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Multi-sensor approach in vessel magnetic wake imaging

M. Amir Fallah *, Habibolah Abiri

School of Electrical and Computer Engineering, Department of Communications and Electronics, University of Shiraz, Engineering Faculty NO. 1, Zand St., Shiraz, Iran

HIGHLIGHTS

- Magnetic anomaly due to vessel motion in a finite depth sea is formulated.
- Shortcomings of single-sensor detection of magnetic anomaly are highlighted.
- Analytical expressions of magnetic wake pattern for a three-layer medium are derived.
- A novel multi-sensor detection system is proposed.
- Parameter study for the novel multi-sensor detection system is performed.

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ABSTRACT

Wake is the hydrodynamic footprint of a vessel at sea. The Earth's magnetic field makes these footprints visible using magnetic sensors. Magnetic wakes induced by the motion of vessels may extend several kilometers and stay up long hours under certain conditions. From remote sensing point of view, in this work physical properties of this magnetic pattern are studied. A mathematical model is derived to simulate the magnetic wakes in a finite depth sea. Estimation of vessel traveling direction using single airborne sensors is reviewed and some problems in this method are remarked. A multi-sensor arrangement of magnetic transducers is proposed to remove these limitations. Estimation of vessel traveling direction with the proposed sensor configuration is performed. Robustness of the proposed method in dealing with Gaussian white noise and various target cutting angles is shown.

1. Introduction

Motion of the electrically conducting seawater across the ambient earth magnetic field produces hydromagnetic phenomena in ocean environment. The motions considered here are due to the vessels. Although dimensions of marine vehicles are limited, the generated wake may extend tens of kilometers and stay up long hours under certain conditions. This effect is an important detectable signature for marine surveillance systems, due to very distinctive pattern and long wavelength of the signature. This large footprint in conductive seawater across the earth magnetic field produces an ELF (Extremely Low Frequency) electromagnetic signature with long detection range. Recent innovations in high accuracy magnetometer with sensitivity of order $100\frac{fT}{m}\cdot\sqrt{\text{Hz}}$ increase the ability of magnetic surveillance systems to detect and track any motion at sea.

There exist two viewpoints for remote sensing. The first one which is more important is detection of vessel presence in all situations of target and surveillance system considering the background noise. The second is processing the received signals to estimate physical parameters of the target such as velocity, size, hull shape, depth and position. Efficiency of the process directly depends on the method used by the surveillance system to capture the wake signals. This work is focused on this subject.

* Corresponding author. Tel.: +98 711 230 3081, 98 7116133006; fax: +98 711 230 3081.
E-mail address: mfallah@shirazu.ac.ir (M.A. Fallah).

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Induced magnetic wake of a ship in an infinite depth sea was studied by Madurasinghe [1–3]. Zou and Nehorai [4] simulated single-sensor detection scenario using an airborne magnetometer flown above an infinite depth sea. Single-sensor detection approach was developed by Yaakobi, Zilman and Miloh [5] in a three layer air–water–soil medium but magnetic permeability and electric permittivity of soil and air layer are the same.

In contrast to the previous works, the primary purpose of this paper is to investigate passive single-sensor acquisition systems such as airborne surveillance system [2,3] and to highlight the shortcomings of single-sensor technique and then to introduce a novel multi-sensor approach for acquiring wake signals of marine targets in the presence of Gaussian white noise. A theoretical model of magnetic field variations due to vessel wake in finite depth water is derived. Here, the finite depth water is one part of a general three layers air–water–soil medium in which magnetic permeability and electric permittivity in each layer are different.

Signal acquisition algorithm is designed and analytical formulations based on hydromagnetic mathematics are derived.

A novel time–space imaging method is introduced to capture the magnetic image of the Kelvin wake using a number of magnetometers. Spectral analysis is performed for the captured magnetic images. Detection scenario is simulated in spectral domain and for improving signal to noise ratio, Radon transform is applied to the magnetic wake images. By a parametric study, advantages of multi-sensor approach are evaluated and verified with simulation results.

2. Hydrodynamic essentials

Consider a marine vehicle moving in a finite depth fluid. The fluid is assumed to be inviscid, homogeneous and incompressible having electrical conductivity. The velocity of a marine vehicle causes some anomalies generated in the vicinity of the vessel hull and extended to far distant from it. There exist two regimes of anomalies, near-field anomaly with a fast decaying feature named turbulent wake and far-field disturbances with surface wave characteristic called Kelvin-wave wake having smaller decaying factor and longer distance effects [6,7]. Here, we focus on the latter regime and explain mathematical formulations that relate fluid velocity to vessel physical parameters in a finite depth fluid.

In the ocean, the hull flow may be taken as a potential flow, since the Reynold number (Re) is large for dimensions and speeds of interest here. Therefore we consider the fluid velocity vector in finite depth media based on the linear wave theory. Suppose that, a moving vessel at a constant speed V in x-direction creates a wavefront moves with an oblique angle θ respect to x-axis. The corresponding velocity potential function of this wavefront can be written as [6,8]:

$$\varnothing(x, y, z, t, \theta) = \frac{A_\theta g}{\omega_0} \frac{\cosh k_0(z+h)}{\cosh k_0 h} e^{-i(\omega_0 t + k_0 x \cos\theta + k_0 y \sin\theta)} \tag{1}$$

were g is the acceleration of gravity, h is the depth of fluid and k_0 is wavenumber related to fluid depth with a transcendental dispersion equation in the form of:

$$k_0 \tanh k_0 h = \omega_0^2/g, \quad \omega_0 = k_0 V \cos\theta. \tag{2}$$

The wavelength $\lambda = 2\pi/k_0$ is determined for given values of the fluid depth and vessel velocity. A_θ is the vessel amplitude coefficient of the wavefront which depends on fluid depth and physical parameters of the moving vessel in fluid. It can be expressed as:

$$A_\theta = \frac{2\omega_0 g}{\cos^3\theta \pi U^3} \frac{e^{k_0 h} - e^{-k_0 h}}{e^{2k_0 h} - e^{-2k_0 h} - 4k_0 h} \kappa_\theta \tag{3}$$

where κ_θ is the Kochin function given by [9]:

$$\kappa_\theta = \iint_s I_\kappa(x', y', z') e^{-ik_0(x'\cos\theta + y'\sin\theta)} \cosh k_0(z'+h) dx'dy'. \tag{4}$$

Here S represents the submerged portion of the vessel for surface vessels and the total outer surface for subsurface vessels. I_κ represents the intensity of sources distributed on S and is proportional to the first derivative of the vessel hull function with respect to x.

The fluid velocity vector is also defined as $\boldsymbol{U} = \nabla\varnothing$.

3. Hydromagnetic view

Now, we discuss the theory of electromagnetic fields to describe the hydromagnetic effects of the Kelvin-waves with velocity vector $\boldsymbol{U}$ in contact with the earth magnetic field. We assume the free surface of fluid to be the plane $z = 0$ and perfectly flat without any noise in the first step. There are three electromagnetic medium here, medium 1 contains air in semi space $z > 0$, medium 2 includes fluid in the region $-h < z < 0$ and finally medium 3 that is soil in region $z < -h$. Electric conductivity, electric permittivity and magnetic permeability of these layers are $(0, \varepsilon_a, \mu_a)$, $(\sigma_w, \varepsilon_w, \mu_w)$ and $(\sigma_s, \varepsilon_s, \mu_s)$, respectively. All these different mediums are immersed in the natural earth magnetic field $\boldsymbol{B_E}$. Cartesian coordinates is chosen as the default coordinate system. Vessel heading is directed to the $-x$ axis. Z-axis is perpendicular to