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Extending the bandwidth of an acoustic beamforming array using phase unwrapping and array interpolation

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Abstract: A method is presented to suppress grating lobes in beamforming using phase unwrapping and array interpolation. When the phase of each cross spectrum is successfully unwrapped, the magnitude and phase of the cross spectral matrix may be interpolated; for cases where these quantities vary smoothly, interpolation is straightforward, even above the spatial Nyquist frequency. Two applications are presented: localization of a broadband source and characterization of a source with frequency-dependent location. In both cases, grating lobes are suppressed and the source is localized at frequencies up to at least 8 times the spatial Nyquist frequency.

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1. Introduction

Conventional beamforming is used for extraction of signals and source localization in low signal-to-noise ratio (SNR) environments,[1] for source analysis,[2] and for spatial filtering.[3] Because of its utility and relatively simple implementation, beamforming is widely used in many areas of acoustics, including underwater acoustics,[4] audio acoustics,[5] and aeroacoustics,[6] as well as other research fields, such as radar,[7] radio astronomy,[8] and communication.[9] Yet beamforming with a small number of array elements is inherently limited in usable bandwidth: fine resolution at low frequencies requires a large array aperture, and avoidance of grating lobes caused by spatial aliasing at high frequencies necessitates small interelement spacing. In this letter, we describe a new method to suppress grating lobes using phase unwrapping and array interpolation, thereby increasing the reliable bandwidth of a conventional frequency-domain beamforming array.

Array interpolation has been used in the past to replace faulty microphones,[10] to lessen the effects of sensor noise,[11] and to simulate a uniform array from non-uniform array data.[12] Investigations have also included extrapolating an array to a larger aperture, allowing greater resolution.[10] These techniques do not attempt to give meaningful results above the spatial Nyquist frequency, f_N, as accurate interpolation requires the array element spacing to be less than half a wavelength.[10] The most promising technique to date for increasing the bandwidth of a beamforming array involves carefully designed non-uniform microphone spacing patterns; even this technique only allows beamforming up to about 6 f_N of the average spacing,[13] and does so at the cost of a significant decrease in SNR.[14]

An essential element of our proposed method to extend the bandwidth above f_N is phase unwrapping, which is the process of computing the absolute phase difference between signals from the $[-\pi, \pi]$ limited argument of the cross spectrum. Phase unwrapping is used extensively in many situations, including radar,[15] optics,[16] robotics,[17] speech processing,[18] medical imaging,[19] and teleconferencing devices.[20] In addition, recent work[21,22] has utilized phase unwrapping to increase bandwidth of acoustic intensity probes using a phase and amplitude gradient estimation method.[23] Many phase unwrapping algorithms have been developed; an overview can be found in Ref. 24. Our current work uses one-dimensional phase unwrapping to gain additional information about the sound field at the array.

The additional information afforded by phase unwrapping allows a new approach to the sparse array problem. We assert that when the source of interest is

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broadband, array interpolation can be performed on undersampled arrays after unwrapping the phase of the cross spectral matrix. This interpolation can be used to construct an arbitrarily dense virtual array, allowing the suppression of grating lobes and increasing the usable bandwidth of the array for conventional beamforming. This process is presented herein on a sparse, uniform linear array for two cases: a single broadband source and a source that changes location with frequency. The method is shown to give accurate source localizations up to at least $8f_N$.

2. The UPAINT method

The Unwrapped Phase Array INTerpolation (UPAINT) method interpolates the phase and magnitude of the cross spectral matrix in the frequency domain. Because the method works on the cross spectral matrix, it has the potential to be applied to advanced beamforming algorithms, acoustical holography, and other inverse methods. The cross spectral matrix at frequency f_0 is defined as

$$\mathbf{C} = \begin{bmatrix} G_{11}(f_0) & G_{12}(f_0) & \cdots & G_{1M}(f_0) \\ G_{21}(f_0) & G_{22}(f_0) & & \\ \vdots & & \ddots & \\ G_{M1}(f_0) & & & G_{MM}(f_0) \end{bmatrix}, \quad (1)$$

where $G_{ij}(f)$ is the cross spectrum between array elements i and j, and M is the number of elements. The phase of the cross spectral matrix $\mathbf{C}$ is denoted as $\mathbf{\Phi} = \arg\{\mathbf{C}\}$, and the magnitude of $\mathbf{C}$ is written as $|\mathbf{C}|$. Interpolation of phase and magnitude, though atypical, is advantageous, as these data can often be assumed to vary smoothly after the phase is unwrapped.

Initially, $\mathbf{\Phi}$ may contain 2π discontinuities where the phase is wrapped, depending on the length of the array relative to the wavelength. Accurate interpolation across these discontinuities is highly problematic, as standard interpolation procedures fill in the discontinuity with intermediate values. To overcome this problem, unwrapping is performed on the phase of each cross spectrum, denoted as $\Phi_{ij}(f) = \arg\{G_{ij}(f)\}$. Unwrapping works along the frequency dimension to compute the actual phase difference between each microphone pair as

$$\tilde{\Phi}_{ij}(f) = \Phi_{ij}(f) + 2\pi k(f), \quad (2)$$

where $k(f)$ is an integer-valued function. The unwrapping process is illustrated in Fig. 1 for two microphone pairs with different spacing in a propagating sound field. The first 2π discontinuity in the wrapped phase occurs at a lower frequency in Fig. 1(a) than in Fig. 1(b) because the microphone pairs have different spacing. This fact that wrapping in $\Phi_{ij}(f)$ occurs at different frequencies for different ij pairs causes the discontinuities in $\mathbf{\Phi}$ and prevents interpolation. However, when the unwrapping is performed for each $\Phi_{ij}(f)$, the resulting $\tilde{\mathbf{\Phi}}$, which contains the values of $\tilde{\Phi}_{ij}(f_0)$ for all ij pairs, is continuous and can easily be interpolated.

As phase unwrapping is performed in the frequency dimension, successful unwrapping requires broadband information for frequencies lower than the frequency of interest f_0. When this is available, phase unwrapping can be performed regardless of the spatial Nyquist frequency. Two-dimensional unwrapping algorithms exist[23] that would allow the unwrapping of the matrix $\mathbf{\Phi}$ across microphone pairs without

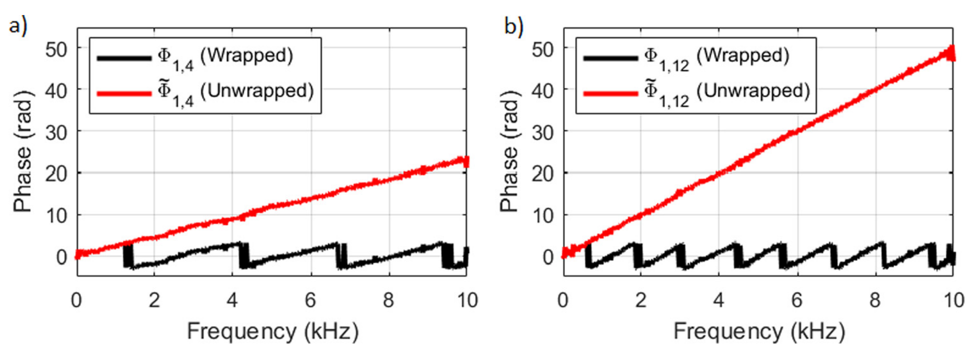

Fig. 1. (Color online) Wrapped and unwrapped phase of the cross spectrum between two microphone pairs from an array placed in a propagating sound field: (a) between mics placed 0.68 m apart and (b) between mics placed 2.04 m apart.

broadband information, but this approach would be useful only for a one-dimensional array and is limited in how far above the spatial Nyquist frequency meaningful results are produced.[25]

Once the phase is unwrapped, UPAINT interpolates $M \times M$ matrices $\tilde{\mathbf{\Phi}}$ and $|\mathbf{C}|$ to $M' \times M'$ matrices $\tilde{\mathbf{\Phi}}'$ and $|\mathbf{C}'|$ using bilinear interpolation, where M' is the total number of array elements after interpolation. These interpolated matrices become the phase and magnitude of the virtual cross spectral matrix $\boldsymbol{C}'$. The source distribution β can then be found by performing beamforming on the resulting $\mathbf{C}'$ as if there were M' microphones at the locations represented by the interpolated data. All source distributions presented in this work are found using conventional beamforming; the algorithm is described in Ref. 26.

3. Application to a single source

A verification of the UPAINT method was performed by localizing a single speaker playing broadband noise in an anechoic chamber. Near-field measurements were taken using a uniform linear array with $M = 22$ microphones spanning an 3.75 m aperture, with $f_N = 1$ kHz. The application of the UPAINT method is shown in Fig. 2 at two frequencies: $2.5f_N$ and $8f_N$. Figure 2(a) shows $\mathbf{\Phi}$ at $2.5f_N$ before unwrapping, and Fig. 2(b) shows the associated $\tilde{\mathbf{\Phi}}$. Unwrapping of two of the $\Phi_{ij}(f)$'s for this case is shown in Fig. 1. At this point, bilinear interpolation is applied to $\tilde{\mathbf{\Phi}}$ and $|\mathbf{C}|$ to create a virtual array with $M' = 53$ and f'_N equal to the frequency of interest. The source distributions found from beamforming using the original array and the virtual array are displayed in Fig. 2(c). Though the correct peak is somewhat apparent in the original source reconstruction, grating lobes are present at the edge of the scan area, creating additional peaks and ambiguity. The UPAINT method removes the grating lobes but

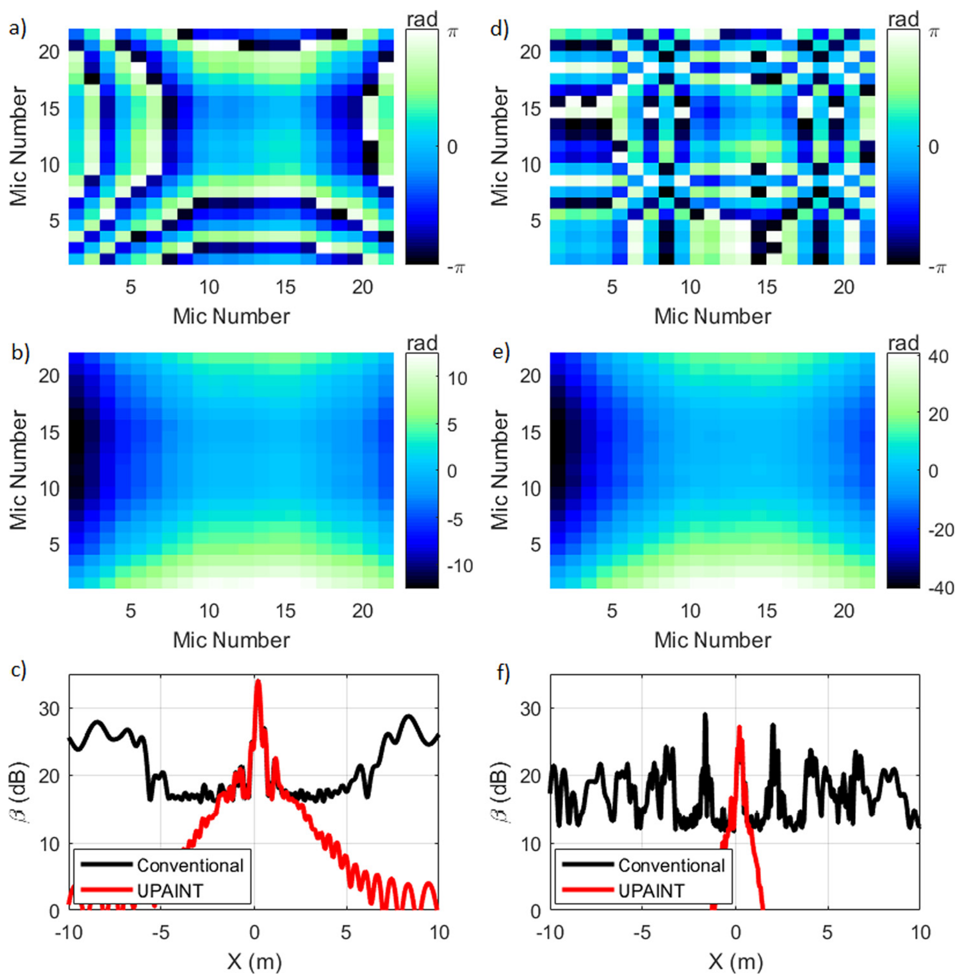

Fig. 2. (Color online) Effects of unwrapping on the phase of the cross spectral matrix and beamforming results for a single broadband source at two frequencies: $2.5f_N$ (left) and $8f_N$ (right). (a) Wrapped phase $\mathbf{\Phi}$ at $2.5f_N$. (b) Unwrapped phase $\tilde{\mathbf{\Phi}}$ at $2.5f_N$. (c) Beamforming results β at $2.5f_N$, for both conventional and UPAINT beamforming. (d) Wrapped phase $\mathbf{\Phi}$ at $8\,f_N$. (e) Unwrapped phase $\tilde{\mathbf{\Phi}}$ at $8\,f_N$. (f) Beamforming results β at $8\,f_N$, for both conventional and UPAINT beamforming.

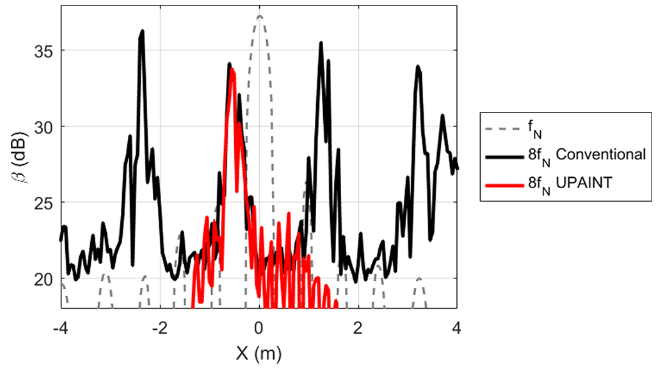

Fig. 3. (Color online) Beamforming response β for a source that moves with frequency. β is shown for f_N with conventional beamforming, for $8f_N$ with conventional beamforming, and for $8f_N$ with UPAINT applied before conventional beamforming. DAMAS (Ref. 27) is applied to the f_N case to remove array artifacts.

preserves the amplitude of the correct peak, allowing the identification of the source. The process is repeated in Figs. 2(d)–2(f) at $8f_N$. In this case it is much harder to identify the correct peak in the original source reconstruction, but beamforming with UPAINT again strips out the grating lobes and identifies the correct source. In both instances the application of UPAINT significantly reduces sidelobe levels.

The successful source localization up to $8f_N$ is possible because $\tilde{\mathbf{\Phi}}$ and $|\mathbf{C}|$ vary smoothly. It should be noted, however, that there are situations in which $\tilde{\mathbf{\Phi}}$ and $|\mathbf{C}|$ are not smoothly varying, such as a sound field that includes nulls or two widely spaced incoherent monopoles; this method may experience difficulties in such cases. The requirements as presently defined for UPAINT to work are that $\tilde{\mathbf{\Phi}}$ and $|\mathbf{C}|$ may be approximated as pairwise linear and that each $\Phi_{ij}(f)$ can be unwrapped up to the frequency of interest. If these two requirements are met, any number of virtual elements may be added between microphone pairs. Note that for there to be a meaningful phase to unwrap, the source must be broadband. Improvements on the method as it is investigated further could relax some of these restrictions. This method also shows promise for extension to other more sophisticated beamforming algorithms that use the cross spectral matrix.

4. Additional results

Though a single broadband monopole can be localized using only frequencies lower than f_N, sound source locations in actual near-field beamforming applications may vary as a function of frequency. In these cases, grating lobes at undersampled frequencies can make the source location indeterminable. The UPAINT method removes the grating lobes present in conventional beamforming and can clearly identify the frequency-dependent source locations.

To test this situation, two speakers were placed 50 cm apart in an anechoic chamber 6.8 m from the beamforming array described in Sec. 3. Broadband noise was generated and filtered through a two-way crossover with a crossover frequency of $2.5f_N$ to send low frequencies to one speaker and high frequencies to the other. Figure 3 shows the beamforming results at f_N with DAMAS (Ref. 27) deconvolution applied to remove array effects, the results at $8f_N$ with conventional beamforming, and the results at $8f_N$ using UPAINT before beamforming. Though source location is ambiguous in conventional beamforming, UPAINT allows the true source location to be resolved at 8 times the Nyquist frequency.

Additional tests were performed numerically to investigate the effect of a low-level interfering source on the unwrapping and beamforming. The numerical tests were setup to match the single-source experiment described in Sec. 3, with a second source the same distance from the center of the array but at various angles. UPAINT was very robust in these tests; unwrapping errors were avoided and beamforming gave the amplitude of the main source within 0.5 dB at all the tested angles, as long as the interfering source was 3 dB down or more relative to the main source.

5. Conclusion

We have described the UPAINT method, which greatly enhances array performance for broadband source environments, particularly where grating lobes are present. The method has been applied to conventional beamforming for both a single broadband source and a source that changes location with frequency. The application of

UPAINT before beamforming allows good source localization up to at least 8 times the spatial Nyquist frequency in these cases. Though the experiments presented in this paper are all near-field scenarios, numerical simulations confirm that UPAINT shows equal promise in the near and far fields for a single source. Further development of the method is needed to address complications that arise for multiple sources, but numerical simulations suggest that the uncovering of sources hidden in grating lobes is possible. Additional investigations are being performed on multiple sources in a small angular area and extended sources, including use of UPAINT to enhance ongoing work on jet noise analysis.[28,29]

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