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수중 환경에서 상호상관을 이용한 시간차이 추정

Estimation of Time Difference Using Cross-Correlation in Underwater Environment

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[요 약]

최근에 수중 음향통신에 대한 연구가 많은 연구자들에 의해 연구되어왔다. 수중 환경 UWAC를 사용하기 위해서는 두 신호들 사이의 시간차이를 추정하는 것이 필요하다. 일반적으로 두 신호 시아의 시간차이를 추정하는 기법으로는 배경 영역이 없는 시간을 추정하여 시간 차이를 추정하는 기법, 시간을 추정하여 두 신호 사이의 상호 상관을 추정하는 기법, 시간 차이 추정을 위한 위상지연을 추정하는 기법이 주로 사용된다. 본 논문에서는 UWAC에 적용하기 위하여 시간 지연 추정에 의한 두 신호 사이의 상호상관을 계산하고 이 상호 상관을 이용한 도착 시간의 추정 결과를 0.003055 초가 됨을 보인다.

[Abstract]

Recently, underwater acoustic communication (UWAC) has been studied by many scholars and researchers. In order to use UWAC, we need to estimate time difference between the two signals in underwater environment. Typically, there are major three methods to estimate the time-difference between the two signals such as estimating the arrival time of the first non-background segment and calculate the temporal difference, calculating the cross-correlation between the two signal to infer the time-lagged, and estimating the phase delay to infer the time difference. In this paper, we present calculating the cross-correlation between the two signals to infer the time-lagged to apply UWAC. We also present the experimental result of estimating the arrival time by using cross-correlation. We get EXCORR = 0.003055 second as the estimation error in mean absolute difference.

Key word : Cross-correlation, Time difference, Underwater acoustic communication, Underwater environment, Hydrophone.

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Ⅰ. Introduction

Because the electromagnetic wave cannot propagate in underwater differ from ground, we use acoustic communication. However, acoustic communication in underwater environment have several problems such as the velocity of sound wave is slow as 1.5km/s, limited frequency bandwidth, time varying multipath according to time, and reflection in sea level and ocean floor. The acoustic signals are reflected, scattered and absorbed by variation of sea level, caused by wind specially. The transmitting signals are also received with large distortion due to media characteristics. Therefore, it is well known that the acoustic communication in underwater environment is very difficult.

Recently, underwater acoustic communication (UWAC) has been studied by many scholars and researchers. Direct-sequence code division multiple access (DS-CDMA) [1]-[4], orthogonal-frequency division multiplexing (OFDM) [1],[5]-[7],and multi-input multi-output (MIMO) [1],[8], modulation and error correction[9], and others [10]-[11], techniques that can transmit high-speed data are used in UWAC.

In order to use UWAC, we need to estimate time difference between the two signals in underwater environment. To do this, we have to acquire two pinger periodically broadcast a signal with stable frequency through hydrophone in underwater environment. Typically, there are several method to estimate the time-difference between the two signals such estimating as the arrival time of the first non-background segment in both signals and calculate the temporal difference, calculating the cross-correlation between the two signal to infer the time-lagged, and estimating the phase delay to infer the time difference.

In this paper, we present calculating the cross-correlation between the two signals to infer the time-lagged to apply UWAC. We also present the experimental result of estimating the arrival time by using cross-correlation.

Ⅱ. Time Difference Estimation using Cross Correlation

2-1 Data preprocessing

There is an array of N_H hydrophones which record the acoustic signal with sampling frequency F_s In the example showed in Fig. 1, there are two impulsive segments locating around 0.7755 and 1.8449 second in the data of the first hydrophone.

The problem is to estimate the time-difference between the two signals, three methods can be applied: (1) estimating the arrival time of the first non-background segment in both signals and calculate the temporal difference.

The input signal from each hydrophone is an integer array which valued in range $(-2^{16}, 2^{16})$. The purpose of preprocessing is to normalized the value range into (-1,1).

$$z_t = \frac{x_t}{\max\limits_{0 \le l \le T-1} |x_l|}, 0 \le t \le T-1 \tag{1}$$

where x_t is a data sample and T is the total number of data sample.

2-2 Preliminaries

Given two discrete-time real-valued signal $x_1(n)$ and $x_2(n)$ of duration N and a lag l, the cross-correlation between x_1 and x_2 is given by equation (2).

$$r_{x_1x_2}(l) = \begin{cases} \sum\limits_{n=0}^{N-1-l} x_1(n+l)x_2^*(n) & l \ge 0 \\ r_{x_1x_2}^*(-l) & l < 0 \end{cases} \tag{2}$$

where x^* denotes the complex conjugate of x.

The calculation of cross-correlation is similar to convolution and thus it can be calculated by using the discrete Fourier transform(DFT). Of course there are many ways to calculate convolution but the calculation of Fourier transform is the fastest. After the cross-correlation is computed, the time difference is calculated as $\Delta_t = \frac{l_0}{F_s}$, where, $l_0 = \underset{l}{\arg\max} |r_{x_1,x_2}(l)|$.

그림 1. 4개의 하이드폰으로부터의 데이터

Fig. 1. Data from four hydrophone.

2-3 Algorithm

An algorithm for calculating sample cross-correlation function is following as:

Input: Real-valued signal $x_1(n)$, $x_2(n)$ of duration N, sampling frequency F_s, number of lags N_l

Output: Time difference Δ_t between x_2 and x_1

1. Find n_{FFT} is the smallest power of 2 which larger than or equal to $2N-1$;
2. Compute the discrete-time Fourier transform $X_1(k), X_2(k)$;
3. Calculate the Cross Power Spectrum:

$$P_{x_1x_2}(k) = X_1(k) \cdot X_2^*(k)$$

where X^* denotes the conjugate of X;

4. Compute the inverse DFT $\hat{x}(n)$ from $P_{x_1x_2}(k)$;
5. Normalization:

$$\hat{x}(n) = \frac{\hat{x}(n)}{A_0}$$

where $A_0 = \sqrt{(\sum_{n=0}^{N-1}(x_1(n))^2)(\sum_{n=0}^{N-1}(x_2(n))^2}$

6. Shift the array $\hat{x}$ such that the maximum value is aligned at the middle of the array;
7. Create r of length $2N_{l+1}$ from $\hat{x}$ from $(\frac{n_{FFT}}{2}-N_l)$ to $(\frac{n_{FFT}}{2}+N_l)$ corresponding to lags $N_l, -N_l+1, ..., 0, ...N_l-1, N_l;$
8. $l_0 = \begin{pmatrix} \mathrm{arg}max\,|r(l)| \\ 0 \le l \le 2N_l+1 \end{pmatrix} - N_l$
9. $\Delta_t = \frac{l_0}{F_s}$

We take a half of 1st and 2nd hydrophone data for demonstration. The first step is to compute the DFT of the two signals. The 1st and 2nd hydrophone data and their corresponding magnitude of the DFT is showed in Fig.2 and 3.

We compute the cross power spectrum and it shows in Fig. 4. Next, we compute the inverse DFT, normalize and shift the result as shown in Fig. 5.

Then, we find in the cross-correlation the peak which corresponds to the time-lagged between 2nd hydrophone data and 1st hydrophone data as shown in Fig. 6.

표 1. 4개의 하이드로폰 데이터의 기준 시간 차이

Table 1. Referenced time difference of four hydrophones' data.

	H_1	H_2	H_3	H_4
H_1	0	-0.000357	0.002877	0.000733
H_2	0.000357	0	0.003233	0.00109
H_3	-0.002877	-0.003233	0	-0.002143
H_4	-0.000733	-0.00109	0.002143	0

The lag value is 466 corresponding to 0.001553 second. The estimation error is Δ_E = $|0.001553-(0.000357)|=0.00191$ second (the number -0.000357 comes from table 1).

Where the data in row x and column y is the time difference between yth and xth hydrophone data. For example, in the second row, the data the data corresponding to $(t_{s_{H1}}-t_{s_{H2}}), (t_{s_{H2}}-t_{s_{H1}}), (t_{s_{H3}}-t_{s_{H1}}), (t_{s_{H4}}-t_{s_{H1}})$ respectively. The estimation error measured by mean absolute difference can be represented by equation (3).

$$\Delta_E = \frac{2}{N_H(N_H-1)}\sum_{l=1}^{N_H}\sum_{l2=l+1}^{N_H}\left|\hat{\Delta}_t[l,l2]-\Delta_l^0[l,l2]\right|[s] \quad (3)$$

where N_H is the number of Hydrophones ($N_H=4$), $\Delta_t^0[l,l2]$ is given in table 2 and $\hat{\Delta}_t[l,l2]$ is the estimated time difference.

For example, with $N_H=4$, we can calculate following equation (4).

$$\Delta_E = \frac{1}{6}(|\hat{\Delta}_t[1,2]-\Delta_t^0[1,2]+|\hat{\Delta}_t[1,3]-\Delta_t^0[1,3]|+ |\hat{\Delta}_t[1,4]-\Delta_t^0[1,4]+|\hat{\Delta}_t[2,3]-\Delta_t^0[2,3]|+ |\hat{\Delta}_t[2,4]-\Delta_t^0[2,4]+|\hat{\Delta}_t[3,4]-\Delta_t^0[3,4]|) \quad (4)$$

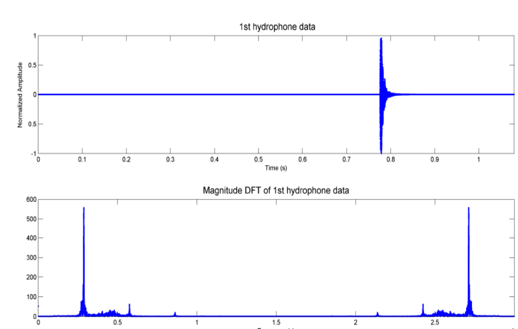

그림 2. 1차 하이드로폰 데이터의 이산 푸리에 변환

Fig. 2. DFT of 1st hydrophone data.

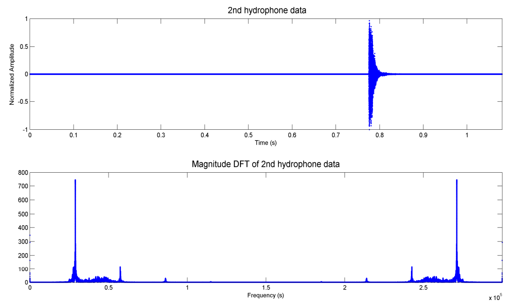

그림 3. 2차 하이드로폰 데이터의 이산 푸리에 변환
Fig. 3. DFT of 2nd hydrophone data.

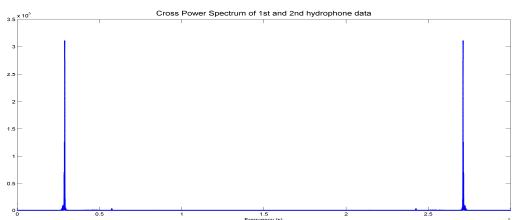

그림 4. 1차와 2차 하이드로폰 데이터의 교차 전력 스펙트럼
Fig. 4. Cross power spectrum of 1st and 2nd hydrophone data.

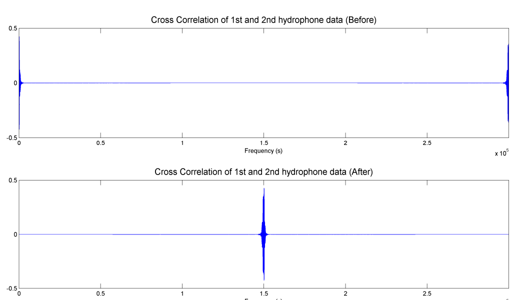

그림 5. 1차와 2차 하이드로폰 데이터의 교차 상관
Fig. 5. Cross-correlation of 1st and 2nd hydrophone data.

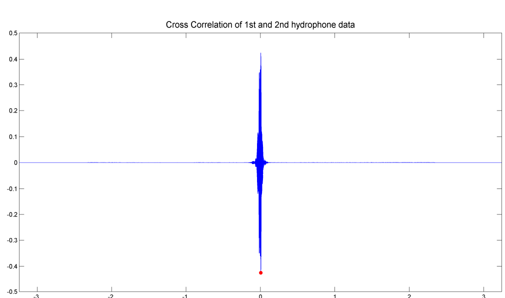

그림 6. 1차와 2차 하이드로폰 데이터의 최대 교차 상관
Fig. 6. Maximum of cross-correlation of 1st and 2nd hydrophone data.

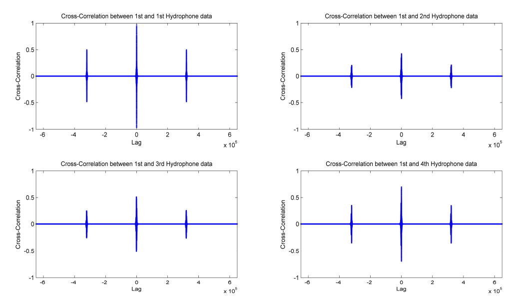

그림 7. 다른 값을 가진 1차와 2차 하이드로폰 데이터의 교차 전력 스펙트럼
Fig. 7. Cross-correlation of 1st hydrophone data with the others.

Ⅲ. Evaluation of method for cross-correlation

In this evaluation, we first use the Matlab function xcorr to calculate the sample cross-correlation function in order to infer the time difference. Fig. 7 shows the cross-correlation result of 1st hydrophone data with the others including the autocorrelation with itself. We then translate those Matlab source code into C programming language with using the FFTW library [2] (http://fftw.org) for FFT computation.

The estimated results are showed in table 2 and 3. In table 2, time lag is the lag at which the cross-correlation γ yields maximum. Given lag l_0, the estimated time is given by $\Delta_t = \frac{l_0}{F_s}$ (seconds). Those result are showed in table 3.

표 2. 교차 상관으로 시간 지연
Table 2. Time lag from cross-correlation.

	H_1	H_2	H_3	H_4
H_1	0	466	−1271	−99
H_2	−466	0	−104	324
H_3	1271	104	0	1208
H_4	99	−324	−1208	0

표 3. 교차 상관을 이용한 시간 차이 추정
Table 3. Time difference estimated(in second) using cross-correlation.

	H_1	H_2	H_3	H_4
H_1	0	−0.001553	0.004237	−0.00033
H_2	−0.001553	0	0.000347	0.00108
H_3	0.004237	−0.000347	0	0.004027
H_4	0.00033	−0.00108	−0.004027	0

The estimation error in mean absolute difference is EXCORR = 0.003055 second. It means that this algorithm with the cross correlation can apply in the underwater system.

Ⅳ. Conclusion

In order to use UWAC, we need to estimate time difference between the two signals in underwater environment. To do this, we have to acquire two pinger periodically broadcast a signal with stable frequency through hydrophone in underwater environments.

In this paper, we presented calculating the cross-correlation between the two signal to infer the time-lagged. We also presented the experimental result of estimating the arrival time by using cross-correlation. we get EXCORR = 0.003055 second as the estimation error in mean absolute difference. In the future, we need to apply into real underwater environments including river and ocean.

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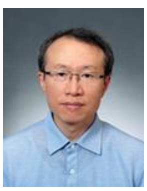

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