OCEAN AVERAGE CURRENT MEASUREMENT USING ACOUSTIC PHASE MONITORING

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Knowledge of water currents is important in several ocean-related activities. Typically, current speed and direction are measured at a certain fixed location and depth (or depth profile) by a suitable current meter. In this paper, we propose a novel method for average current speed measurement along a path, based on acoustic phase monitoring. In this method, a transmitter and a receiver are installed at the ends of a designated path. A transmitted sinusoidal signal propagates along the path to the receiver. Intervening currents will introduce Doppler frequency shifts that can be measured as a rate of phase change in the received signal. The phase is recovered by means of a phase detector and unwrapping techniques. The desirable feature of the proposed method is that average current speed is monitored along the entire path. Moreover, the estimated frequency shift via the phase measurement achieves a higher accuracy in current measurement than does a measure of frequency directly by an FM demodulator.

INTRODUCTION

Ocean currents are the continuous movement of bulk seawater in a certain direction for a considerable duration of time. Ocean currents can be categorized into surface ocean currents and deep ocean currents based on their depths [1]. Surface ocean currents flow horizontally within the upper 400 meters of the ocean and are driven by the wind. Deep ocean currents move between the ocean bottom and 400 meters below the surface. They are usually driven by seawater density and temperature gradients (called thermohaline circulation [2]).

A number of currents flow in the oceans around the world. Important examples include Arctic Ocean currents, Atlantic Ocean currents, Pacific Ocean currents, and Indian Ocean currents. Their speeds and directions differ and vary in time [3]. In the northeast Pacific off the coasts of British Columbia, Washington, and Oregon, three currents flow, namely the Alaska Current, the North Pacific Current, and the California Current. The speeds of these currents may be as high as 1 m/s [4].

Knowledge of ocean currents is important for the shipping industry, the oil production industry, and for ocean meteorology. Frequently, current speed is measured at a fixed location using electro-mechanical, magnetic, or acoustic methods. An Acoustic Doppler Current Profiler (ADCP) can measure current speed along a relatively short depth profile. All these methods provide a time series of current speed at a single geographic location.

In this paper, we propose a novel method for ocean average current speed measurement along a path, based on acoustic phase monitoring. In this method, a transmitter and a receiver are installed at the ends of a designated path. A transmitted sinusoidal signal travels along the path to the receiver. A current will introduce a Doppler frequency shift and, consequently, a phase change in the received signal. The phase is recovered by means of phase detection and unwrapping techniques. Taking a derivative of the recovered phase with respect to time gives the frequency shift and, consequently, the speed of the current. The novel feature of this method is that the average speed of the current is monitored along the entire path, instead of from the single location provided by a conventional current meter. Furthermore, the speed estimated via the phase measurement achieves much better resolution than that derived from Doppler frequency measurement using an FM demodulator.

In Section 2, we provide a brief review of conventional ocean current measurement methods. The proposed method is presented in Section 3, where the measurement error caused by multipath interference and solutions to mitigate this effect are also discussed.

1. MEASUREMENT OF OCEAN CURRENT SPEED

Many methods for measuring ocean current speed have been proposed. The first generation current meter relies on a mechanical rotor for sensing current motion. Since a mechanical rotor always has a threshold speed and will easily be inhibited or fouled by drifting seaweed, this type of current meter is not presently used widely.

An electromagnetic principle is commonly used for current measurement. Since seawater is conductive, a magnetic field applied perpendicularly to a flow induces an electric potential. In this type of system, an electromagnet generates an alternating magnetic field around the sensor. By measuring the alternating voltage induced between two electrodes in water, the current perpendicular to the magnetic field can be calculated.

Another method often used for measuring ocean current speed is based on estimating the time of travel of an acoustic pulse (ping) over a fixed distance. The travel time will decrease if the water is moving in the same direction as the acoustic wave, and will increase when the direction of movement of the water is opposite that of the ping. In this type of system, one transducer transmits a ping; when a second transducer receives this ping, it will send back a similar pulse to the first transducer and so on. The difference between the travel times along the two directions will then be a measure of the current speed [5]. Current measurements based on the Doppler effect have been extensively investigated in recent years and many systems have been developed successfully. These systems include the Acoustic Doppler Velocimeter and the ADCP.

A Doppler measurement starts by sending out a ping. Due to particles and bubbles in the water, a fraction of the transmitted sound is reflected backwards. A receiver, normally the same transducer used for transmitting the ping, then receives this echo. If the reflecting particles are moving, the frequency of the reflected signal will change in accord with the Doppler principle. Assuming that the reflectors have the same speed as the water, the frequency difference between the transmitted sound and reflected sound will be a measure of the current speed. The accuracy of the Doppler measurements depends on the transmitted frequency, the length of the pulse, and the beam geometry.

2. AN ACOUSTIC PHASE MONITORING METHOD TO MEASURE OCEAN CURRENT SPEED

A new method to measure ocean current speed is proposed in this paper. Instead of measuring the Doppler frequency directly, as in the conventional methods, it estimates the phase shift in the received acoustic signal first, and then converts it into the frequency by a derivation.

In the simplest form, the proposed system consists of two stations A and B. The stations are fixed above the sea floor at point A and point B and are connected by a tether cable. Each station has a transponder (or transponder array) for signal transmission and reception.

At $t = 0$, an electrical sinusoidal signal,

$$s_0(t) = \cos(2\pi f_0 t) = \cos[\phi_0(t)] \,, \tag{1}$$

is transmitted from A to B via the tether cable as shown in Figure 1. In (1), f_0 is frequency of the transmitted signal. Upon receiving $s_0(t)$, the transponder at B transmits it back to A in an acoustic form through the water. Due to the distance between A and B, the received signal $s(t)$ has a phase shift, that is,

$$s(t) = \cos(2\pi f_0 t + \Delta\phi) = \cos[\phi(t)], \tag{2}$$

where $\Delta\phi$ is the phase shift caused by the time-of-flight from A to B and $\phi(t)$ is the phase of the received signal. Since we assume no movement between stations A and B, $\Delta\phi$ is a constant. If a current is flowing from A to B with a constant average speed v_{AB} over the path, then, according to the Doppler principle, the frequency of the received signal will shift by:

$$\Delta f = \frac{f_0}{c} v_{AB} \,. \tag{3}$$

Accordingly, the received signal in the presence of the current becomes:

$$s(t) = \cos[2\pi(f_0 + \Delta f)t + \Delta\phi] = \cos[2\pi f_1 t + \Delta\phi] = \cos[\phi_1(t)]. \tag{4}$$

The instantaneous frequency is the rate of change of the phase. Therefore, by taking a derivative of $\phi_1(t)$ with respect to *t*, we obtain

$$f_1 = f_0 + \Delta f = \frac{1}{2\pi} \cdot \frac{d\phi_1(t)}{dt}. \tag{5}$$

Combining (4) and (5), the current speed can be estimated as

$$v_{AB} = \frac{c}{2\pi f_0} \cdot \frac{d\phi_1(t)}{dt}. \tag{6}$$

Figure 1 presents a flowchart of the proposed system. A sinusoidal signal generated by an oscillator located at station A is transmitted to station B through the tether cable. It is also a reference signal and is fed into a phase detector for further processing. Upon receiving this electrical signal, the transducer installed on station B sends back a responding acoustic signal through water. The received signal is passed into a signal amplifier and a bandpass filter to reduce the ambient noise, and then fed into a phase detector. The phase detector will use a suitable algorithm, for instance, the traditional quadrature phase estimation algorithm, to measure the phase difference between the received signal and the reference signal, and produce an output waveform representing the estimated phase $\hat{\phi}_1(t)$.

The phase detector usually requires an inverse tangent computation to obtain $\hat{\phi}_1(t)$. As the inverse tangent function is a many-to-one function, all values of $\hat{\phi}_1(t)$ outside the interval (-π, π) will be mapped back into this interval. As shown in Figure 2(a), $\hat{\phi}_1(t)$ monotonically increases from (-π, π). When the value of $\hat{\phi}_1(t)$ reaches π, it flips back to -π. We call this one segment. To get the estimated frequency $\hat{f}_1$, we can either calculate the slope of $\hat{\phi}_1(t)$ in each of the segments and average these values, or perform an unwrapping on $\hat{\phi}_1(t)$.

Unwrapping $\hat{\phi}_1(t)$ involves the monitoring of $\hat{\phi}_1(t)$ and detecting every 2π phase jump. These jumps are then accounted for by adding to the monitored phase a constant 2π per jump. After unwrapping, the “saw-tooth” shape of $\hat{\phi}_1(t)$ is stretched as shown in Figure 2(b) and its slope is easily obtained.

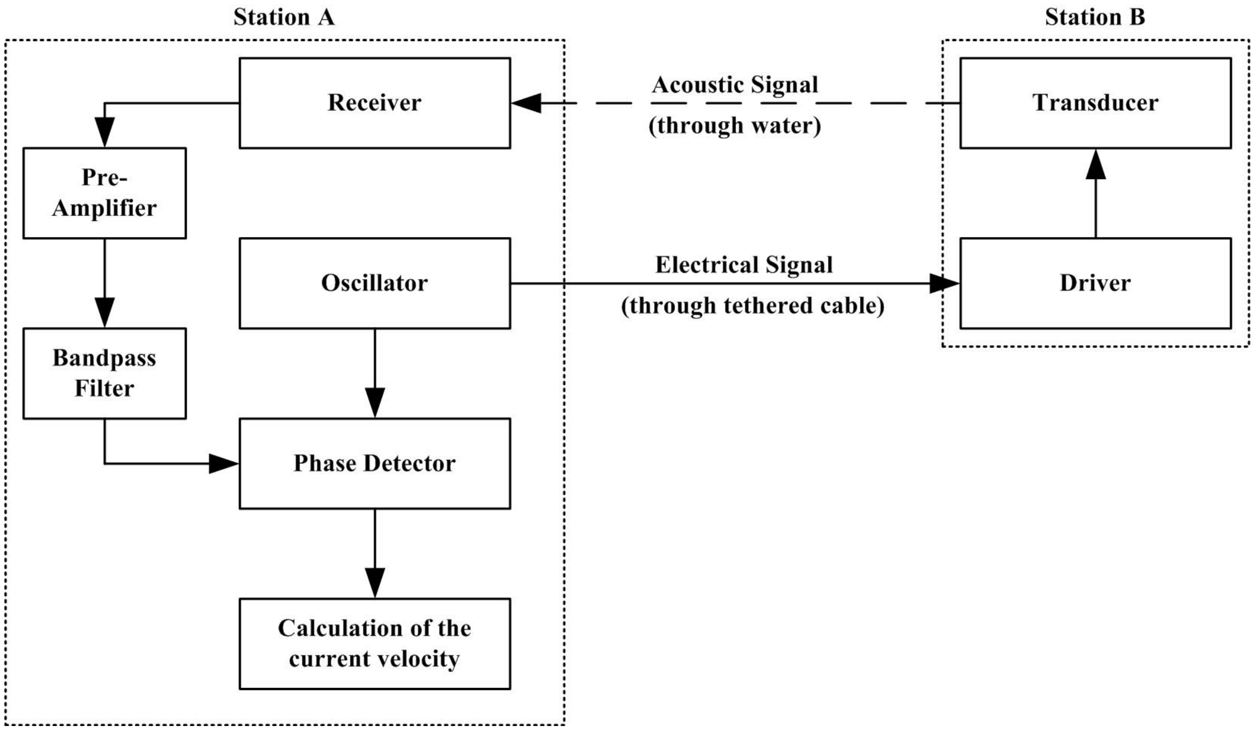

Fig.1 System Flowchart

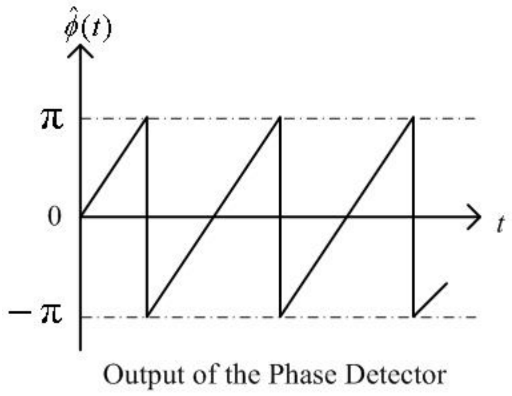

Fig.2 (a)

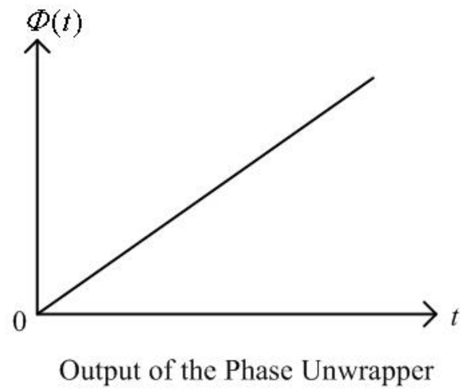

Fig.2 (b)

One feature of the proposed method is that it could monitor the average current speed along a path with a considerable length, whereas a conventional current meter measures the current at a single location or within a very small volume around the current meter.

Deep ocean currents exist at a depth over 400 m. At this depth, the water temperature and density vary slowly. Therefore, a deep ocean current has a rather stable speed and direction. To detect such a slowly moving current, high frequency resolution is required. For example, assume a current speed of $v = 5$ cm/s, a transmitted acoustic signal frequency $f_0 = 20\,\text{kHz}$, and a speed of sound in seawater of $c = 1500\ \text{m/s}$. The subsequent Doppler frequency shift introduced by the current is $\Delta f = \frac{v}{c} f_0 \approx 0.67\ \text{Hz}$. Accordingly, the FM demodulator should have an absolute frequency resolution able to detect such a small frequency shift. The proposed method measures the phase, which is an integral of the frequency over the observation time. According to (5), we have

$$\phi_1(t) = 2\pi \int_t^{t+T} (f_0 + \Delta f) d\tau = 2\pi f_0 T + 2\pi \Delta f T, \tag{6}$$

where T is the duration of the observation window. In (6), $2\pi f_0 T$ is a known constant. Assuming an observation window $T = 0.1\text{s}$, the phase shift over the observation window is about 24°. This value is large enough for reliable detection. Then the slope of the unwrapped phase is calculated and so is the current speed according to (6).

In a realistic scenario, for various reasons a signal loss may occur at the receiver. For example, a fish could block the line-of-sight from the transmitter to the receiver for a few seconds. Therefore, a conventional current meter is still needed at station A to provide readings when signal loss occurs. To obtain the current speed, we also need the sound speed along the path, as shown in (6). An important assumption of the proposed method is that the sound speed along the path is constant and equals that at the receiver. For this purpose, a sound velocimeter is installed at the receiver. Its averaged reading over the observation time T is used for current speed calculation.

The measurement error of the proposed method is also due to the multipath signal. In an earlier paper [6], we provide an example that shows the phase error caused by bottom-reflected signals. This phase error has a boundary determined by the energy of the reflected signal. To minimize the error introduced by multipath signals, one solution is to choose the transmitted signal length so that the direct path signal and the boundary-reflected signals have no overlap in time. This method becomes complicated when more than one multipath signal is presented. As well, as the range between the transmitter and the receiver increases, the travel time along the direct path becomes close to that along the reflected path. To separate the direct path signal, the transmission should have a short duration, which means a decreased observation window for phase measurement. The consequence is that the phase measurement error will increase.

One can also separate the direct path signal in the spatial domain. Given a prior knowledge of the depth of the stations and the range between them, it is reasonable to assume that the multipath signals come from a small number of specific directions. This advantage provides feasible solutions for multipath cancellation, which include suitable beamforming and array design methods.

In the above discussion, v_{AB} is the projection of the current speed on the AB axis. A third station, C, installed in the same horizontal plane as A and B, and will provide the projection of the current speed on the AC axis. The station positions are controlled by a GPS on a surface vessel employed to anchor these stations. The angle between the AB axis and AC axis is obtained using proper beamforming techniques. Ideally, the AB axis is perpendicular to the AC axis for easy calculation. Since these stations are fixed a few meters above the sea floor, we can assume that no current moves vertically. The current under observation is moving horizontally in the A-B-C plane as shown in Figure 3. A complete representation of the current speed in a vector form is given as follows:

$$\mathbf{v} = v_{AB}\mathbf{i} + v_{AC}\mathbf{j}, \tag{7}$$

where **i** and **j** are unit vectors that point in the increasing directions of the AB and AC axes, respectively.

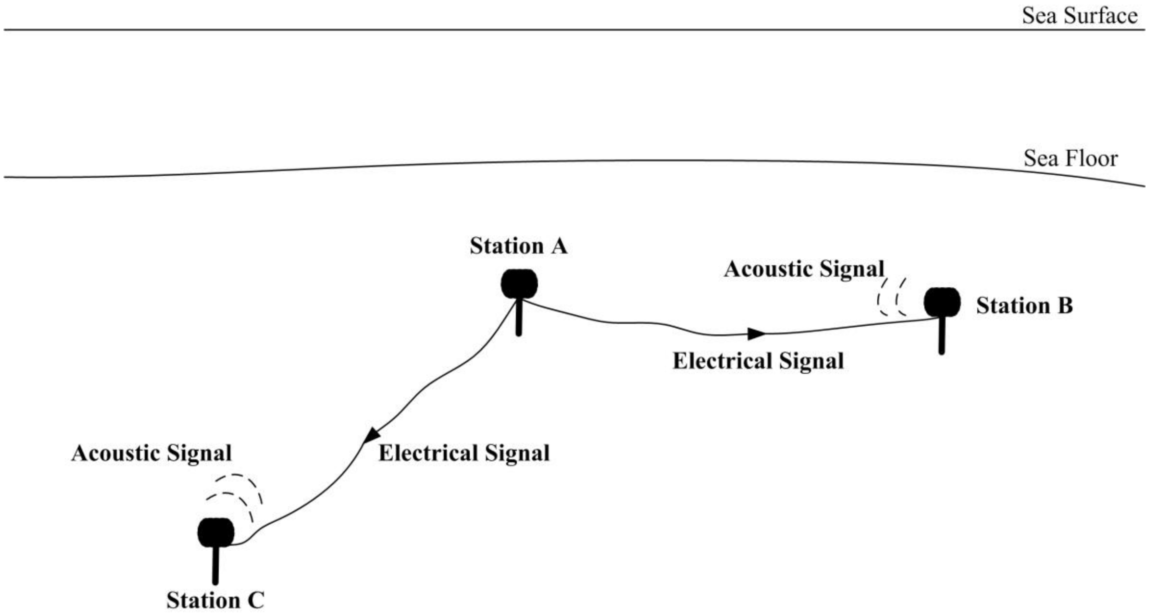

Fig.3 System Configuration for Current Measurement with Three Stations

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