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Fundamental study on the effect of Doppler in biomimetic pulse trains for underwater acoustic localization

Hanako Ogasawara†, Takanobu Kuroyama, and Kazuyoshi Mori
(National Defense Academy)

1. Introduction

Recently, autonoumous underwater vehicles (AUVs) are widely used for underwater research and development. They are also beginning to be used for security purposes at coastal area for automation and labor saving[1]. As AUVs can move freely in the water, they are suitable for monitoring suspicious divers and other intruders underwater.

Generally, AUVs move by rotating propellers, but research focuses on biomimetic AUVs that use artificial muscles to mimic fish movements, resulting in much lower radiated noise. This allows for stealthy surveillance and tracking. For autonomous navigation, AUVs estimate their position based on direction and speed, but errors accumulate over time. Thus, position correction is done using acoustic ranging with seafloor transponders, like global navigation satellites. However, while biomimetic AUVs are quiet, using artificial sound for ranging may affect their stealth.

We have proposed biomimetic pulse trains that mimic dolphin sounds as acoustic ranging signals[2,3]. The proposed signals have been verified through numerical simulations in shallow coastal waters and the addition of recorded ambient noise, assuming conditions typical of Japan with recorded ambient noise. The simulations confirmed that the signal can be detected at distances of up to approximately 300 meters and can also be separated by source from received waveforms containing multiplexed signals.

Previous studies assumed fixed sources and receivers, but the moving AUV and current flow cause Doppler shifts in the real signals. This presentation evaluates the impact of these Doppler shifts on our proposed biomimetic pulse train signals.

2. Biomimetic pulse train signals

Dolphins use pulse called as clicks for their communication, feeding and localization. They use the pulse train varying timing, intervals, range according to the application. It is known that they use different pulse train in their search phase, approach, and buzz phase. We have proposed the use of searching-phase signals, which consist of multiple evenly spaced dolphin clicks, as acoustic sounding signals. A single pulse of the dolphin clicks has sharp, impulse-like waveform, and its cross-correlation function also exhibits a distinct peak as shown in Fig.1[4]. As shown in the middle panel of Fig. 1, when this signal is arranged with N evenly spaced intervals to gain amplitude, the peak of the correlation function becomes N times that of a single signal, but large side lobes appear on both sides. These large side lobes must affect the accurate measurement of propagation time when considering multipath effects and ambient noise. Even when emitting clicks at regular intervals, dolphins, being biological entities, cannot produce pulses with perfectly equal intervals and amplitudes as a machine would. Thus, we introduced fluctuations both in the pulse interval and amplitude of each pulse. As the fluctuations vary randomly between pulse intervals, the main peak of the cross-correlation function maintains approximately N times the amplitude while reducing the side lobes as shown in the bottom panel of Fig. 1.

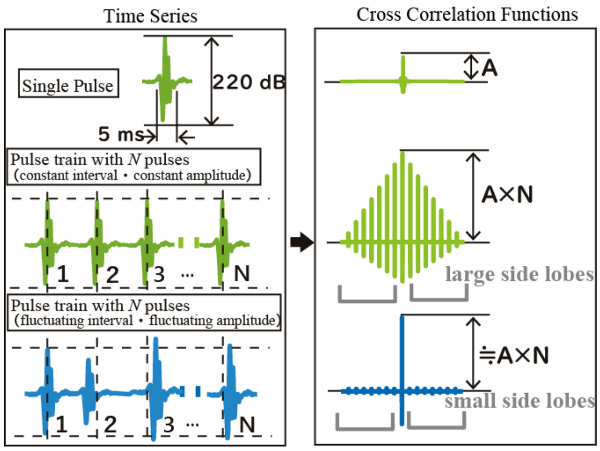

Fig. 1 Diagram of the time-series signal and cross-correlation function of the biomimetic pulse signals.

According to the simulation of our previous studies, 101 pulse repeated signal with the interval fluctuation within 10 ms and amplitude fluctuation within 0.1 times was selested for the suitalbe signal for acoustic ranging[2,3].

3. Effect of Doppler shift

A signal is transmitted from an AUV moving toward a fixed transponder at a speed v from a horizontal distance d away. For simplicity, we consider this in a one-dimensional space where the direction of sound propagation is the same as the direction of AUV's movement. Assuming a water

E-mail: †ogasawar@nda.ac.jp

current of u in the opposite direction to the AUV's movement and a constant sound speed of c, when the transmitted signal frequency is f_T , the received frequency f_R of the signal with Doppler shift is give by the following equation:

$$f_R = \frac{c + u + v}{c} f_T.$$

Figure 2 shows the absolute value of the cross-correlation function between the original signal and the Doppler shifted signal. The data is normalized by it maximum value. The value of relative speed, $u+v$ varied from 0.3 cm/s to -0.3cm/s every 0.1 cm/s. The time lags of the peak in cross-correlation function shifted according to the speed changes. It was confirmed that even a velocity of 0.1 cm/s can affect the calculation of propagation time. Furthermore, as the velocity change increases, the peak of the cross-correlation function decreases sharply. Since the Doppler shift is determined by relative velocity, it is necessary to prepare multiple replica signals on receiving side, each with added Doppler shifts. By calculating the cross-correlation function between the received waveform and the replica signals, the time lag τ and the relative velocity can be estimated by identifying the maximum among all the cross-correlation functions. Figure 3 shows the block diagram of the proposed received signal processing.

Since we are considering a one-dimensional case, the effects of multipath are ignored, focusing only on the direct wave. Assuming v=0.5 m/s, u=0.05 m/s, and d=300 m, the received signal, with added propagation attenuation and ambient noise, was analyzed following the procedure in Fig. 3, and the relative speed was estimated. For convenience, the correct propagation time of the received waveform was assumed to be τ=0. Figure 4 shows the results of cross-correlation function. From the maximum value of the cross-correlation function, estimated relative speed was 0.551 m/s and τ=1.5 μs, which means less than 3 mm error in distance estimation.

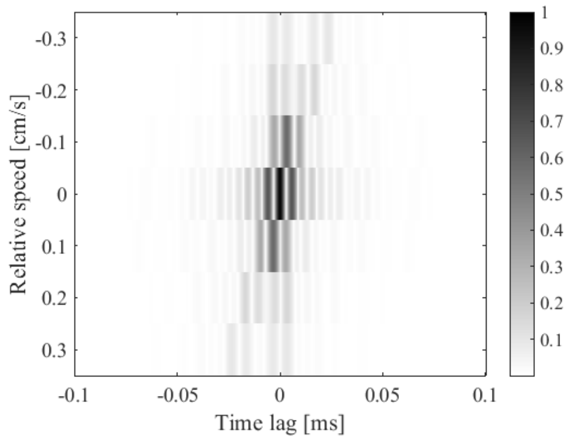

Fig. 2 Absolute value of the cross-correlation function of the sending signal and the Doppler shifted signal.

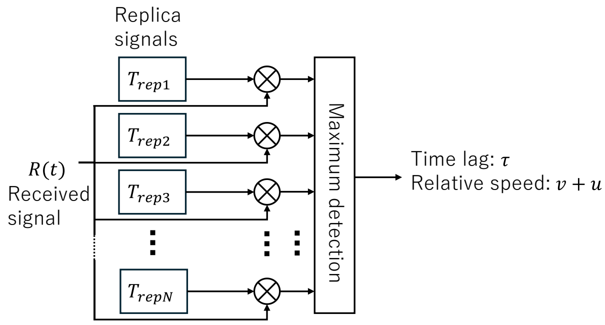

Fig. 3 Block diagram of travel time estimation from Doppler shifted signal.

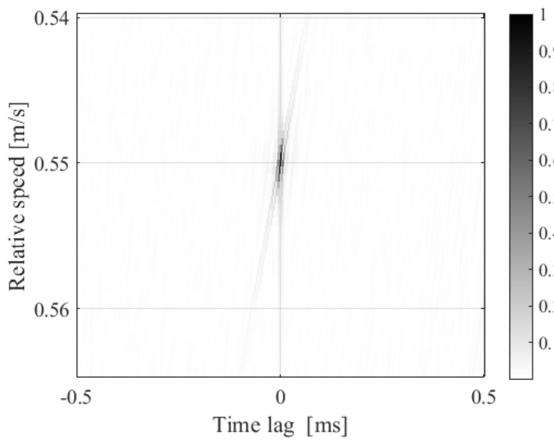

Fig. 4 Absolute value of the cross-correlation function of the received signal and the replica signals.

4. Conclusion

The sensitivity of Doppler shift for the proposed biomimetic pulse trains has confirmed. The proposed signal was very sensitive for the Doppler effect. Using replica signals which calculate the Doppler effect of the sending signal, travel time and relative speed could be estimated from 300 m propagated signal with ambient noise in one-dimensional simulations. In future work, we will advance our analysis to a two-dimensional space (range-depth) that considers the effects of multipath.

Acknowledgment

The dolphin sound waveforms used in this study were taken from Dr. Tomohito Imaizumi's paper [4].

References

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