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Acoustical holography and proper orthogonal decomposition methods for the analysis of military jet noise[a]

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ABSTRACT

Acoustical holography methods have been used to image the three-dimensional sound field of a jet from the installed engine on a military fighter aircraft. The characterization of the large-scale turbulent structures of jet-noise sources can lead to improved noise diagnosis and reduction methods. Jet noise sources are partially spatially coherent. In this work, proper orthogonal decomposition methods are employed to represent the jet sources as sets of equivalent, mutually incoherent wave packets (partial fields). The decomposition method, which is based on the multiple signal classification (MUSIC) algorithm, utilizes optimally located virtual references to generate physically meaningful partial fields. These source models demonstrate the number of independent sources in a jet, their relative distributions, and their spatial coherence.

1. INTRODUCTION

JET noise emitted by military aircraft is a major source of hearing loss for military personnel, especially those who work on the deck of an aircraft carrier. The overall jet noise source region is comprised of an ambiguous number of extended, partially spatially coherent subsources. This work presents an attempt to isolate individual components of jet noise as a step toward the identification of independent source mechanisms. This has application to noise-reduction methods that are targeted towards specific, physical source mechanisms.

More than six decades of research have gone into understanding the acoustic sources of turbulent mixing noise in jets. One analysis tool that has been employed is proper orthogonal decomposition (POD) of jet fields, based on the theory of principal component analysis,[1,2] in conjunction with near-field acoustical holography (NAH).[3-7] POD allows for the decomposition of a total sound field into a set of mutually incoherent partial fields through a projection of the sound field onto a linearly independent basis set. POD has been often employed to simplify the representations of partially coherent jet sources. Decompositions have historically been performed for various quantities in the jet field, including directly measured flow quantities, the pressure signatures of the hydrodynamic (or acoustic) near field, and acoustic quantities outside this regime.[8,9] The application of POD methods to decompose the pressures in the acoustic regime (outside the flow) are distinguished here as a partial field decomposition (PFD).[4,6,10-13]

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Several types of PFD methods exist, each based on a different type of basis set for the decomposition. Theoretically, the sum total of partial fields, on an energy basis, will give the same result: a total field with the same levels as the original measured field. However, the partial fields generated are not unique. Hence, to understand the significance of individual partial fields, the basis set and decomposition method must be understood. In general, a PFD of an arbitrary sound field does not generate partial fields that are "physically meaningful," i.e., that represent independent source components, even if those sources are well-separated spatially. This is because each transducer in a measurement array receives information from multiple subsources. The PFD applications that most successfully generate physically relevant partial fields are performed with a set of reference transducers located close to individual subsources, which emphasizes the contribution of a single source to each reference measurement. Such a deployment is not feasible in a jet field because the distinction between subsources is ill-defined.

In this paper, a PFD method is discussed that attempts to isolate what might be considered "independent" sources in a full-scale jet. Kim *et al.*[14] developed a method that is called here the optimized-location virtual reference method (OLVR). This is a post-holography PFD procedure that makes it possible to identify optimal reference sensor locations and then to place "virtual references" at those locations. Other PFD methods that utilize virtual references exist,[15-17] but this one was developed specifically to find the optimal virtual reference locations. The optimal locations are defined as those at which the multiple signal classification (MUSIC) power[18] is maximized in the three-dimensional region near the source.

Previously, OLVR was implemented on planar NAH reconstructions for the full-scale jet.[19] The results of this paper are obtained from the improved, multisource-type statistically optimized near-field acoustical holography (MSTR SONAH),[20,21] reconstruction. Comprehensive theory and methodology of OLVR is reviewed elsewhere by Wall *et al.*,[21,22] with a modification to account for the partially spatially coherent nature of aeroacoustic sources.

2. THEORY

The OLVR procedure[21] relies on the sub-processes of back propagation toward the source through the use of NAH, the multiple signal classification (MUSIC) algorithm,[18] and the Gauss elimination technique (Cholesky decomposition) that is integral to the PFD algorithm used here, called partial coherence decomposition (PCD).[23] In summary, MSTR SONAH is first used to reconstruct the three-dimensional sound field in the jet vicinity. Second, the virtual reference locations are selected from all reconstruction locations through an automated optimization using the MUSIC algorithm. They are selected such that they correspond to independent source regions. Source locations do not need to be known for this optimization, which is one of the greatest advantages of this method. Third, with virtual references selected, the virtual references are decomposed to form a linearly independent basis set. This is performed with the PCD method, which iteratively allocates and removes energy from the virtual reference cross-spectral matrix. Finally, the OLVR partial fields are generated from the basis set of the new, decomposed virtual references. These are the physical partial fields radiated by independent subsources insomuch as each virtual reference senses one and only one independent subsource, and insomuch as the holographic reconstruction is accurate.

3. EXPERIMENT

Sound pressures in the near field of a jet on a Lockheed Martin/Boeing F-22A Raptor were recorded with a dense array of microphones, with one engine operating at military power, and the other engine held at idle. A brief summary of the experiment is provided here. A comprehensive description is provided by Wall *et al.*[24] An approximately 2 x 24 m vertical planar region 5.6 m from the shear layer was scanned, which measurement was used as the hologram for NAH. This is shown by plane 2 in Figure 1. Plane 1, plane 3, and the arc measurement with radius 22.9 m are not used in this work, but serve as benchmark measurements to verify accuracy of the reconstruction.[20] The results of this paper are for the sound field radiated at 400 Hz.

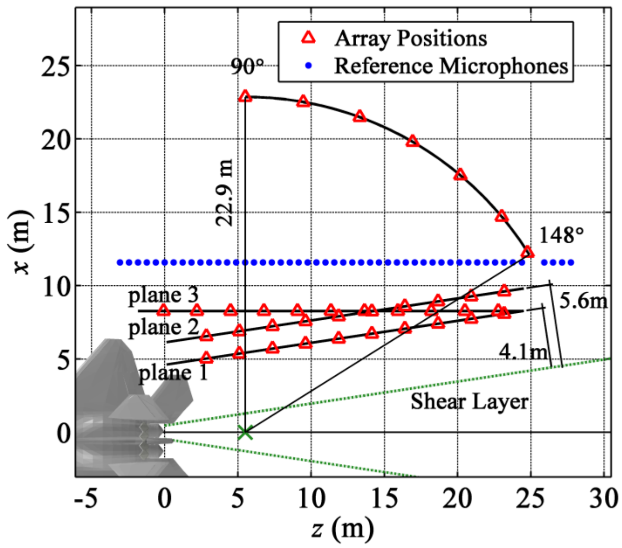

Figure 1: Schematic of the measurement locations, relative to the aircraft. The estimated shear layer boundary is marked by green dashed lines, and the green "x" delineates the estimated maximum noise source region and the center of the arc. Data from plane 2 are used for the holographic field reconstruction.

4. RESULTS

Figure 2 shows the total reconstructed field from NAH at a vertical height of y = 1.9 m for the case of 400 Hz and military engine conditions. Figure 3 shows the first six partial fields (PFs) that are generated with the OLVR method from this reconstruction. A comparison of the strengths of these PFs reveals that the radiation at 400 Hz and military engine conditions is dominated by several independent sources, represented by PF 1 through 5 in Figure 3. The directionality of each lobe varies among the several partial fields. For example, the radiation lobe of PF 1 points farther upstream than does the lobe of, say, PF 5, by about 10-20°. It is important to note that these main independent components are not resolvable in the overall field of Figure 2, where they combine to make one wide lobe, nor is this distinction clear from alternative PFD methods.[21] Only in the PFD based on virtual references located near the jet sources is this apparent.

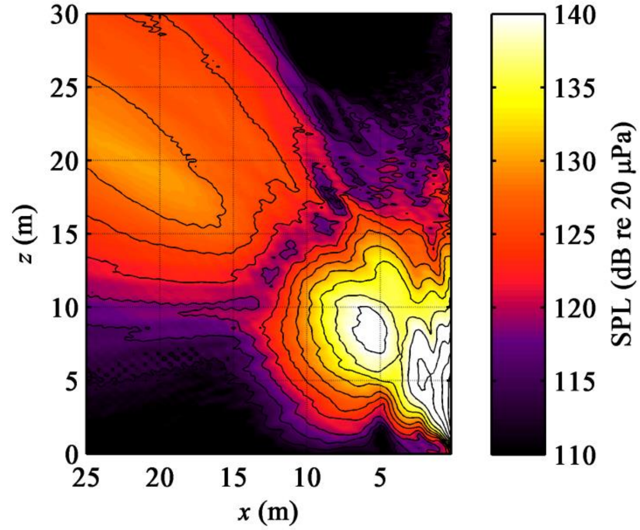

Figure 2: Reconstructed SPLs in the jet vicinity, at a vertical height of y = 1.9 m, after the application of MSTR SONAH to the measured data, for 400 Hz and at military engine conditions.

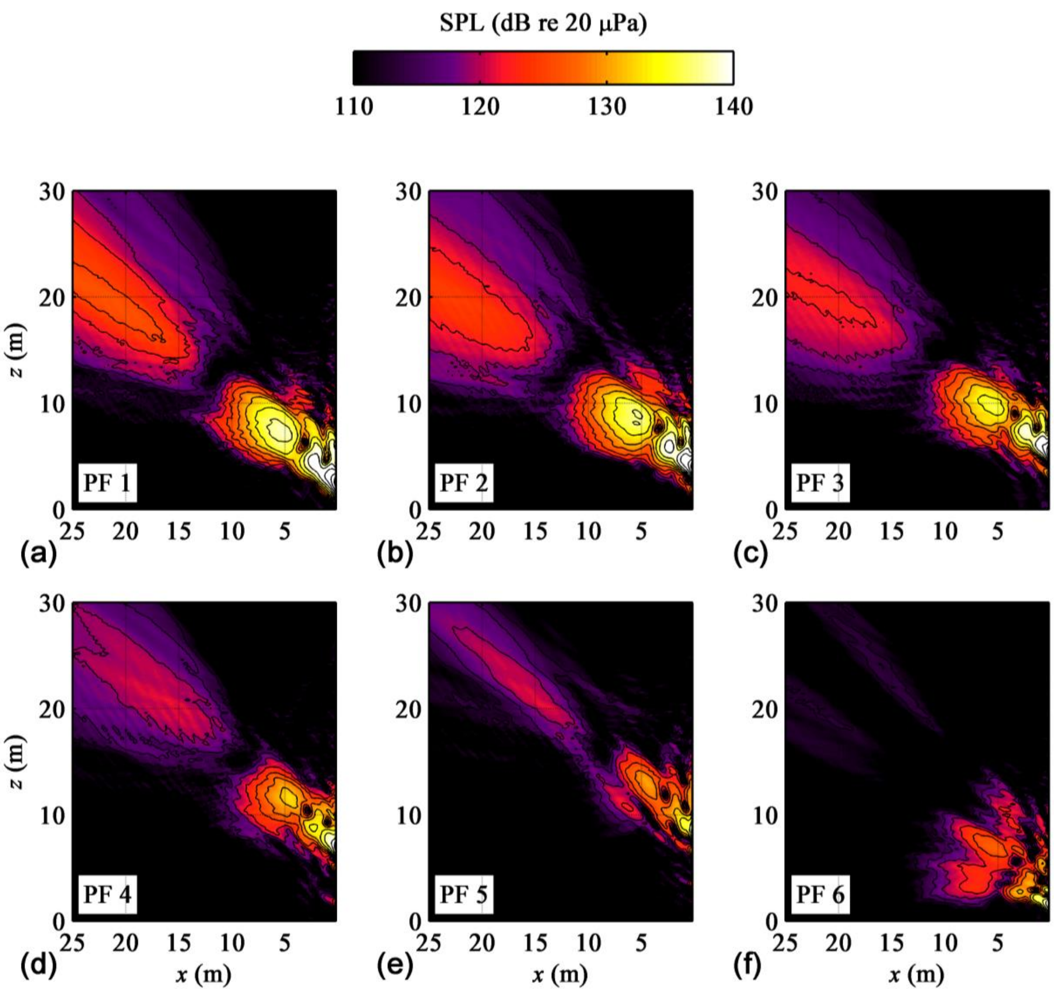

Figure 3: The first six partial fields generated from OLVR on jet noise data, at a vertical height of y = 1.9 m, at 400 Hz and at military engine conditions.

Care must be taken in the interpretation of the independent PFs generated by OLVR. It is possible that the multi-lobe scenario described above could be attributed to one partially spatially coherent source mechanism. In such an interpretation, two well-separated virtual references that are both in the region of a source with spatially decaying coherence (which has been demonstrated in jet field measurements and jet models[25,26]) could result in two seemingly "independent" lobes emitted by the same source. For example, the 10-20° difference in directivity could be explained in the context of Mach wave radiation. An extended object with an irregular surface that convects at supersonic speed will emit highly directional sound waves. This is often called the "wavy wall" interpretation of large-scale jet noise sources.[13,18] The directivity angle of such radiation is dictated by the convection velocity—faster objects emit radiation closer to perpendicular to the direction of travel. Hence, it is logical to suppose that the lobe of PF 5 comes from turbulent structures that have slowed down as they have moved farther downstream compared to the faster-moving structures of PF 1, which originate closer to the nozzle.

However, there is further evidence to support the idea that these lobes are caused by truly independent source mechanisms. Figure 4 is a spatial/spectral map of measured one-third-octave sound pressure levels along the ground-based "reference array" (see blue dots in Figure 1) at military engine conditions. There is a clear separation in the spatial/frequency levels as shown by the null region, which suggests the existence of multiple source mechanisms contributing to the overall field. Note that these data were on the ground, so the null cannot be ascribed to a coherent interference pattern. The investigation of the true independence of sources will be carried out in future work.

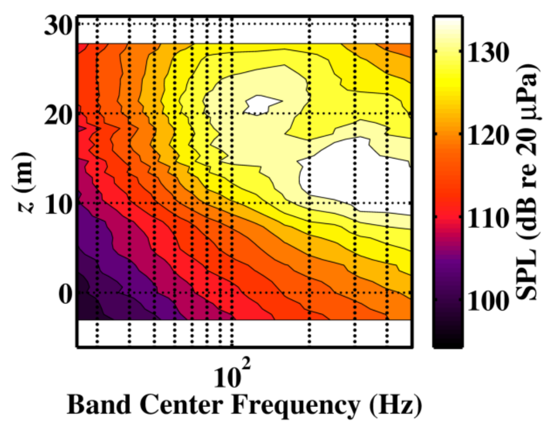

Figure 4: One-third octave spectral variation over location along reference array at military engine conditions.

5. CONCLUSION

The optimized-location virtual reference method (OLVR) for partial field decomposition (PFD) of jet noise sources has been applied to a full-scale jet. OLVR generates an optimal virtual reference set for the decomposition from complex pressures obtained through holographic reconstruction of the three-dimensional field. In the application of OLVR to a jet source, it is important to remember that turbulent flow fields are generally characterized by extended sources of decaying spatial coherence. Hence, the separation of independent source mechanisms is complicated. Nevertheless, OLVR is shown here to generate a set of partial fields for a full-scale jet noise source that are intuitive and provide physical insight about source coherence and distributions. For the sources at 400 Hz, with the engine operating at military conditions, it has been shown that multiple, localized radiation lobes were generated by independent source mechanisms. The application of OLVR to the jet noise field at multiple frequencies and engine conditions provides extensive information about source distributions and coherence properties, and further substantiates the evidence for multiple, independent source mechanisms in the full-scale jet.[21]

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