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Study of an expendable current profiler detection method

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ABSTRACT

In this study, the induced electric field model for current movement is established, and the measurement principle of an expendable current profiler (XCP) is obtained through model analysis. Based on this analysis, a method is proposed for the measurement of the nanovolt-scale ocean-current-induced electric field. The proposed procedure moves the frequency of the ocean-current-induced electric field signal to the super-low noise range of the ocean current electric field sensor though amplitude modulation. This is then followed by amplifier filter extraction, while compensating the ocean-current-induced electric field, in terms of the circuit, to offset the strong interference of the induced electric field caused by the subsidence of the XCP probe. Inside the XCP probe, the ocean current electric field signal and the compass coil signal are converted into the in-phase component I_n, quadrature component Q_n, and baseline component B_n, and the data processing method that calculates the eastward and northward relative velocity components of the ocean current from the values of In, Qn, and B_n is established.

1. Introduction

Approximately 70% of the earth's surface is covered by water. Oceans provide humankind with significant resources and they play an important role in human life (Halpern et al., 2012). As an important parameter of the marine environment, ocean currents have significant effects on global climate change, coastal erosion, marine engineering, and the migration patterns of marine organisms. Thus, measurements of ocean current flow fields have long been a focus of marine scientists and marine engineers (Jonathan et al., 2012). As marine scientific research matures and the scale of ocean engineering projects increases (Cui, 2013.), the requirements for ocean current measurement techniques grow. The principal objective of the development of such techniques is to achieve rapid, accurate, real-time, large-scale ocean current measurements targeted on the measurement object and specific to the measurement purpose.

Measurement of ocean currents considers the parameters of speed and direction. According to their physical principles, the instruments used for measuring ocean currents can be classified into one of several types, e.g., mechanical, pressure, electromagnetic, and acoustic current meters (Bouferrouk et al., 2016). Similarly, the measurement methods of these instruments can be divided into several groups: drifting buoy, fixed point, vessel-mounted moving, and expendable moving flow measurement methods (Zhang et al., 2013). An expendable current profiler (XCP) is a disposable low-cost observational instrument that can quickly obtain the parameters of the seawater velocity profile (Liu and He, 2010). The XCP technology is based on the theory of electromagnetic induction. Movement of seawater in a geomagnetic field produces an induced electromotive force (EMF) (Kuvshinov et al., 2006; Tyler, 2015; Hewson-Browne, 1973), the magnitude of which is linearly proportional to the speed of the current. Therefore, ocean current speed can be inferred by measuring the EMF (Sanford, 1971; Stephenson and Bryan, 1992; Tyler and Mysak, 1995), which is a convenient method for the indirect measurement of ocean current speed (Szuts, 2010).

Because the XCP uses a geomagnetic field as the excitation source, an emitting source does not need to be designed for the equipment itself, which makes the front end of the probe more portable. During the measurement process, the XCP uses a no-recycle non-stop operation mode, which makes it faster and more convenient than comparable instruments. Therefore, XCPs could not only greatly improve the detection efficiency of ocean currents but could also be more competent in providing marine environmental parameter measurements in controversial special regions (Liu and Chen, 2011). Currently, only a US company, Sippican, owns the XCP technology and manufactures the related instruments. However, its products have not been updated since 2005, and also are prohibited to be sold in certain countries. Therefore, it is critical that we conduct in-depth study on the XCP detection method and promote the further development of this type of instruments.

This article introduces an ocean-current-induced electric field detection method, which is the basis of the development of China's

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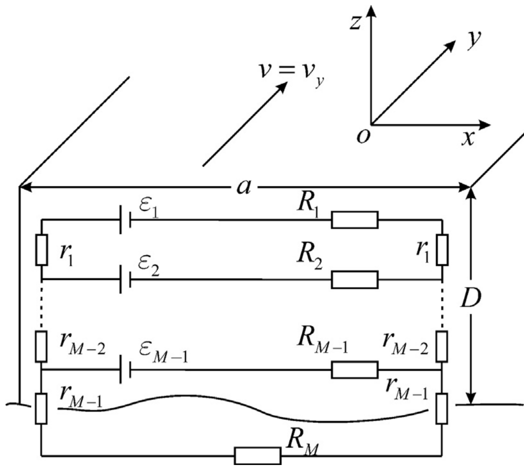

Fig. 1. Equivalent circuit of ocean-current-induced electric field.

first iteration of the XCP instrument (Zhang et al., 2013). The second section of this paper analyzes the current induced electric field model. Section 3 introduces the measurement principles and specific detection method. Section 4 derives the XCP data processing method. Section 5 compares the method to what has been previously developed and Section 6 provides our conclusions.

2. Analysis of ocean-current-induced electric field model

To facilitate theoretical research, ocean currents can be simplified to multi-level uniform currents (ignoring vertical flow).

Fig. 1 shows a horizontal current of width a along the y-direction (Sanford et al., 1978). The ocean current model comprises M layers that are isolated from each other, provided that the flow speeds of the M flowing layers are v_1, v_2,...,v_M, respectively. The electric current induced by the ocean current can be described using the equivalent circuit diagram also shown in Fig. 1. The EMF induced in each layer is ε_i, equivalent resistance is R_i, and vertical resistance between the layers is r_i. For convenience of presentation and consistency in the expression of the formula, the seabed is also regarded as one layer (layer M), where v_M =0 and ε_M =0.

In the operation of the XCP, the actual parameter measured is the potential difference between the two electrodes of the XCP caused by the layer in which the XCP is located. First, considering the simplest case, two electrodes are arranged horizontally in the seawater perpendicular to the flow direction, where the electrode spacing is equal to the width of the ocean currents. In Fig. 1, $R_i = a/\sigma_i D_i b$, $r_i = D_i/\sigma_i ab$, and $\varepsilon_i = H_Z a v_i$, wherein σ_i is the conductivity of each current layer, Di is the thickness of each current layer, b is the length of the ocean currents, and H_Z is the vertical component of the geomagnetic field. Generally, in ocean currents $D_i \ll a$ and $R_i >> r_i$, which means it is possible to ignore r_i. Thus, the equivalent circuit can be simplified to that shown in Fig. 2 (Sanford et al., 1978).

In Fig. 2, ε_i and R_i are the induced EMF and equivalent resistance, respectively, of the current layer in which the electrode is located, and ε_E and R_E are the equivalent induced EMFs and equivalent resistances,

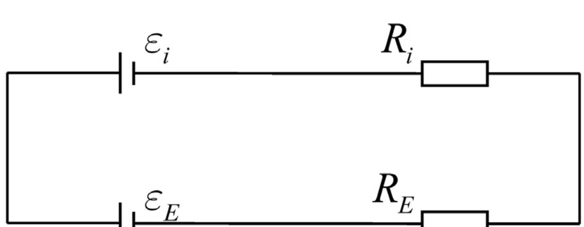

Fig. 2. Equivalent circuit for XCP measurement of ocean-current-induced electric field.

respectively, of the other layers and the seabed:

$$R_E = \frac{1}{\sum_{k=1}^{i-1}\frac{1}{R_k} + \sum_{k=i+1}^{M}\frac{1}{R_k}} \tag{1}$$

$$\varepsilon_E = R_E\left(\sum_{k=1}^{i-1}\frac{\varepsilon_k}{R_k} + \sum_{k=i+1}^{M}\frac{\varepsilon_k}{R_k}\right) = \frac{\sum_{k=1}^{i-1}\frac{\varepsilon_k}{R_k} + \sum_{k=i+1}^{M}\frac{\varepsilon_k}{R_k}}{\sum_{k=1}^{i-1}\frac{1}{R_k} + \sum_{k=i+1}^{M}\frac{1}{R_k}} \tag{2}$$

The actual value measured by the XCP is the potential difference between the two ends of R_i, namely:

$$\Phi_{AB} = (\varepsilon_i - \varepsilon_E)\frac{R_i}{R_i + R_E} \approx \varepsilon_i - \varepsilon_E = H_z a(v_i - \bar{v}) \tag{3}$$

where $\bar{v} = \frac{\sum_{k=1}^{i-1}\sigma_k D_k v_k + \sum_{k=i+1}^{M}\sigma_k D_k v_k}{\sum_{k=1}^{i-1}\sigma_k D_k + \sum_{k=i+1}^{M}\sigma_k D_k}$, can be approximated as the average speed of the currents, which is relevant to the conductivity and speed of each layer. Therefore, for the XCP electrodes, with spacing L along the x-direction in some layer of the ocean current, the measured potential difference is

$$\Phi_i = H_z L(v_i - \bar{v}) \tag{4}$$

It can be seen from Eq. (4) that the current speed measured by the XCP is the net current speed after subtracting the average current speed from the local current speed. Strictly, the measurement obtained by the XCP is a type of relative measurement (Sanford, 1971; Liu and He, 2010).

To detect the profile of ocean current speed at different depths, XCP devices commonly freefall through the seawater column. Therefore, when analyzing the EMF measured by the XCP device, the movement of the XCP device itself must be considered. If it is assumed the XCP device is within a uniform current in the horizontal direction and that it is falling with uniform velocity v_p, the induced EMF detected by the electrodes is

$$\Phi = \vec{L}\bullet(\vec{v}\times\vec{H}) \tag{5}$$

In Eq. (5), $\vec{L}$ is the position vector of the two electrodes, $\vec{v}$ is the relative velocity of the seawater flowing through the electrodes, and $\vec{H}$ is the three-dimensional geomagnetic vector. During the fall, the electrodes cutting the geomagnetic field horizontally also produce an induced EMF, which can be regarded as the equivalent EMF caused by the upward movement of the ocean currents. Thus, $\vec{v}$ comprises of two parts: the unknown absolute velocity of the ocean current $\vec{v_s}$ and the relative velocity of the XCP equipment falling through the seawater $\vec{v_p}$.

If one of the two electrodes is set as the origin with the geographical east and geographical north taken as the positive directions of the x-axis and y-axis, respectively, and the direction perpendicularly upward taken as the positive direction of the z-axis, a spatial Cartesian coordinate system can be established (as shown in Fig. 3). If it is

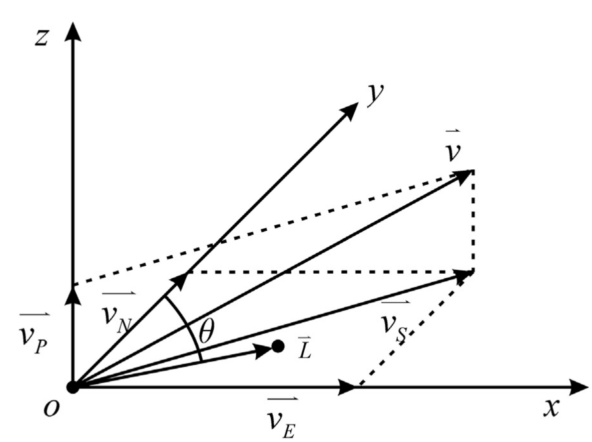

Fig. 3. Schematic of freefall movement of electrode.