Estimating the Position of Underwater Targets Based on the Emission of Noise Caused by Spinning the Propeller of Surface Vessels

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***Abstract*—The purpose of this article is to localize the underwater targets based on the reflecting the noise of the commercial ships propeller rotation from the targets. Full details of the commercial ships including the type of ships, their speed and geographic location are available using satellites and global positioning system (GPS). The proposed method has fewer challenges and limitations than existing mechanisms such as wireless sensor networks. In the proposed technique, the produced noise of spinning propellers (in cavitation or non-cavitation mode) plays the role of pings in active sonars. The noise is continuously released from the propeller and is reflected from the underwater targets. The recurrent echo is continuously received by the towable hydrophone array. The geographic location of this array is available at any moment. Using the existing localization algorithms, position of target is determined. So this idea uses the existing signals in the environment for target localization. The proposed method was simulated by the COMSOL and MATLAB.**

Keywords*—*Active sonar, Localization, Spinning propellers, Towable hydrophone array, Underwater targets

I. Introduction

Identifying the location of inanimate objects and underwater animals such as pieces of airplanes dropped in the water, submerged vessels, underwater mammals and so on as well as population density of underwater animals is very important. Today the methods used for these goals are sonar-based. This paper proposes an idea that examines and simulates the noise propagation ability of a ship propeller to identify the underwater targets. Along with active sonar, this idea can be used as an object location estimator. It is worth noting that the proposed method has lower limitations and higher speed than the active sonar (In active sonar all angles must be mechanically scanned, but in the proposed method it is software-driven). Other advantages of the proposed method compared to the active sonar are larger bandwidth and no need for a transmitter.

The passive localization of an unknown acoustic source in shallow water is an important and challenging problem that has received considerable attention. Various schemes have been developed which work not only in idealized simulations but also in realistic scenarios that include studies discussing the passive localization [1-7]. Also existing passive localization methods use three types of physical measurements: time delay of arrival (TDOA), the direction of arrival (DOA), and received signal strength or energy. DOA can be estimated by extracting the phase difference measured at receiving sensors [8]. TDOA is suitable for broadband acoustic source localization and is also applicable for the acoustic source that emits a coherent and narrowband signal. It has been extensively investigated in [8]. Also, the localization algorithms related to the DOA category, such as MUSIC, ESPRIT, ROOT MUSIC and MVDR are reviewed in [9-11]. There are other famous localization methods such as matched field processing (MFP) [12], that are not included in these three categories. The MFP algorithm has commonly used in shallow underwater for source detection and localization by applying a vertical or horizontal array of hydrophones.

In this paper, we focus on the target location estimation using an innovative passive technique in heterogeneous underwater medium. Due to the simulations, the proposed method has reasonable resolution despite some challenges in shallow water area. The remainder of this paper is organized as follows.

In the section II, underwater signaling methods are described. The types of noise generated by spinning propeller and challenges of underwater acoustic channels are defined in the section III and the section IV, respectively. Simulation results are presented in section V. Finally, the conclusions are presented in section VI.

II. Underwater Signaling Methods

Most existing active sonar methods use pulse signals, such as linear frequency modulated (LFM) signals, hyperbolic frequency modulated (HFM) signals and generalized frequency-modulated (GFM) signals. The sonar receiver has to listen for a long time to detect targets after a pulse was transmitted. Due to the low speed of sound in underwater, a large pulse repetition interval (PRI) is necessary to distinguish the target echoes of contiguous sonar pings. Otherwise, target range ambiguities will be caused. We introduce some conventional underwater signaling methods in the sections A-C.

A. Linear Frequency Modulation Signal

The LFM signal is widely applied in communications, radar, sonar, and many other fields as a special non-stationary signal. The LFM waveform which is commonly known as linear chirp, has good range resolution and more Doppler tolerant than nonlinear frequency modulation (NLFM) [13].

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The complex exponential version of the LFM waveform is formulated as follows.

$$S(t) = \exp(j\,2\pi(f_0 + k\,t^2)), \quad (1)$$

where f_0 is the Carrier frequency, k is chirp rate, $t \in [0,T]$ and T is the length of transmitting signal.

B. Hyperbolic Modulation Frequency Signal

Under the condition of the strong Doppler Effect, the Doppler resistance of the HFM signal is better than that of the LFM signal [14]. The HFM signal with rectangle envelop is presented as follows.

$$S(t) = \frac{1}{\sqrt{T}}\,\mathrm{rect}\,(\frac{t}{T}) \times \exp\left(-j\,2\pi k\,\ln(1-\frac{t}{t_0})\right), \quad (2)$$

where $t_0 = \frac{f_0 T}{B}$, B is bandwidth of signal and rect(.) denotes the rectangular function.

C. Generalized Frequency-Modulated Signal

Equation (3) presents the GFM signals definition [15].

$$\begin{cases} S(t) = A\,\alpha(t)\exp\left(j\,2\pi(c\,\xi(t/t_r) + f_0\,t)\right) \\ 0 < t < T\,, \end{cases} \quad (3)$$

where $\xi(t/t_r)$ is the phase function, f_0 is the Carrier frequency, A is the amplitude, $c \in \mathbb{R}$ is the frequency modulation (FM) rate, $\alpha(t)$ is the modulation index and t_r is a positive reference time.

To detect the underwater moving targets in the active sonar systems, the methods LFM, GFM and HFM have poor performance, because the bandwidths of them are not wide enough for detection. Also, they cannot remove the undesirable signals easily in the shallow water region where the influence of noise and reverberation are large. In addition, they require a lot of energy for detection and have hardware limitations. But the continuous active sonar transmits a 100% duty cycle waveform to illuminates targets continuously in order to improve detection performance. In this paper, we propose a new continuous signaling method for underwater identification, based on the emission of noise caused by spinning the propeller of surface ships.

III. Propeller Noise of Ships

Nowadays, ships and submarines that are more than 30 meters in length, are mainly driven by a mechanical system in the water, which includes a propeller. A large portion of energy of the propeller is released in the form of acoustic waves in water. The sources of noise emission in ships are divided into following categories [16]:

- The parts of the driving force generators include engine, gear, piston movements and combustion system of cylinder.
- Spinning propeller.
- Movable accessories include generator, ventilation system and pumps.
- Hydrodynamic effects.

The noise produced from the spinning propeller is one of the most energetic noises due to the ship moves. The rotation of the blades causes the cavitation phenomenon. In the cavitation, rapid changes of pressure in a liquid lead to the small vapor-filled cavities formation in places where the pressure is relatively low. At higher pressures, these cavities, called "bubbles" or "voids", collapse and can generate an intense shock wave. Fig. 1 shows the cavitation.

The basic equation for sound propagation is the Lighthill equation obtained from the continuity and momentum equations [17]. Then, the two-step Fflowcs Williams and Hawkings (FW-H) equations are used to calculate hydrodynamic pressure. The FW-H is a developed solution of the Lighthill equation. The FW-H formulation is represented in (4) [17].

$$\frac{\partial^2 P'}{\partial t^2} - c^2 \frac{\partial^2 P'}{\partial x_i^2} = \frac{\partial q}{\partial t} + \frac{\partial f_i}{\partial x_i} + \frac{\partial^2 \tilde{\tau}_{ij}}{\partial x_i \partial x_j} \quad (4)$$

The terms in the right side of (4) from left to right are called monopole, dipole, and quadruple sources, respectively. P' is the sound pressure at the far-field, c is the far-field sound speed and $\tilde{\tau}_{ij}$ is the Lighthill stress tensor defined in (5). f=0 indicates the moving surfaces.

$$\tilde{\tau}_{ij} = \rho u_i u_j + p_{ij} - c^2 \rho\,\delta_{ij}\,, \quad (5)$$

where δ_{ij}, ρ, u_i and p_{ij} are Dirac delta functions, density, velocity component and the turbulence velocity fluctuations, respectively. The FW-H acoustics model in ANSYS/FLUENT14.5 and COMSOL codes allow you to select multiple source surfaces and receivers. The main purpose of the cavitation physical model is to extract mass fraction of the vapor and liquid phases. In this study, we used the COMSOL Software for solving the FW-H equation.

IV. Underwater Acoustic Channel Characteristics

Underwater acoustic channels are generally recognized as one of the most difficult communication medium. Acoustic propagation is characterized by three major factors: attenuation that increases by increasing signal frequency, time-varying multipath propagation, and speed of sound [18]. A distinguished property of acoustic channels is the fact that path loss depends on the signal frequency. This dependence is a consequence of absorption. In addition to the absorption loss, signal experiences a spreading loss, which increases by increasing distance.

Fig. 1. Cavitation phenomenon.

In the underwater medium, the factors water salinity, temperature and pressure make the sound speed dependent on the depth [19]. There are some techniques used to measure the sound speed in different depths of water. The graph known as sound speed profile (SSP) presents the dependence of sound speed on the depth. In fact, variation of sound speed makes the acoustic wave bends and propagates along a curve.

Noise in an acoustic channel consists of ambient noise and site-specific noise. Ambient noise is always in the background of the quiet deep sea. Site-specific noise, on the contrary, exists only in certain places. For example, ice cracking in Polar Regions creates acoustic noise as do snapping shrimp in warmer waters. The ambient noise comes from sources such as turbulence, breaking waves, rain and distant shipping. The ambient noise is often approximated as Gaussian, it is not white. Unlike the ambient noise, site-specific noise often contains significant non-Gaussian components.

Multipath formation in the ocean is made by sound reflection at the surface, bottom and any targets in the water.

There are two sources of the channel time variability: inherent changes in the propagation medium (i.e., variable sound speed with depth) and those that occur because of the transmitter/receiver motion (i.e., Doppler spreading due to the changing path length).

In this study, the effects of acoustic attenuation, the reflection from the ocean surface, bottom and target and the SSP model for simulation are considered, and other challenges are neglected.

V. Simulations

In order to simulate the underwater environment, we have used the 3D model wizard in COMSOL software. All the conditions of the true ocean environment are taken into account in the COMSOL. Then, for localization we used the MATLAB software. The geometries of the objects are defined in the sections A-D.

A. *Propeller Geometry*

The properties of vessel propeller are shown in Fig. 2. This propeller is designed in the CAESES software. Then, the created model is loaded into COMSOL with the coordinates (480 m, 50 m, 5 m) of ocean. Its material is defined as aluminum with sound speed 6320 m/s.

B. *Ocean Geometry*

The ocean geometry is considered as a 3D cube with dimensions 1000 m in length, 100 m in width and 500 m in depth. Ocean water features are defined according to Table I. The Francois and Garrison equations have been used to model the sound attenuation in the ocean environment. Also, the sound speed in the water follows the sound speed profile according to Fig. 3.

Parameter	***Value***
Number of blades	4
Skew angle	30 degrees
Diameter of propeller	4 m
Rake angle	0 degrees

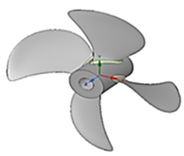

Fig. 2. Schematic of propeller designed in CAESES Software.

TABLE I. Ocean Water Features

Features	**Value**
Temperature	293.15 K
Salinity	0.2 g/kg
pH	8
Sound speed in water	According to sound speed profile
Water density	1000 kg/m^3

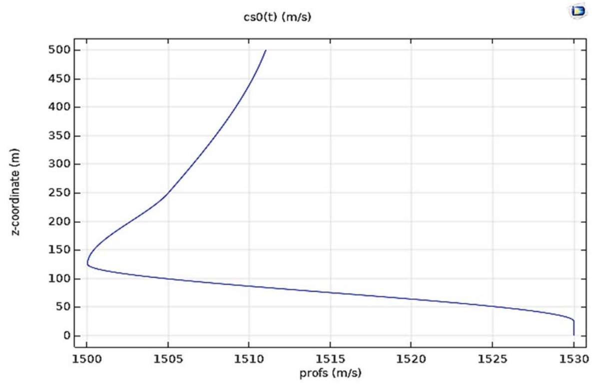

Fig. 3. Profile of sound speed.

C. *Air Geometry*

Top of the ocean surface is filled by a three-dimensional cube of air with sound speed of 350 m/s, viscosity of 1 Pa/s with dimensions 1000 m in length, 100 m in width and 10 m in depth.

D. *Target Geometry*

We defined a target (hollow sphere) with radius of 1 meter in the depths of the ocean with the coordinates (200 m, 50 m, 100 m).

E. *Results*

In this section, the acoustic physics of the problem is determined. We entered the FW-H equation and initialized the parameters of the problem with boundary conditions. Then, the total geometry of the problem was meshed. To increase the processing speed, the ocean and air environments were meshed with coarse resolution. Also, the propeller and the target were meshed with fine resolution. Fig. 4 shows an overview of the meshed geometry of the problem in the 3-dimensional model by COMSOL.

Finally, after implementing and running the problem, the pressure diagrams in terms of frequency and ocean dimensions, and also pressure on the propeller blades were extracted. The diagrams are shown in Figs. 5-8.

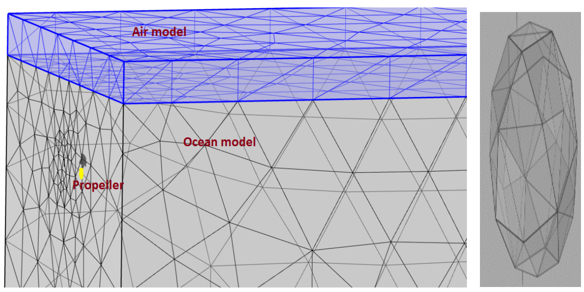

Fig. 4. An overview of the meshed geometry of the problem.

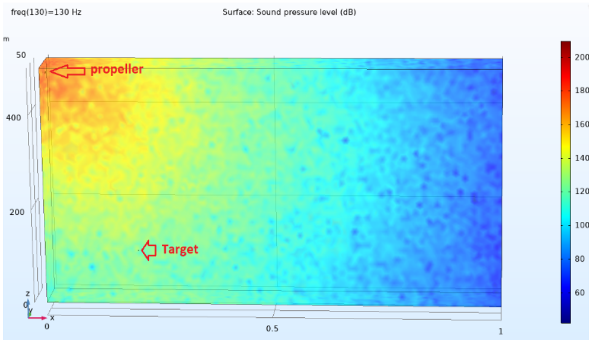

Fig. 5. Sound Pressure Level which produced by a spinning propeller in the ocean environment at frequency 130 Hz.

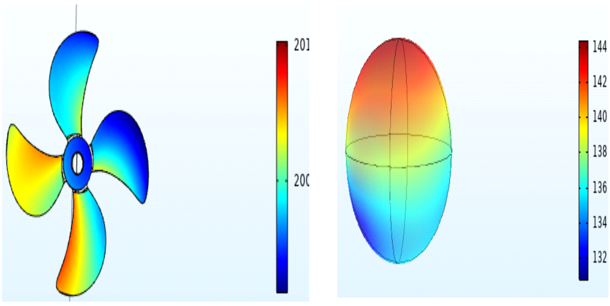

Fig. 6. Sound Pressure Level which produced on surface of blades and target at frequency 130 Hz.

F. Localization test

In this section, we positioned a uniform and vertical linear array of four hydrophones with a distance of 5 m from each other (this distance follows from (6)). The coordinates of hydrophones are given in TABLE II.

$$d \leq \frac{\lambda_{\min}}{2}, \tag{6}$$

where d is the distance between the two hydrophones and $\lambda_{\min}$ is the minimum value of wave length. The frequency responses of the hydrophones are shown in Fig. 9.

Finally, by calculating the Fourier transform and employing a simple localization algorithm based on the highest correlation (presented in (7) and (8)) by MATLAB simulation, the position of target and propeller have been identified. In this test, the target and propeller are located at angles of 125 degrees and 85 degrees relate to the length of array, respectively.

$$\tau = \arg\max_{\forall t}\left(r''_{y_1 y_2}(t)\right) \tag{7}$$

$$\tau_L(\theta) = \frac{d \times (L-1) \times \cos(\theta)}{C}, \tag{8}$$

TABLE II. POSITIONS OF HYDROPHONES

	Location (Z)	Location (Y)	Location (X)
Hydrophone #1	250 m	50 m	400 m
Hydrophone #2	245 m	50 m	400 m
Hydrophone #3	240 m	50 m	400 m
Hydrophone #4	235 m	50 m	400 m

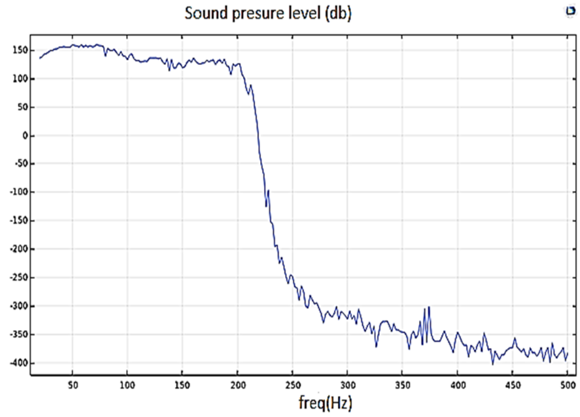

Fig. 7. Frequency band of sound pressure level.

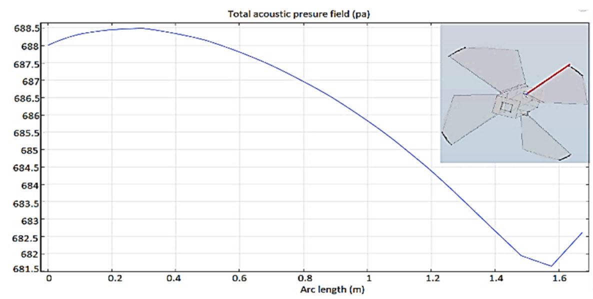

Fig. 8. Sound Pressure Changes on the marked edge.

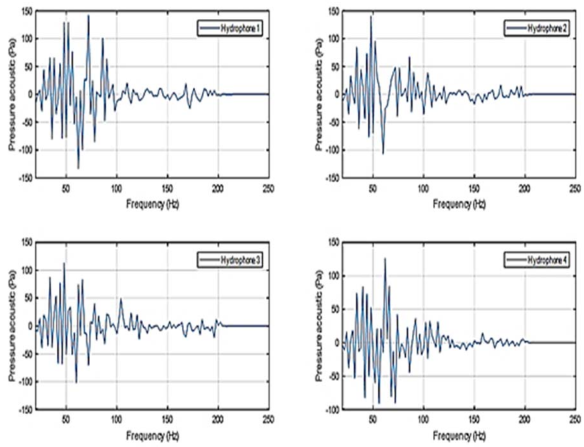

Fig. 9. Frequency responses of the hydrophones.

where L, $r''_{y_1 y_2}(t)$ and C are hydrophone number in the array, cross-correlation and the sound speed, respectively.

In Fig. 10, peaks represent approximately the identified position of the target and propeller (approximately 75 degrees and 125 degrees, respectively).

VI. CONCLUSION

In this paper, the use of the noise generated by the spinning propeller to detect the positions of the underwater targets was proposed (similar to the Passive sonar). The simulation results showed that the proposed idea can estimate the positions of the underwater targets by using a hydrophone array, with considering the effects of acoustic attenuation, the reflection from the ocean surface, bottom and target, and also the SSP model. The proposed technique is a new continues signaling

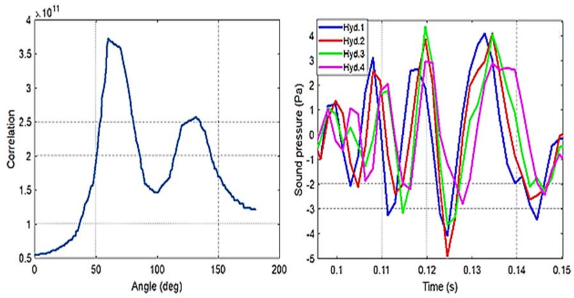

Fig. 10. The time responses of the hydrophones and detected positions.

method that have fewer limitations than other signaling methods such as LFM.

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