DIVER RANGE ESTIMATION BASED ON SHALLOW WATER CAVITATION

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ABSTRACT

There are many underwater passive algorithms used to determine the range of a target like a diver, using its acoustic signals which are radiated through underwater environment. In this paper, we introduce a new underwater diver range estimation algorithm based on shallow water cavitation. Through this algorithm we apply diver's bubble oscillation frequency and ocean surface bubble's behaviour as two new carrier frequencies for our proposed method. Then, we utilize a dual frequency technique with the above new carrier frequencies, due to its robustness to shallow water noise, in time-frequency domain, yields to a new passive range estimation algorithm. We demonstrate through real data simulations that this algorithm is suitable for passive diver range estimation in shallow water environment. We used SWeIIEx-96 experiment data to compare our simulation result.

***Index Terms*—** Diver Range Estimation,Shallow Water Cavitation, Dual Frequency

1. INTRODUCTION

There exist many underwater passive range estimation algorithm that have been extended during the past decades. Most of these algorithms like bearing of arrival (BOA), time of arrival (TOA) and time delay of arrival (TDOA) are geometry-calculations based to obtain target range estimation according to time difference of target's radiated signals from sensors [1], [2], [3]. In addition, it is well known that the underwater environment is infested with interference, ambient, and thermal noise, and also high degree of lowpass nature of the reverberation underwater channel. Therefore, the target parameters estimation like range and depth in underwater environment requires more computation. On the other hand, in shallow water, noise power, reverberation effects, and frequency absorption [11] are minuscule, hence, better range estimations for divers are possible. As discussed above, there are some small amount of different anomaly phenomena in shallow water environment which makes range estimation a complicated task. Having taken these phenomena into consideration there exist some algorithms for anomaly cancellation that improve range estimation for shallow water environment [7]. Due to human nature, divers in different scenes are an important group of underwater targets. Perhaps due to very low SNR for divers [6] there is a small amount of research on diver's parameter estimation and localization in shallow water environment. In [5], the authors showed a new passive detection method for divers with open breathing system. The main source of acoustic signals of a diver is its breathing system which produces low frequency cavitation in shallow water environment. We will show later that the diver's emitting signals which produce bubbles have low frequency features travel long distances in shallow water environment, due to shallow water little absorption features. This behaviour shows that divers range estimation is to some extent different from other target range estimation methods which are based on time domain analysis using time delay approach.

The focus of this paper is to use phase estimation to determine the range of divers with open breathing systems emitting acoustic low frequency signals by using dual frequency method with two new carrier frequencies. This is plausible methodology because of diver's behaviour that correspond almost nearly to shallow water environment. In signal processing techniques, the phase of a signal is more robust to underwater noise and reverberation than amplitude. This capability permits us to apply dual frequency approach on the received signal to estimate the range of a diver. Time-frequency analysis is the corner stone of our new approach because of the ability to estimate the diver's Doppler frequency [8]. Therefore we utilize a dual-frequency technique in time-frequency domain because it provides the phase information of the received acoustic low frequency signals that is necessary for range estimation in shallow water environment. Finally, combining phase and Doppler information of diver radiating signals, we obtain the range of diver.

This paper consists of seven sections. In section 2 we describe underwater signal attenuation behaviour in shallow water environment, and in section 3 we will explain about the shallow water carrier frequencies which consist of diver's bubble oscillation frequency and ocean surface bubble radiated frequency that are used for our algorithm. In section 4, we formulate acoustic model of diver's radiating signals using those two carrier frequencies. In section 5 we evaluate the sensitivity of initial range. Simulation result is shown in section 6 to demonstrate the effectiveness of our algorithm. Conclusion is given in the final section of this paper.

2. UNDERWATER SIGNAL ATTENUATION FEATURE

The first step to analyse the signal transmission in underwater environment is to determine the shallow water acoustic attenuation features. The signal received at hydrophone is different from the radiated signal because of noise which is highly dependent upon the underwater channel features. Understanding these features provides the opportunity to gain information of the radiated signal. There are different levels of power absorption in underwater environment that change with depth, frequency and temperature. When an underwater source propagates an acoustic sound, its power intensity will diminish to some extent because of this mentioned absorption [4]. Xavier [11] shows that the attenuation increases rapidly with frequency

$$\alpha = C_1 \frac{{f_1}^2 f^2}{{f_1}^2 + f^2} + C_2 \frac{{f_2}^2 f^2}{{f_2}^2 + f^2} + C_3 f^2 \tag{1}$$

by factoring out f^2 from (1) we notice the proportionality to square of radiated frequency as follows

$$\alpha = k f^2 \tag{2}$$

where α is attenuation coefficient and C_1, C_2 and C_3 depend on viscosity, temperature and pressure of water. Since the diver's acoustic radiated signals are low frequency signals, the attenuation will decrease because of the presence of low frequency features as seen from (2). Diver's shallow water frequencies are useful handles for range estimation in far distances in contrast to other underwater targets that propagate high frequency acoustic signals.

3. SHALLOW WATER CARRIER FREQUENCY ACQUISITION

According to dual frequency method, we need two carrier frequencies to obtain the phase difference of received signals.These frequencies are consist of diver's bubble oscillation and ocean surface bubble oscillation.Because of our passive scenario for shallow water diver range estimation, we consider these two carrier frequencies in our algorithm as follow.

3.1. Diver's Bubble Oscillation

When a diver swims in shallow water environment, his breathing open system makes group of bubbles that lead to propagation of acoustic sound regularly. This regularity is due to its breathing system which consists of two regular and continuous processes, inhaling and exhaling. The first one is insertion of air into the diver's valve and the last one is when he emits it to the limited water surrounding him which is more compressed in contrast with the first state(breathing gas cylinder). By exhaling the compressed air into the water, a group of bubbles will be generated that make a low frequency sound by their volume pulsations in the water. These bubbles have natural frequency about 2kHz and a pick frequency in 1.5 kHz which is generated by its pulsation in shallow water environment and will be used as first carrier frequency in our algorithm. Using the equation of frequency pulsation that is given by [12] will show the advantage of shallow water environment property

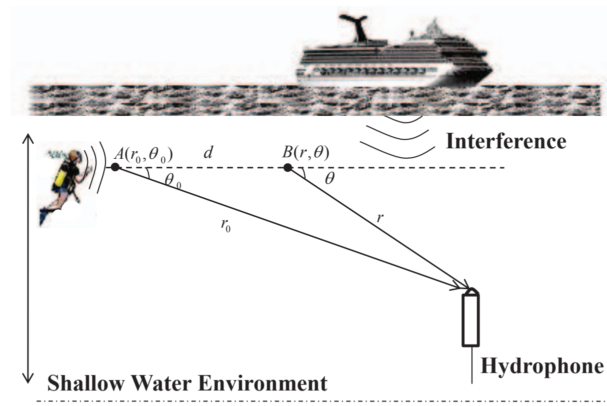

Fig. 1. Typical scenario for shallow water diver range analysis problem.

$$f \propto \sqrt{P} \tag{3}$$

where f is frequency of shallow water radiated signal. The pressure of water, P, around the bubbles and consequently the frequency of pulsation, is changed by the bubble generation depth. In shallow water environment, the pressure around the bubbles leads to a low frequency bubble oscillation because of its little depth. Therefore we can obtain accurate range estimation due to low absorption of mentioned carrier frequency.

3.2. Ocean Surface Bubbles

Ocean surface bubbles are the next source of emitting sound in our proposed algorithm that we will use its produced frequency as second carrier frequency. These bubbles are made by non-breaking wave. We know that the bubble's sounds which are created in ocean surface are proportional to wind speed and therefore its frequency contents decrease as the wind velocity degrades to zero. The minimum frequency for bubble motion in ocean sea at low wind velocity is 300 Hz [9]. It shows that this frequency is always present at the ocean surface. We will use this frequency as the second carrier frequency in our algorithm. It's notable that at very high wind speed, the bubble motion frequency will increase and it leads to an increase in attenuation coefficient α in (2)

4. ACOUSTIC MODEL OF THE DIVER SIGNAL

The scenario of the diver range estimation we introduced, is shown in Fig 1. As we discussed above, the radiating received signals are low frequency acoustic signals which are produced by the diver's oscillation bubbles. Hence, we consider a dual-frequency situation that is made by the diver open breathing system and an echo of ocean surface bubble sound as described in subsections 3.1 and 3.2. We define these signals with two frequencies f_1 and f_2. They can be expressed as

$$x_i(t) = A_i(t)e^{-j\varphi_i(t)}, \quad i = 1, 2 \tag{4}$$

where $x_i(t)$ is the received signal from diver, $i = 1$, and ocean surface, $i = 2$, $A_i(t)$ and $\varphi_i(t)$ are amplitude and phase of the received propagated signals. We know that these signals are in different frequencies that have been discussed in section 3. Finding these frequencies shows that our problem is similar to a CW radar [10] problem that estimates the range of a target based on these two frequencies. It shows that the sea surface behaves similar to an active radar too which is the is one novelty of this paper to determining the range of diver. After we find these frequencies we can obtain the range of diver based on phase difference of $x_1(t)$ and $x_2(t)$ in (4) and also time delay of the same two signals in (4) as follows

$$R(t) = \frac{c(\varphi_2(t) - \varphi_1(t))}{2\pi(f_2 - f_1)} \tag{5}$$

where c is the shallow water velocity of sound, f_1 and f_2 are received carrier frequencies for $x_1(t)$ and $x_2(t)$ respectively, and $R(t)$ is the range of the diver. As we discussed above, the phase difference information, $\varphi_2(t) - \varphi_1(t)$, obtained using dual frequency analysis [10] in the time-frequency domain is much more robust to noise as compared to signal amplitude. We know the Doppler frequency shift of a moving target, $f_{D,i}$, and subsequently the range of target that radiates sound will be achieved. By using Doppler frequency shift relation to phase we can obtain

$$f_{D,2} - f_{D,1} = -\frac{1}{2\pi}\frac{d}{dt}(\varphi_2(t) - \varphi_1(t)) \tag{6}$$

where $f_{D,2}$ is Doppler frequency shift of ocean bubble surface and $f_{D,1}$ is Doppler frequency shift of diver. As the Doppler frequency shift is proportional to carrier frequencies, We can find $f_{D,2}$ as

$$f_{D,2} = \frac{f2}{f1} f_{D,1} \tag{7}$$

subsequently the phase difference of two radiated signal is

$$\varphi_2(t) - \varphi_1(t) = \varphi_0(t) + 2\pi \int_0^t (1 - \frac{f_2}{f_1})\frac{v_d \cos\theta}{\lambda} dt \tag{8}$$

where v_d is the velocity of diver and λ is the wavelength of diver's radiated signals. We can obtain θ using triangulation geometry. From Fig. 1, we see

$$\theta = \theta_0 + \sin^{-1}(\frac{d \sin\theta_0}{r}) \tag{9}$$

where d is diver's distance to it's origin. As diver breathing system work periodically we can find time delay of received radiating signal,τ, using diver breathing rate. Therefore we obtain current range as

$$r = r_0 + c\tau \tag{10}$$

Using triangulation geometry we obtain initial diver distance, r_0 , as

$$r_0 = \frac{d^2 - c^2\tau^2}{2(c\tau + d\cos\theta_0)} \tag{11}$$

where θ_0 is calculated by initial beamforming. Substituting (10) and (11) into (9) we obtain

$$\theta = \theta_0 + \sin^{-1}\left(\frac{2d(c\tau + d\cos\theta_0)\sin\theta_0}{d^2 + c^2\tau^2 + 2d\cos\theta_0}\right) \tag{12}$$

Therefore diver's range will be achieved by substituting (8) and (12) into (5). In diver range estimation scenario, $\Delta\tau$ will be known after choosing diver's berating rate.

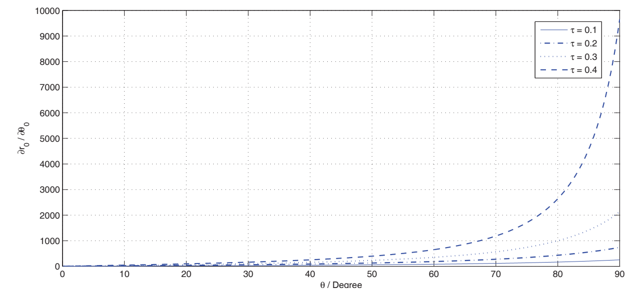

Fig. 2. The sensitivity of r_0 to θ_0 for different τ.

5. INITIAL RANGE ERROR ANALYSIS

Using (11) and taking a differentiating r_0 with respect to θ_0 we have

$$\frac{\partial r_0}{\partial \theta_0} = \frac{d\sin\theta_0(d^2 - c^2\tau^2)}{2(c\tau + d\cos\theta_0)^2} \tag{13}$$

This equation shows the sensitivity of the initial range, r_0 to initial angle, θ_0. The (12) is evaluated for different τ to show its effect on initial range sensitivity with respect to θ_0. The sensitivity results are shown in Fig.2. As we see in fig. 2, the sensitivity of r_0 to θ_0 increase as the θ_0 increase. In addition, Fig. 2 shown that sensitivity of initial range to θ_0 decreases as the τ decreases. Therefore, τ should be as small as possible to find an accurate estimation for initial range. According to Eq. (9), it's necessary to find an accurate estimation for initial range ,r_0, to improve the accuracy of θ estimation.

6. SIMULATION AND RESULT

One of the most benefits of this algorithm is that we can find the range of diver and other moving target like Sperm Whale by means of their radiating signals and their breathing system's features in shallow water environment. In this section, we show the performance of mentioned algorithm to estimate the range of a moving target. We used the data of SWeIIEx-96 experiment event S5 for our simulation. The frequency which is radiated through it is in the range 50Hz to 250Hz and the velocity of the S5 is about 2.5 m/s. For clarification of our algorithm, we would define the steps of our method more precisely as outlined below

1. Calculate the initial angle θ_0 by beamforming.
2. Calculate the current angle of diver θ, by equation (11).
3. Use the proposed method to calculate the phase difference by equation (6).
4. Calculate diver's range using equation (5) which is obtain by phase difference.

Simulation result is shown in Fig 3. This figure depicts the comparison between the new range estimation and real data from SWeIIEx-96 experiment.

7. CONCLUSION

In this paper we introduce a new algorithm for diver range estimation in shallow water environment. We used dual-frequency method based on two new carrier frequencies consisting of diver's bubble oscillation and ocean surface bubble motion as to estimate the range of diver. The result of the simulations verifies that the proposed algorithm using dual-frequency with the above newly understood carriers is suitable for shallow water environment for diver's range estimation. We can extent this algorithm to more divers by using sensor array networks to obtain the localization data too.

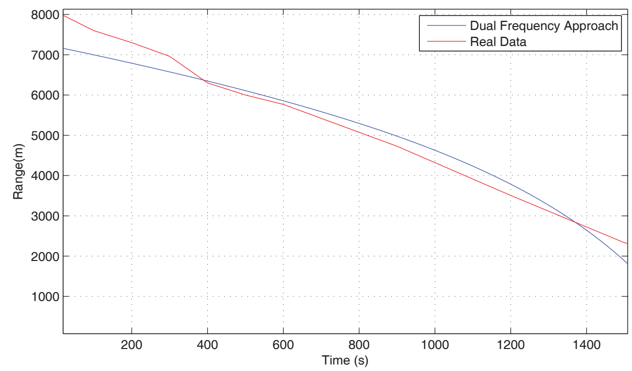

Fig. 3. Target Simulation Result

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