Long Range Acoustic Navigation of Cruising AUV Based on Bearing Estimation

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***Abstract*-In this paper, a basic study on acoustic navigation for long range cruising AUV is described. Typically the position of AUV can be estimated by measuring the range between the AUV and acoustic sources or bearing of the acoustic signal. In long range observation, it is difficult to estimate these parameters in three dimensional. Depth can be directly sensed by depth sensor, then we can estimate the AUV position with measuring the range or bearing only horizontally. In this paper, feasibility of navigation for long range cruising AUV based on bearing estimation is considered. The bearing is estimated by measuring direction of arrival (DOA) of acoustic signal received by a receiver array equipped on the body side of the AUV. The array is horizontal long due to the shape of typical cruising AUV, and it is good to measure especially horizontal DOA. Estimation of the horizontal DOA with two method, delay-and-sum beam-forming (BF) and multiple signal classification (MUSIC) method, were simulated. Carrier frequency of the acoustic signal was assumed as 1kHz, and the signal was received by a planer receiver array, which size is 0.7m for height and 4.9m for width. The acoustic signal was a coded by eighth order maximum length sequence (M-seq.) code. The pulse width was about 1 second. The accuracy of estimation of the horizontal DOA were considered especially about characteristics in Gaussian noise and influence of multipath wave. MUSIC is said to be super resolution method. However, the accuracy of horizontal-DOA estimation is not so good comparing with the beam-forming. The sharpness of the peak in MUSIC spectrum is much sharp rather than beam-forming, but the top of the peak is not stable. On the other hand, when influential multipath exists, MUSIC may be more accurate than BF. However, the result of MUSIC is depending on decision of number of incoming waves. In case of longer range, namely signal to noise ratio (SNR) is low, BF is considered to be simpler, more robust and reliable. On the other hand, in case of comparatively short range, such as several dozen km, MUSIC may be more useful, because SNR is higher and multipath wave considered to be more influential.**

I. INTRODUCTION

In recent years, autonomous underwater vehicles (AUVs) have been energetically researched and developed. AUVs are becoming the main player in the field of ocean observation. General type of AUV is cruising AUVs that cruise at several knots to observe the ocean. Small AUVs whose body length

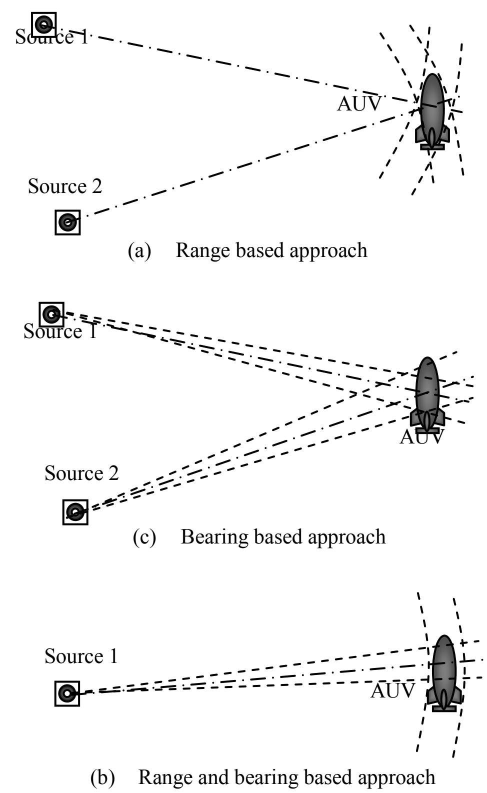

Figure 1. Three ways to navigate AUV in long range.

are several meters are used for precision observation at very near the sea bottom. On the other hand, there is a concept of long range cruising AUV, which cruises long range and long term at once without mother ship. Basic study on acoustical absolute navigation of this type of AUV is described in this paper.

Many fundamental technologies are necessary to operate an AUV. For example, there are on power source, vehicle control, autonomous algorithm, sensing, communication and navigation. Navigation is one of most critical technology for AUV. There some ways to navigate AUV. An inertial navigation system[1] (INS) is typically equipped an AUV. INS senses accelerations and angler velocities along three orthogonal axis, and integrate these sensed values to gain the AUVs position. Other navigation sensors aim the INS. Doppler velocity log[2] (DVL) senses velocity of AUV by detect the Doppler shift rate of acoustic wave. These sensors do not senses directly the AUVs position. Then a significant problem is the drift error in positioning result as well known. This problem becomes more significant in long term operation. AS aiding sensors, depth sensor, altimeter, and magnetic compass are often equipped. Acoustic navigation system[3] (ANS), such as ultra short baseline (USBL) or long baseline (LBL), is adopted to estimate absolute position of AUV. Moreover, local positioning technique, called as simultaneous localization and mapping[4] (SLAM), have been proposed. These navigation devices have each particular characteristics and are integrated to navigate AUV more accurately.[5],[6]

ANS is necessary to gain temporal absolute position. USBL an LBL system are often used. However these systems are for short range up to about 5,000 meters for horizontal range and 10,000 meters for slant range. Then another longer range ANS is desired. As well known, sound speed distribution in the ocean is layered horizontally and the ray path of acoustic wave propagates with dynamic refraction. Therefore it is difficult to estimate three dimensional position of AUV by only analysis of acoustic wave. A depth sensor is equipped on an AUV as mentioned above. Then we should estimate horizontal position of AUV by acoustics. Typically there are three patterns to measure the horizontal position, as shown in Fig. 1. Horizontal range between the acoustic source and the AUV is measured by propagation time of the acoustic signal. Ray path of the acoustic signal is refracted and the propagation time is difficult to be measured accurately. However if the sound fixing and ranging (SOFAR) channel exists and the AUV is near it, horizontal range can be estimated within zero point several % of the horizontal range. Synchronous between the acoustic source and the AUV is necessary to measure the propagation time. On the other hand, we can estimate the AUVs position by measuring horizontal direction of arrival (DOA) of acoustic signal. Body of cruising AUV is horizontally long, and the DOA can be estimated using received acoustic signals by receiver array allocated on the body side of AUV. However the position of estimation by DOA estimation depends on the horizontal range as same as USBL. Then the DOA estimation should be estimated more accurately for longer range positioning. In this paper, basic analysis of the accuracy of the horizontal DOA estimation by simple delay-and-sum beam-forming[8] (BF) and multiple signal classification[7],[8] (MUSIC) methods.

In section II, conditions of analysis and methodology of estimation of DOA are explained. Basic analysis and consideration of feasibility of estimation of horizontal DOA is described in section III. And in section IV, this paper is concluded.

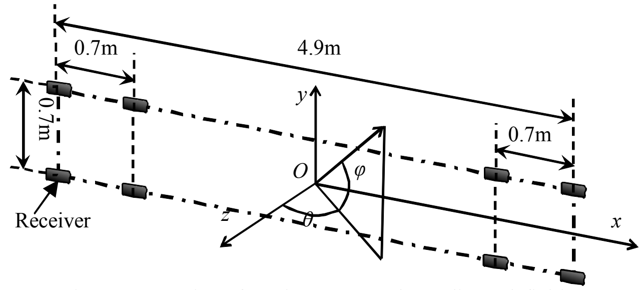

Figure 2. Location of receiver array and coordinate definition.

Table I. Parameters of transmitted signal.

Items	Values
Carrier frequency	1kHz
Chip rate	200 chips per second
PN code	Eighth order M-sequence
Code length	255
Acoustic signal width	1.275 sec
Modulation	BPSK

II. Estimation of Direction of Arrival

A. Acoustic signal and condition

The acoustic signal for positioning is assumed a direct-sequence spread spectrum (DSSS) signal. Eighth order maximum length sequence (M-seq.) is used as pseudo noise (PN) code. Transmitted signal is modulated with binary phase shift keying (BPSK) by the PN code. Base-band signal and pass-band signal of the transmitted signal are respectively represented as

$$S_{Tx}^{base}(t) = \sum_{l=0}^{L_{chip}-1} C_l h(t - lT_c), \tag{1}$$

$$S_{Tx}(t) = real\left\{\left[\sum_{l=0}^{L_{chip}-1} C_l h(t - lT_c)\right]\exp(-j\omega t)\right\}, \tag{2}$$

where S_{Tx}^{base} is the base-band signal and S_{Tx} is the pass-band signal, actual physical acoustic waveform. t is time in second, ω angular frequency of carrier. C_l represents l-th chip of the PN code and T_c is chip period. Then C consists of -1 or +1 and length of the PN code is L_{chip}. h represents function of the square-root-raised-cosine (SRRC) roll-off filter (ROF) for band limitation of the transmitted signal.

Table I shows parameters of transmitted signal. Carrier frequency of the acoustic signal is 1kHz. Chip rate of the BPSK modulation is 200 chips per second. The acoustic signal is received a receiver array equipped on the body side of AUV. Then the array is horizontally long. In this paper, the receiver array is assumed to be set as shown in Fig. 2. The array is horizontally long planer array and consists of eight hydrophones. The shortest baseline of the array is 0.7m. The total size of the array is 0.7m in height and 4.9m in width. Cartesian coordinate $(x\ y\ z)^T$ is defined as in Fig. 2. The horizontal and vertical DOA are represented by θ and φ respectively in Fig. 2.

Process of the DOA estimation is performed for base-band signal received by the receiver array. The base-band signal is fractionally sampled at 5 samples per chip. The base-band signals by respective elements of the array are represented as

$$S_{Rx,k}^{base}(t)=\sum_{n=1}^{N}A_n\left[\sum_{l=0}^{L_{chip}-1}C_l h\left(t-lT_c-\tau_{k,n}\right)\right]\exp(j\omega\tau_{k,n})+W(t), \quad (3)$$

where $S_{Rx,k}{}^{base}$ is base-band signal received by k-th receiver. N represents the number of incoming wave to the array. An is amplitude of the n-th wave. $\tau_{k,n}$ is arrival time of n-th wave to k-th receiver. $W(t)$ represents time-dependent white Gaussian noise.

B. Beam-forming

The estimation of horizontal DOA is performed with two method. One is delay-and-sum BF. The BF is executed with correlated signal between the received signal and replica signal for specific DOA (θ, φ). The replica signal for (θ, φ) is represented as

$$r_{k,(\theta,\varphi)}(t)=\left[\sum_{l=0}^{L_{chip}-1}C_l h\left(t-lT_c-\delta\tau_{k,(\theta,\varphi)}\right)\right]\exp(j\omega\delta\tau_{k,(\theta,\varphi)}), \quad (4)$$

where $\delta\tau_{k,(\theta,\ \varphi)}$ is different time between arrival time to k-th element and arrival time to the origin of the array when the DOA of acoustic wave is (θ, φ). $\delta\tau_{k,(\theta,\ \varphi)}$ is represented as

$$\delta\tau_{k,(\theta,\varphi)}=-\frac{\mathbf{d}_{(\theta,\varphi)}{}^{T}\mathbf{p}_k}{c}, \quad (5)$$

where $\mathbf{d}_{(\theta,\ \varphi)}$ is the DOA of acoustic wave in Cartesian coordinate,

$$\mathbf{d}_{(\theta,\varphi)}=\left[\cos(\varphi)\sin(\theta)\quad \sin(\varphi)\quad \cos(\varphi)\cos(\theta)\right]^{T}, \quad (6)$$

$\mathbf{p}_k$ is position of k-th element in Cartesian coordinate, and c is sound speed around the array. Then the output of BF is described as

$$Bf_{(\theta,\varphi)}(t)=\sum_{k=1}^{K}\sum_{l=0}^{L_{corr}-1}S_{Rx,k}^{base}(t-lT_s)r_{k,(\theta,\varphi)}(t-lT_s), \quad (7)$$

where T_s is sampling period, and L_{corr} is length of the replica signal.

C. Multiple Signal Classification

Another method of the DOA estimation is MUSIC algorithm. MUSIC is based on eigen analysis of input signal. Correlated signal by PN code,

$$S_{Corr,k}(t)=\sum_{l=0}^{L_{corr}-1}S_{Rx,k}^{base}(t-mT_s)r_k(t-mT_s), \quad (8)$$

is assumed to be input for the MUSIC algorithm. $r_k = r_{k,(0,0)}$ in equation (4). The correlation matrix of the input signal is obtained as average of those of two sub-arrays. One consists of elements (1, 2, 3, 4), and another consists of elements (5, 6, 7, 8). These two arrays are set as same shape. The correlation matrices for two arrays are represented as,

$$\mathbf{R}(t)=\frac{1}{M}\sum_{m=0}^{M-1}\mathbf{S}_{Corr}(t-mT_s)\mathbf{S}_{Corr}^{*}(t-mT_s), \quad (9)$$

where $\mathbf{S}_{corr}$ is matrix of correlated signal by PN code. The superscript (*) represents conjugate transpose. In equation (9),

$$\mathbf{S}_{Corr}(t)=\left(S_{Corr,1}(t)\quad S_{Corr,2}(t)\quad\cdots\quad S_{Corr,Kn}(t)\right)^{T}. \quad (10)$$

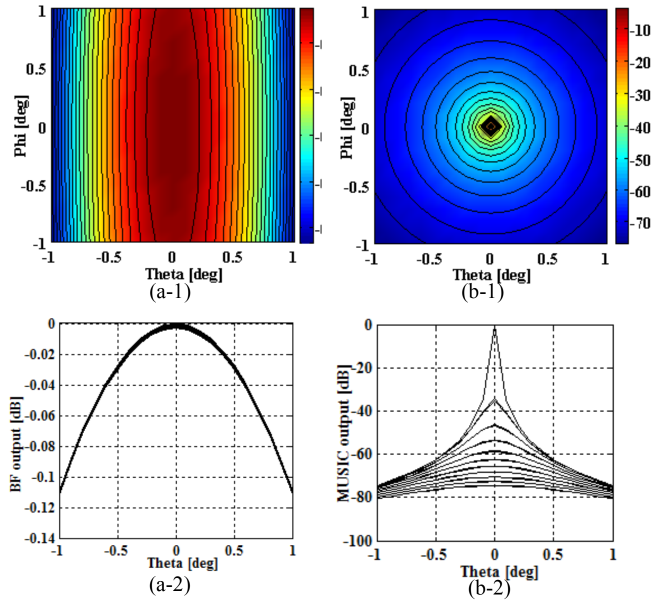

Figure 3. BF and MUSIC outputs in ideal condition.

M is sample number with which samples the correlation matrix is averaged. M is assumed, in this paper, twice the fractional rate of sampling to chip, equal to 10. Kn in equation (10) is number of elements of a sub-array. Eigen values ($\lambda_1 \ldots \lambda_K$) and respective eigen vectors ($\mathbf{e}_1 \ldots \mathbf{e}_K$) are obtained from the correlation matrix in equation (9). The eigen vectors consists of signal subspace and noise subspace, orthogonal to each other. Power output of MUSIC corresponding to direction (θ, φ) is represented by steering vector,

$$\mathbf{a}_{(\theta,\varphi)}=\left(\exp(j\omega\delta\tau_{1,(\theta,\varphi)})\quad \exp(j\omega\delta\tau_{2,(\theta,\varphi)})\quad\cdots\quad \exp(j\omega\delta\tau_{K,(\theta,\varphi)})\right)^{T}, \quad (11)$$

and matrix consists of eigen vectors of noise subspase,

$$\mathbf{E}_{noise}=\left(\mathbf{e}_{Kn-N}\quad \mathbf{e}_{Kn-N+1}\quad\cdots\quad \mathbf{e}_{Kn}\right), \quad (12)$$

as,

$$P_{M,(\theta,\varphi)}=\frac{\mathbf{a}_{(\theta,\varphi)}^{*}\mathbf{a}_{(\theta,\varphi)}}{\mathbf{a}_{(\theta,\varphi)}^{*}\mathbf{E}_{noise}\mathbf{E}_{noise}^{*}\mathbf{a}_{(\theta,\varphi)}}. \quad (13)$$

The number of incoming acoustic waves is decided by the eigen values. The numerator in right side in equation (13) is scaling factor.

III. Feasibility Analysis

In this section, characteristic analysis of the estimation of horizontal DOA by two method mentioned in previous section, and feasibility to adopt to AUV navigation is considered, especially about influence of noise and multipath wave. $W(t)$ represents time-dependent white Gaussian noise.

A. Estimation accuracy in Gaussian noise

In long range navigation, signal to noise ratio (SNR) of the received signal is expected to be low in most cases. Figs. 3 show a result of DOA estimation. In Figs. 3, (a-1) and (a-2) are result by delay-and-sum BF, and (b-1) and (b-2) are result by MUSIC method. The upper figures are contour of

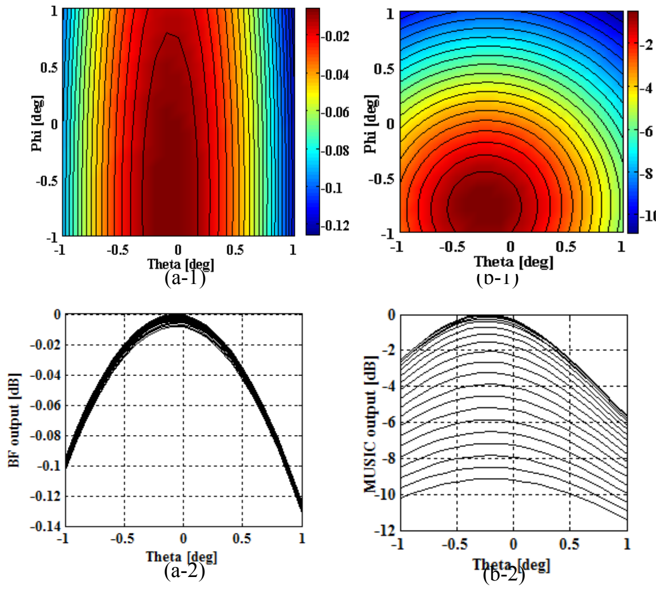

Figure 4. BF and MUSIC outputs at SNR=0dB.

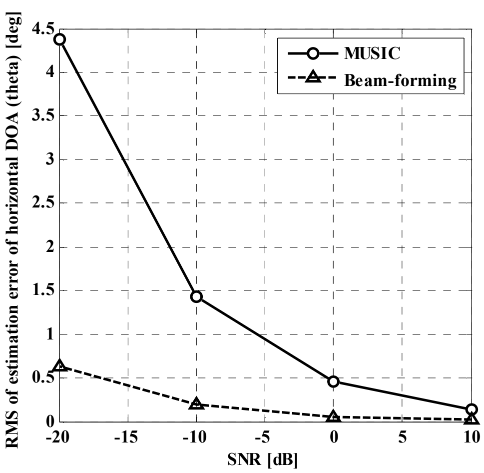

Figure 5. SNR vs estimation error of horizontal DOA.

amplitude of outputs, and the lower figures are those θ, horizontal DOA as the desired value, section. In the lower figures of Figs. 3, drawn lines are for each 0.1 degrees of vertical DOA φ. The true DOA is (0, 0) for (θ, φ) and the SNR is 40dB. Note that scale of vertical axes of (a-2) and (b-2) are different. Peak of output of MUSIC is obviously sharp and can be found to have much high resolution.

On the other hand, Figs. 4 show another results of BF and MUSIC outputs. These figures are allocated as same as Figs. 3. In this figure, most conditions are same as the case for Figs. 3, but the SNR. The SNR is 0 dB. It can be found that the peak of output of MUSIC becomes vividly round, but the is still much sharper than BF. However, the top of peak is totally moved, and the error becomes even larger than BF. Fig. 5 shows the error characteristics depending on the SNR of input base-band signal. The vertical array represents the root mean square (RMS) of estimation error of horizontal DOA, θ.

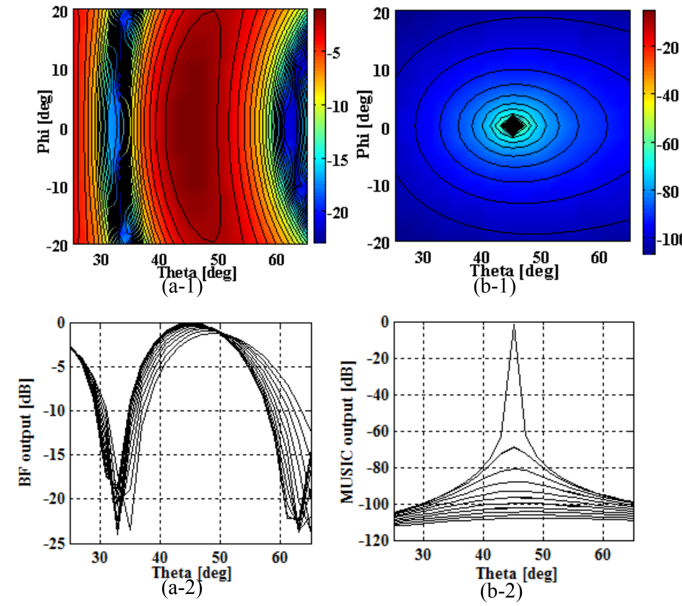

Figure 6. BF and MUSIC output. (θ, φ) is (45° 0°) and SNR is 40dB.

The RMS was calculated with 100 results of random simulations. θ was estimated as the top of the peak, and the top was searched by the steepest gradient method. In Fig. 5, the error of MUSIC is clearly larger. MUSIC is said as high resolution method. However, the (basic) MUSIC method in this paper seems not to be stable against noise.

If we desire the AUV position at under 1% of horizontal range in accuracy. The horizontal DOA should be estimated with error under about 0.5 degree. Then the MUSIC can be used only with more than 0 dB of SNR of received signal. In long range observation, the received acoustic signal is considered to be very low level and the SNR may be almost under 0dB. The MUSIC can be used in comparatively short range, such as several dozen km.

B. Influence of multipath wave

The acoustic signal reaches to the AUV in many paths due to refraction and reflection, especially in SOFAR channel. Here the influence of multipath wave to the estimation of horizontal DOA is described. The sound speed distribution in the ocean is typically layered horizontally. Then the horizontal DOA of multipath wave is same as that of main largest wave. The multipath wave is assumed to have same horizontal DOA θ, but different vertical DOA, φ. If the horizontal DOA is 0 degree, the multipath wave having different vertical DOA is not influential to the estimation of the horizontal DOA. On the other hand, if horizontal DOA is larger, the multipath wave becomes more influential. Figs. 6 shows BF and MUSIC output. SNR is 40dB, and horizontal DOA is 45 degrees. Especially in BF result, it can be found that the main lobe of output is curved. This is cause of the influence of multipath wave. The output of MUSIC is almost same as in Figs. 3. However, MUSIC is also influenced as mentioned bellow.

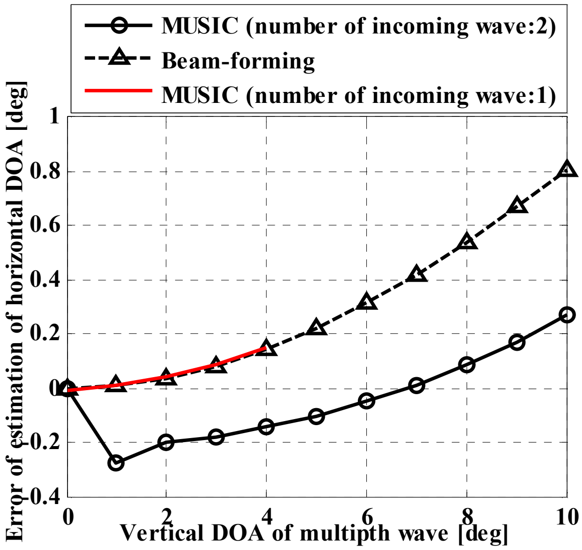

Figure 7. Estimation error of horizontal DOA depending on vertical DOA of multipath wave.

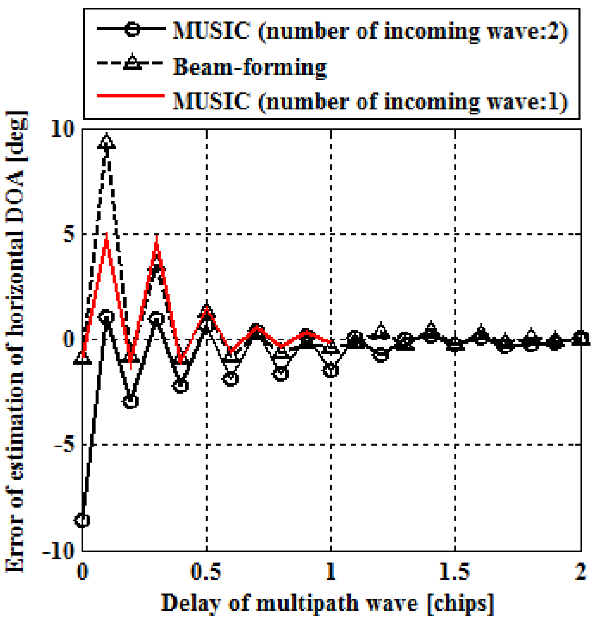

Figure 8. Estimation error of horizontal DOA depending on delay of multipath wave.

Fig. 7 shows estimation error of horizontal DOA depending on the vertical DOA of the multipath wave. In Fig. 7, one multipath wave exists except for direct wave. The DOA of direct wave is same to Figs. 6. Amplitude of multipath wave is 0.6 of direct wave. Delay of multipath wave is 0.3 chips, corresponding to 1.5ms in this paper. The error by BF becomes larger when the vertical DOA of multipath wave is farer from that of direct wave. In case of MUSIC, the error is smaller in 4 or more of horizontal axis than BF. MUSIC is totally with lower error. There is additional result in Fig. 7. The red line is also result of MUSIC, but the decision of number of incoming wave is wrong. The result is even close to result of BF. In MUSIC method, estimation result is much dependent on the decision of number of incoming wave. Fig. 8 shows same error as Fig. 7 depending on the delay of the multipath wave. The DOA of direct wave is same to Fig. 7. Amplitude of multipath wave is 0.8, and vertical DOA of multipath wave is 20 degrees. The error is small when the delay is over about one chip due to effect of pulse compression of coded broadband signal. The multipath wave is separated from the direct wave and its influence become very small. The error of MUSIC is totally smaller than that of BF in the range of short delay. The red line is another MUSIC result with wrong number of incoming wave. The result is close to that of BF as same as in Fig. 7. The influence of multipath wave is a little small for MUSIC method totally. However, it seems not to be enough to deny the disadvantage of instability against noise. Note that the decision of number of incoming wave varies the result largely.

IV. Conclusions

In this paper, acoustic navigation of AUV for long range based on bearing estimation were considered with simulation. The bearing is estimated by measuring the horizontal DOA of acoustic signal to the receiver array equipped on the body side of AUV. The estimation of horizontal DOA was implemented by two method, BF and MUSIC.

MUSIC have higher resolution. However it is instable against noise. After searching the very top of the peak, MUSIC has disadvantage to BF in noisy condition. On the other hand, the influence of multipath wave is totally smaller in MUSIC than BF. However this advantage is small. When the range is comparatively short, SNR is high and multipath wave is influential, MUSIC may more useful than BF. Finally BF is simpler and more robust in this paper.

In the future, derivative method of MUSIC and BF will be also considered. Using multiple pulse such as synthetic aperture technique, and analysis Doppler will be considered for more accurate estimation.

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