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Hyperbolic localization of incipient tip vortex cavitation in marine propeller using spectral kurtosis

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ABSTRACT

Incipient tip vortex cavitation is one of the primary concerns for propeller design in commercial- or naval- vessels. This paper attempts its hyperbolic localization, which should be preceded by accurate estimation of time delay between measured acoustic signals. Although the generalized cross-correlation with phase transform can be considered as a conventional algorithm for time delay estimation, it is prone to be vulnerable to the noise dwelling outside the frequency band of signal. In order to nullify these noise effects, a weighting function, resembling the rectangular window in frequency domain, is introduced. By further noting that the signal arisen by the tip vortex cavitation can be categorized into the cyclostationary type, the spectral kurtosis is adhered to design the optimum band of the frequency weights. Finally, the proposed method is shown to be valid by two experimental demonstrations of artificial source and propeller cavitation.

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1. Introduction

While a marine propeller operates in a non-uniform wake, it is subjected to periodic occurrences of tip vortex cavitation (TVC) [1]. Taking place in a very short time duration of several microseconds, the cavitation phenomenon accompanies collapse of vapor bubbles with a radiation of bursting- or impulsive- noise to the environment [2]. Then the acoustic signature of cavitating propeller contains high frequency components ranging several tens of kilo-Hertz, repeated in a periodic manner.

Recent regulation on the marine environment [3] begins to restrict shipping noise, mainly coming from the propeller cavitation, as it may potentially cause a negative effect on the marine life [4]. Furthermore, the cavitation noise carries diagnostic evidences of the target (such as revolution rate of the propeller, number of blades), it accordingly becomes a great interest for an underwater surveillance of the naval vessel. In either case, a low noise propeller is desirable, which is often accomplished by iterative design modification based on model scale tests in a water cavitation tunnel. Thus, one major scope of the model test is to localize the incipient TVC of propeller.

Although visual inspection using a high speed camera is commonly practised in the test, it is allowable only for well-developed cavitation, a situation that is far beyond the inception stage. Because invisible cavitation still produces a detectable signal, it would be a natural alternative to rely on acoustic measurements for the localization. Using a hydrophone array installed in the water tunnel, Park et al. [5] attempted the method of matched field processing (MFP) [6] to find the location

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Nomenclature

c	speed of sound in water (=1500) [m/s]
D	diameter of propeller [m]
f	frequency [Hz]
f_s	sampling frequency [Hz]
$G(f)$	cross-spectral density
K_t	thrust coefficient
M	number of hydrophones
n	revolution per second of propeller, rps [Hz = 1/s]
p	tunnel pressure [N/m^2]
p_v	vapor pressure [N/m^2]
ρ	density of water [kg/m^3]
r	distance between the source and hydrophone [m]
R	ordinary cross-correlation
R^g	generalized cross-correlation
σ_n	cavitation number
τ	time delay [s]
T	thrust force of propeller [N]
V_T	water flow speed in the water tunnel [m/s]
$\psi(f)$	weighing function for generalized cross-correlation R^g
$\psi_{mod}(f)$	modified weighing function for generalized cross-correlation R^g

Abbreviations

GCC	generalized cross-correlation
MFP	matched field processing
PHAT	phase transform
SK	Spectral Kurtosis
SNR	signal-to-noise ratio
TDOA	time-difference of arrival
TVC	tip vortex cavitation

of underwater noise source. In brief, MFP evaluates a resemblance between measurement- and replica- vectors (prediction of acoustic pressure on the receiving array for an assumed source location). If one of the source candidates is in a close proximity to the true source location, its replica would have a high degree of resemblance with the measurement. This implies the true source is possibly at the location of the candidate being considered. Obviously, the replica should be priorly available via either experimental- or numerical- way. The approach of Park et al. [5] was to measure directly the replica vectors by roaming a known source within a domain of interest. It was impractical however, since there should be a greater number (>800) of measurements in order to cover the domain with a high spatial resolution.

Among the references dealing with numerical approaches, Lee et al. [7] discussed modeling of sheet-type cavitation generating an acoustic signal in low frequencies. Due to a reverberation effect in the tunnel, the acoustic boundary element method with complicated geometries of hull and tunnel was necessarily employed for calculations of the replica pressure field. The reverberation can be significant in low frequencies, whereas this is not the case for high frequencies where the TVC concerns. In the water, moreover, sound absorption affected by viscosity, heat conduction, and relaxation losses from dissolved compounds generally increases with frequency [8,9]. These factors make the test environment more anechoic in the high frequency range. Thus, the authors' previous work [10] discussing the localization of TVC calculated the replica of a monopole source with direct path only, which could be justified by a comparison with multiple reflection model. As the direct path signal was taken into account only, there was no need to be bothered with the hull geometry information at all. In spite of such a simplified model, numerous computations of the replica pressure field for an interested domain were unavoidable due to an inherent nature of MFP.

The anechoic characteristic in the high frequencies motivated us to deliberate the classical hyperbolic localization scheme [11,12]. Compared to the MFP, the method of hyperbolic localization can be efficiently implemented without a tedious calculation of replica; once hyperbolic- curves or surfaces are drawn by the estimated time delay between the hydrophones (or time-difference of arrival, TDOA), their intersection denotes the true source location. In the present study, TDOA is estimated by the generalized cross correlation with phase transform (GCC-PHAT) [13], which is being popularly used even in a highly reverberant environment. Yet, GCC-PHAT has a limitation in that the signal should possess an abundance of frequency contents. It alone may fail for a signal with a band-limited characteristic, such as the TVC noise. One major strategy for this is to suppress noise outside the band by introducing additional frequency weights. Besides, it is noteworthy that impulsive TVC

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