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Extraction and imaging of aerodynamically generated sound field of rotor blades in the wind tunnel test

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ABSTRACT

The acoustic beamforming has been widely applied in the imaging of flow-induced aeroacoustic sound sources. However, the measured signals of the rotor blades often accompanied with the unwanted interference from other components of the experimental setup in the wind tunnel test (for example, the rotor shaft and the stand), which results in the undistinguished sources in the beamforming result. In this paper, the signals of rotor blades are defined first as the cyclostationary process based on the Ffowcs Williams-Hawkings (FW-H) equation in the form of Wold-Cramer decomposition, which connects the statistical definition of rotor blades signals with the wave propagation model of moving sources. Then the developed cyclostationary signal processing tools of a second order, specifically the reduced-rank cyclic Wiener filter, can be applied in the wind tunnel test of rotor blades. The rotor blades signals can be extracted from the noisy measurements with other interferences, which aide to purify the image results of beamforming in the final experiment of wind tunnel test.

1. Introduction

During the operation of any equipment with rotor blades (for example, helicopters [1,2] or wind turbines [3–5]), the undesirable aerodynamic noise is usually generated. The physical mechanism of the generating noise is due to the interaction between the rotor blades and the surrounding air. This strong noise not only affects the physical and mental health of the occupants near the noise sources, but also causes the side effects such as acoustic-structural coupling, acoustic fatigue and so on, which affects the safety of the equipment. Therefore, studying the physical mechanism of rotor blades aerodynamic noise generation and effectively reducing aerodynamic noise are important research topics in the development of modern equipment.

The earlier aeroacoustic theory is based on the Lighthill's analogy, which specifically addresses the problem of the sound generation by a region of high-speed turbulent flow instead in a stationary medium [6]. By introducing the generalized function theory, Ffowcs Williams-Hawkings generalized Lighthill's acoustic analogy approach to tackle a wider range of the problem, such as very general types of surfaces and motions [7]. Thus, the Ffowcs Williams-Hawkings (FW-H) equation has been generally accepted as the foundation for modeling the aerodynamically generated sound of main rotor. Thickness noise is caused by the displacement of the fluid in the flow during the passage of the blade, which is modeled as the monopole term in the FW-H equation; the loading noise is due to the forces that the blades exert on the surrounding fluid during their

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periodic motion (Blade-Vortex Interaction (BVI) noise and Broadband noise are two important types of loading noise), which is modeled as the dipole term in the FW-H equation; and the quadrupole term model the high-speed-impulsive (HSI) noise when the flow becomes transonic and shocks appear. With the FW-H equation, the computational fluid dynamics (CFD) [8,9] and its application to rotor blades aerodynamics have become an inevitable step for accurate noise prediction.

The cause and effect are seen to be clear from a theoretical perspective. However, the aerodynamic noise of rotor blades in the experimental research of wind tunnel still encounter difficulties. The cause is usually required to be sought with the effect of the experimental research, which is known as the inverse problem. Moving Beamforming [10,11] is one of the most exploited acoustic visualization method by phased microphone array measurements for rotor blades noise, which is an extended technique to identify moving sources by combining the de-Dopplerization technique with conventional beamforming. However, one problem is the rotor blades noise measurement usually accompany with the aerodynamic noise of wind tunnel (the background noise or the interference of other facilities), and the extraction of rotor blades noise from the total measurement is needed in the experimental research of wind tunnel.

In the conventional setting, the signals are supposed to be stationary and the extraneous noise is assumed to be uncorrelated with the signals. After the computation of the cross-spectral matrix (CSM), the uncorrelated noise will concentrate on the diagonal elements of the CSM. A common practice is thus to set the CSM diagonal to zero, which is known to improve the dynamic range of the source localization maps. However, diagonal removal technique also leads to under-estimated source levels. More advanced methods have been recently proposed to avoid such problems by preserving the source information that lies in the CSM diagonal. Diagonal Reconstruction [12,13] was proposed to remove as much noise as possible as long as the denoised CSM remains non-negative. Wavenumber decomposition to filter out high wavenumbers associated with turbulent boundary layer noise have been proposed in Ref.[14]. Robust Principal Component Analysis [15] was proposed to recover the acoustic signal in case of poor signal-to-noise ratio due to the boundary layer noise, which is based on a low rank and sparse decomposition of the CSM. Probabilistic Factor Analysis [16] was proposed to de-noise the CSM in a probabilistic framework, which is based on the decomposition of the CSM into a low-rank part and a residual diagonal part attached to the unwanted noise. All these methods can not be directly used to de-noise the rotor blades sound signals due to the aforementioned fundamental assumption, both the rotor blades and interference noise of other facilities may not be stationary.

The cyclostationary signal processing methods [17,18] has been widely applied in the machine fault diagnosis, identification of machine systems and separation of mechanical sources. However, few researchers have addressed the problem of aerodynamic noise generated by the rotor blades with the cyclostationary signal processing tool. One fundamental problem is the lack of formal definition of cyclostationary noise based on the partial wave equation which has been generally accepted and used in the aerodynamic noise engineering. This also becomes the main knowledge gap to further apply the cyclostationary signal processing tools in the wind tunnel test of rotor blades [19]. In this paper, the cyclostationary signal is defined firstly from the Wold-Cramer decomposition of non-stationary signals by imposing the periodic Green's function. Then the moving sources forward model is derived in the form of Wold-Cramer decomposition, which connects the signal processing definition of the cyclostationary signal with the wave propagation model. By this work, then the developed cyclostationary signal processing tools can be applied in the wind tunnel test of rotor blades. Finally, the results of moving Beamforming can be further purified with the proposed signal extraction method.

In this paper, the propagation model of moving monopole source is first given in Section 2, and the rotor blades noise is mathematically formulated as a cyclostationary process based on a periodic Green's function, and a formal definition of the cyclostationary process of rotor blades noise is described; a signal extraction problem of the rotor blades noise from noisy measurements is formulated in Section 3, and extraction and visualization of rotor blades signals is given in Section 4. The experimental validation is shown in Section 5: one typical background noise is generated from the rotor shaft and the stand that interact with the flow, which is the main interference of aero-acoustic measurements of the rotor blades. The beamforming results show that the rotor shaft noises are eliminated from the image after the signal extraction.

2. Cyclostationary process modeling of rotor blades noise

2.1. The Wold-Cramer decomposition of non-stationary signals

The basic definition of Wold-Cramer decomposition [20] is briefly described in this subsection for the preparation of the derivation of the next. In the stationary case, Wold's decomposition uniquely describes any stationary stochastic process $Y(t)$ as the output of a causal, linear, and time-invariant system $h(t)$ excited by strict white noise $X(t)$:

$$Y(t) = \int_{-\infty}^{t} h(t-\tau)X(\tau)d\tau. \tag{1}$$

Wold's decomposition imposes no other restriction on $X(t)$ than having a flat spectrum almost everywhere. The frequency counterpart of wold's decomposition is known as Cramer's decomposition,

$$Y(t) = \int_{-\infty}^{\infty} H(f)e^{j2\pi ft}dX(f), \tag{2}$$