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RANGE ESTIMATION METHOD IN A SHORT-RANGE FMCW SONAR

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ABSTRACT
We propose a range estimation method for a short-range frequency-modulated continuous wave (FMCW) sonar. Due to the slower sound wave and the greater Doppler effect of the FMCW sonar, the beat frequency of the FMCW sonar cannot keep the constant duration unlike the beat frequency of the FMCW radar. To cope with the drawback of the FMCW sonar, in the proposed method the rising edge and the falling edge of the beat frequency are utilized. This leads us to normally estimate the range of a high-speed underwater vehicle in short-range situation. Simulation results show that the proposed method can estimate the range from the measurements where the Doppler effect is exactly reflected according to the maneuver scenario of high-speed underwater vehicles.

KEY WORDS
FMCW, beat frequency, near-field, active sonar

1. Introduction

Frequency-modulated continuous wave (FMCW) is attractive for various short-range applications, such as proximity fuse, collision avoidance radar, and level measurement radar [1]. In these FMCW radars, the Doppler effect of a high-speed vehicle is sufficiently small to suppose that the repetition interval of the received FMCW is identical with the repetition interval of the transmitted FMCW. However, the Doppler effect occurred in an underwater FMCW sonar is not sufficiently small and thus we cannot presume that the repetition intervals of the transmitted and received FMCWs are identical. Furthermore, the Doppler effect is drastically changed in short-range situation where a high-speed target approaches close to a high-speed receiver. Therefore, the conventional range estimation method used in the FMCW radar could not be directly applied to the FMCW sonar.

In order to estimate the range of a high-speed underwater vehicle using the FMCW sonar, we utilize the rising and falling edges of a beat frequency computed by the short time Fourier transform (STFT). If the bandwidth of the transmitted FMCW is sufficiently larger than the Doppler frequency, the proposed method can effectively estimate the range of a high-speed underwater vehicle. In addition, the proposed method does not require large-size fast Fourier transform to obtain an accurate frequency value. Instead of these advantages, the proposed method could estimate the accurate times of the rising and falling edges when the sufficiently short shift length is applied to the STFT. The shorter shift length of the STFT is used to obtain the accurate edges, the larger computation burden is required.

This paper is organized as follows. In Section 2, the beat frequency of an FMCW sonar is described according to the maneuver scenario of a high-speed underwater vehicle. The proposed method is explained in Section 3, and simulation results are covered in Section 4. Finally, the conclusion of this paper is drawn in Section 5.

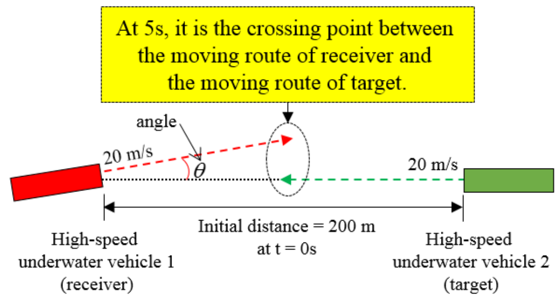

Figure 1. Maneuver scenario of the receiver and the target.

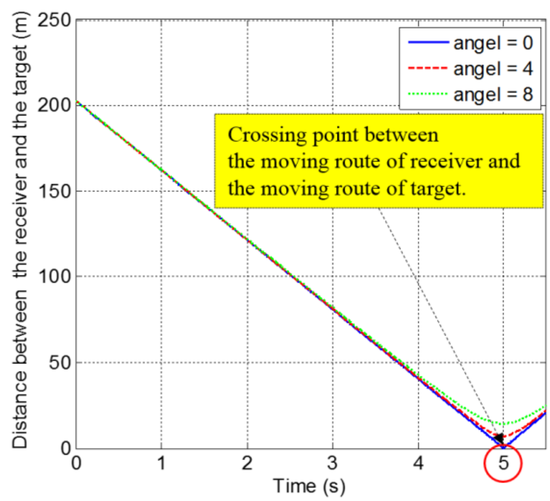

Figure 2. Distance between the receiver and the target according to the maneuver scenario.

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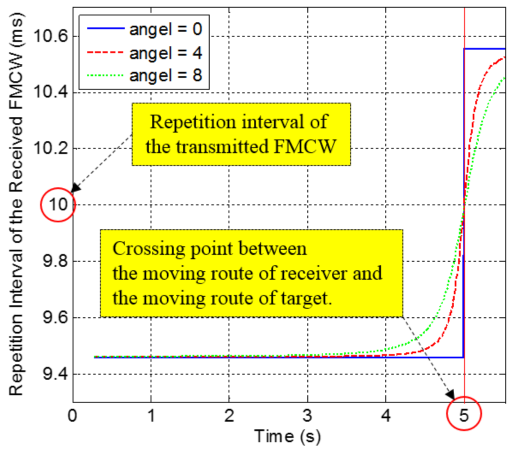

Figure 3. Repetition interval of the received FMCW according to the maneuver scenario.

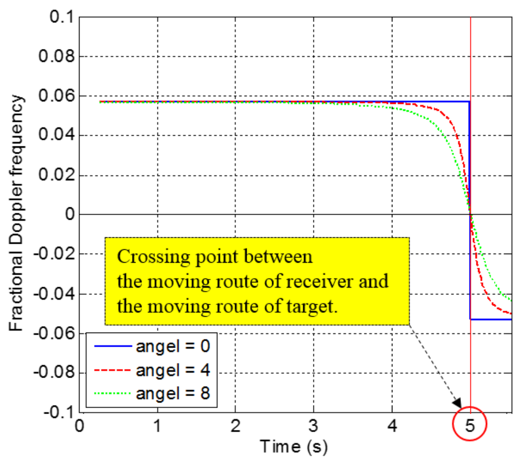

Figure 4. Ratio of the Doppler frequency according to the maneuver scenario.

2. Beat Frequency of an FMCW Sonar

When a high-speed underwater target approaches a high-speed underwater receiver as illustrated in Fig. 1, the repetition interval and the frequency of the received FMCW are drastically changed due to the Doppler effect. In order to generate a received signal involving this Doppler effect, each delay of discrete samples of the received signal should be correctly calculated considering the position vectors and the velocity vectors of a high-speed underwater receiver and a high speed underwater target. The change amounts of the repetition interval and the Doppler frequency depend on the angle θ between the velocity vectors of the receiver and the target (Fig. 1) and the distance d_{RT} between the receiver and the target (Fig. 2). Fig. 3 shows the repetition interval of the received FMCW, T_R when the repetition interval of transmitted FMCW, T_T, is 10 ms. The difference between T_T and T_R denotes the shrinkage T_S defined by

$$T_S = |T_T - T_R| . \tag{1}$$

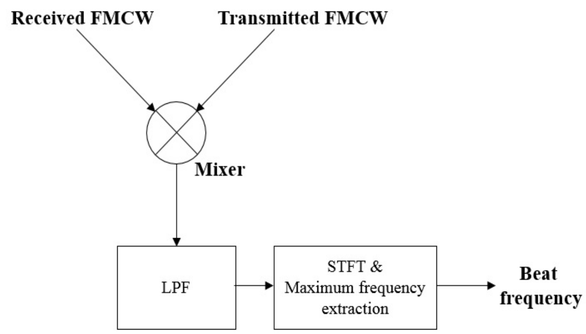

Figure 5. Simple block diagram for the beat frequency calculation.

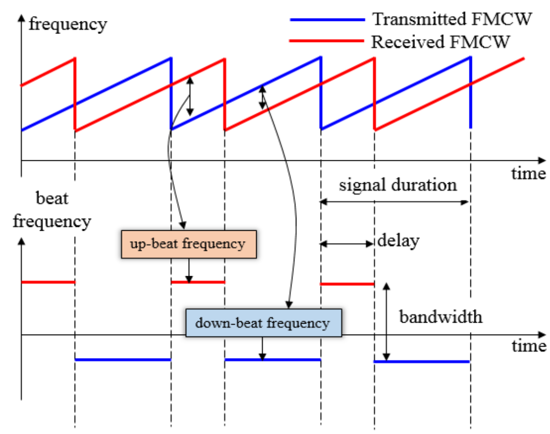

Figure 6. Beat frequency of an FMCW radar.

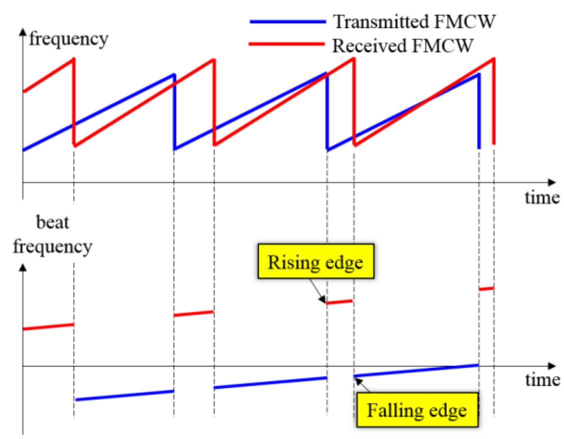

Figure 7. Beat frequency of an FMCW sonar.

Let the ratio of the center frequency f_C and the Doppler frequency f_D be called the fractional Doppler frequency γ written as

$$\gamma = \frac{f_D}{f_C} . \tag{2}$$

Referring to Fig 3, it is clear that T_S is not quite small to be ignored in an underwater sonar system. Also, it is not appropriate to apply the Doppler shift property to the

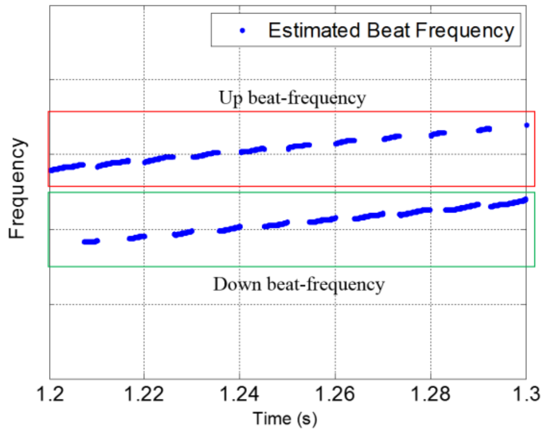

Figure 8. Beat frequency about a high-speed underwater vehicle.

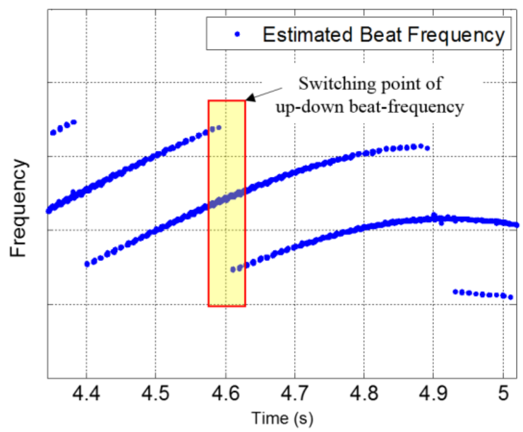

Figure 9. Beat frequency in the proximity situation.

received FMCW because γ of an underwater sonar is not sufficiently small as depicted in Fig. 4. Furthermore, T_R and γ is drastically changed in the situation of proximity where d_{RT} is less than 50 m.

In these underwater acoustic environment, it is so difficult to obtain the range of a high-speed underwater vehicle using the conventional method used in the FMCW radar which is based on the beat frequency $b[n]$ computed by the short time Fourier transform (STFT) as depicted in Figs. 5 and 6 [2]. The discrete time index n of $b[n]$ is concerned with both the sampling interval T_s and the shift length of STFT N_{shift}, and this relationship between $b(t)$ in the continuous time domain and $b[n]$ in the discrete time domain is given by

$$b(n \cdot T_s \cdot N_{shift}) = b[n]\,. \tag{3}$$

In the FMCW sonar system, up-beat frequency and down-beat frequency do not keep the constant value and the constant duration as depicted in Fig. 8 because the repetition interval of the received FMCW is not identical with the repetition interval of the transmitted FMCW as described in Fig 7. Furthermore, $b[n]$ is more drastically changed in the situation of proximity where d_{RT} is less than 50 m as illustrated in Fig. 9.

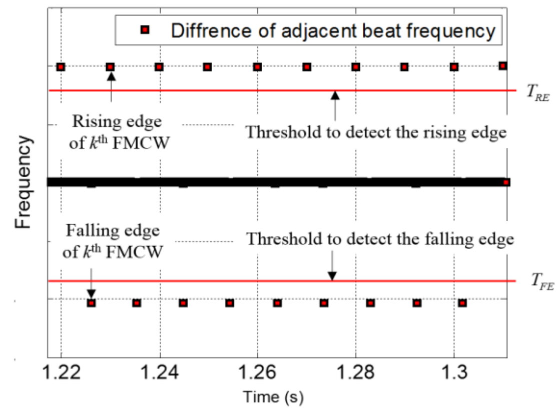

Figure 10. Detection of the rising and falling edges.

3. The Proposed Range Estimation Method

In order to estimate the range of a high-speed underwater vehicle in an FMCW sonar, we utilize the rising and falling edges of $b[n]$ as illustrated in Fig. 7. The rising edge denotes the starting point of the current transmitted FMCW, and the falling edge denotes the starting point of the current received FMCW. These rising and falling edges can be obtained from the difference of adjacent beat frequency defined by

$$b_d[n] = b[n] - b[n-1]\,. \tag{4}$$

The rising edge $r_e[k]$ is the time index n of $b_d[n]$ greater than the threshold T_{RE}, and the falling edge $f_e[k]$ is the time index n of $b_d[n]$ smaller than the threshold T_{FE} for k^{th} transmitted and received FMCW as described in Fig. 10. The discrete time difference between $f_e[k]$ and $r_e[k]$ indicates the delay of target echo. Therefore the target range $R[k]$ of k^{th} FMCW is simply computed as

$$R[k] = \frac{v_c \cdot \left[T_s \cdot N_{shift} \cdot \left(f_e[k] - r_e[k] \right) \right]}{2}\,, \tag{5}$$

where v_c is velocity of the acoustic wave. The time interval of the STFT is $T_s \cdot N_{shift}$ as denoted in equation (3), and it means that the range estimate based on the STFT contains the maximum range ambiguous $0.5 \cdot v_c \cdot T_s \cdot N_{shift}$ in noise free environment. The proposed method could estimates the range of a high-speed underwater vehicle, but the estimation performance is limited by the shift length of STFT N_{shift}.

4. Simulation Results

Simulation was performed under the situation where a high-speed underwater vehicle 2 (target) approaches close to a high-speed underwater vehicle 1 (receiver) as illustrated in Fig. 1, and simulation parameters are summarized in Table 1. Range estimation errors are calculated each $T_s \cdot N_{shift}$, and are represented in Figs. 11

Table 1. Simulation parameters

Parameters	Value
receiver speed	20 m/s
target speed	20 m/s
angle	8°
repetition interval of the FMCW	10 ms
shift length of the STFT	10, 100 samples

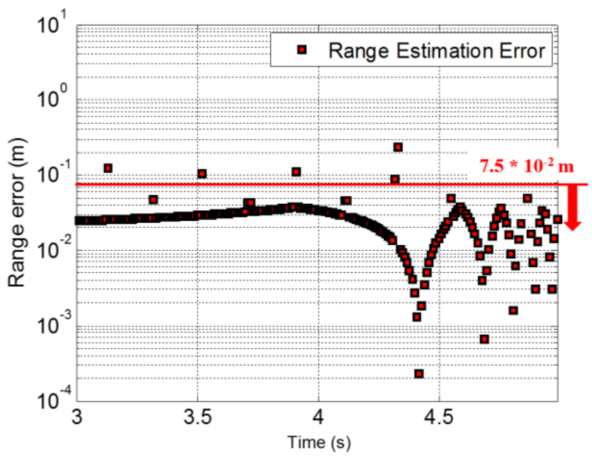

Figure 11. Range estimation error; N_{shift} is 100 samples.

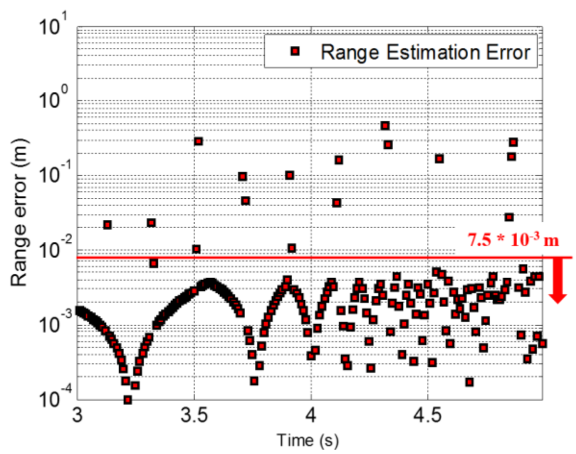

Figure 12. Range estimation error; N_{shift} is 10 samples.

and 12. It can be noted that the proposed method could estimate the range of a high-speed underwater vehicle in the situation where up-beat frequency and down-beat frequency do not keep the constant value and the constant duration as depicted in Fig 8. Also, the proposed method was normally operating in the situation of proximity where T_R and γ are drastically changed. However, it was clearly found out that the performance of range estimation is limited by N_{shift} as described in Figs. 11 and 12. The error points, which were greater than $0.5 \cdot v_c \cdot T_s \cdot N_{shift}$ as $7.5 \cdot 10^{-2}$ m in Fig. 11 and as $7.5 \cdot 10^{-3}$ m in Fig. 12, were occurred when up and down beat frequencies are switched each other as depicted in Fig. 9.

5. Conclusion

In this paper, a new range estimation method for a short-range FMCW sonar has been proposed. It is shown that the shrinkage caused by the Doppler effect is not quite small to be ignored and this shrinkage is drastically changed in the short-range situation. In this undesirable situation, it is so difficult to estimate the target range applying the conventional method used in the FMCW radar. However, the proposed method can normally estimate the range of a high-speed underwater vehicle by utilizing the rising and falling edges of the beat frequency.

References

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[2] Masanori Kunita, “Range Measurement in Ultrasound FMCW system”, *Electronics and Communications in Japan*, vol. 90, no.1, 2007.