ACOUSTIC TIME DOMAIN CORRELATION TECHNIQUE (ATDCT) IN OCEAN WAVE AND CURRENT OBSERVATION

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Abstract

There are two general techniques to observe particle movements in fluid. One is the acoustic time domain correlation technique and another is the frequency domain Doppler-shift techniques. Both techniques were reviewed and mentioned their some merits and demerits in ocean wave and current observation. Some possible application of acoustic time domain correlation technique in ocean wind wave measurement was discussed.

I. Introduction

There are two general techniques to observe particle movements in fluid. One is the time domain echo-location technique and another is the frequency domain Doppler-shift techniques [1]. The time domain echo-location technique is based on the time delay measurement from consecutive echo-signals from the targets. The frequency domain Doppler-shift technique uses the frequency shift of incident wave due to the target movement. Both techniques are well used in the radio detecting and rangning (RADAR) operations. Applications of these methods in acoustics are ship speedometer such as correlation sonar speedometer and ocean current meter such as acoustic Doppler current profiler (ADCP) [1,2]. The Doppler-shift technique (DT) becomes popular in the measurements of liquid flux in pipes and blood flux in human body [3]. Some new possibilities of acoustic time domain correlation technique (ATDCT) have been demonstrated in recent works [4]. They measured the blood particle velocity measurement in blood vessel. In this paper we reviewed the techniques of ATDCT and DT and mentioned their some merits and demerits in ocean wave and current observation.

II. Relation between ATDCT and DT

The schematic diagram of ATDCT measurement [4] is shown in Fig.1.

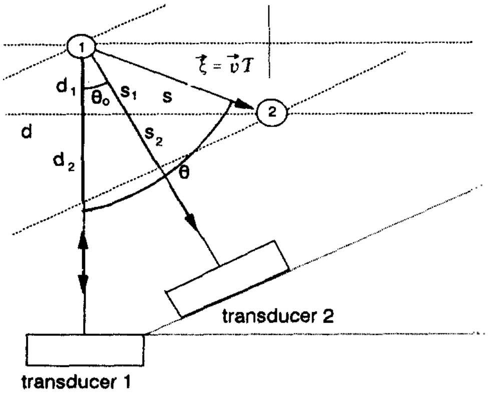

Fig.1. The setup of ATDCT particle velocity measurement.

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Transducer 1 produces a series of pulses of frequency f_0 with pulse repetition period T. Scattered signal from a particle is received with the transducer 1 and an additional receiver (transducer 2). They allow to locate a particle position in two-dimensional coordinate system in the plane of two transducers. Since the particle moves, its echo-location also varies from pulse to pulse. Consequently the travel time changes. Denoting the travel time corresponding to two consequent pulses with superscript (1) and (2) and using the geometrical configuration in Fig.1, it is possible to relate travel time differences of $\Delta t_1^{(1)} - \Delta t_1^{(2)}$ and $\Delta t_2^{(1)} - \Delta t_2^{(2)}$ to the particle displacement vector $\vec{\zeta}$. The particle velocity and its directional angle are given by

$$\upsilon = \frac{\Delta t_1^{(1)} - \Delta t_1^{(2)}}{T} \frac{c_0}{2\cos\theta} \tag{1}$$

$$\tan\theta = \frac{2}{\sin\theta_0}\left(\frac{\Delta t_1^{(1)} - \Delta t_1^{(2)}}{\Delta t_2^{(1)} - \Delta t_2^{(2)}} - \frac{1}{2}\right) + \cot\theta_0 \tag{2}$$

where Δt_1, Δt_2 is pulse travel times for transducers 1 and 2, c_0 is sound speed in water, θ_0– angle between the beam axises of transducers 1 and 2.

Let us describe the same scheme of particle velocity measurements in terms of Doppler-shift technique. Since for the Doppler method only wave phase is important, we will use the normalized amplitude coefficient everywhere. Suppose that acoustic wave generated by transducer 1 is

$$P_0 = e^{i(\omega_0 t + k_0 y)} \tag{3}$$

where

$$k_0 = \frac{\omega_0}{c_0}$$

Then the signal arrived at the moving target is [1]

$$P_p = e^{i\omega_p t} \tag{4}$$

where

$$\omega_p = \omega_0\left(1 + \frac{\upsilon\cos\theta}{c_0}\right)$$

The acoustic wave is returned from moving particle in a medium is [1]

$$P = e^{i(\omega t - \vec{k}\cdot\vec{r})} \tag{5}$$

where

$$\omega = \frac{\omega_p}{1 - \upsilon\cos\frac{\theta'}{c_0}} \tag{6}$$

Transducers 1 and 2 receive signals from the particle which are describes by the last equation. To have a concrete formulae for signal form registered by each transducer it is necessary to substitute into Eq.(6) the corresponding value of angle θ'. For the transducer 1 $\theta' = \theta$ and $\theta' = \theta - \theta_0$ for the transducer 2. Therefore, the frequency of signal received by the transducer 1 is

$$\omega_1 = \omega_0 \frac{1 + \upsilon\cos\frac{\theta}{c_0}}{1 - \upsilon\cos\frac{\theta}{c_0}} \simeq \omega_0\left(1 - 2\upsilon\cos\frac{\theta}{c_0}\right) \tag{7}$$

and, the signal received by the transducer 2 is

$$\omega_2 = \omega_0 \frac{1 + \upsilon\cos\frac{\theta}{c_0}}{1 - \frac{\upsilon\cos(\theta - \theta_0)}{c_0}} \simeq \omega_0\left[1 + \left(\frac{\upsilon}{c_0}\right)(\cos\theta + \cos(\theta - \theta_0))\right] \tag{8}$$

Hence, for the frequency differencies $\Delta\omega_1 = \omega_1 - \omega_0$, and $\Delta\omega_2 = \omega_2 - \omega_0$ Eqs.(7), and (8) yield the next system of equations:

$$\Delta\omega_1 = \omega_0\left(\frac{2\upsilon}{c_0}\right)\cos\theta \tag{9}$$

$$\Delta\omega_2 = \omega_0\left(\frac{2\upsilon}{c_0}\right)\cos\left(\frac{\theta_0}{2}\right)\cos\left(\theta - \frac{\theta_0}{2}\right). \tag{10}$$

From Eqs.(9) and (10), υ and θ are given by,

$$\upsilon = \left(\frac{\Delta\omega_1}{\omega_0}\right)\frac{c_0}{2\cos\theta} \tag{11}$$

$$\tan\theta = \frac{2}{\sin\theta_0}\left(\frac{\Delta\omega_1}{\Delta\omega_2} - \frac{1}{2}\right) + \cot\theta_0 \tag{12}$$

Comparing Eqs. (11), and (12) for υ and θ got from DT with Eqs.(1) and (2) got from ATDCT, we can see their similarities.

It is not a simple coincidence, of course. There exist a more deep meaning of this fact. The physics of it can be explained by the following way. It is supposed that transducer 1 produces a coherent pulse sequence, i.e. the phase of the cw signal inside the pulse envelope is stable for time more than pulse repetition period. In this case the pulse sequence can be represented as a multiplication of cw signal by pure pulse sequence. A spectrum of such a signal contains a component at the frequency of cw filling and it can be filtered. Therefore, it is possible to measure the Doppler shift of this component. Let us show how the Doppler shift in this case is tranfered to additional time delay of the signal which is connected to the sound scattering particle movement. The period μ_0 of one cw wavelength produced by transducer 1 is given by

$$\mu_0 = \frac{2\pi}{\omega_0} \tag{13}$$

The period of one wavelength received by transducer 2 is

$$\mu = \frac{2\pi}{\omega} \tag{14}$$

The period difference is, for $\omega \gg \Delta\omega$,

$$\Delta\mu = \mu - \mu_0 \approx \frac{2\pi}{\omega_0^2}\Delta\omega \tag{15}$$

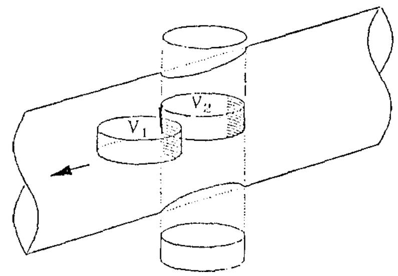
Evidently that change of wavelength period leads to additional time shift Δt of signal in a time T, which is proportional to the number of wavelengthes, N

$$\Delta t = N\Delta\mu = \left(\frac{T}{\mu_0}\right)\Delta\mu \tag{16}$$

Comparison of Eqs.(15), (16) and (13) yields

$$\frac{\Delta t}{T} = -\frac{\Delta\omega}{\omega_0} \tag{17}$$

Eq.(17) represents the relation between time domain and Doppler techniques for particle velocity measurements. Now we will discuss the possible schemes and principal restrictions of Doppler and time domain measurements. Fig.2 shows the example of two consequent waveforms which were registered by one of the transducers in the experiment with human blood velocity measurements.



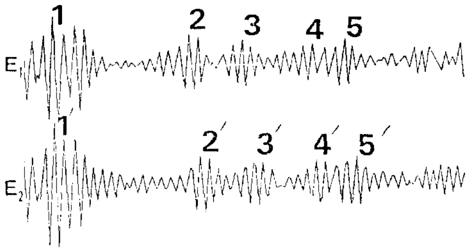


Fig.2. Two echo-signals got from the ATDCT blood particle velocity measurement.

The schematic diagram of the experimental setup was the same as in Fig.1. Two waveforms are correspond to the two consequent pulses produced by the transducer 1 in a pulse repetition period. One can see several signals which are due to ultrasonics reflections by different blood particles. The comparison of two correspondent signals develops the time shift which is due to blood particle displacement during the time of pulse repetition period. The measurement of such a time shift can be made by correlating of two corresponding reflections, that is ATDCT. To use Doppler method in this case it is necessary to select the corresponding reflections from the signal which is received by the transducer and make the Fourier transformation of waveform of duration T. The frequency shift of the peak of spectrum with respect to the radiating frequency ω_0 is connected with the particle velocity to expressions (11),(12). According to (17) the transformation between time and doppler shift is described by substitutions

$$\frac{\Delta t_1^{(1)} - \Delta t_1^{(2)}}{T} = -\frac{\Delta\omega_1}{\omega_0} \tag{18}$$

$$\frac{\Delta t_2^{(1)} - \Delta t_2^{(2)}}{T} = -\frac{\Delta\omega_2}{\omega_0} \tag{19}$$

This example shows that there is no principal difference between ATDCT and DT.

High velocity and spatial resolution of both techniques considered above is connected with the usage of coherent pulse signals and possibility to select different particles sound reflections. They make possible to measure time shift which is much less than pulse duration and frequency shift which is much less than the width of signal spectrum. For them, it is necessary to have a high value of the signal to noise ratio. If the pulse duration is not short enough to select different reflections, they are overlapped. The result is that the coherence of signal decreases and it becomes possible to measure only time difference and frequency shift which are comparative or more than pulse duration and the width of spectrum. The usual uncertainty principle [1] which relates the time (position) and frequency (velocity) resolution is valid in this case:

$$\Delta f \Delta t \approx 1 \tag{20}$$

while the this principle improves for high - coherence techniques. Turning back to the high coherence ATDCT and DT one can conclude that they are based on the next principle restrictions :

- small pulse duration making possible to select different signal irrivals due to sound scattering by particles,
- high signal to noise ratio and high signal coherence, making possible to measure time or frequency shifts which are much less than wavelength period or spectrum width correspondively.

III. Application of ATDCT in underwater acoustics

Both ATDCT and DT can be applied to the ocean measurements. While there is no principal differences between them, sometimes one could see some practical convience and obviousness of the time domain correlation technique or Doppler technique. Doppler description is widely used now in underwater current measurements by well-known ADCP. We will consider the example of ATDCP application to the wind wave diagnostics. The possible experimental setup is shown in Fig.3.

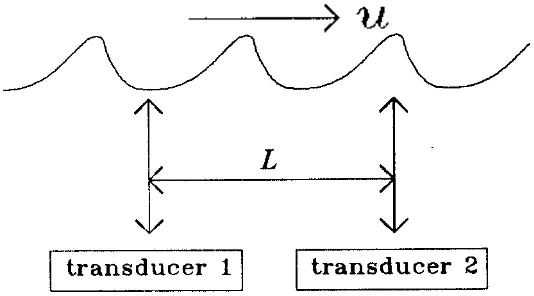


Fig.3. The setup of ATDCT surface wave observation.

A rough surface is insonified by two-beam sonar. For simplicity it will be considered the two-dimensional case. The sonar transducers are placed apart of each other at the distance L and directed upward. It is supposed that the roughnesses are smooth and the sonar beam are narrow enough. It means that size of insonified zone on the surface from sonar beam is small compared with wavelengths of wind wave which are being observed. Each transducer produces an acoustic pulse which comes back to the transducers after the reflection by the surface. The pulse travel time is connected with the distance between any transducer and reflection point at the surface. Therefore, every beam works as a roughness height measuring unit. If the surface wave moves with a speed $\vec{u}$ as it is shown in Fig.3 any waveform due to surface roughnesses will be registered at first by one of the transducers and then by another after a time interval t_d which is connected with the distance L between transducers and surface wave phase speed u by the relation

$$t_d = \frac{L}{u} \tag{21}$$

Using the correlation technique it is possible to measure the value of time delay t_d and then to calculate u. It is the main idea of this method. It is rather clear that it can be adapted to the three-dimensional case, i.e. by using at least three upward sonar beams it becomes possible to measure the vector $\vec{u}$ of surface wave phase velocity in horizontal plane. Modification of this technique were used in measurements of wind wave parameters. Two upward directed transducers were placed at the bow and deck-cabin of the research submarine "Bentos". During the experiment, submarine was mobing along the circle. The wind wave spectrum registered by a single transducer obserbation was narrow. It is shown in Fig. 4.

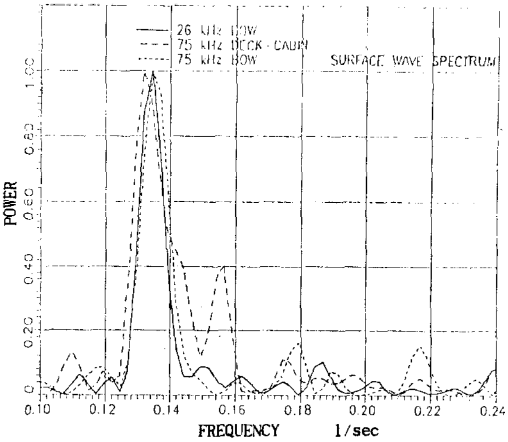


Fig.4. A power spectrum of surface waves, measured by using upward sonars of different frequencies from the research submarine.

Due to narrow wind wave spectrum it was possible to observe the main surface waveform during all the time when submarine was going along the circle. The submarine speed was small compare with the wind waves phase velocity. For this case Eq.(22) becomes

$$t_d = \frac{L \cdot \cos \alpha}{u}, \qquad (22)$$

where α is angle between the longitudinal axis of submarine and wind wave phase velocity vector. The phase speed u and angular frequency Ω of wind wave were derived from the data in Fig. 4, where $u = \sqrt{g / \Omega}$. As observations were made at different angles α it was possible to determine the wind wave propagation direction, which was the same as wind direction.

VI. Conclusions

Feasibility of acoustic time domain correlation technique (ATDCT) in fluid velocity measurement was discussed. The methods of ATDCT and DT were reviewed. There was no principal difference besides the domains of observation. Both methods give the same spatial and velocity resolution. By using high signal to noise ratio and selecting different arrivals from different scattering particles it is possible to get a very high particle velocity resolution. Some possible application of ATDCT in ocean wind wave measurement was discussed. An experiment shows that ATDCT can be applied to the measurements of wind wave spectrum and vector flow velocity in the ocean.

Acknowlegments

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