TELKOMNIKA Indonesian Journal of Electrical Engineering
Vol.12, No.1, January 2014, pp. 280 ~ 285
DOI: http://dx.doi.org/10.11591/telkomnika.v12i1.3968

A New Underwater Acoustic Navigation Method Based on the Doppler Principle

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Abstract

In this paper, a new underwater acoustic navigation method is proposed, which is named from Doppler Acoustic Omnirange Beacon (DAOB). It is borrowed from the idea of Doppler VHF Omnirange (DVOR) and based on the Doppler principle. The cause of Doppler effect in the received signal is the motion or position change of one or two sources. The effect of multipath is analyzed, and an improved signal form is presented to solve the rigorous multipath environment underwater. Some simulation is presented to verify the performance.

***Keywords**: DVOR, underwater acoustic navigation, Doppler*

1. Introduction

With the increased use of underwater robotics in both Navy and commercial applications, underwater navigation becomes more and more important. As researchers attempt to make these vehicles smaller and less expensive, simple systems for the navigation of multiple vehicles become important. In Octobers 2010, a research team from Naval Research Laboratory, the University of Washington, and Naval Surface Warfare Center developed and tested an underwater navigation system that uses a spiral shaped acoustic wave to determine aspect [1-3]. They stacked with a source generating circular wave fronts and a source generating spiral wave front on top of one another to make a navigational beacon. The single stationary beacon can provide a navigation signal for any number of underwater vehicles. The biggest advantage of this system over more traditional baseline techniques is simplicity. The remote vehicles need only have a single hydrophone available, and can even repurpose one from its sonar or acoustic communications system.

However, the spiral sound method has a high navigation error up to 5 and 15 degrees. Its directional precision is dependent on the surface accuracy of spiral array. Furthermore, it suffers from the multipath in underwater.

In this paper, a new underwater acoustic navigation method based on the Doppler principle is proposed, whose idea is borrowed from the Doppler VHF Omni-directional Range (DVOR)[4]. The new method is named from Doppler Omni-directional Acoustic Beacon (DOAB). The cause of Doppler in the received signal is the motion or position change of one or two sources. The proposed method has the same advantages as the spiral sound method over the traditional baseline techniques. The effect of multipath is analyzed, and an improvement on DVOR is presented to solve the problem from the rigorous multipath environment underwater.

2. The Basic Principle of DOAB

In an attempt to explain briefly the operation of DOAB, an ideal transducer will be assumed, i.e., it is located on the circumference of a circle and rotated around the center of the circle at a uniform velocity. The receiver is assumed to be motionless. Figure 1 displays the situation in the horizontal plane. Where, R is the radius of the circle, ϕ is the azimuth angle of the receiver, γ is the azimuth angle of transducer, r is the distance from the center of antenna rotation to the receiver.

Received June 23, 2013; Revised August 17, 2013; Accepted September 16, 2013

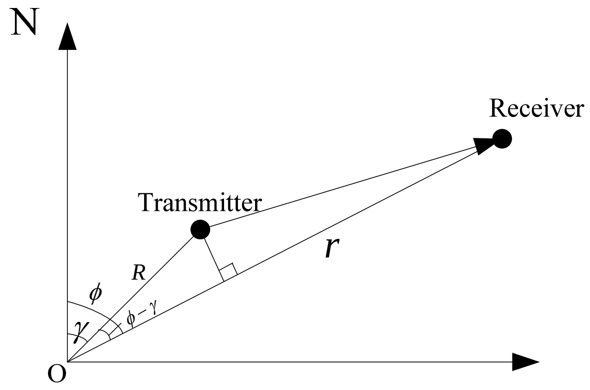


Figure 1. The coordinate system for one transmitting transducer

The transducer transmits a signal, and its frequency is f_v. The wave traveling from the transducer to the receiver will generate a phase delay:

$$\varphi = \frac{2\pi f_v}{C}\sqrt{\left[r - R\cos(\phi-\gamma)\right]^2 + \left[R\sin(\phi-\gamma)\right]^2} \tag{1}$$

where C is the sound speed. The transducer is rotated in the counterclockwise direction at a uniform angular velocity ω and $\gamma = \omega t$, the received signal can be expressed as:

$$s_v(t) = \cos\left[2\pi f_v\left(t - \frac{\sqrt{\left[r - R\cos(\phi-\omega t)\right]^2 + \left[R\sin(\phi-\omega t)\right]^2}}{C}\right)\right] \tag{2}$$

The instantaneous frequency $f(t)$ of the wave represented by (2) is obtained by differentiation of the instantaneous angular velocity:

$$\begin{aligned} f(t) &= \frac{1}{2\pi}\frac{d}{dt}\left[2\pi f_v\left(t - \frac{\sqrt{\left[r - R\cos(\phi-\omega t)\right]^2 + \left[R\sin(\phi-\omega t)\right]^2}}{C}\right)\right] \\ &= f_v + f_d \end{aligned} \tag{3}$$

where f_d is the Doppler frequency shift caused by the motion of transducer, and it can be expressed as:

$$\begin{aligned} f_d &= -\frac{f_v}{C}\frac{d}{dt}\sqrt{\left[r - R\cos(\phi-\omega t)\right]^2 + \left[R\sin(\phi-\omega t)\right]^2} \\ &= -\frac{f_v}{C}\frac{-\omega R\left[r - R\cos(\phi-\omega t)\right]\sin(\phi-\omega t) - \omega R^2\sin(\phi-\omega t)\cos(\phi-\omega t)}{\sqrt{\left[r - R\cos(\phi-\omega t)\right]^2 + \left[R\sin(\phi-\omega t)\right]^2}} \\ &= \frac{f_v}{C}\frac{\omega R\sin(\phi-\omega t)}{\sqrt{\left[1 - \frac{R\cos(\phi-\omega t)}{r}\right]^2 + \left[\frac{R\sin(\phi-\omega t)}{r}\right]^2}} \end{aligned} \tag{4}$$

In the general situation, $R \ll r$, (4) can be simplified as:

$$f_d \approx \frac{\omega R f_v \sin(\phi - \omega t)}{C} \tag{5}$$

From (5), it can be found that by rotation a transducer at a uniform angular velocity, a phase modulated wave is transmitted to the receiver. The significant fact about the phase-modulated wave is that the phase of modulation frequency is the azimuth angle of the receiver ϕ. The phase modulated signal is named from variable phase signal (VPS). When the signal is put into a frequency discriminator where the amplitude of the output voltage is a linear function of the instantaneous frequency of the input signal, the discriminator output is a wave of frequency f_v which varies as the receiver azimuth angle ϕ.

The DVOR utilized this principle to navigate the aircraft, it placed another transmitter, and Omni-directionally transmitted another amplitude modulated signal named reference phase signal (RPS), which can be expressed as:

$$s_{Rs}(t) = \left(1 + m\cos\left(\omega t\right)\right)\cos 2\pi f_0 t \tag{6}$$

where f_0 is the carrier frequency of the reference phase signal and the original phase of modulation signal of reference phase signal is zero.

In the receiver, the two modulation signals can be modulated from the variable phase signal and reference phase signal. By comparing the phase of the two modulation signals, the azimuth angle ϕ can be obtained.

Because of the multipath environment underwater, in this paper, we propose that a frequency modulated signal is used as reference phase signal. It will improve the performance of DOAB in the rigorous multipath environment underwater.

$$s_{Rs}(t) = \cos\left(2\pi f_0 t + \frac{\omega R f_v \cos(\omega t)}{C}\right) \tag{7}$$

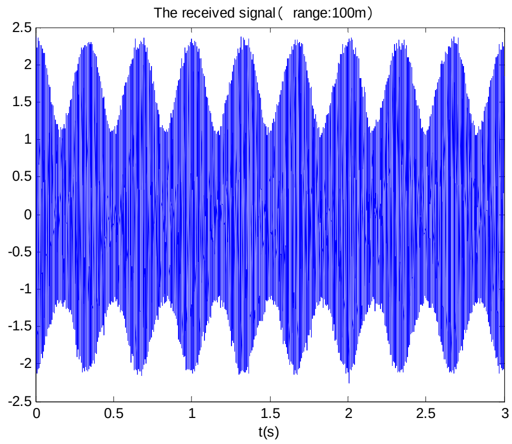
3. Performance Investigation

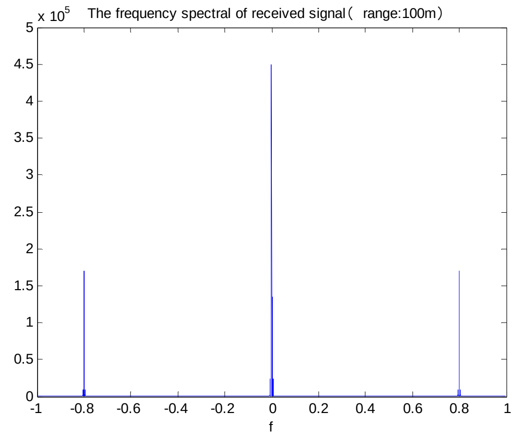
In this section, some simulations is presented to investigate the performance of the DOAB, especially in the rigorous multipath environment underwater. The results using traditional DVOR signal form and the proposed improved signal form is compared. The simulated parameters of the DOAB system are listed in Table 1.

Table 1. the simulated parameters of the DOAB system

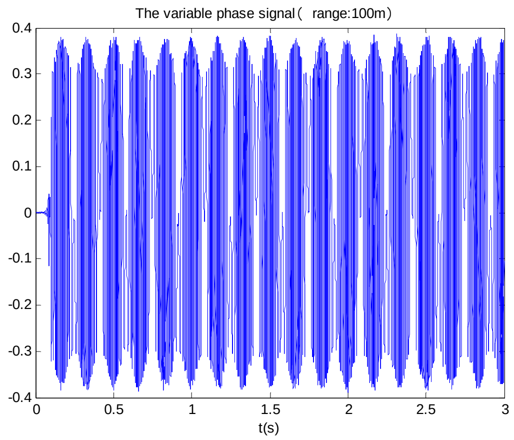
Parameter	Value	Parameter	Value
f_0 (VPS center frequency)	60KHz	R	20cm
f_v (RPS center frequency)	65KHz	ω	2π
f_s (sample frequency)	300KHz	m	0.3
SNR	20dB		

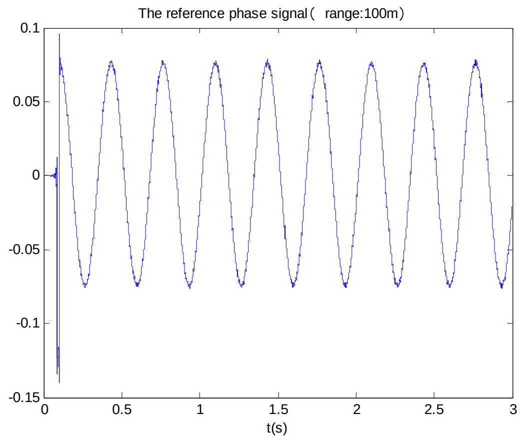
The simulated signal using the traditional DVOR signal form is shown as Figure 2, and using the proposed improved signal form shown as Figure 3, where (a) is the received signal, (b) is the frequency spectral of the received signal, (c) is the variable phase signal and (d) is the reference phase signal.





(a) received signal using traditional DVOR form (b) frequency spectral of the received signal



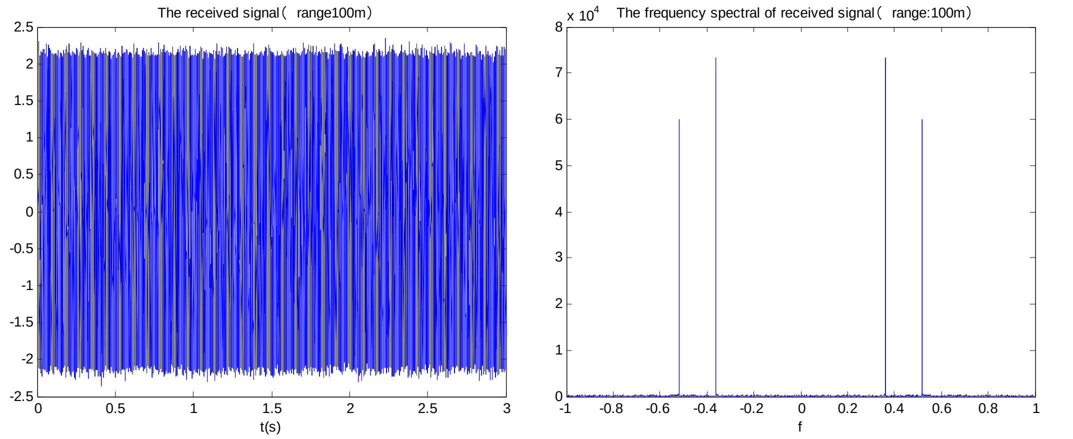


(c) variable phase signal after demodulation (d) reference phase signal after demodulation

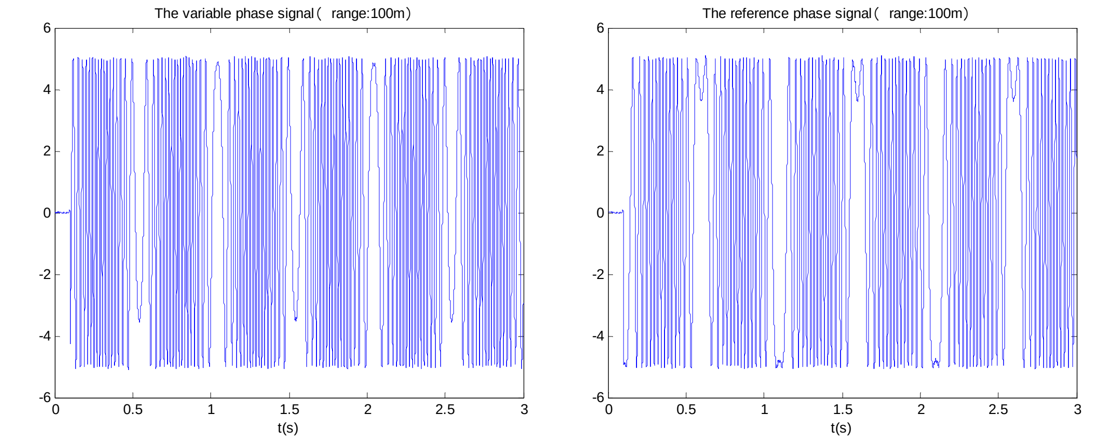
Figure 2. The simulated signal of DOAB using the traditional DVOR signal form

We establish a multipath model shown as Figure 4. Using the established model, we simulate the multipath environment and obtain the error of direction estimation. The estimated root mean square error (RMSE) is evaluated using 500 Monte Carlo trials. The influence of the multipath signal intensity of the simulated RMSE is shown in Figure 5. The signal intensity is the unitary to the one of straight path.

From Figure 5, it can be noted that RMSE of the estimated angle using the proposed signal form is much less than the one using the signal form of DVOR, especially in the large multipath environment. The reason is that the multipath effect causes mainly the change in the amplitude of the signal, which will cause a large direction error using the signal form of DVOR.



(a) received signal using proposed signal form (b) frequency spectral of the received signal



(c) variable phase signal after demodulation (d) reference phase signal after demodulation

Figure 3. The simulated signal of DOAB using the proposed signal form

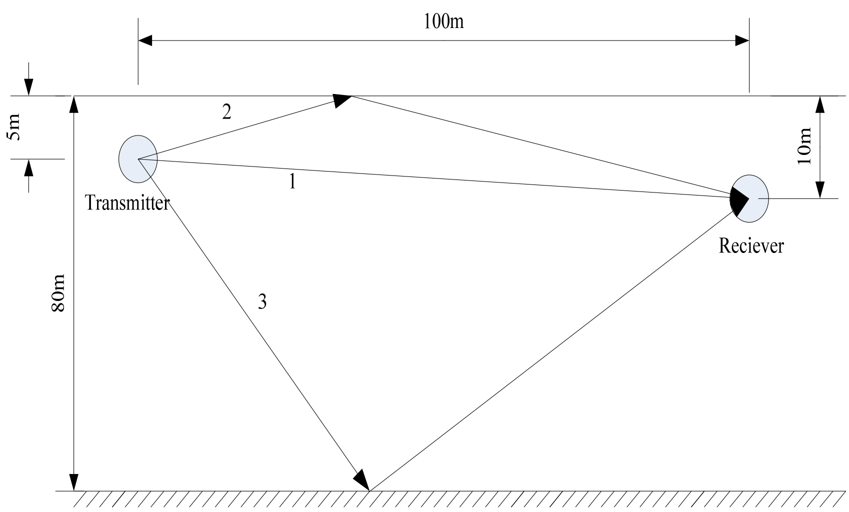


Figure 4. Multipath model used in the simulation

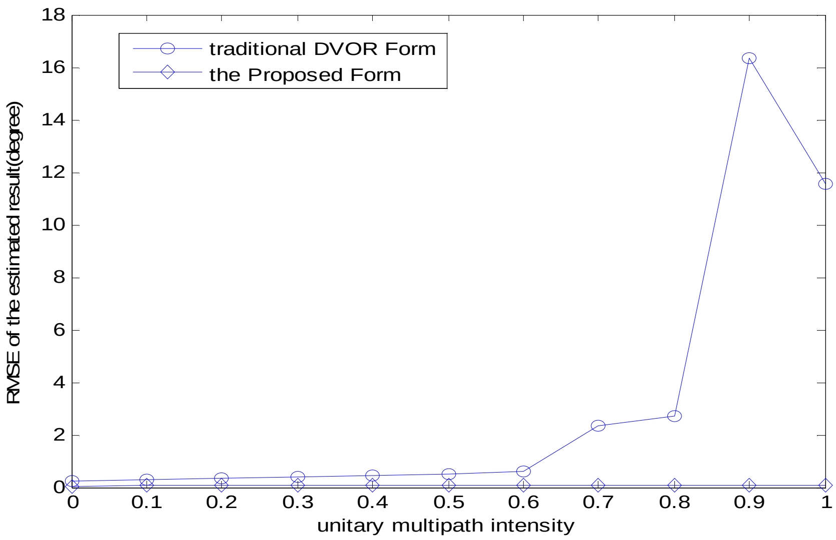


Figure 5. The RMSE versus the unitary multipath signal intensity

4. Conclusion

In this paper, a new underwater acoustic navigation method based on the Doppler principle is proposed. Its principle is presented and analyzed. To decrease the influence of the multipath environment, an improved signal form is proposed. The simulation is verified the performance improvement.

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