LETTER

Ultrasonic Measurement of the Thin Oil-Slick Thickness Based on the Compressed Sensing Method

Di YAO[†,††], ***Member***, **Qifeng ZHANG**[†,††], **Qiyan TIAN**[†,††], ***and*** **Hualong DU**[†,††a)], ***Nonmembers***

SUMMARY A super-resolution algorithm is proposed to solve the problem of measuring the thin thickness of oil slick using compressed sensing theory. First, a mathematical model of a single pulse underwater ultrasonic echo is established. Then, the estimation model of the transmit time of flight (TOF) of ultrasonic echo within oil slick is given based on the sparsity of echo signals. At last, the super-resolution TOF value can be obtained by solving the sparse convex optimization problem. Simulations and experiments are conducted to validate the performance of the proposed method.

key words: *ultrasonic measurement, thickness of thin oil slick, TOF estimation, compressed sensing*

1. Introduction

The oil spill accidents often happen when the offshore oil is exploited and transported overseas. The risks of leakage, blowout of pipelines is increasing significantly as the demands on the offshore oil are increasing. Because of the smaller density in comparison to water, most of spilled oil have long-term hazardous effects to the sea environment [1]. To quickly reduce the impacts of spilled oil, the efficient oil spill responses have been developed and the general spilled oil cleanup methods. Although each option has specific advantages during a response to an oil spill, effectively estimating the volume of the spilled oil is critical in making response plans. Therefore, measuring the thickness of oil slick has become one of the key features impacting the effectiveness of the selected technique [2].

Basically, the methods used to estimate oil thickness can be categorized into following four aspects: the first one is visual observation, it is the simplest method but would be severely affected by the viewing conditions [3]; secondly, microwave reflectivity is a proven technique for remotely measuring the thickness of fresh oil on the water surface while its ability is severely influenced by sea conditions and water uptake [4]; thirdly, hyperspectral imaging has been studied by many researchers to estimate slick thickness, so far, it is still a big challenge to apply in the field [5]; last one is laser ultrasound, however, the measurement ability can be affected by sea states, waves on the surface and oil weathering [6].

To overcome the shortcomings of current techniques and concepts, underwater ultrasonic method was proposed to measure the thickness of oil slick underneath the oil slick using a Remotely Operative Vehicle (ROV) as a platform [7]. The slick thickness can be obtained by calculate the transmit time of flight (TOF) of ultrasound within oil slick. However, its performance is severely degraded when the TOF is short. Unfortunately, this is an often case in open seas.

In this paper, a mathematical model was developed for underwater ultrasonic echo of a single pulse. The time-domain sparse representation of the ultrasonic echo was derived. Then, an sparse optimization model of the TOF was proposed, and a simultaneous orthogonal matching pursuit (SOMP) method is applied to solving the above optimization problem. Finally, The simulation and experiment results show that the proposed method can lead to a higher TOF estimation accuracy and thinner thickness estimation ability comparing with the generalized cross correlation (GCC) [8] and second cross-correlation (SCC) [9].

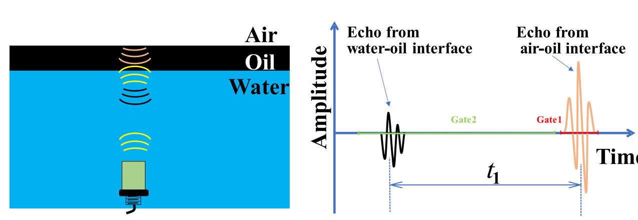
2. Echo Model and Sparse Representation

2.1 Principal and Method

The principal of measuring the oil slick thickness with ultrasound hinges on the ability to measure echoes from the oil-water and oil-air interfaces. The measuring schematic of the oil slick thickness using an ultrasonic transducer in the pulse-echo mode is shown in Fig. 1(a), the thickness of the oil slick can be calculated by the following equation,

$$d = \frac{V(T) \cdot t_1}{2} \tag{1}$$

where d denotes the thickness of oil slick, $V(T)$ is the speed



(a) (b)

Fig. 1 The measurement schematic of the oil slick thickness.

Manuscript received September 29, 2022.
Manuscript revised November 11, 2022.
Manuscript publicized January 17, 2023.

[†]The authors are with State Key Laboratory of Robotics, Shenyang Institute of Automation, Chinese Academy of Sciences, Shenyang, 110016, China.
[††]The authors are with Institutes for Robotics and Intelligent Manufacturing, Chinese Academy of Sciences, Shenyang, 110169, China.
a) E-mail: duhualong@sia.cn

DOI: 10.1587/transfun.2022EAL2081

of sound in oil which is relevant to temperature T, t_1 is the TOF of ultrasound within oil slick and is denoted in Fig. 1(b).

2.2 Single Pulse Echo Model

According to [10], the mathematical model of a single pulse ultrasonic echo can be expressed as:

$$s(t) = \beta e^{-\alpha(t-\tau)^2} \cos(2\pi f_c(t-\tau) + \phi) + \sigma n(t) \tag{2}$$

where $t = 0, 1, 2, \ldots N-1$. $s(t)$ stands for the echo signals, and $n(t)$ represents the Gaussian random noise, ϕ denotes the orientation of the reflector, τ indicates the time-delay value, f_c represents the center frequency of echo, and α is bandwidth factor. However, due to the movement of the ROV, the center frequency would be drifted. The drift value depends on the speed of the ROV, the Eq. (2) need to be rewritten as

$$x(t) = \beta e^{-\alpha(t-\tau)^2} \cos(2\pi(f_c + \Delta f)(t-\tau) + \phi) + \sigma n(t) \tag{3}$$

where $\Delta f = \frac{2vf_c}{c}$ denotes the drifting frequency, c is the speed of sound in water.

2.3 Sparse Representation

From the Fig. 1(b), we can know that the echoes show obvious sparsity in the time domain. According to the compresses sensing theory, the sparse representation of the echo can be given by building a time-domain transformation matrix with the discrete form. The transformation matrix is expressed as

$$A = \begin{bmatrix} blk(x) & 0 & \cdots & 0 \\ 0 & blk(x) & \cdots & 0 \\ \vdots & \vdots & \cdots & \vdots \\ 0 & 0 & \cdots & blk(x) \end{bmatrix} \in \mathbb{R}^{I\times J} \tag{4}$$

where $blk(x) = x(1), x(2), \cdots, x(K)$ is a discrete form of the Eq. (2), K indicates the number of sampling points of the transmitted signal, it just depends on the bandwidth factor and sampling rate f_s. I denotes the number of sampling points of the interested time range, $J = I - K + 1$. Now, the ultrasonic echo signal expression is rewritten as

$$X = A \cdot S + N \in \mathbb{R}^{J\times 1} \tag{5}$$

$$S = [0, \cdots, s_1 \cdots, s_2, \cdots, 0, \cdots, s_M, \cdots, 0]^T \tag{6}$$

where S is the signal amplitude, M denotes the number of the desired signals. Usually, we focus only on the reflection signals from the oil-water and oil-air interfaces, which ensures that the signals are much smaller than the discrete samples and satisfy sparsity.

In the signal amplitude S, the number of interval points between the oil-water and oil-air signals corresponds to the TOF. In order to estimate the signal amplitude, the sparse optimization model need to be built, which is expressed as

$$\arg\min_{S,N} \|N\|_F^2 + \lambda\|S\|_1 s.t. \quad X = A \cdot S + N \tag{7}$$

where $\|\cdot\|_F$ and $\|\cdot\|_1$ indicate Frobenius norm and l_1 norm, respectively, λ is a regularization factor.

3. TOF Estimation

From the Eq. (7) can be seen that it is a convex function, which can be solved by the l_1 minimisation, alternating direction method of multipliers or alternatively by the greedy approaches. In this paper, we choose the SOMP [11] algorithm considering estimation accuracy and computation complexity. The estimation procedure of the TOF based on SOMP is shown as:

1. Initialize the residual $r_0 = X$, the index matrix $\Lambda_0 = \emptyset$, the number of iterations $t = 1$, and stopping condition of iteration ε.
2. Let a_j denotes the j-th column of matrix A, then, find index λ_t that solves the optimization problem

$$\lambda_t = \arg\max_{j=1,2,\cdots,J} \left|\left\langle r_{t-1}, a_j \right\rangle\right| \tag{8}$$

3. Augment the index set $\Lambda_t = \Lambda_{t-1} \cup \{\lambda_t\}$ and the matrix of chosen atoms

$$\theta_t = \left[\theta_t, a_{jt}\right] \tag{9}$$

where θ_0 is usually assumed to be empty.
4. Solve a least squares problem to obtain a new signal estimate

$$x_t = \arg\min_x \|y - \theta_t x\|_2 \tag{10}$$

5. Calculate the new approximation of the data and the new residual $r_t = y - \theta_t x_t$.
6. Increment t, and return to Step 2 if $r_t > \varepsilon$.
7. The estimate S for the ideal signal has nonzero indices at the components listed in Λ_m. Select two largest values in S as oil-water and oil-air echoes, respectively.
8. Assume that there are L sampling points between oil-water echo and oil-air echo, the TOF and thickness can be calculated by

$$TOF = L/f_s, \quad thickness = TOF \times c/2 \tag{11}$$

4. Performance Analysis

In this section, the simulation and experiment trials were conducted to demonstrate the superiority of the proposed method. In the simulation, the bandwidth factor was set 60 MHz, the orientation of the reflector was set 0, $N = 2000$, $f_s = 25$ MHz, $\lambda = 1$. The signal amplitudes of oil-water, oil-air and noise were 10, 66, 1, respectively. When calculating the thickness with GCC and SCC methods, the oil-water and oil-air echoes need to be obtained with gate1 and gate2 in

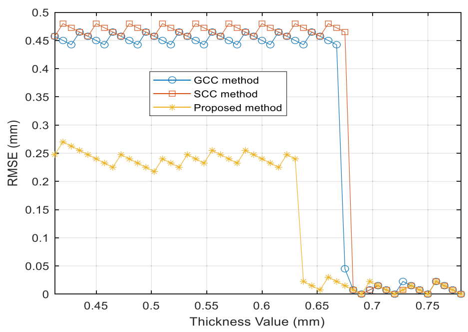


Fig. 2 The RMSE estimation with different thickness.

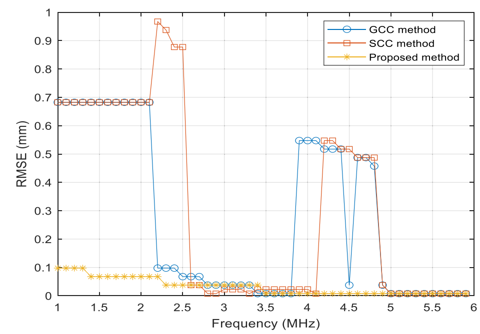


Fig. 3 The RMSE estimation with different frequency.

advance. The widths and beginning points of the gate1 and gate2 were set according to reference [7].

4.1 Performance Analysis with Different Thickness

The estimation accuracy of the different thickness of oil-water and oil-air echoes were first evaluated. Then, based on 500 times Monte Carlo trials, the root-mean squared error (RMSE) were given to show the comparison result, and the center frequency was set to 5 MHz. Figure 2 shows the RMSE estimation result with thickness uniformly distributed from 0.4125 mm to 0.78 mm with the interval 0.0075 mm. In comparison with the other methods. It can be seen that the estimation accuracy of our proposed method has a nearly double improvement when the thickness is less than 0.6825 mm.

4.2 Performance Analysis with Different Frequency

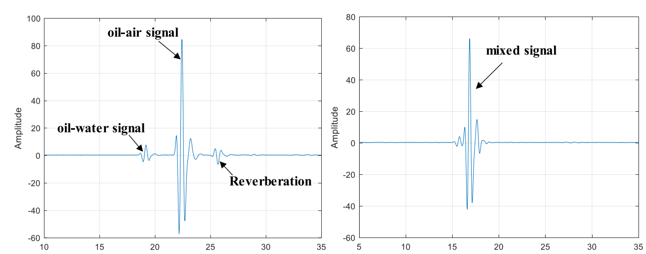
The ultrasonic wavelength is determined by the frequency of the signal, which ultimately affects estimation accuracy and the minimum detectable thickness of oil slick. In this simulation, the thickness between oil-water and oil-air was set to 0.6825 mm, the frequency uniformly distributed from 1 MHz to 6 MHz with interval 0.1 MHz, 500 times Monte Carlo trials were done. The comparison result was given in Fig. 3, which shows that our proposed method has excellent frequency robustness and is significantly superior to other methods. Especially in low frequency, our method still has high resolution performance and accuracy, which benefits from super-resolution ability of our method.

4.3 Performance Analysis with Experiment Data

To build the experimental system, An observer class ROV developed by Sirio was used as a platform to integrate two unfocused ultrasonic immersion transducers, Fig. 4(a) shows two transducers were installed in the front of the ROV. Two channels of a 8-channel micropulser was used to transmit ultrasonic pulses and receive ultrasonic reflections in the pulse-echo mode in the experiment. Fig. 4(b) shows a water tank used for measuirng the thickness of oil slick in the laboratory experiment. A data acquisition program was developed with Matlab for making a connection

(a) (b)

Fig. 4 The experiment system of measuring thickness of oil slick.



(a) (b)

Fig. 5 The measurement echoes of the oil slick.

with the Micropulser and collecting ultrasonic signals. The pulse width was set 100 ns, center frequency was 5 MHz and f_s = 25 MHz.

Based on the above system, the measured echoes used for proving the algorithm effectiveness are shown in Fig. 5. In Fig. 5(a), the oil-water signal is generated when partial energy is reflected from the oil-water interface due to the difference of acoustic impedances. Besides, when partial energy reach the oil-air interface, the much stronger oil-air signal will be obtained due to the larger difference of acoustic impedances between oil and air. At last, some remaining energy can reverberate twice within the oil slick, which corresponds to the reverberation. However, if the thickness of oil slick is thin, i.e. the TOF is very short. The above three types of signals are merged into a mixed signal, can not be directly distinguished in time domain. The mixed signal is shown in Fig. 5(b). For the Fig. 5(a) and Fig. 5(b), the true thicknesses of oil slick are around 2.43 mm and 0.465 mm, respectively. The estimation results were given in Table 1.

Table 1 Estimation results (mm).

True Value	GCC Value	SCC Value	Proposed Method
2.43	2.43	2.43	2.43
0.6	0.93	0.93	0.63
0.585	0.96	0.96	0.54
0.525	0.75	0.75	0.54
0.465	0.81	0.81	0.45

Based on the results, we can see that our algorithm still has better super-resolution ability and performance for the experiment data.

5. Conclusion

In this letter, we proposed a super-resolution algorithm for measuring thickness of oil slick based on the compressed sensing method. A mathematical model of a single pulse underwater ultrasonic echo was firstly constructed using a ROV platform. On this basis, the sparse optimization model of the TOF was built in time domain. The simulation and experiment results indicate that it has a better performance versus different thickness and frequency. For future research, we will focus on the research on the further performance improvements using multiple measurement data.

Acknowledgments

The authors would like to thank the associate editor for their helpful suggestions. This study was funded by State Key Laboratory of Robotics (Grant No. E21Z0204, 2021-Z04-03) and in part by the Liaoning Province Revitalization Talents Program, Department of Science and Technology of Liaoning Province, Shenyang, China under Grant XLYC2008008.

References

[1] J. Beyer, H.C. Trannum, T. Bakke, P.V. Hodson, and T.K. Collier, "Environmental effects of the deepwater horizon oil spill: A review," Mar. Pollut. Bull., vol.110, no.1, pp.28–51, 2016.

[2] P.D. Panetta, R. Byrne, and H. Du, "The direct quantitative measurement of in-situ burn (ISB) rate and efficiency," International Oil Spill Conference Proceedings, vol.2017, no.1, pp.1006–1019, 2017.

[3] M.F. Fingas, "The challenges of remotely measuring oil slick thickness," Remote Sensing, vol.10, no.2, 319, 2018.

[4] J.P. Hollinger and R.A. Mennella, "Oil spills: Measurements of their distributions and volumes by multifrequency microwave radiometry," Science, vol.181, no.4094, pp.54–56, 1973.

[5] G. Ren, J. Guo, Y. Ma, and X. Luo, "Oil spill detection and slick thickness measurement via UAV hyperspectral imaging," Acta Oceanologica Sinica, vol.41, no.5, pp.146–158, 2019.

[6] Y. Li, X. Qi, and H. Wang, "Experimental study on thickness measuring method of oil-on-water using laser-ultrasonic technique," Nami Jishu yu Jingmi Gongcheng/Nanotechnol. Precis., vol.15, pp.159–167, 2017.

[7] H.L. Du, D. Yao, and Q.F. Zhang, "Ultrasonic measurement on the thickness of oil slick using the remotely operative vehicle (ROV) as a platform," IEEE Trans. Instrum. Meas., vol.72, 2022.

[8] S.A. Pelyushenko, "Microwave radiometer system for the detection of oil slicks," Spill Sci. Technol. Bull., vol.2, no.4, pp.249–254, 1995.

[9] J. Bennsty, J.D. Chen, and Y.T. Huang, "Time-delay estimation via linear interpolation and cross correlation," IEEE Trans. Speech Audio Process., vol.12, no.5, pp.509–519, 2004.

[10] J.A. Tropp, A.C. Gilbert, and M.J. Strauss, "Simultaneous sparse approximation via greedy pursuit," IEEE International Conference Acoustics, Speech, and Signal Processing, vol.5, 2005.

[11] Y. Yan, D. Liu, B. Gao, G.Y. Tian, and Z.C. Cai, "A deep learning-based ultrasonic pattern recognition method for inspecting girth weld cracking of gas pipeline," IEEE Sensors J., vol.20, no.14, pp.7997–8006, 2020.