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1pSAb1. Aperture extension for near-field acoustical holography of jet noise

Alan T. Wall*, Kent L. Gee, David W. Krueger, Tracianne B. Neilsen, Scott D. Sommerfeldt and Michael M. James

***Corresponding author's address: Department of Physics and Astronomy, Brigham Young University, N283 ESC, Provo, Utah 84663, alantwall@gmail.com**

It is generally true that larger measurement apertures (relative to the source size) produce more accurate reconstructions of sound fields in near-field acoustical holography (NAH) applications. When such apertures are infeasible, numerical extrapolation of the sound field can be implemented to recover data, allowing a successful NAH reconstruction. When the limited aperture is due to a large standoff distance from the source, accurate recovery of data outside the measurement region becomes increasingly critical. In the present paper three data extrapolation methods are implemented on a simulated sound field from two extended, coherent sources. The methods are compared based on their relative accuracy of extrapolated data with distance from the measurement aperture.

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1. Introduction[1]

This work was presented at the 161st Meeting of the Acoustical Society of America in San Diego, California, 23-27 May 2011, under the title "Aperture extension for near-field acoustical holography applied to jet noise."[1]

The apertures of array-based sound field measurements are, by their nature, discretized and spatially limited in extent. Near-field acoustical holography (NAH) is an inverse method, by which a sound field in three-dimensional space is reconstructed from data on a two-dimensional measurement surface (the hologram). In general, an increase in the hologram aperture leads to a more accurate reconstruction. However, in some instances, large-aperture measurements can be expensive and difficult to obtain. The number of measurements required to ensure the same solid-angle coverage of source radiation increases with distance between the hologram and source (standoff distance). This can be especially problematic when proximity to the source is limited by transducer capabilities in the presence of high-amplitude sources. If a hologram aperture is too small to avoid significant reconstruction errors, it is desirable to numerically extend (extrapolate) the data outward, tangent to the measurement surface, effectively increasing the aperture size. Analytic continuation is an extrapolation method that has been used to successfully extend measured pressure fields into an area nearly double that of the original field, with high accuracy near the boundary of the original measurement.[2] This allowed for an accurate reconstruction of a vibrating plate from a close-proximity hologram measurement. However, in a measurement with a larger standoff distance, it is desirable to obtain an accurate prediction of data farther outside the measurement aperture than analytic continuation can provide.

The extrapolation of data is a useful problem-solving technique in any field where information is desired outside the range of a given data set. NAH is, in fact, an extrapolation. For each iteration in the analytic continuation method, a two-dimensional spatial Fourier transform of the data is taken, a filter is applied, and the inverse Fourier transform is taken. Only the lack of a spatial propagator separates the algorithm of analytic continuation from that of traditional NAH.[3] Restoration (extrapolation) of missing (damaged) data is a common signal processing problem. Often, an autoregressive model is used to provide a linear prediction (LP) of data in the missing portion.[4-6] Metrics for a comparison of data extrapolation methods for an NAH application include a graceful (gradual) taper of pressure amplitudes from the boundary of the measurement toward zero and an accurate (physical) prediction of values outside the measurement.

The data extrapolation methods investigated in the present paper have application to a jet noise experiment.[7] The characterization of jet noise sources with NAH assists in the development and verification of noise reduction technologies. Holographic measurements of full-scale jets (tens of meters in length and up to meters in diameter) require thousands of data points, and an aperture that fully covers the source region is difficult to obtain. Coverage of the source region is made more difficult by the fact that measurements must be taken at a relatively large standoff distance, due to microphone limitations in the high-amplitude sound fields of full-scale jets. Hence, three extrapolation methods are implemented in a numerical experiment, in which the relative locations of the sources and the simulated measurement surface mimic those of a recent full-scale jet experiment.[8] It is not within the scope of this paper to propagate the extended fields using NAH, nor to substantiate the effectiveness of any extrapolation method by the accuracy of its NAH projection. Rather, the success of each method is quantified by the accuracy of the data predicted outside the simulated measurement boundary in the numerical experiment.

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This paper is organized as follows. The physical experiment that motivates this investigation is briefly described in Section 2. Each step of the aperture extension process is illustrated with physical data. The numerical experiment which mimics the geometry of the physical experiment is provided. In Section 3, the numerical data are extrapolated using three different methods: analytic continuation, a method based on statistically optimized near-field acoustical holography (SONAH), and linear prediction. The relative merits of these methods are discussed, and a quantitative comparison is made of the accuracy of their respective extended fields. Conclusions are presented in Section 4.

2. Experiment Setup

Sound pressures were measured in the geometric near field of the jet from one of the two engines installed on a Lockheed Martin/Boeing F-22A Raptor. A comprehensive description of the physical measurement on a full-scale jet is presented by Wall *et al.*[8] The centerline of the jet was located 1.9 m above the surface of a concrete run-up pad. Pressures were recorded on several planar surfaces. The measurement used in this study is called plane 2, and its location relative to the jet is shown in the schematic in Figure 1. (Plane 1 and the reference array, shown in Figure 1, apply to NAH experiments and are not used in this study.) Plane 2 was a 2 m x 24 m grid with regular 0.15 m (6 in) spacing, which ran parallel to, and was located 5.6 m from, the estimated shear layer boundary.

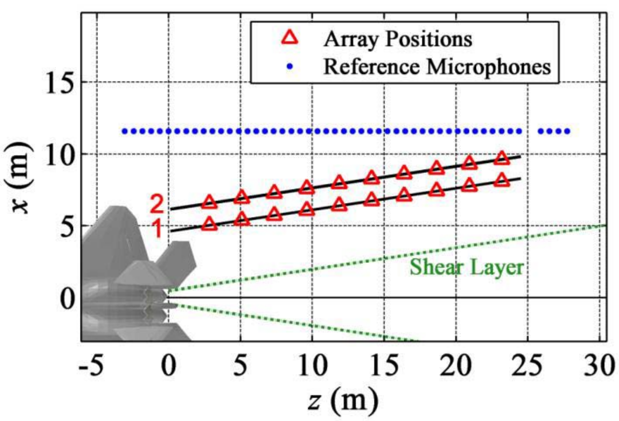

Figure 1 Schematic of the measurement locations, relative to the aircraft. The estimated shear layer boundary is marked by green dashed lines, and the green "x" delineates the estimated maximum noise source region and the center of the arc.

The concrete pad introduced a reflecting surface to the sound field, which may be considered perfectly rigid for the frequencies of interest. Based on the theory of the method of images, it is therefore assumed that the sound field was generated by the jet noise source and an equivalent, inverted image source below the ground. By the same principles, the data on the measurement surface are inverted and copied below the reflecting plane (mirrored). The result is a real and image source with two separate planar measurements in a free field, as shown in Figure 2a (for measured jet noise at 105 Hz, military engine power). Then, as shown in Figure 2b, pressure values are interpolated between the original and reflected data. Finally, in Figure 2c, numerical data extrapolation methods (analytic continuation shown here) are applied to estimate pressure values outside the new aperture.

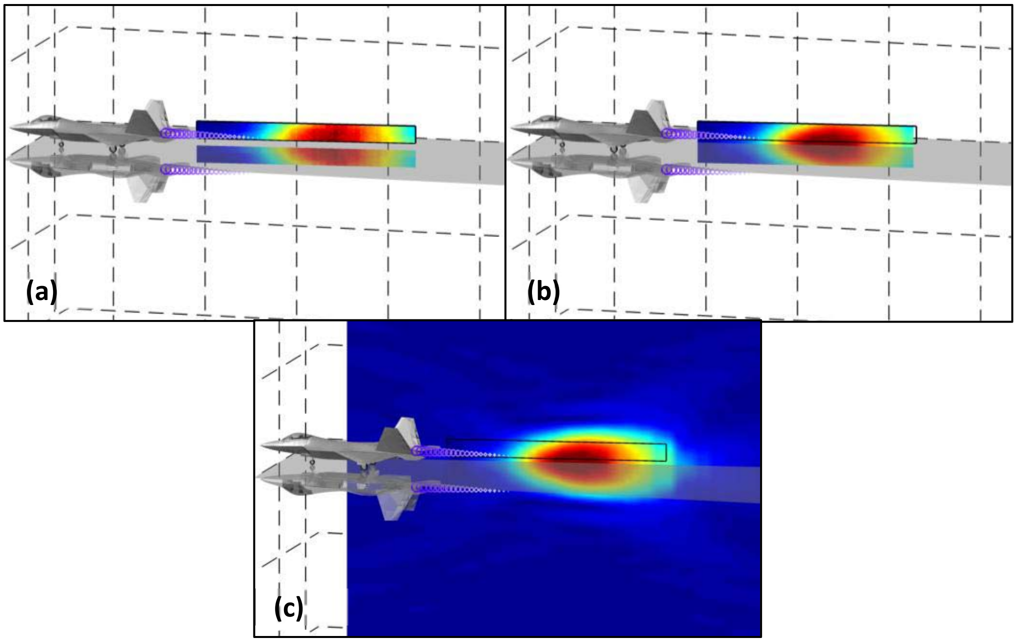

Figure 2 Visual representation of a data-extrapolation process. A rigid reflecting plane along the ground is assumed, and the measured pressures are (a) mirrored over the reflecting plane, (b) interpolated between the two surfaces, and (c) extrapolated outward using one of several methods (analytic continuation shown here).

The numerical experiment of is designed to mimic the measurement geometry of the jet noise experiment, relative to the source region. Two coherent line arrays of point monopoles are located parallel to each other and separated by 3.8 m, representing the same locations of the original and image sources in a free-field environment. Each source array consists of 100 monopoles spaced evenly between $z = 2.0$ m and 9.9 m (downstream of the nozzle exit). The phase of each monopole is adjusted to give the source arrays a directivity of 135° (downstream) relative to the front of the aircraft. (No equivalent jet-noise source model is attempted here.) These are shown relative to the assumed aircraft location in Figure 3. A mirroring of the data and gap interpolation are bypassed, in favor of a direct measurement of the entire (limited) aperture at the same locations as the data shown in Figure 2b. This simulated measurement shown in Figure 3, which is for sources radiating at 315 Hz, is marked by a black dashed outline. The extrapolation methods investigated here are performed on these data. The pressure values outside of the dashed box in Figure 3 are the benchmark measurements for comparison and extrapolation-error calculation.

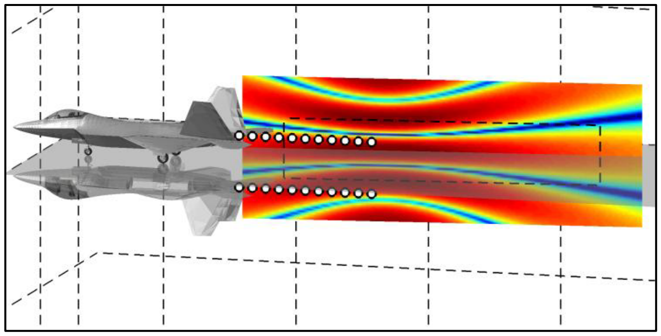

Figure 3 The relative locations of the numerical source array (jet centerline and centerline image locations), the simulated measurement surface (inside the black dashed rectangle), and the benchmark measurement for comparison to extrapolations (outside the black dashed rectangle).

3. Numerical Data Extrapolation

Analytic continuation[2] is a relatively robust and simple data extrapolation method. It is based on the Green's functions (transfer functions) relating acoustic quantities on the measurement surface to those on the extended surface. The resulting field after the application of analytic continuation for the sources at 315 Hz is shown in Figure 4. Note first that the data within the measurement aperture (inside the dashed line) are well preserved. A benchmark measurement is provided in Figure 5. In the extended region, levels are predicted with physical accuracy very close to the boundary, and then taper away (toward some low-amplitude artifacts) within about the distance of one wavelength (1.1 m for this frequency). Such an extrapolation is characteristic of the same field for different frequencies tested, with the boundary tapering away within about one wavelength.

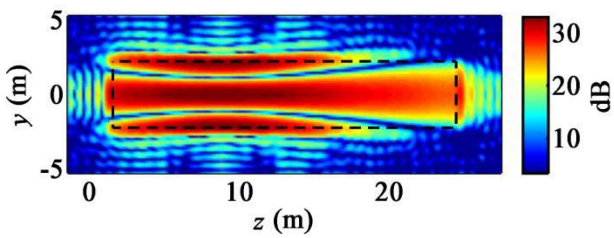

Figure 4 Numerical extrapolation of the measured field of a correlated line array source and its image, radiating at 315 Hz, using analytic continuation.

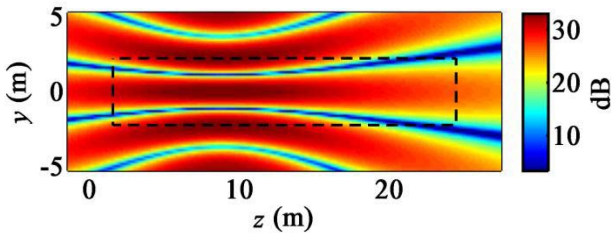

Figure 5 The benchmark radiation pattern measured near a correlated line array source and its images source (315 Hz). The black dashed line shows the boundary of the original measurement surface, from which data the field is extrapolated outwards, numerically.

The second method applied is based on the holography method, SONAH.[9] SONAH is designed for reconstructing sound fields when the aperture is limited. It is also based on Green's functions, directly calculating the transfer functions between the measurement and reconstruction locations in a field prior to prediction. These predictions are typically made out-of-plane (not tangent to the measurement surface), but a Green's function (wave function) representation of the field allows SONAH to predict values in any desired location in the field vicinity, so long as the necessary wave functions are sufficiently represented at the measurement in a least-squares sense. Hence, it is applied here to project outward (extrapolate) the data.

Here, the functions used to represent this field are plan-wave functions. As is typical, regularization is required to filter high-wavenumber components.[9] SONAH results are shown (for 315 Hz) in Figure 6. Spatial features of the levels in the field are predicted with higher accuracy, farther out than those from the analytic continuation method, but the artifacts beyond this region are of higher amplitude. The sacrifice for accuracy in this SONAH-based method is mainly in the computational cost.

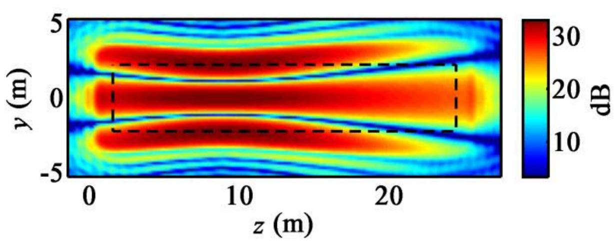

Figure 6 Numerical extrapolation of the measured field of a correlated line array source and its image, radiating at 315 Hz, using a SONAH-based in-plane projection.

The final method investigated here is linear prediction.[4,10] In signal processing, linear prediction is used to predict future values of a discrete signal based on a linear function of previous (measured) values. In this experiment, the prediction is performed first in the horizontal direction (row by row) to extrapolate the data in the directions of increasing and decreasing z. Then, prediction is performed in the vertical direction (y, column by column). The extrapolated field is shown in Figure 7. Of particular note is that linear prediction is able to capture the shapes of the interference patterns of the sound field out to 3 m (vertical direction), with a gradual taper in level. Its success in the horizontal direction is comparable to that of both the analytic continuation and SONAH-based methods.

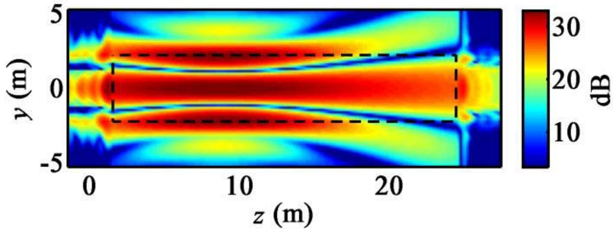

Figure 7 Numerical extrapolation of the measured field of a correlated line array source and its image, radiating at 315 Hz, using linear prediction.

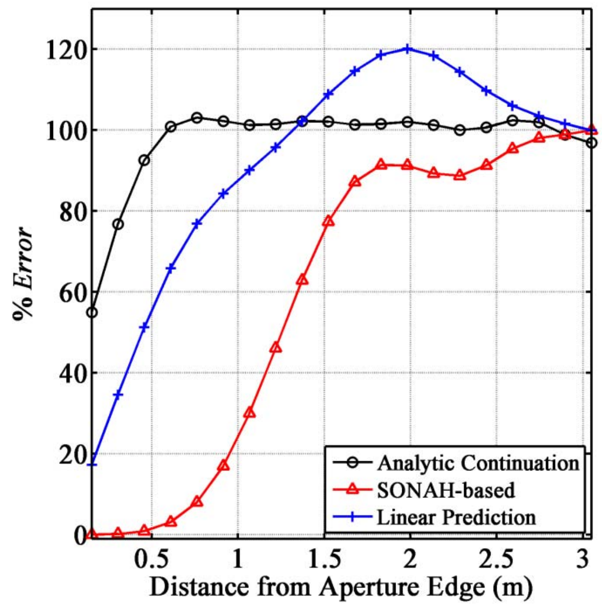

Figure 8 Percent error of each concentric (rectangular) ring of data in the extrapolated region as a function of distance from the measurement boundary (315 Hz).

To quantify the quality of extrapolation for each method, the normalized L_2 errors are calculated for concentric square rings, one point wide, as a function of distance from the measurement boundary, with the formula

$$\% \, Error = 100 \times \frac{\left\| p_{\mathrm{exact}} - p_{\mathrm{extrapolated}} \right\|_2}{\left\| p_{\mathrm{exact}} \right\|}, \tag{1}$$

where p_{exact} are the complex pressure values of the benchmark measurement, and $p_{\mathrm{extrapolated}}$ are the extrapolated pressures. The errors for each method are shown in Figure 8, as a function of distance from the measurement boundary. Note that a taper toward zero results in $p_{\mathrm{extrapolated}}$ values of zero, so error near 100% is expected far from the measurement. Within about 1-2 m of the measurement, it is clear that the SONAH-based method provides an extrapolation with the least error. The low error within 0.5 m is due to the fact that levels do not taper off dramatically with distance. Accordingly, the error of the linear prediction rises rapidly with the faster level tapering, even though many of the interference pattern features are represented. Once again, it can be seen that the analytic continuation error reaches 100% within about 1 m, which is on the order of a wavelength.

4. Conclusion

In this paper, three methods for numerically extending the aperture of a spatially finite sound field measurement are investigated for a simulated experiment where the measurement surface was far from the sources. Based strictly on an error calculation as a function of distance from the original measurement boundary, a SONAH-based projection of the field produces the most accurate extrapolation close to the measurement, for this experiment. Linear prediction represents more of the interference pattern features far from the measurement boundary than do the SONAH-based and analytic continuation methods, although its levels taper more rapidly away. For future data extrapolations beyond the scope of this work, it might be instructive to investigate the accuracy of extrapolation and near-field acoustical holography reconstruction with the variation of solid-angle coverage of the source, which is influenced by all aspects of the measurement geometry, including measurement aperture size, source distribution, and standoff distance. It might also be instructive to explore the ranges of acoustic wavelengths (or frequencies), relative to the size of the measurement aperture, over which the various methods provide sufficiently accurate extrapolations. In general, the optimal data extrapolation method depends on several factors, including frequency, measurement geometry, and source properties.

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References

[1]A. T. Wall, K. L. Gee, D. W. Krueger, T. B. Neilsen and M. M. James, "Aperture extension for near-field acoustical holography applied to jet noise," J. Acoust. Soc. Am. **130**, 2344 (2011).

[2]E. G. Williams, "Continuation of acoustic near-fields," J. Acoust. Soc. Am. **113**, 1273-1281 (2003).

[3]E. G. Williams, *Fourier acoustics: Sound radiation and nearfield acoustical holography* (Academic Press, San Diego, 1999).

[4]L. B. Jackson, *Digital filters and signal processing*, Second ed. (Kluwer Academic Publishers, 1989), pp. 255-257.

[5]I. Kauppinen and J. Kauppinen, "Reconstruction method for missing or damaged long portions in audio signal," J. Audio Engin. Soc. **50**, 594-602 (2002).

[6]S. Vaseghi and R. Frayling-Cork, "Restoration of old gramophone recordings," J. Audio Engin. Soc. **40**, 791-801 (1992).
[7]A. T. Wall, K. L. Gee, T. B. Neilsen, D. W. Krueger, M. M. James, S. D. Sommerfeldt and J. D. Blotter, "Full-scale jet noise characterization using scan-based acoustical holography," AIAA Paper 2012-2081, June 4-6, 2012.
[8]A. T. Wall, K. L. Gee, M. M. James, K. A. Bradley, S. A. McInerny and T. B. Neilsen, "Near-field noise measurements of a high-performance military jet aircraft," Noise Control Eng. J. **60**, 421-434 (2012).
[9]J. Hald, "Basic theory and properties of statistically optimized near-field acoustical holography," J. Acoust. Soc. Am. **125**, 2105-2120 (2009).
[10]R. Scholte, I. Lopez, N. B. Roozen and H. Nijmeijer, "Truncated aperture extrapolation for Fourier-based near-field acoustic holography by means of border-padding," J. Acoust. Soc. Am. **125**, 3844-3854 (2009).