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Identification and localization of the sources of cyclostationary sound fields

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ABSTRACT

A cyclostationary sound field is approximately regarded as a stationary sound field when analyzed by the traditional planar near-field acoustic holography (PNAH), which ignores the periodical time-variant property and makes it hard to reflect accurately the radiation characteristics based on the hologram results. In this article, a cyclostationary planar near-field acoustic holography (CPNAH) technique is proposed in which the cyclic spectral density (CSD) instead of the complex sound pressure is adopted as reconstructing physical quantity and the physical properties of CSD are utilized. And to avoid plenty of calculation and improve accuracy of extracting the cyclic property, pre-processing of holographic data, the method known as the gathering slices of CSD is also proposed. The experiment results demonstrate that the cyclic properties of cyclostationary sound fields can be extracted and the sources of cyclostationary sound fields can be exactly identified and localized by means of CPNAH.

1. Introduction

The cyclostationary sound field is a special kind of non-stationary sound field which exists widely in engineering practice. For example, the sound field radiated from the rotating machinery or the reciprocating machinery has a significant periodical time-variant characteristic due to the symmetrical or approximate symmetrical structure and the periodic operating mode of the machine [1–4]. Such a sound field is usually treated as a stationary sound field and its properties in frequency domain are analyzed by the Fourier analysis tool. This processing method is simple by which some engineering problems have been solved, however, the loss of some information about the frequency change with the passage of time cannot be avoided.

The cyclic statistics theory is an appropriate analysis tool for cyclostationary sound fields [5,6]. The non-stationary character i.e. periodical time-variant properties extracted by means of analyzing the cyclic statistics of the cyclostationary sound field can fully reflect the operating state and physical properties of the rotating machinery or the reciprocating machinery. Nowadays the second-order cyclic statistics have been used in engineering practice more widely than other cyclic statistics, and some tangible results have been obtained.

In near-field acoustic holography (NAH), an acoustic quantity in near field, such as complex sound pressure, is used to reconstruct the sound field on the surface of the radiator for the sake of identifying and localizing the sound source [7,8]. However the sound field is usually treated as the stationary field to this day when it is generated by the rotating machinery or the reciprocating machinery, this is restricted to some extent. A near-field acoustic holography technique for cyclostationary sound fields was presented in Ref. [9]. In the research, a pair of cyclic cross-spectral density functions of the sound pressure at holographic measuring points and at reference point were adopted as the reconstruction physical quantity of NAH and two times space reconstructions were carried out to get the CSD distribution on the reconstruction plane. The traditional time domain smooth periodogram method was used for the pre-processing of measured signals. Obviously, it is difficult to adopt the complicated technique.

The CSD, which belongs to the second-order cyclic statistics, is adopted as the reconstruction quantity of NAH in this article. The advantage is that the cyclic components of cyclostationary sound field may be extracted accurately, noise suppressed greatly, and phase information of the signal reserved [10,11]. The disadvantage lies in its calculation complexity and a long length of data accumulation in order to obtain higher estimation accuracy. To

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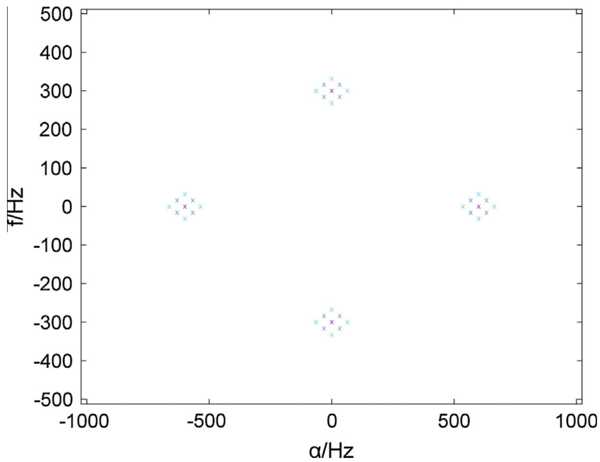

Fig. 1. Amplitude of CSD.

solve the calculation problem, a gathering slices method of CSD is proposed by referring to time aliasing methods on time series [12]. With the help of analyzing zero delay slice of the cyclic autocorrelation function of the signal, the peak frequencies of interest on the cyclic frequency axis are selected to calculate CSD slices, and the interference between overlapping terms is eliminated by analyzing gathering CSD slices, consequently feature frequencies of sound signal are extracted exactly and the planar NAH (PNAH) reconstruction based on two-dimensional Fourier transform is carried out at feature frequencies. Generally speaking, the advantages of both PNAH and CSD are employed in this method, and feature frequencies of the sound field can be extracted, while the sound energy at feature frequencies can be visualized.

2. Theory

2.1. PNAH of stationary sound field

Suppose that the complex sound pressure on hologram plane is $p(x_h, y_h, z_h)$ and Green's function under Dirichlet boundary conditions is $G_D(x, y, z)$, the complex sound pressure on any plane parallel with hologram plane can be expressed as

$$p(x,y,z) = \iint_s (p(x_h,y_h,z_h)G_D(x-x_h,y-y_h,z-z_h))dS \tag{1}$$

The two-dimensional Fourier transform is carried out on both sides of Eq. (1) and the convolution theorem is used, the following expressed can be derived,

$$p(x,y,z) = F^{-1}[\tilde{p}(k_x,k_y,z)] = F^{-1}[\tilde{p}(k_x,k_y,z_h)\widetilde{G}_D(k_x,k_y,z-z_h)] \tag{2}$$

where $\tilde{p}(k_x,k_y,z)$, $\tilde{p}(k_x,k_y,z_h)$ and $\widetilde{G}_D(k_x,k_y,z-z_h)$ express two-dimensional Fourier transform of $p(x,y,z)$, $p(x_h,y_h,z_h)$ and $G_D(x,y,z-z_h)$ respectively. Eq. (2) is the space transformation formula of the sound field.

$\widetilde{G}_D(k_x,k_y,z-z_h)$ may be derived by function integral table or the wave equation, the result is

$$\widetilde{G}_D(k_x,k_y,z-z_h) = \begin{cases} e^{j(z-z_h)\sqrt{k^2-(k_x^2+k_y^2)}}, k^2 \geq k_x^2+k_y^2 \\ e^{-(z-z_h)\sqrt{(k_x^2+k_y^2)-k^2}}, k^2 < k_x^2+k_y^2 \end{cases} \tag{3}$$

Once the complex sound pressure on a near field plane is obtained by scanning, the complex sound pressure on any plane parallel to the near field plane can be obtained by Eq. (2).

2.2. PNAH of cyclostationary sound field

In PNAH technique, the data on hologram plane is sampled within a two-dimension aperture by scanning and the holography reconstruction is actually a problem of data processing based on two-dimensional matrix.

When the complex sound pressure is replaced by the CSD as the reconstruction physical quantity, according to the physical character of CSD, the delay effect of the measurement data between two close scanning steps must be eliminated to ensure spatial phase relationship of the two-dimensional holography data matrix.

The power spectral density (PSD) is insensitive to time delay, whereas the CSD is sensitive due to the presence of cyclic frequency domain. Suppose a signal is $v(t) = x(t-\tau_n)$, where τ_n is the time delay. The CSD of $v(t)$ is

$$S_v^\alpha(f) = S_x^\alpha(f)e^{-j2\pi\alpha\tau_n} \tag{4}$$

from which it can be seen that a delay factor $e^{-j2\pi\alpha\tau_n}$ in cyclic frequency domain (α domain) exists between the initial signal and the delayed signal. The delay factor between two close scanning steps can be obtained using a fixed reference microphone in scanning process.

Suppose the pressure measured by the reference microphone at the nth scanning step is $\hat{r}_n(t) = r(t-\tau_n)$, where $n = 1{:}N$, $\tau_1 = 0$, N is total step number. The CSD of $\hat{r}_n(t)$ is $S_{\hat{r}_n}^\alpha(f)$, then the delay factor can be obtained by the following expression,

$$e^{-j2\pi\alpha\tau_n} = S_{\hat{r}_n}^\alpha(f)/S_{\hat{r}_1}^\alpha(f) \tag{5}$$

Let the CSD of signals measured by the microphone array at the nth scanning step be $S_{\hat{p}_n}^\alpha(f)$.

After eliminating the effect of time delay, the CSD can be written as

$$S_{p_n}^\alpha(f) = S_{\hat{p}_n}^\alpha(f)S_{\hat{r}_1}^\alpha(f)/S_{\hat{r}_n}^\alpha(f) \tag{6}$$

When time delay between two close scanning steps is eliminated by Eq. (6), measuring data on the hologram plane is equivalent to synchronous acquisition, and phases of CSD at the cyclic frequencies are reserved, then the spatial phases of data matrices on the two-dimensional hologram plane exist. So if the CSD rather than the complex sound pressure is adopted as the reconstruction variable, the reconstruction can be carried out directly using Eq. (2). This technique is named cyclostationary planar near-field acoustic holography (CPNAH). There exist some substantial differences between the PNAH technique and the CPNAH technique in

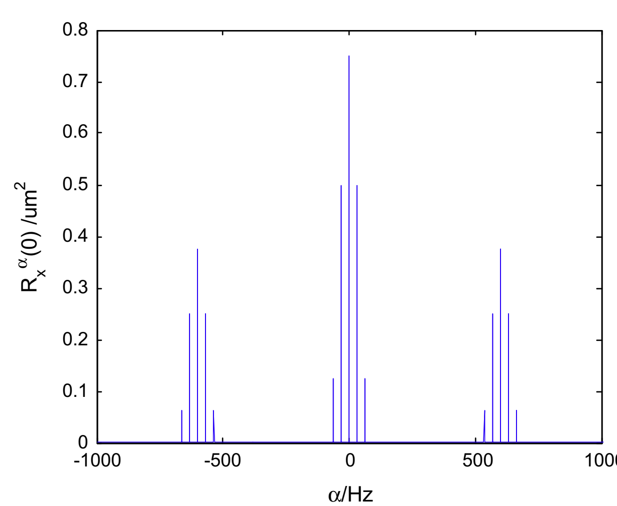

Fig. 2. The cyclic autocorrelation function ($l = 0$).