Regular paper

Journal of the KIECS. pp. 365-372, vol. 11, no. 4, Apr. 30 2016, t. 72, pISSN 1975-8170 | eISSN 2288-2189
http://dx.doi.org/10.13067/JKIECS.2016.11.4.365

수중 환경에서의 위상 지연을 이용한 음향 신호의 시간 차이 추정 기법

이영필[*] · 문용선[**] · 고낙용[***] · 최현택[****] · 이정구[*****] · 배영철[******]

Estimation Technique of Time Difference of Acoustic Signal by phase delay in Underwater Environments

Young-Pil Lee[*] · Yong-Seon Moon[**] · Nak-Yong Ko[***] · Hyun-Taek Choi[****] · Jeong-Gu Lee[*****] · Young-Chul Bae[******]

요 약

최근에 UWAC에 대한 연구가 많은 연구자와 학자들에 의해 연구되고 있다. 수중 환경에서 두 신호 사이의 시간 차이 추정 기법은 배경이 없는 영역에서 도착 시간 추정, 상관관계 추정, 그리고 시간 지연 추정의 3가지가 제시되어 있다. 이 논문에서는 위상 지연에 기반하여 두 신호 사이에서의 시간 차이 추정 기법을 제시한다.

ABSTRACT

Recently, UWAC(: UnderWater Acoustic Communication) has been studied by many scholars and researchers. 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 estimating method by the phase delay to infer the time difference in two signals.

키워드

Underwater Environments, Signal Processing, Time Difference, Acoustic Signal, Phase Delay
수중 환경, 신호 처리, 시간 차이, 음향 신호, 위상 공간, 위상 지연

Ⅰ. Introduction

In underwater environment, there is a pinger periodically broadcast a signal with stable frequency.

Recently, UWAC(: UnderWater Acoustic

---

* 레드원테놀러지(994451@hanmail.net)
** 순천대학교 정보통신공학부(moon@sunchon.ac.kr)
*** 조선대학교 제어계측로봇공학과(nyko@Chosun.ac.kr)
**** KIOST(htchophd@kiost.ac)
***** KISTI(jglee@kisti.re.kr)
****** 교신저자 : 전남대학교 전기·전자통신·컴퓨터공학부

・접 수 일 : 2016. 02. 26
・수정완료일 : 2016. 04. 13
・게재확정일 : 2016. 04. 24

・Received : Feb. 26, 2016, Revised : Apr. 13, 2016, Accepted : Apr. 24, 2016

・Corresponding author : Young-Chul Bae
Division of Electrical · Electronics Communication and Computer Engineering, Chonnam National University
Email : ycbae@jnu.ac.kr

Communication) has been studied by many scholars and researchers. DS-CDMA[1],[6],[12],[14-15], OFDM (: Orthogonal-Frequency Division Multiplexing) [1-3],[7], and MIMO (multi-input multi-output) [1],[4], modulation and error correction[5], and others [8-11],[13] techniques that can transmit high-speed data are used in UWAC.

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 estimating method by the phase delay to infer the time difference in two signals.

Ⅱ. 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 figure 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).

$$x_t = \frac{x_t}{\max\limits_{0 \le l \le T-1} |x_l|}, 0 \le t \le T-1 \qquad (1)$$

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

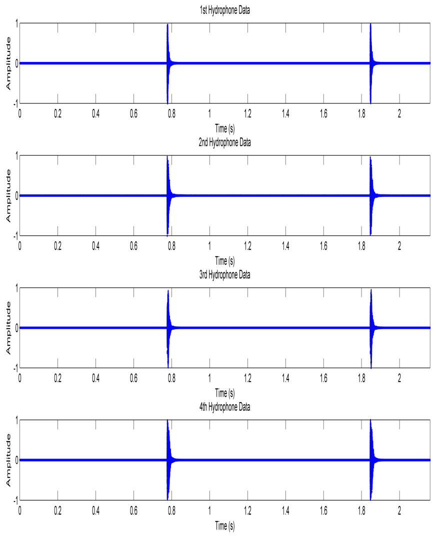


Fig. 1 Data from four hydrophones

Ⅲ. Time difference estimation using phase delay

3.1 Preliminaries

We consider a source signal which is a sinusoid with unknown frequency f_0c like equation (1).

$$s(t) = A\cos(2\pi f_0 t + \theta) \qquad (2)$$

Assume that there is two receivers which have the sampling frequency F_s the real-valued signals which received are equation (3).

$$x_l(n) = A\cos\left(2\pi\frac{f_0}{F_s}n + \phi_l\right) \tag{3}$$
$$= \frac{A}{2}\left(e^{j(2\pi\frac{f_0}{F_s}n+\phi_l)} + e^{-j(2\pi\frac{f_0}{F_s}n+\phi_l)}\right)$$
$$\approx \frac{A}{2}e^{j(2\pi\frac{f_0}{F_s}n+\phi_l)} \quad l = 1,2$$

The Discrete Fourier Transform (DFT) of equation (3) can be described by equation (4).

$$X_l(f) = \sum_{n=0}^{N-1}\frac{A}{2}e^{j(2\pi\frac{f_0}{F_s}n+\phi_l)}e^{-j2\pi\frac{f}{F_s}n} \tag{4}$$
$$= \sum_{n=0}^{N-1}\frac{A}{2}e^{j(\phi_l+2\pi\frac{f_0-f}{F_s}n)}$$
$$= \frac{A}{2}\frac{\sin\frac{2\pi(f_0-f)N}{2F_s}}{\sin\frac{2\pi(f_0-f)}{2F_s}}e^{j(\phi_l+2\pi\frac{f_0-f}{2F_s}(N-1))}$$

$l = 1,2$

Where N is the length of the sampled signals. When $f = f_0$, we get equation (5) from equation (4).

$$X_l(f_0) \approx N\frac{A}{2}e^{j\phi_l} \tag{5}$$

The Cross Power Spectrum of x_1 and x_2 at f_0 is given by equation (6).

$$P_{x1x2}(f_0) = X_1{}^*(f_0)X_2(f_0) \tag{6}$$
$$= N^2\frac{A^2}{4}e^{j(\phi_2-\phi_1)}$$

From equation (6), the phase delay between x_2 and x_1 is calculated by equation (7).

$$\Delta_\phi = \angle X_1^*(f_0)X_2(f_0) = \arctan\frac{RX_1^*(f_0)X_2(f_0)}{IX_1^*(f_0)X_2(f_0)} \tag{7}$$

where $R(X), I(X)$ are correspondingly the real part and imaginary part of X. Because f_0 is unknown, we can estimate it as following equation (8).

$$\hat{f_0} = \frac{1}{2}\left(\frac{\operatorname{argmax}|X_1(f)|^2}{f} + \frac{\operatorname{argmax}|X_2(f)|^2}{f}\right) \tag{8}$$

Finally, the time difference between x_2 and x_1 is calculated by equation (9).

$$\Delta_t = \frac{\Delta_\phi}{2\pi\hat{f_0}} \tag{9}$$

3.2 Algorithm

Algorithm for calculating sample cross-correlation function is following as:

Input: real-valued signal x_1, x_2, duration N, sampling frequency F_s

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 N;
2. Compute the DFT $X_1(f)$, $X_2(f)$ of $x_1(n), x_2(n)$;
3. Estimate f_0 using equation 8;
4. Calculate the phase delay Δ_ϕ using equation 7;
5. Calculate the time different Δ_t using equation 9;

Ⅳ. Example and evaluation

4.1 Example

We take all 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 figure 2 and 3.

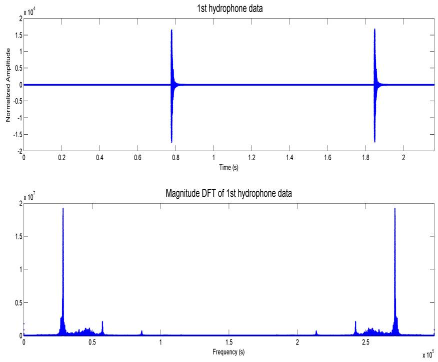


Fig. 2 DFT of 1st hydrophone data

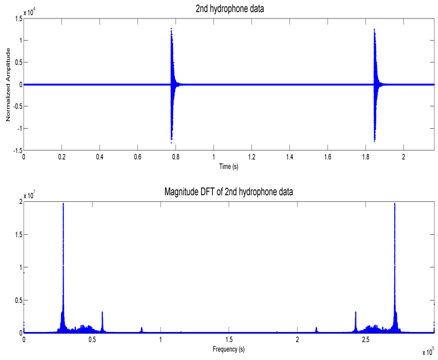


Fig. 3 DFT of 2nd hydrophone data

Then, we compute the square of magnitude of the DFT and find the frequency at maximum value of those peaks as shown in figure 4.

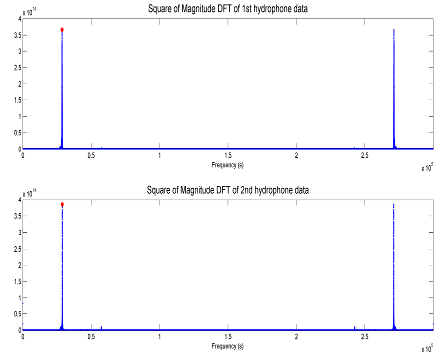


Fig. 4 Square of magnitude of DFT of 1st and 2nd hydrophone data

The frequency is $\widehat{f}_0$ = 28774.17 Hertz, and the corresponding phase delay is 0.130122 radian. The time difference is estimated at 0.000001 second with estimation error is Δ_E = $|0.000001-(-0.000357)|=0.000358$ second (the number -0.000357 comes from table 1).

4.2 Evaluation

We experiment on the four hydrophones' data as showed in figure 1. To make a reference, we plot out the original data at the first non-background segment from 0.775 to 0.777 second, as shown in figure 5.

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

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 (10)

$$\Delta_E=\frac{2}{N_H(N_H-1)}\sum_{l=1}^{N_H}\sum_{l2=l+1}^{N_H}\left|\widehat{\Delta}_t[l,l2]-\Delta_l^0[l,l2]\right|[s] \tag{10}$$

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

For example, with $N_H=4$, we can calculate following equation (11).

$$\Delta_E = \frac{1}{6}(|\widehat{\Delta}_t[1,2] - \Delta_t^0[1,2] + |\widehat{\Delta}_t[1,3] - \Delta_t^0[1,3]| + \\ |\widehat{\Delta}_t[1,4] - \Delta_t^0[1,4] + |\widehat{\Delta}_t[2,3] - \Delta_t^0[2,3]| + \\ |\widehat{\Delta}_t[2,4] - \Delta_t^0[2,4] + |\widehat{\Delta}_t[3,4] - \Delta_t^0[3,4]|) \quad (11)$$

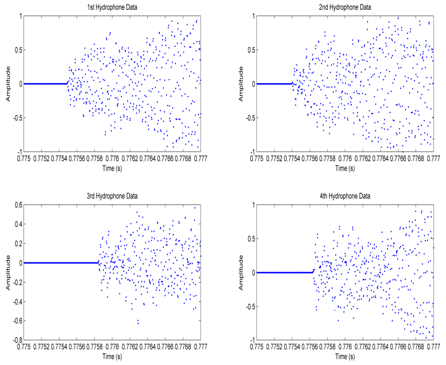


Fig. 5 Start position of the first non-background segment

We implement algorithm using both Matlab and C programming language with using the FFTW library [16] (http://fftw.org) for FFT computation. We get estimated Sinusoid Frequency and Phase Delay (in radian), they are represent at table 2 and 3, respectively.

Table 2. Sinusoid Frequency estimated using phase delay

	H_1	H_2	H_3	H_4
H_1	28,702.64	28,774.27	28,768.16	28,664.30
H_2	28,774,16	28,845.69	28,838.68	28,735.83
H_3	28.767.16	28,838.68	28,831.67	28,728.82
H_4	28,664.30	28,735.83	28,728.82	28,625.97

Table 3. Estimated phase delay

	H_1	H_2	H_3	H_4
H_1	0	0.130122	3.104033	0.927931
H_2	-0.130122	0	0.927931	0.799809
H_3	-3.104033	-0.927931	0	-2.176103
H_4	-0.927931	-0.799809	2.176103	0

We acquire that the estimation error in mean absolute difference is $\Delta_{EPHEASEDEALY=0.000235}$ second.

Ⅴ. Conclusion

In this paper, we presented estimating method by the phase delay to infer the time difference in two signals.

Acknowledgments

“This research was a part of the project titled 'R&D center for underwater construction robotics', funded by the Ministry of Oceans and Fisheries(MOF) and Korea Institute of Marine Science &Technology Promotion(KIMST), Korea.”

Reference

[1] A. Ranjan and Ashish Ranjan, “Underwater Wireless Communication Network,” *Advance in Electronic and Electric Engineering*, vol. 3, no. 1, 2013, pp. 41-46.

[2] P. J. Gendron, “Orthogonal frequency division multiplexing with on-off keying: Noncoherent performance bounds, receiver design and experimental results,” *U.S. Navy J. of Underwater Acoustics*, vol. 56, no. 2, 2006, pp. 267-300.

[3] M. Stojanovic, “Low complexity OFDM detector for underwater channels,” In *Proc. Of MTS/IEEE OCEANS Conf.*, Boston, USA, Sept., 2006.

[4] B. Li, S. Zhou, M. Stojanovic, L. Freitag, and P. Willett, “Multicarrier communication over underwater acoustic channels with nonuniform Doppler shifts,” *IEEE J. of Oceanic Engineering*, vol. 33, no. 2, Apr. 2008, pp. 198-209.

[5] Y. Labrador, Masoumeh Karimi, Deng Pan, and Jerry Miller, “Modulation and Error Correction in the Underwater

Acoustic Communication Channel," *Int. J. of Computer Science and Network Security*, vol. 9, no. 7, July 2009, pp. 123-130.

[6] H. Kang and W. Han, "Performance analysis of Variable Rate Multi-carrier CDMA under an underwater acoustic channel," *J. of Korean Institute of Intelligent Systems,* vol. 7, no. 1, 2012. pp. 33-38.

[7] Y. Im and H. Kang, "Performance analysis of an adaptive OFDM over an underwater acoustic channel," *J. of Korean Institute of Intelligent Systems,* vol. 5, no. 5, 2010, pp. 509-515.

[8] D. Lee and Y. Yang, "Two-Dimensional Localization Problem under non-Gaussian Noise in Underwater Acoustic Sensor Networks," *J. of the Korean Institute of Intelligent Systems,* vol. 23, no. 5, 2013. pp. 418-422.

[9] S. Noh, N. Ko, and H. Choi, "Implementation and Performance Comparison for an Underwater Robot Localization Methods Using Seabed Terrain Information," *J. of the Korean Institute of Intelligent Systems*, vol. 25, no. 1, 2015, pp. 70-77.

[10] H. Son, J. Park, and Y. Joo, "Intelligent Range Decision Method for Figure of Merit of Sonar Equation," *J. of the Korean Institute of Intelligent Systems,* vol. 23, no . 4, 2013, pp. 304-309.

[11] D. Shin, S. You Na, and J. Kim, "Fuzzy Distance Estimation for a Fish Robot," *Int. J. of Fuzzy Logic and Intelligent Systems,* vol. 5, no. 4, 2005, pp. 316-321.

[12] H. Kang and W. Han, "Performance analysis of Variable Rate Multi-carrier CDMA under an underwater acoustic," *J. of the Korea Institute of Electronics Communications Sciences*, vol. 7, no. 1, 2012, pp. 33-38.

[13] Y. Im, P. Lim, J. Lee, and C. Kim, "Interface Effect Analysis between Undersea Fiber Optic Cable and Underwater Acoustic channel," *J. of the Korea Institute of Electronics Communications Sciences*, vol. 10, no. 9, 2015, pp. 979-986.

[14] Y. Lee, Y. Moon, N. Ko, H. Choi, L. Huang, and Y. Bae, "Measurement of DS-CDMA Propagation Distance in Underwater Acoustic Communication Considering Attenuation and Noise," *Int. J. of Fuzzy Logic and Intelligent Systems,* vol. 15, no. 1, 2015, pp. 25-26.

[15] Y. Lee, Y. Moon, N. Ko, H.Choi, L. Huang, and Y. Bae, "DSSS-based Channel Access Technique DS-CDMA for Underwater Acoustic Transmission," *Int. J. of Fuzzy Logic and Intelligent Systems,* vol. 15, no. 1, 2015, pp. 53-59.

[16] Y. Im and H,Kang, "Performance analysis of an adaptive OFDM over an underwater acoustic channel," *J. of the Korea Institute of Electronics Communications Sciences*, vol. 5, no. 6, 2010, pp. 509-515.

저자 소개

이영필(Young-Pil Lee)

2006년 2월 : 순천대학교 전자공학과(공학사)

2008년 2월 : 순천대학교 전자공학과(공학석사)

2008년 ~ 현재 : 레드원테크놀러지(주) 연구원

※ 관심분야 : 로봇 제어, 모터 제어, 산업통신망

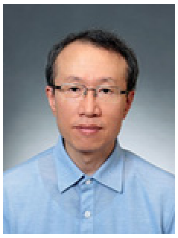
문용선(Yong-Seon Moon)

1983년 2월 : 조선대학교 전자공학과(공학사)

1989년 2월 : 조선대학교 대학원 전자공학과(공학박사)

1992년 ~ 현재 : 순천대학교 정보통신공학부교수

※ 주 관심분야 : 산업통신망 및 로봇, 실시간 모션제어



고낙용(Nak-Yong Ko)

1985년 2월 : 서울대학교 제어계측공학과(공학사)
1987년 2월 : 서울대학교대학원 제어계측공학과(공학석사)
1993년 2월 : 서울대학교 대학원 제어계측공학과(공학박사)
1997～1998, 2004～2005 미국 Carnegie Mellon Univ. Visiting research scientist
1992년～현재 조선대학교 제어계측로봇공학과 교수
※ 주 관심분야 : 지상로봇과 수중로봇의 자율주행

최현택(Hyun-Taek Choi)

1991년 : 한양대학교 전자공학과(공학사)
1993년 : 한양대학교 대학원 전자공학과(공학석사)
2000년 : 한양대학교 대학원 전자공학과(제어 및 로보틱스)(공학박사)
1993년～1995년 : KT 연구개발S/W 연구소 전임연구원
2000년～2003년 : 하와이 주립대학교 기계공학과 Post-Doc.
2003년～현재 : 한국해양과학기술원, 선박해양플랜트연구소 책임 연구원
※ 관심분야 : 수중로봇, 해양시스템, 강인제어

이정구(Jeong-Gu Lee)

1989년 충북대학교 전기공학과 졸업
1991년 충북대학교 대학원 전기공학과 졸업(공학석사)
2008년 충북대학교 대학원 전기공학과 졸업(공학박사)
1991년~2000년 산업기술정보원 책임연구원
2015년～한국과학기술정보연구원 책임연구원
※ 관심분야 : Display, Solar Cell, Information Communication, Information Analysis, Technology Commercialization etc.

배영철(Young-Chul Bae)

1984년 광운대학교 전기공학과(공학사)
1986년 광운대학교대학원 전기공학과 (공학석사)
1997년 광운대학교대학원 전기공학과(공학박사)
1986년～1991년 한국전력공사
1991년～1997년 산업기술정보원 책임연구원
1997년～현재 전남대학교 전기・전자통신・컴퓨터공학부 교수
2002년～2002년 Brigham Young University 방문교수
2011년～2011년 University of Utah 방문교수
※ 관심분야 : Chaos Control and Chaos Robot, Robot control etc.