Journal of Multidisciplinary Engineering Science and Technology (JMEST)
ISSN: 2458-9403
Vol. 3 Issue 8, August - 2016

Finding Cyclic Frequency In High-Frequency Broadband Via Fundamental Tonal In Low-Frequency Band For Unmanned Underwater Vehicle Warning System

Seungnam Kim[a], Yeon-Mo Yang[b]
[a]Electronic Eng., Korea Polytechnic University, Siheung-Si, Korea
[b]School of Electronic Eng. Kumoh National Inst. of Tech., Korea
[a]snkim01@kpu.ac.kr, [b]yangym@vivaldi.kumoh.ac.kr

***Abstract*— An unmanned underwater vehicle (UUV) or torpedo warning system is essential for the ships to detect UUVs and maneuver to avoid them as quickly as possible. To satisfy this requirement, the Detection of Envelope Modulation on Noise (DEMON) process and other processes are employed in many situations for passive sonar systems. In this paper, a new method for a UUV warning system is introduced. This new process is similar to others in that it uses beamforming; however, additional hydrophone sensors and accelerometers are employed to overcome the deficiencies of other methods. In the low-frequency band, the analysis of these additional sensors reveals a cyclic frequency that is related to the UUV propeller rotation and can easily be found in the high-frequency band resulting from beamforming.**

Keywords— Detection of Envelope Modulation on Noise (DEMON); unmanned underwater vehicle (UUV) propeller rotation; beamforming; accelerometer; cyclic frequency; detection

I. INTRODUCTION

An unmanned underwater vehicle (UUV) or torpedo warning system is essential for the ships to detect UUVs and maneuver to avoid them as quickly as possible. The main function of a UUV warning system is to indicate the existence and location of UUVs. To satisfy these objectives, many passive UUV warning systems have been developed and operated. For example, the Detection of Envelope Modulation on Noise (DEMON) [1, 2, 3] process is employed in many situations for passive sonar systems. In principle, the DEMON process is a frequency-shift process from the high-frequency band, which is corrupted by broadband noise in underwater situations, to the low-frequency band, which is referred to as the envelope signal of the signal received by the sonar system. The shifted frequencies of the signal result from various acoustic sources. One of the frequencies is related to the rotation speed of the propellers of the UUV, which is a critical factor in determining whether a UUV-generated acoustic signal exists. Other frequencies, which are generated by the mechanical movements of the ship and their harmonics, are difficult to use for the detection of UUVs [4]. Another process for detecting UUVs involves finding a cyclic frequency in the higher spectrum band without a frequency shift to the lower band. The cyclic frequency, which may be due to the rotation speed of the UUV propellers, is modulated by the high frequencies generated by the explosion of air bubbles, i.e., the cavitation effect [5, 6]. Because there are modulated harmonics of the rotation speed in the higher spectrum band, finding cyclic frequencies is the same as determining the rotation speed, without a frequency shift to the lower spectrum band, in contrast to DEMON. However, in the higher spectrum band, there are many spike-like frequencies, making it difficult to detect the existence of the cyclic frequency due to the UUV propeller rotation.

In this paper, a new method for a UUV warning system as a passive sonar system, which alleviates the real-time computing load, is introduced. To satisfy the main objective of warning systems, that is, detecting the existence and the angle of a UUV location, we introduce two types of sensors operating in different spectrum bands. In the lower spectrum band, to determine the rotation speed of the UUV propellers, various acoustic and mechanical sensors are introduced. In the higher spectrum band, to determine the angle location, a beamformer comprising multiple linear acoustic sensors is introduced. Hence, the existence of a UUV is determined by the existence of a cyclic frequency in the lower band, and the angle location is identified by the beamformer, in which the beam indicates the existence of the cyclic frequency.

In Section II, the modeling of a UUV acoustic sound is introduced to explain the amplitude modulation of tonal and its harmonics due to the UUV propeller rotation. To determine the angle of a UUV location for a passive sonar system, one of the constraints on the aperture size of the beamformer is analyzed. With the limited aperture size, the signal generated by the beamformer eventually enters in the high-frequency band, making it difficult to distinguish the tonal. Hence, new sensors are introduced to find the tonal not in the high-frequency band but in the low-frequency band. In Section III, a flowchart of the proposed method is presented, and one of the validation examples is introduced. Section IV is the conclusion.

II. PROBLEM STATEMENTS

A. *Underwater acoustic sound modeling*

UUVs generate acoustic signals underwater mainly because of their rotating propellers. These acoustic signals can be described as follows [7]. Let m(t) be the acoustic signal generated by a UUV. It is an amplitude-modulated signal, as follows:

$$m(t) = \left[1 + \sum_{i=1}^{N} A_i \cos(2\pi i f_r + \varphi_i)\right] n_c(t),$$

where N is the number of propeller blades, f_r is the rotation speed of the propellers, and n_c (t) is the cavitation noise. The other terms represent the amplitudes and phases. The rotation speed f_r is usually less than 100 rps and is precisely determined. However, the cavitation noise n_c (t) is stochastic, and its spectrum is broadband in nature and far higher than f_r, on the general order of O(KHz) to O(100KHz), depending on the UUV depth and the shape of the blades. Hence, the spectrum of the acoustic signal is decomposed in two parts: the deterministic nature of the rotation speed of the propellers and the stochastic nature of the cavitation noise, which is broadband. In [8], the author illustrates the spectrum of the underwater sound generated by a submarine as shown in Fig. 1.

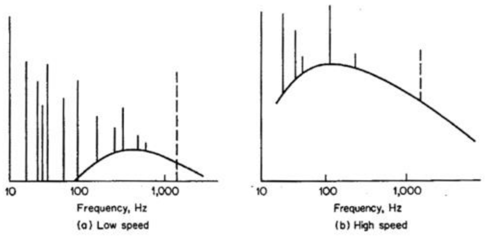

Fig. 1. *Diagrammatic spectra of submarince noise at two speeds*

The spectrum consists of the lines and broadband. The lines (called tonal), which are deterministic in nature, are due to mechanical noise, including the propeller rotation of the ship and the combustion-engine vibration of the ship and UUV. The broadband, which is stochastic in nature, is due to the cavitation caused by the own ship or a UUV. If the lines in the broadband are separated by a constant value (e.g., f_r in the UUV acoustic signal), the frequency is called a cyclic frequency [6].

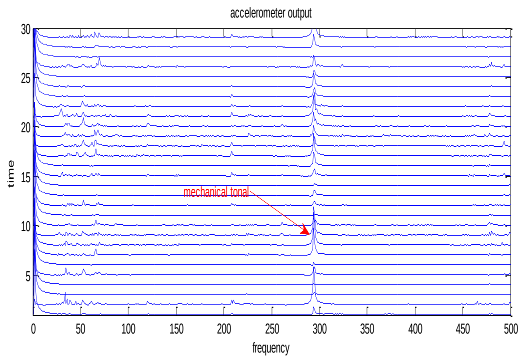

Fig. 2. *Output of an accelerometer attached to a cruise ship*

In principle, the objectives of the UUV warning system are to characterize the tonal, determine whether it is generated by a UUV, and locate the detected UUV in which the angle of UUV is located.

B. *Constraint on the beamformer*

One of the main functions of the UUV warning system is to determine the angle of a UUV location in order for the ship to maneuver away from the UUV. In a passive acoustic system, an acoustic beamformer is implemented using various sensors. One of the characteristics of a beamformer is the beam width. In general, the beam width is determined by the physical structure of the beam aperture and the pre-determined acoustic frequency of interest. For example, for a uniform distributed linear aperture beamformer of length L(m) and frequency of f_in, the 3-dB beam width φ_3dB is given as [9]

$$\varphi_{3dB} = \sin^{-1}\left(0.885\,\frac{\lambda_{in}}{L}\right) \approx 50\frac{\lambda_{in}}{L} \quad (\text{deg}),$$

i.e.,

$$L \approx \frac{50}{\varphi_{3dB}}\lambda_{in} \quad (\text{m}).$$

Hence, the aperture length L is proportional to the acoustic wave length λ_in for the fixed beam width of φ_3dB. We assume φ_3dB =5 (deg), for example. Then, if the acoustic-wave frequency is 1,000 Hz, the wavelength λ_in is

$$\lambda_{in} = \frac{\text{speed in wter}}{f_{in}} \approx \frac{1500}{1000} \ (\text{m}).$$

Hence, the aperture length L is

$$L \approx 15 \ (\text{m}),$$

which is reasonable to implement for a typical UUV warning system. However, if the acoustic-wave frequency is 100 Hz, e.g., in the low-frequency band range, the length L is 150 m, which is difficult for realizing a beamformer for a UUV warning system. As this physical constraint determines the angle of the UUV location, the beamformer should be designed for a higher frequency range, i.e., >1,000 Hz.

C. *Cyclic frequency in the lower band*

The other objective of the UUV warning system is to indicate the existence of UUVs. The existence of a UUV may be determined by the existence of the tonal, which corresponds to the UUV propeller rotation speed f_r. As the output of the beamformer steered to a specific angle to find the UUV location is in the higher frequency range, which is broadband as previously stated, owing to the physical constraint of the aperture size, it may be difficult to find the tonal in the high-frequency band.

Instead, in this study, the low-frequency band tonal is found. In the low band of an acoustic signal, there are lines due to the UUV propeller rotation and others caused by the mechanical vibrations of the ship, etc. One of methods for distinguishing the lines in the low band is the DEMON process, e.g., squaring and filtering the output of hydrophones [2]. The acoustic signal generated by the hydrophones includes not only the UUV propeller rotation but also the mechanical noises of the ship. For example, if a hydrophone is attached to the ship, there are noises due to the structural vibrations of the ship. These noises are represented by lines or bands in the frequency domain; the lines corresponding to the UUV propeller rotation should be differentiated from the lines due to the noise caused by the ship.

In this paper, two types of sensors are introduced to find lines (i.e., tonal) in the low-frequency band. One is a hydrophone for sensing low-frequency acoustic sound, and the other is an accelerometer for eliminating the tonal generated by the mechanical vibrations of the ship. The output of the hydrophone consists of not only the acoustic sound but also the acoustic pressure variances caused by mechanical vibrations. For this purpose, an accelerometer is attached to the same place as the hydrophone for a low frequency. Fig. 2 illustrates the output of an accelerometer bound to the same plane as the beamformer, which is attached to the side of a ship. The visible tonal is around 300 Hz, which may be generated by the mechanical vibrations and in turn appears in the output of the hydrophone. Hence, the cyclic frequency fr , which is the rotation frequency, is determined by subtracting the tonal of the hydrophone from the tonal of the accelerometer.

III. NEW SHEMES

A. Proposed UUV detection scheme

The scheme proposed in this paper is divided into two parallel processes. To find the tonal generated by UUV propeller rotation, a hydrophone and an accelerometer are simultaneously employed. Finding the angle of the UUV location involves determining which angle is contained the UUV propeller rotation speed, i.e., the cyclic frequency.

First, in the lower band the hydrophone can be utilized to find various tonal (mode). Let these tonal denote as Tonal$_{hydro}$. It may be composed by Tonal$_{Hyd_selfship}$, Tonal$_{Hyd_selfship}$, and Tonal$_{Hyd_others}$, which are generated due to acoustic pressure by the self ship's mechanical vibration, the UUV and other ships respectively. Simultaneously using the accelerometer the tonal generated by the self ship's mechanical vibration Tonal$_{Acc_selfship}$ can be to find, since Tonal$_{Acc_selfship}$ is equivalent to Tonal$_{hyd_selfship}$, so that it maybe be possible to cancel the self ship's mechanical noise tonal.

Between the tonal Tonal$_{Hyd_UUV}$ and Tonal$_{Hyd_others}$, it should be decide which tonal is generated by the UUV. These can be solved by the beam former. In the higher band, at the specific beam angle possibly the UUV being located, which may be determined taking into account the maximum acoustic energy by the beam former, if there may be only the UUV in, there may be only tonal as Tonal$_{Hyd_UUV}$. Hence to decide the existence the cyclic frequency (harmonics of tonal Tonal$_{Hyd_UUV}$) due to the UUV propeller rotation at the specific beam angle, is to check the periodicity of TonalHyd_UUV or Tonal$_{Hyd_others}$. If the periodicity may be found one of Tonal$_{Hyd_UUV}$ or Tonal$_{Hyd_others}$, corresponding tonal may be generated by UUV.

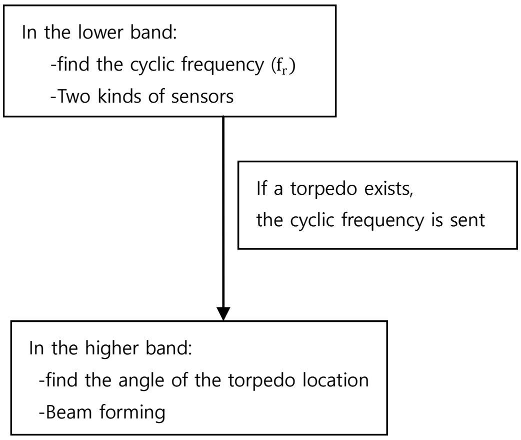

Fig. 3. *Flowchart of the proposed UUV warning system*

B. Validation of the proposed scheme

Because it is difficult to obtain a real UUV acoustic sound, in this study, UUV acoustic-sound data published by www.sonatech.com are reviewed. The data from Sonatech represent a real UUV sound recorded during an initial firing, the closing of the outer hatch, and an explosion. The operating time is ~41 s. In Fig. 4, the data are sampled as acoustic signals, where the initial firing, the closing of the outer hatch, and the explosion are represented. These data are filtered and processed appropriately, and the resulting data in the frequency domain are depicted in the spectrogram of Fig. 5.

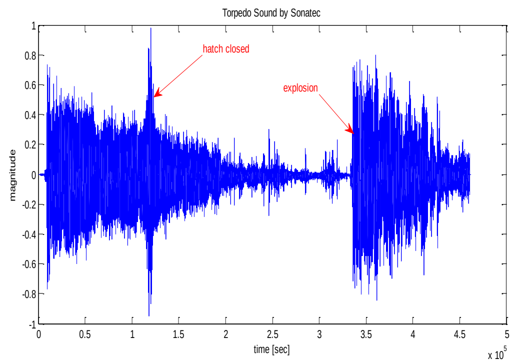

Fig. 4. *Real UUV acoustic sound from Sonatech*

In this spectrogram, there is a clearly correlated tonal in the lower band and in the high band as time goes by. In the lower-band tonal, there are five noticeable tonals separated by ~70 Hz. These may indicate the fundamental frequency and the 2nd, 3rd, 4th, and 5th harmonics. Hence, it may be concluded that the fundamental frequency around 70 Hz is the UUV propeller rotation speed. In the higher band tonal modulated by the cavitation, there are two noticeable tonals separated by 7 times the fundamental frequency. However, the high-band tonal is not bright compared with the low-band tonal, and there are not as many lines as in the lower tonal. Because the data may have been recorded by a single hydrophone sensor and may not have been beam-steered by a beamformer, which in general multiple hydrophones are used to have a better signal-to-noise ratio with respect to this high-frequency band. This may be the reason why the high-band tonal is unclear compared with the low-band tonal. However, in the case of a beamformer, the signal-to-noise ratio in the high band may be increased by increasing the number of hydrophones, whereby it may be easy to identify the existence of the tonal and verify the interval of the tonal to be the cyclic frequency.

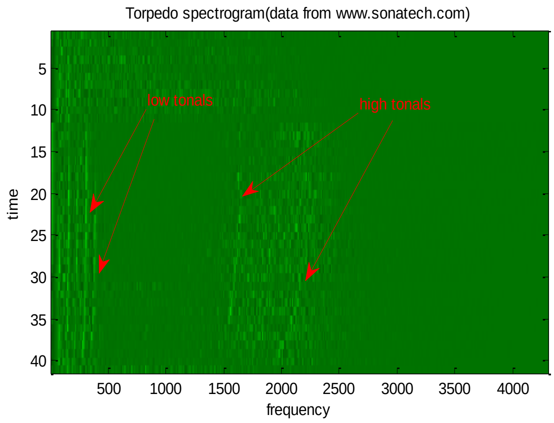

Fig. 5. *UUV acoustic spectrogram*

IV. Conclusion and Further Studies

The main functions of a UUV or torpedo warning system are to indicate the existence of UUVs and the angle of the UUV location. Various methods have been developed to improve these functions. The method introduced in this paper is similar to previous methods in that it employs beamforming but differs from the previous methods because it uses additional sensors to determine the cyclic frequency in the lower band.

X. Acknowledgment

" This paper was supported by Research Fund, Kumoh National Institute of Technology."

References

[1] Luo Xinwei, Fang Shiliang, "An method for demodulation from non-stationary amplitude modulated broad band signal", ICISE, 4-6 Dec. 2010 2nd international Confrence.

[2] Kil Woo Chung, Alexander Sutin, Alexander Sedunov, and Michael Bruno, " DEMON Acoustic Ship Signature Measurements in an Urban Harbor", Hindawi Publishing Corporation. Advances in Acoustic and Vibration, Volume 2011, Article ID 952798, 13 pages.

[3] Dsa, "Classification of ships using underwater radiated noise", Communications and Signal Processing, 1988. Proceedings., COMSIG 88. Southern African Conference on 24 Jun 1988.

[4] JinSeok Kim,Soo bok Hwang, and Cul Mok Lee, " A DEMON Processing Robust to Interference of Tonals", The Journal of the Acoustic Society of Korea, Vol. 31, No.6(2012)

[5] Jaekwon Jung, Seung-Jae Lee, and Jae-Moon Han , "Study on Correlation between Cavitation and Pressure Fluctuation Signals Using High-Speed Camera System", Proceedings of the 7th international Symposium on Cavitation, CAV2009-Paper No.#27.

[6] D.Hanson, J.Antoni, G.Brown, and R.Emslie, "Cyclostationarity for Passive Underwater Detection of Propellor Craft: A Development of DEMON Processing", Acoustic 2008, Geelong, Victoria,Australia 24 to 26 Nov. 2008.

[7] Fei Bao, Xinlong Wang, and Zhiyong Tao, "Adaptive extraction of modulation for cavitation noise", J. Acoustic. Soc. Am.126 (6), December 2009.

[8] Robert J. Urick, " Principles of Underwater Sound", 3rd . Peninsula Publishing, 1983. Chaper 10.

[9] M.A.Mazur , "Spatial Signal Processing(Beamfroming)", www.personal.psu.edu/faculty/m/x/mxm14/sonar/beamforming.pdf