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A Novel Joint Estimation Algorithm for Multi-parameter of Underwater Acoustic Channels

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Abstract: A novel joint estimation algorithm is proposed for the multi-path number, the delay and the Doppler shift in the underwater acoustic channels. A single-frequency signal and a Chirp signal are sent with a fixed time interval T. And the fractional Fourier transform (FRFT) is applied to analyze the received signal. Two equations are listed according to FRFT and decorrelation and then the relation table of Doppler shift and delay is got. Besides, it's not necessary to search for the order of received signal as the result of the invariant characteristic of the chirp rate, which greatly improves the algorithm efficient. The simulation results show the effectiveness of the algorithm.

Key words: Multipath, delay, doppler shift, FRFT, underwater acoustic channels

INTRODUCTION

Underwater acoustic channels are characterized by multipath, delay and Doppler shift (Calvo and Stojanovic, 2008). Therefore, the parameters of underwater acoustic channels should be estimated so that the effects of underwater acoustic channels are overcome and the reliability of communication is guaranteed.

Existing algorithms are almost exclusively based on Chirp signals for the multi-parameter estimation of underwater acoustic channels, shown in literatures (Sharif *et al*., 2000; Zheng *et al*., 2007, 2008, 2010). Above of them the sending signal is consist of two Chirps and a m sequence and the merit of previous literatures is solving the estimation of Doppler shift and delay. Moreover, the algorithms based on arrays increase the estimation accuracy of delay and improve the SNR. However, these literatures also provide several shortcomings:

- The receiver is consist of arrays, which results in the complex structure and high cost
- The structure of pilot signal is complex because the signal is consist of a m sequence and two Chirps
- A bank of self-correlators is taken to estimate the channel parameters, which results in the complex computation for the estimation of Doppler shift

Although, Li *et al.* (2006) avoids the use of arrays and takes advantage of the prior knowledge of the sending signal, it suffers from the complex signal process since it takes one FRFT and one fractional frequency domain correlation. Moreover, it can not process the multi-path signals of similar Doppler shifts and lacks delay estimation.

The Double-Chirp Algorithm is proposed in Literature (Yang *et al*., 2009) and this algorithm also avoids the use of arrays. Besides, the multi-path number, the delay and the Doppler shift can be directly estimated by using the prior knowledge of the sending signal and taking only one FRFT, which effectively decreases the computational complexity. Also, the algorithm is still valid when the Doppler shifts are very close from each path. However, the estimation accuracy is slightly worse.

Therefore, a novel joint estimation algorithm is proposed in this study. The Doppler shift can be got through the FFT of high resolution for the single-frequency part according to the character that is the energy of single-frequency signal focusing on a single frequency at frequency domain. Two equations are listed according to FRFT and decorrelation and then the relation table of Doppler shift and delay is accepted. Finally, the delay is accurately extracted through the estimated Doppler shifts according to the relation table.

The novel joint estimation algorithm provides several advantages:

- The multi-path number, the delay and the Doppler shift can be accurately estimated
- The algorithm is still valid when the Doppler shifts from each path are very close
- The multi-path number can be directly obtained and the Doppler shift can be also got at once through the FFT of high resolution for the single-frequency part

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- A bank of self-correlators is avoided, which results in small complex computation for the Doppler shift estimation

THE JOINT ESTIMATION BASED ON FRFT AND DECORRELATION

Pei and Hsue (2006) have defined the pth-order FRFT of f(u') as:

$$f_p(u) = \{F^p[f(u')]\}(u) = \int_{-\infty}^{+\infty} K_p(u,u')f(u')du'$$
$$= \begin{cases} \sqrt{\dfrac{1-j\cot\alpha}{2\pi}}\displaystyle\int_{-\infty}^{+\infty} \exp(j\frac{u'^2+u^2}{2}\cot\alpha - \frac{ju'u}{\sin\alpha})f(u')du' & \\ & \alpha \neq n\pi \\ f(u') & \alpha = 2n\pi \\ f(-u') & \alpha = (2n\pm 1)\pi \end{cases} \quad (1)$$

where $\alpha \equiv p\pi/2$.

Underwater acoustic channels can be seen as a slow time-varying coherent multi-path channel. The acoustic signals from the source arrive at the receiving point along the different acoustic rays. Assume that the dispersion phenomenon and the absorption of the medium are ignored. Let the sending signal be x(t). Then the received signal r(t) (Stojanovic *et al*., 1993) would be:

$$r(t) = A_0 x(t) e^{j2\pi\varepsilon_0 t} + \sum_{i=1}^{N-1} A_i x(t-\tau_i) e^{j2\pi\varepsilon_i (t-\tau_i)} + n(t) \quad (2)$$

where, the channel parameters are shown in Table 1.

Employing FRFT upon Eq. 2, we get:

$$\begin{aligned} R_p(u) &= A_0 X_p(u-\varepsilon_0\sin\alpha) \\ &\times\exp(-j\pi\varepsilon_0{}^2\sin\alpha\cos\alpha - j2\pi\varepsilon_0\cos\alpha) \\ &+\sum_{i=1}^{N-1} A_i X_p(u-\varepsilon_i\sin\alpha-\tau_i\cos\alpha) \\ &\times\exp(j\pi\tau_i{}^2\sin\alpha\cos\alpha - j2\pi(u-\varepsilon_i\sin\alpha)\tau_i\sin\alpha) \\ &\times\exp(-j\pi\varepsilon_i{}^2\sin\alpha\cos\alpha - j2\pi u\varepsilon_i\cos\alpha) + N_p(u) \end{aligned} \quad (3)$$

Equation 3 shows that the module value of the received signal for FRFT will form a series of peaks in the corresponding u domain when the best order pis taken. The direct path shifts ε_0 sin α in comparison with the standard direct path and multi-path signals shift $\varepsilon_0\sin\alpha+\tau_i\cos\alpha$ (i = 0,..., N-1) corresponding to the standard direct path (Yin *et al*., 2007).

Table 1: Channel parameters

Parameters	Details
N	The eigen-ray number
A_0	The amplitude of direct path
A_i	The amplitude of the ith path
$\tau_0 = 0$	The delay of direct path
τ_i	The delay of the ith path
ε_0	The Doppler shift of direct path
ε_1	The Doppler shift of the ith path
n(t)	White Gaussian noise

A peak can be shown at a specific order for any Doppler shift due to the decomposition characteristic of FRFT of the Chirp signal. Several peaks will be shown for the FRFT of received signal when the multi-path signals are contained in the received signal. The order will be a certain value when the sending signal is fixed. So the order may be set at the receiver according to the prior knowledge and it is not necessary for one-dimensional or two-dimensional search (Li *et al*., 2006).

Tsimenidis *et al.* (2005) make the mathematical description of a linear Chirp signal, so we can use it as:

$$s(t) = A\sin 2\pi(f_1 + \frac{f_2-f_1}{2T_2}t)t \quad (4)$$

where, f_1 is the initial frequency of Chirp, f_2 is the termination frequency of Chirp and T_2 is the length of time domain. Then the Chirp rate k would be:

$$k = \frac{f_2-f_1}{T_2} \quad (5)$$

THE STRUCTURE AND THE PROCESSING OF NOVEL ALGORITHM

A Chirp signal and a sine signal are sent with a fixed time interval T. Let the pulse width of Chirp signal be T_1, chirp rate be k, the center frequency be f_0 and the bandwidth be B. Let the frequency of sine signal be f_0 and the pulse width be T_2. Because the Doppler shift and delay will be made when signal traverses underwater acoustic channel. So, the Chirp signal are reconstructed at the start point of received signal according to the prior knowledge and let the length of reconstructed signal and the length of received signal be the same. Two equations are listed according to FRFT and decorrelation and then the relation table of Doppler shift and delay is got. The estimated delays from the relation table are extracted through the Doppler shift from each path got by the sine signal. The structure of sending signal is depicted in Fig. 1.

Assume that the center frequency of received Chirp signal f_0 shifts ε_0, meanwhile the frequency of sine signal also shifts ε_0. Let the intervals between the peak of reconstructed signal and the peaks of received Chirp signal in the u domain be $u_{c,i}$ (i = 0,..., N-1). Let, the intervals of the peak after the autocorrelation of reconstructed signal and the peaks after the decorrelation between reconstructed signal and received Chirp signal in

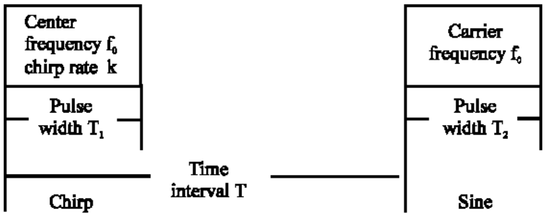

Fig. 1: The structure of sending signal

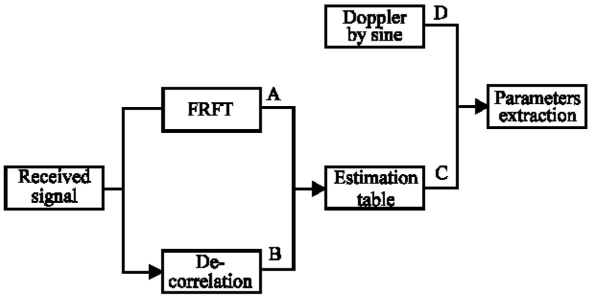

Fig. 2: The flow of joint estimation algorithm

the time domain be $t_{c,i}$ (i = 0,..., N-1). Let, the delay points be $t_{d,i}$ (i = 0,..., N-1). Let the Doppler shift points be $\varepsilon_{0,i}$ (i = 0,..., N-1). Let the best angle of received Chirp signal for FRFT be α. Then the two listed equations will be:

$$u_{c,i} = t_{d,i} \times \cos(\alpha) + \varepsilon_{0,i} \times \sin(\alpha) \quad (6)$$

$$t_{c,i} = t_{d,i} + \frac{\varepsilon_{0,i}}{k} \times f_s \quad (7)$$

From Eq. 6 and 7, we get:

$$\varepsilon_{0,i} = \frac{u_{c,i} - t_{c,i} \times \cos(\alpha)}{\frac{f_s}{k} \times \cos(\alpha) - \sin(\alpha)} \quad (8)$$

$$t_{d,i} = t_{c,i} - \frac{(u_{c,i} - t_{c,i} \times \cos(\alpha)) \times f_s}{f_s \times \cos(\alpha) - k\sin(\alpha)} \quad (9)$$

The fine searching of small range is carried out because it is loose to estimate the parameters of underwater acoustic channels due to the use of fast algorithm and decorrelation. And then the estimation table of Doppler shift and delay is got. The delays are directly extracted according to the estimated Doppler shifts. The flow of the Joint Estimation Algorithm is shown in Fig. 2.

Remark: A is carrying out FRFT for received signal; B is conducting decorrelation for received signal with the reconducted signal; C is executing fine search of small range and listing the parameter estimation tables according to the simultaneous equations of the A and the B; D is getting Doppler shifts from each path through sine signal; finally, the estimated channel parameters are extracted according to the estimation value from each Doppler shift.

The proposed Joint Estimation Algorithm includes the following steps:

- Equation 6 is listed through the u domain interval and Eq. 7 is listed through the time domain interval
- The Doppler shift and the delay are acquired through Eq. 8 and 9 and the relation table of Doppler shift and delay of multi-path signals is got by fine search of small range
- The channel parameters are extracted from the relation table through the estimated Doppler shifts got by sine signal

SIMULATION

A Chirp signal and a sine signal are sent with a fixed time interval 1s. Let the pulse width of Chirp signal be 0.5 sec, chirp rate be 2 kHz sec^{-1}, the center frequency be 1 kHz, the bandwidth be 800 Hz and the sample rate be 4000 Hz (4000 points sec^{-1}). Let, the frequency of sine signal be 1 kHz, let the pulse width be 0.6 sec and let the sample rate be 12 kHz. Let channel parameters be as follows: there are three paths. The delay of direct path is 120 points and the amplitude is 1. The delay of sea surface-direct path is 160 points and the amplitude is 0.7. The delay of sea surface-bottom reflection is 180 points and the amplitude is 0.5. SNR is 0 dB. The Doppler shift of direct path is 8.333 Hz. The Doppler shift of sea surface is 15.777Hz. The Doppler shift of bottom reflection is -10.777Hz.

The received signal without noise and with SNR = 0 dB is shown in Fig. 3a and b.

The decorrelation is conducted for the received signal with the reconducted signal, as is shown in Fig.4.

From Fig. 4, we get:

$$t_{c,0} = 103 \text{ points}, t_{c,1} = 248 \text{ points}, t_{c,2} = 481 \text{ points}$$

The FRFT is carried out for the received signal, as is shown in Fig. 5.

From Fig. 5, we get:

$$u_{c,0} = -31 \text{ points}, \; u_{c,1} = -75 \text{ points}, u_{c,2} = -146 \text{ points}$$
$$\sin(\alpha) = -0.9525, \; \cos(\alpha) = -0.3044$$

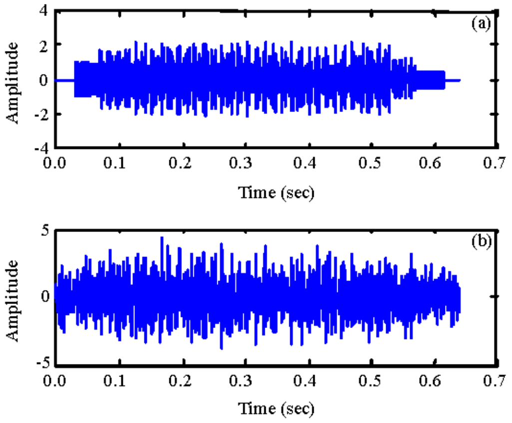

Fig. 3: The received signal without noise and with SNR = 0 dB

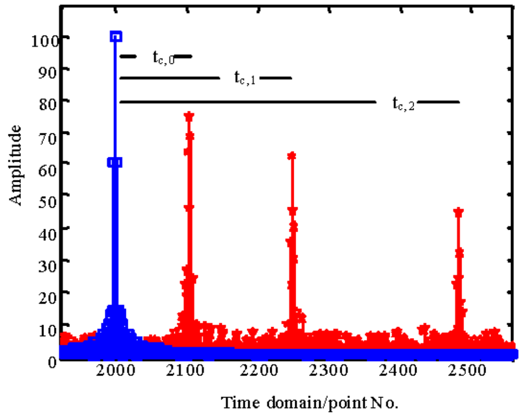

Fig. 4: The enlarged decorrelation of received signal

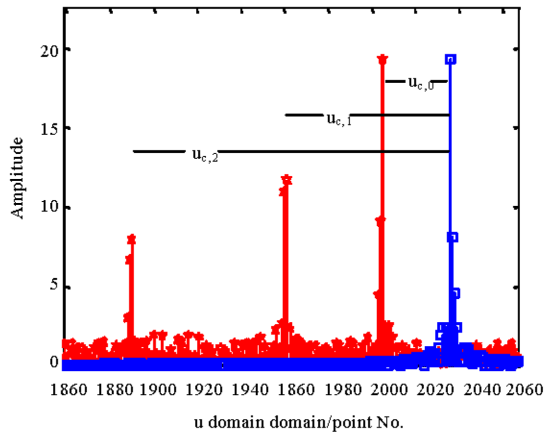

Fig. 5: The enlarged u domain of received signal

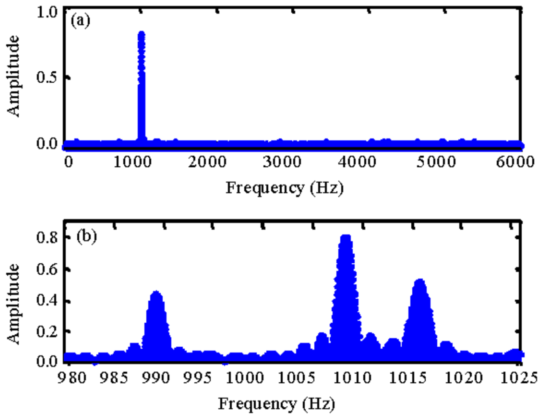

Fig. 6: The FFT and the FFT zoom of high resolution on the sine signal

Table 2: The Doppler shift-delay estimation of direct path

	14	15	16	*17	18	19	20
Points	119.73	119.70	119.68	119.66	119.63	119.61	119.59
Hz	8.3638	8.3522	8.3406	8.3289	8.3173	8.3057	8.294

Table 3: The Doppler shift-delay estimation of sea surface

	14	15	*16	17	18	19	20
Points	279.6627	279.633	279.6034	279.5737	279.544	279.5143	279.4847
Hz	15.8313	15.8165	15.8017	15.7868	15.772	15.7572	15.7423

Table 4: The Doppler shift-delay estimation of bottom reflection

	11	12	13	*14	15	16	17
Points	459.46	459.46	459.45	459.45	459.44	459.43	459.43
Hz	-10.7688	-10.7717	-10.7746	-10.7775	-10.7804	-10.7833	-10.7862

Table 5: The Doppler shift estimation

Doppler shift	Direct	Sea surface	Bottom reflection
Real	8.333 Hz	15.777 Hz	-10.777 Hz
Estimation	8.3375 Hz	15.8083 Hz	-10.7789 Hz
Error rate	0.05%	0.20%	0.02%

The Doppler shift and the delay are got according to Eq. 8 and 9 and then fine search of small range is carried out and the relation table of Doppler shift and delay of direct path, sea surface and bottom reflection are accepted, as is shown in Table 2-4.

The FFT of high resolution is carried out on the sine signal part of received signal, as is shown in Fig. 6a and b. The three-path Doppler shifts can be directly got according to Fig. 6.

The statistical datas of Doppler shift estimation based on the joint estimation algorithm are shown in Table 5.

The estimation values are directly extracted according to the estimated Doppler shifts got by the sine signal from the Table 2-4. That is:

$$t_{d0} \approx 120 \text{ points},\ t_{d1}-t_{d0} \approx 160 \text{ points},\ t_{d2}-t_{d1} \approx 180 \text{ points}$$

The statistical datas of delay estimation based on the Joint Estimation Algorithm are listed in Table 6.

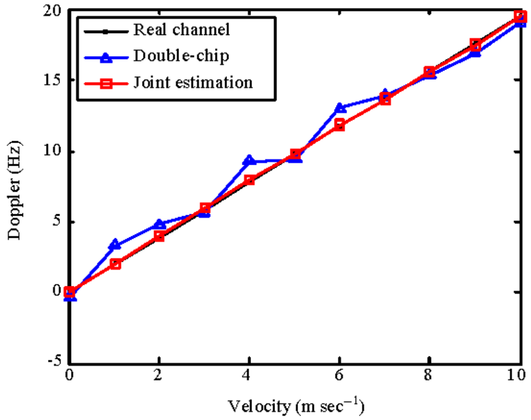

Fig. 7: The Doppler shift estimation of direct path

Table 6: The delay estimation

Delay	Direct	Direct-surface	Surface-bottom
Real	120 points	160 points	180 points
Estimation	120 points	160 points	180 points
Error rate	0	0	0

The error rates of delay estimation are 0, which verifies the effectiveness of this algorithm in the situation where the delays are short and the Doppler shifts are very different with SNR = 0 dB.

The parameters of sending signal are the same as above. Let channel parameters be as follows. The Doppler shift of direct path is made by relative motion of 0-10 m sec^{-1} of literature (Yang *et al.*, 2009) and the amplitude is 1. The Doppler shift of sea surface is 12.67 Hz and the amplitude is 0.7. The Doppler shift of bottom reflection is -18.333 Hz and the amplitude is 0.5. The synchronous head of the Chirp part is 120 points, the delay of sea surface-direct path is 160 points and the delay of bottom reflection - sea surface is 180 points. The simulation results are shown in Fig. 7-9.

From Fig. 7, the Doppler shift estimation of direct path through Joint Estimation Algorithm is better than through the Double-Chirp Algorithm.

From Fig. 8, the Doppler shift estimation of sea surface and bottom reflection through Joint Estimation Algorithm is also better than through the Double-Chirp Algorithm.

From Fig. 9, the delay estimations are still more stable and better through Joint Estimation Algorithm than through the Double-Chirp Algorithm.

In conclusion, both algorithms have a good anti-noise character at the aspect of estimating underwater acoustic channel parameters and the estimation performance through Joint Estimation Algorithm is more stable and better than through the Double-Chirp Algorithm.

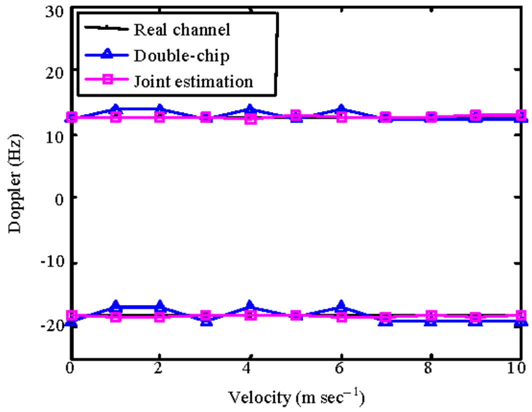

Fig. 8: The Doppler shift estimation of sea surface and bottom reflection

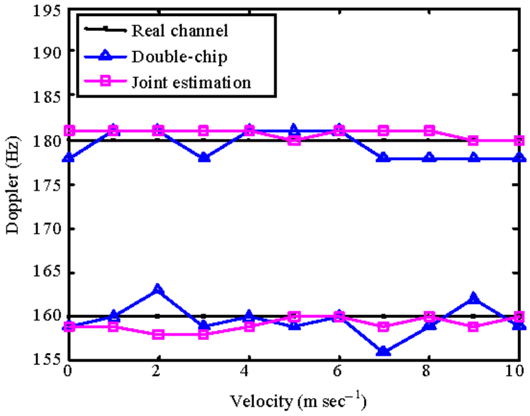

Fig. 9: The delay estimation of surface-direct and bottom-surface

CONCLUSION

The novel Joint Estimation Algorithm is proposed in this study. The parameters of underwater acoustic channels are accurately estimated by the listed relation table according to FRFT and decorrelation. And the multi-path number, the delay and the Doppler shift can be directly and accurately estimated through the Joint Estimation Algorithm. Besides, it's not necessary to search for the order of received signal as the result of the invariant characteristic of the chirp rate, which greatly improves the algorithm efficient. Especially, the algorithm can be also used to process the signals of similar Doppler shift and the proposed algorithm has a good anti-noise character. The simulation results show the performance of Joint Estimation Algorithm is more stable and better than the performance of Double-Chirp Algorithm.

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