# Design of a Hopping-Frequency Coding based Transmission Method for Underwater Detection

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## Abstract

*We design a hopping-frequency coding based transmission method to obtain the distance of a high-speed underwater vehicle in the near-range situation. Due to the greater Doppler effect and the longer echo delay of the sonar, frequency-modulated continuous wave (FMCW) technology could not be applied to the proximity underwater sonar. The proposed method utilizes the frequency hopping to overcome the greater Doppler Effect and the hopping-frequency coding to frequently update the range estimate regardless of the reflected signal's delay. This paper addresses the design background of the proposed transmission method and explores the problems considered in terms of transmission for the effective distance estimation.*

**Keywords:** proximity sonar, FMCW, sonar

## 1. Introduction

Frequency-modulated continuous wave (FMCW) is representative technology for various short-range applications, such as proximity fuse, collision avoidance radar, and level measurement radar [1-2]. In these FMCW radars, the Doppler Effect is negligibly and thus does not cause any problem of the time-frequency slope mismatch between the transmitted and the received FMCW signals. However, due to the slower sound wave, the Doppler effect in underwater sonars is not negligible. Furthermore, the Doppler effect is rapidly changed in proximity situation where a high-speed receiver approaches close to a high-speed target. Due to such a difference in the Doppler effect between a radar and a sonar, it is difficult to apply the FMCW radar technology to the proximity sonar.

In order to obtain the distance information of a high-speed and near-range underwater vehicle, we propose a hopping-frequency coding based transmission method. In the proposed method, the frequency-hopping is utilized to overcome the Doppler Effect of high-speed underwater vehicles and hopping-frequency coding is involved to frequently update the range estimate regardless of the delay. Finally, we present how to avoid the huge volume reverberation in the proximity environment through the proposed transmission method.

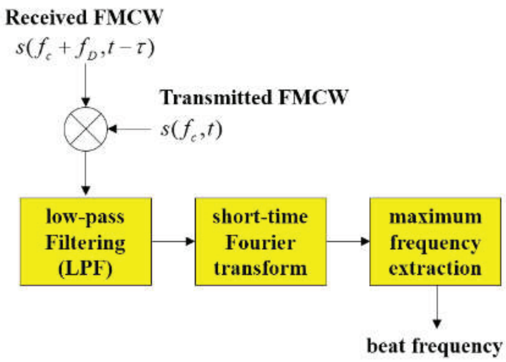


**Figure 1. Simple block diagram for beat-frequency calculation.**

This paper is organized as follows. In Section 2, problem of the FMCW sonar is described. The proposed transmission method is described in Section 3, and the simulation results are covered in Section 4. Finally the conclusion of this paper is drawn in Section 5.

## 2. Problem of the FMCW sonar

In the FMCW radar, the distance of the target is estimated from the beat-frequency as shown in Fig. 1. The beat-frequency means the frequency difference between the transmitted FMCW and received FMCW, which is determined by the delay as depicted Fig. 2. If the delay of received FMCW is sufficiently smaller than the repetition period of the FMCW, the distance $R$ can be simply obtained as

$$R = \frac{v_c f_{db}}{-2m_T}, \tag{1}$$

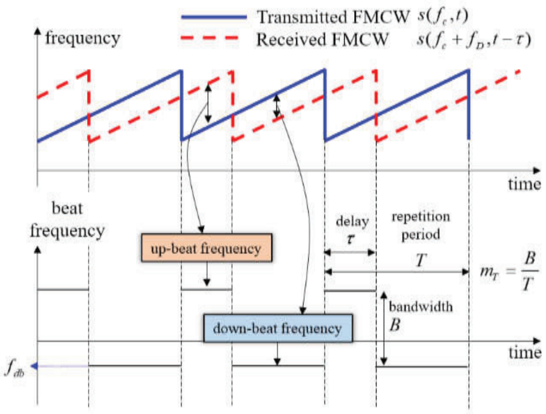


**Figure 2. Beat frequency of an FMCW radar.**

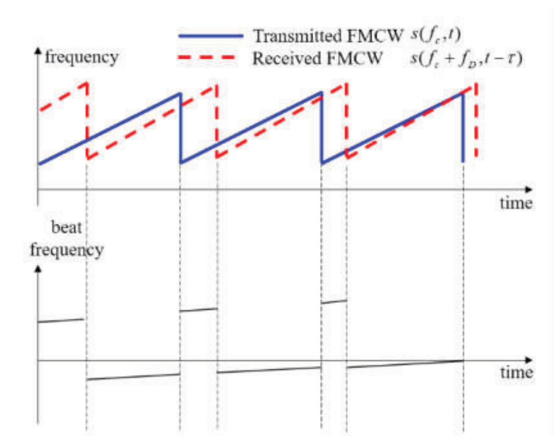


**Figure 3. Beat frequency of an FMCW sonar.**

where $v_c$ is the velocity of the acoustic wave, $f_{db}$ is the down beat-frequency, $m_T$ is the time-frequency slope of the transmitted FMCW [1].

The signal length and bandwidth changes due to the Doppler Effect are negligible in the FMCW radar, regardless of the speed of the target. However, in the FMCW sonar, it can't be ignored when the target speed is fast. For this reason, the beat-frequency of the FMCW sonar is not constant as shown in Fig. 3, and the distance of the target can't be estimated from this beat-frequency.

## 3. The proposed transmission method

The proposed transmission method is designed to allow the receiver to frequently update the distance estimate after approaching within a few tens meters of the high-speed underwater vehicle *B* as described in Fig. 4 with basic active sonar search process. Ultimately, it detects the moment when the high-speed underwater vehicle ***B*** comes within the limit distance as shown in Fig. 4.

In order to design a transmission method suitable for this situation and purpose, the following three points are considered.

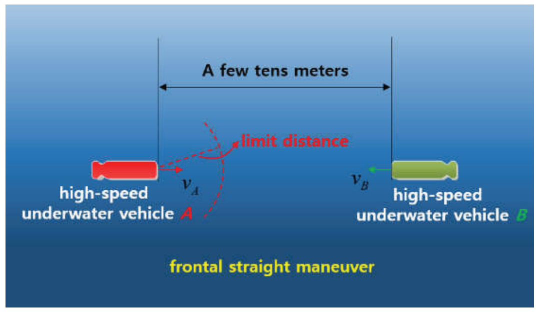


**Figure 4. Frontal straight maneuver of high speed underwater vehicle *A* and *B*.**

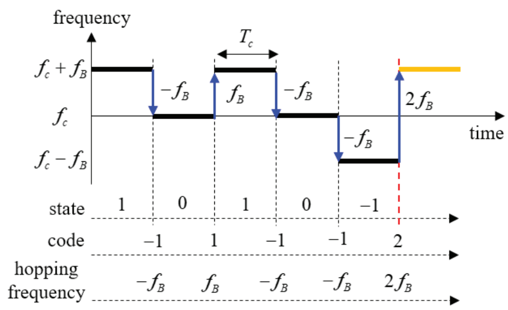


**Figure 5. An example of the proposed signal transmission method.**

1. Designed to update the distance estimate regardless of the reflected signal's delay.
2. Designed to unaffected by the Doppler Effect.
3. Designed to allow the receiver to detect the frequency hopping in the reverberation environment.

In order to satisfy the first condition, it is needed that singular points changes in a shorter period than the delay of reflected signal. For this purpose, the frequency hopping is used as the singular point in the proposed transmission method, and coding is applied to distinguish each hopping frequency as shown in Fig. 5. Also, since the frequency hopping does not change significantly even if the Doppler frequency occurs, the second condition is also satisfied. Finally, in order to achieve the third condition, the frequency band of transmitted and received signal must be distinguished. For this, the hopping frequency is set smaller than the expected Doppler frequency.

Since the proposed transmission method is used after the basic search process, it can be assumed that the initial distance $R_0$ and Doppler frequency $f_0$ of the high-speed underwater vehicle ***B*** are known. The hopping frequency $f_B$, frequency hopping period $T_c$, and codeword length $L_c$ are set based on $R_0$ and $f_0$. The basic parameters setting and characteristics of the proposed transmission method can be summarized as follows.

- In order to overcome the effects of the volume reverberation in near-field situation, $f_B$ is set as follows.

$$f_B < \frac{f_0}{2}. \quad (2)$$

- To detect when frequency hopping occurs in the near-range reverberation environment, $T_c$ should be set as follows.

$$T_c > \frac{2}{f_B}. \quad (3)$$

- $L_c$ is an integer number and set as follows considering $R_0$ and $T_c$.

$$L_c > \frac{2R_0}{v_c T_c}. \quad (4)$$

- $L_c$ is always an add integer number, consisting of an even number of 1 or -1 code and a 2 or -2 code. The codeword examples are as follows.

$$\begin{aligned} &Inital\ state\ is\ 1 \ \ \rightarrow[-1,+1,-1,-1,+2], \\ &Inital\ state\ is\ 1 \ \ \rightarrow[-1,-1,+1,+1,-2], \quad (5) \\ &Inital\ state\ is\ -1\rightarrow[+1,-1,+1,-1,+2]. \end{aligned}$$

- The hopping-frequency for each code is as follows.

$$\pm1 \rightarrow \pm f_B, \ \pm2 \rightarrow \pm2 f_B. \quad (6)$$

- $\pm 2 f_B$ are utilized to detect that the codeword has changed.

- Since the proposed transmission method uses only three frequencies $\{f_c - f_B, f_c, f_c + f_B\}$, codewords containing $[1, 1, 1]$ or $[-1,-1,-1]$ can't be used.

- The start and end state of a transmitted signal is always 1 or -1 as depicted in Fig. 5. The state means the frequency of the transmitted signal.

- The transmitted signal is a continuous wave in which frequency hopping occurs.

The distance estimation method corresponding to the proposed transmission method can be designed in various directions to detect the frequency hopping and obtain the hopping frequency.

**Table 1: Simulation parameters**

| parameters | value |
|---|---|
| center frequency | $f_c$ |
| $T_c$ | 10, 20, 30 ms |
| $f_B$ | $0.005 f_c < f_B < 0.045 f_c$ |
| Doppler coverage of the correlators | $1.03 f_c < f_{\text{cov}} < 1.1 f_c$ |
| $L_c$ | 9 |
| velocity ( $v_A = v_B$ ) | 25 m/s |
| $R_0$ | 102.8 m |

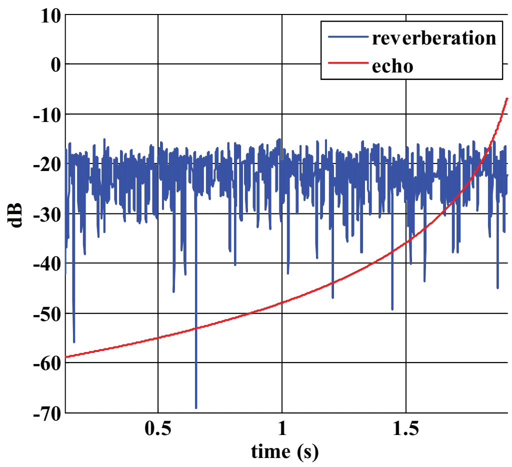


**Figure 6. Signal level of the echo (reflected signal) and the volume reverberation.**

## 4. Simulation

A simulation is performed to verify the applicability of the proposed transmission method in near-range reverberation environment. The volume reverberation is generated by convolution operation between the transmitted signal and the reverberation channel having the scattering coefficient at all times, and the transmission loss is considered in both the volume reverberation and the reflected signal [3-4]. Finally, the detection results of the frequency hopping occurrence point in the received signal are summarized according to $f_B$ and $T_c$. In order to detect the frequency hopping time and to obtain the hopping frequency, we constructed a filter bank with a number of Doppler correlators, detected the time when the output frequency of the filter bank changed, and estimated the hopping frequency.

The simulation parameters are shown in Table 1. In the case of the initial distance of 102 m, after 2 seconds, high-speed underwater vehicle ***A*** and ***B*** become close within the limit distance. In this situation, the reverberation and reverberation levels over time of 2 seconds is shown in Fig 6. The level

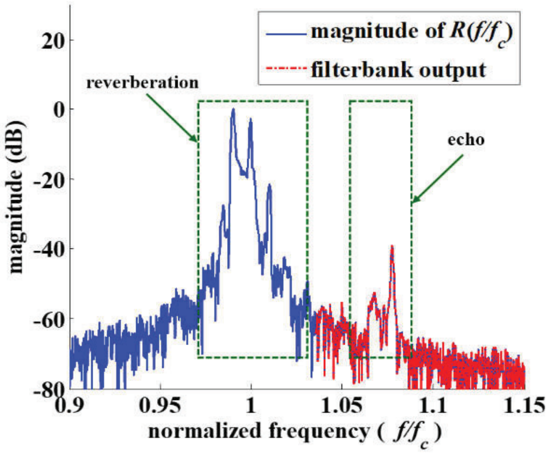


**Figure 7. Magnitude of frequency response and filter-bank output according to received signal at time = 0.13 sec of Fig. 6.**

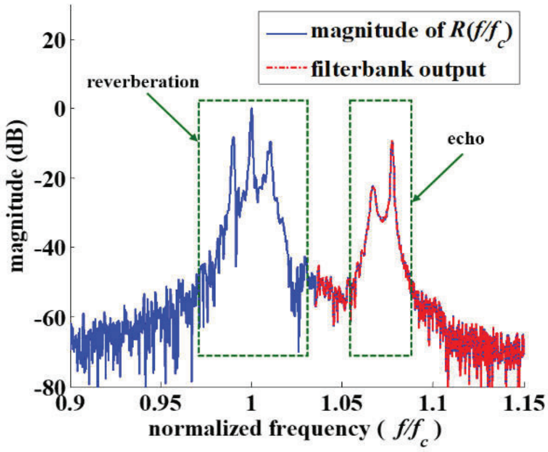


**Figure 8. Magnitude of frequency response and filter-bank output according to received signal at time = 1.54 sec of Fig. 6.**

of the volume reverberation for continuous wave is maintained at a constant level regardless of the distance(time), but the level of the reflected signal increases as the distance gets closer. Figs. 7 and 8 show the frequency response of the received signal with $f_B = 0.01 f_c$ and $T_c = 20\,ms$ . The received signal is distinguished from the reverberation band even when the reflection signal is very weak. Also, it can be seen that when the Doppler correlator is configured in the initial Doppler frequency band, the frequency hopping time can be detected.

Table 2 summarizes the occurrence of miss-detection of frequency hopping according to $f_B$ and $T_c$. In the case where the hopping frequency is too small or larger than $f_0 / 2$, miss-detection occurs. In order to reliably detect all the frequency hopping times, it is necessary to use $f_B$ close to $f_0 / 2$ and a sufficiently long $T_c$.

**Table 2: Organizing the occurrence of miss-detection of frequency hopping (o : occurrence, x : non-occurrence)**

| $f_B$ \ $T_c$ | 10 ms | 20 ms | 30 ms |
|---|---|---|---|
| $0.005 f_c$ | o | o | o |
| $0.015 f_c$ | o | o | x |
| $0.025 f_c$ | o | x | x |
| $0.035 f_c > 0.5 f_0$ | o | o | o |
| $0.045 f_c > 0.5 f_0$ | o | o | o |

## 5. Conclusion

In this paper, a new transmission method was proposed to obtain the distance of a high-speed underwater vehicle. The proposed transmission method was designed to frequently update the distance estimate, regardless of the delay time of the reflected signal, the Doppler Effect, and the volume reverberation. Through the simulation, we have shown that it is possible to stably detect the frequency hopping time of the received signal when the appropriate hopping-frequency and hopping-period are applied. It is expected that the proposed transmission method will be useful in the field where the distance estimation of a high-speed underwater vehicle is required.

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