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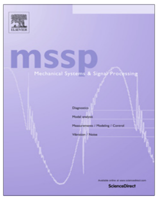

A patch near-field acoustical holography procedure based on a generalized discrete Fourier series

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ABSTRACT

Planar near-field acoustical holography (NAH) can be used to reconstruct a three-dimensional sound field from sound pressure data measured by a planar microphone array. The conventional planar NAH makes use of the discrete Fourier transform (DFT) to process the measured data, yielding a low computational cost. However, if the measurement aperture does not fully cover the sound source extension, the spatial windowing will lead to severe reconstruction errors. Many patch NAH methods have been proposed to allow measurement apertures smaller than the source size, such as the statistically optimized NAH (SONAH), which is not based on the DFT. These methods have proven to outperform the conventional NAH for small measurement apertures, but with an increased computation time and more complex implementation. This paper introduces an alternative patch procedure for planar NAH that replaces the DFT with a so-called "generalized discrete Fourier series" (GDFS). Unlike the DFT, the periods of the two-dimensional GDFS and the number of Fourier coefficients are made larger than the measurement aperture and the number of microphones, respectively. Then, the Fourier coefficients are evaluated in the least-norm sense. This reduces the spectral leakage due to the spatial windowing, improving the NAH results. As a numerical example, a simply supported plate driven by a point force is considered, and patches of the plate normal velocity are estimated from simulations of the radiated sound pressure on a small microphone array. It is shown that the GDFS-based method might lead to reconstructed velocity fields as accurate as SONAH, or even more accurate. However, unlike SONAH, the proposed method presents a low computational cost and a straightforward implementation. Therefore, it is a worthy alternative to the currently available patch procedures for planar NAH.

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1. Introduction

Near-field acoustical holography (NAH) is an experimental technique to estimate the sound field in a fluid volume around a measurement surface, on which acoustic sensors are placed. It was introduced in the early 1980s [1,2] and has been constantly improved and extended since then, so that many variants of NAH are presently available, such as the statistically optimized NAH (SONAH) [3,4] and the Helmholtz equation least-squares (HELS) method [5,6]. NAH is especially useful in inverse sound source reconstruction due to its ability to identify the spatial distribution of the sources with high resolution, as well as the sound field they produce. In this case, the measurement surface must be in the source near field. Because the reconstruction surface contains the sources or lies somewhere between the measurement and source surfaces, it is an

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inverse problem that must be carefully dealt with. Indeed, sound source reconstruction via NAH is a physically ill-posed inverse problem that requires regularization to yield stable solutions [7].

The computation of the acoustic variables from data taken at the measurement surface (the "hologram" surface) relies on solving an appropriate mathematical model describing the sound propagation [8], the most common being the homogeneous Helmholtz equation subjected to free-field conditions, which will be used in this paper. In its original form, NAH is restricted to separable geometries, so that an efficient numerical evaluation of the propagation model is achieved [2,9]. In particular, the planar NAH proposed in the pioneering work by Maynard et al. [2] makes use of two-dimensional discrete Fourier transforms (DFT) to approximate the linear convolution in the space domain relating the sound fields on the measurement and reconstruction planes. Accordingly, a planar array of evenly spaced microphones must be used, which is not required by later planar NAH procedures, such as SONAH, that can also operate with non-regular planar microphone arrays. However, the use of the DFT leads to an efficient implementation and very fast computation that have not yet been outperformed by more recent NAH techniques. Because this paper deals only with planar NAH, the standard DFT-based NAH in planar coordinates will be simply referred to as DFT-NAH.

The main drawback of the DFT-NAH is the requirement of a large measurement aperture to avoid severe errors in the holographic reconstruction, which will take place if the microphone array does not fully cover the source extension. These errors are due to windowing effects (spectral leakage) and space-domain aliasing (wraparound error) [9,10]. The latter can be made negligible by increasing the hologram size through zero-padding. However, this procedure does not eliminate the windowing effects because the missing data will hardly be zero for small holograms. Williams [9] states that, in practice, the measurement aperture must be at least twice the source size. This almost always ensures that the sound pressure will be very small at the borders of the measurement aperture. In this case, a zero-padded hologram together with a suitable spatial window leads to an accurate sound field reconstruction. Nevertheless, since the sampling theorem imposes a maximum spacing between microphones to avoid aliasing in the spatial frequency (wavenumber) domain, a number of microphones prohibitively large might be necessary to suppress the finite measurement aperture effects. A small microphone array can alternatively be used to scan the whole source extension, and thus a block convolution can be undertaken [11]. However, such a time-consuming method cannot be applied to real-time NAH or non-stationary signals.

Several "patch" NAH procedures have been proposed to reduce the finite measurement aperture effects, making it possible to use microphone arrays smaller than the source size. For planar NAH, such procedures can be divided into two categories: those which do and which do not keep using the DFT. The DFT-based procedures rely on a conditioning of the hologram data prior to DFT processing, most of them aiming to artificially extend the measurement aperture by using an extrapolation algorithm. Then, the conventional DFT-NAH is applied to the extended hologram. Several extrapolation methods have been proposed, such as iterative methods [12–15], the superposition method [16], and the linear predictive border padding method [17,18]. A DFT-based procedure using a wavelet preprocessing has also been proposed [19]. All these methods have proven to outperform the standard DFT-NAH for specific test cases, although there seems to be no published studies comparing their performances. The iterative method by Williams and co-workers [13,14] is the most referenced one for patch NAH based on the DFT, but it requires many iterations and a complex implementation. At the present time, SONAH is the most popular patch procedure for planar NAH, which does not make use of the DFT and works directly in the space domain. Compared to other techniques, it has proven to yield small reconstruction errors in different academic and industrial case studies for small measurement apertures, and thus SONAH will be considered as a benchmark method in this paper. However, compared to DFT-NAH, SONAH presents an increased computational time and a more complex implementation. In addition, it requires a proper choice of the position of a so-called "virtual source plane", as it will discussed in Section 2.3. The HELS method is another patch procedure that is not based on the DFT. This method is not restricted to planar NAH, but, if it is used in this case, SONAH or the iterative DFT-based NAH should generally be preferred [20,21].

This paper presents an alternative patch procedure for planar NAH. The proposed method is based on a decomposition of the sound field that will be referred to as "generalized discrete Fourier series" (GDFS), whose principles are borrowed from the regressive discrete Fourier series (RDFS) introduced by Arruda [22,23]. As the DFT, the RDFS is a decomposition of a discrete signal into a finite set of harmonically related complex exponentials. However, unlike the DFT, the period of the RDFS is made larger than the data length, whereas the number of Fourier coefficients is made arbitrarily small. Then, a curve fitting in the least-squares sense is used to approximate the Fourier coefficients. This approach makes zero-padding unnecessary and reduces the spectral leakage compared to the DFT. In addition, the RDFS does not require a uniform sampling in the space domain. However, the overdetermined system that must be solved to compute the RDFS coefficients might yield numerical instabilities, which can be dealt with by using a regularized least-squares solution [24].

The RDFS has been used in applications that require smoothing densely sampled noisy signals and computing spatial derivatives, such as in parameter identification of structural materials through laser Doppler vibrometry measurements [25]. A modified RDFS was also proposed to tomography applications [26]. Moreover, the author of this paper presented a preliminary study on the application of the RDFS to planar NAH in Ref. [27]. It was shown through numerical simulations that the NAH results may be significantly improved by replacing the DFT with the RDFS for small measurement apertures. However, in that work, the simulated microphone array was made up of 1024 "measurement" points, whereas 64 wavenumber lines were used. Because real microphone arrays must have a number of sensors as small as possible, the RDFS requirement of less Fourier coefficients than measurement points may lead to a poor wavenumber representation of the signal for NAH applications. Therefore, we propose here to use more Fourier coefficients than microphones, leading to an underdetermined system that can be solved in the least-norm sense. In this case, it is no longer appropriate to refer to such a Fourier

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