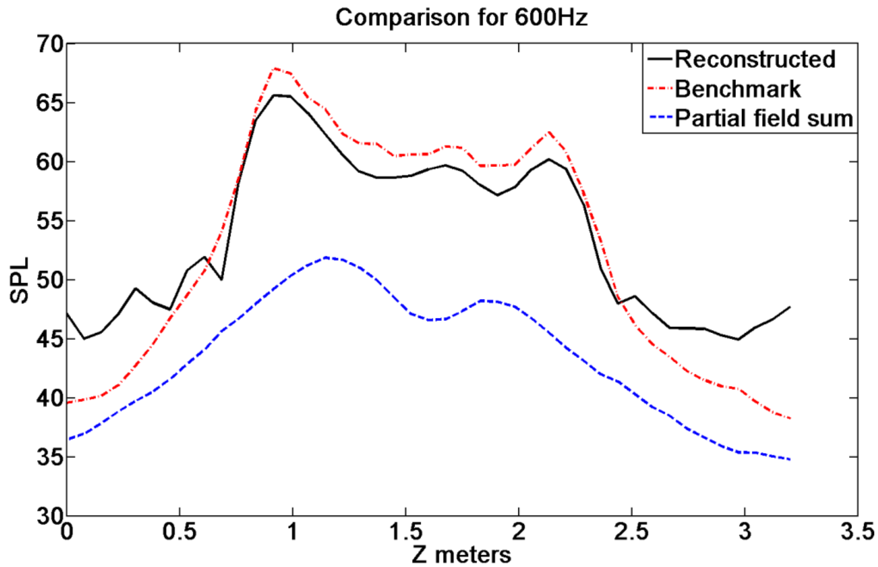

Figure 7: Comparison of SPL between the reconstruction and benchmark on moderately correlated sources at 7.5 cm and the partial field sum at 47.5 cm (what was sent to SONAH) at the center line of the grid in Y where the amplitude was maximum showing results at 600 Hz. Result is when using 4 reference microphones ***directly above*** the loudspeaker sources.

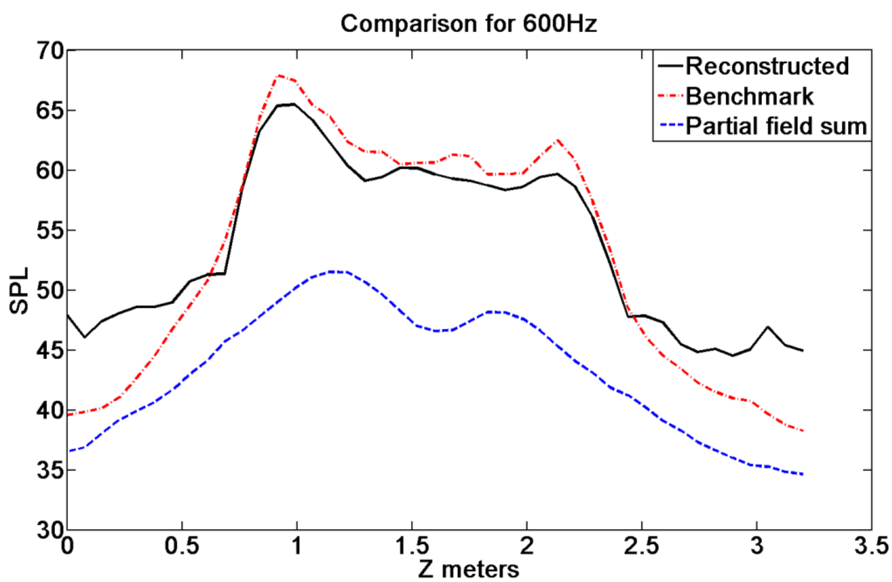

Figure 8: Comparison of SPL between the reconstruction and benchmark on moderately correlated sources at 7.5 cm and the partial field sum at 47.5 cm (what was sent to SONAH) at the center line of the grid in Y where the amplitude was maximum showing results at 600 Hz. Result is when using 4 reference microphones ***in between*** the loudspeaker sources.

The second case shows results for when the four reference microphones between the sources were used. The RMS dB error is very similar at 3.00 dB and the comparison looks similar as well (compare the similarity of figures 7 and 8). Using four reference microphones that were off the source axis, results were still equally good. Without showing any graphs for this case, the RMS dB error was 3.23 dB, very similar to the results obtained using the other two sets of reference microphones. This means that with all three sets of reference microphones, we have accurately captured the source region. In fact, we were not able to pick *any* set of 4 reference microphones out of the 18 we had in the setup (see Fig. 3) that would give poor results (the worst error was 4.23 dB). It seems that our reference microphones were ideally located for this experiment. Similar results were obtained at other frequencies. Obviously, at some extreme, the location of the reference microphones will matter (e.g. if two microphones are right on top of each other the results would be poor due to the linear dependent nature of those two received signals).

Instead of changing the location of the reference microphones, we now change the number of reference microphones and the results are quite different. Table 1 shows error results as a function of reference microphone number and degree of correlation.

Table 1: Error (in dB) of the reconstructions of the physical experiment for various quantities of reference microphones and for different degrees of correlation

No. of references	Fully Correlated	Highly Correlated	Moderately Correlated	Uncorrelated
18	4.53	5.76	4.49	2.29
4	5.09	4.04	3.18	2.48
3	4.86	4.23	5.67	4.09
2	4.25	4.95	7.45	6.90
1	4.29	5.38	10.1	11.0

For the fully correlated case, no practical gain in accuracy is achieved by using more than the one reference microphone that is required. For the highly correlated case, the error drops from 5.38 dB with the one reference to 4.04 dB with the four references. This represents a greater increase in accuracy than is observed for the fully correlated case but is not as significant of an increase as is observed in the moderately correlated case. Here, the error drops from 10.1 dB to 3.18 dB for the one reference and four references, respectively. Notice that we can accurately reconstruct four partially correlated sources with only three reference microphones. The uncorrelated case shows the most dramatic improvement upon adding reference microphones. We remark that using all 18 reference microphones sometimes increased the error slightly; we attribute this to the added noise that is brought in with the extra partial fields linearly unrelated to the sources. Table 1 shows that once a critical number of references is reached, increasing that number does not increase the reconstruction accuracy. However, if there are not enough references, the errors increase significantly. Therefore, in comparing location and number of reference microphones, quantity is a more important factor than placement. Finally, Fig. 9 shows two reconstructions, one for the physical experiment with loudspeakers and the other for the numerical experiment for point sources.

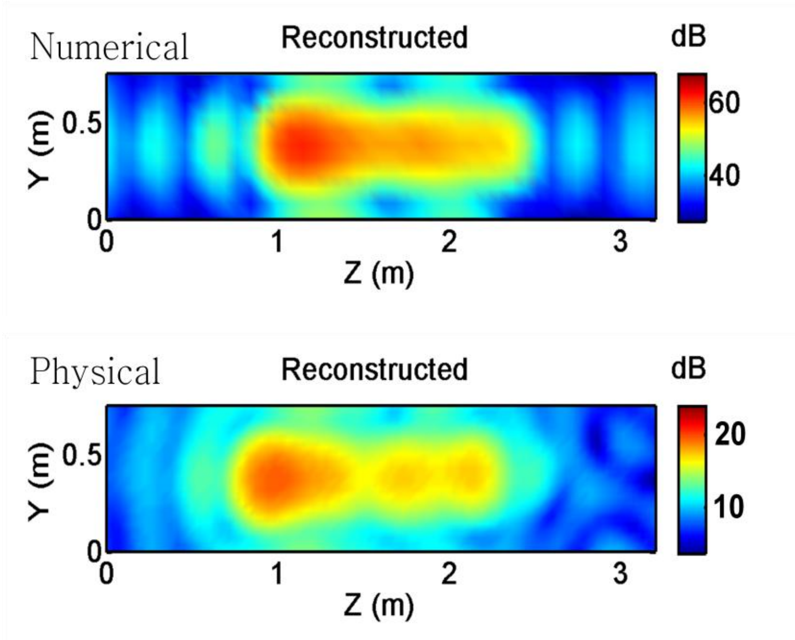

Figure 9: Comparison of reconstructions for 4 partially correlated numerical sources (point sources,) and 4 partially correlated physical sources (loudspeakers,) at a frequency of 510 Hz showing similarity in shape.

The amplitudes do not match exactly, as can be expected when comparing a point source (numerical) to a distributed source (physical), but the general shape is consistent. All results obtained in the physical experiment verify those that were obtained in the numerical experiment, showing that we can perform further experiments numerically that we could not easily perform physically. We can reliably examine cases with many sources, closely spaced, to simulate the extended, continuous nature jet noise.

4. CONCLUSIONS

We have shown that scan-based NAH can be performed on discrete partially correlated sources both numerically and physically. Reference microphone placement does not seem to contribute significantly to the error in comparison to number of reference microphones. We desire to further look into the limiting case wherein reference microphone placement does matter relative to the sources. Because the physical and numerical experiments agree, further work can be done numerically, thus saving time, and allowing us to continue to investigate this subject in order to prepare for full-scale tests of scan-based NAH on a military aircraft jet.

ACKNOWLEDGMENTS

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