Ocean Engineering 116 (2016) 21–31

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

Enhancement of rolling energy conversion of a boat using an eccentric rotor revolving in a hula-hoop motion

Yu-Jen Wang*, Jui-Hsin Yu

Department of Mechanical and Electromechanical Engineering, National Sun Yat-sen University, 70 Lienhai Road, Kaohsiung 80424, Taiwan

ARTICLE INFO

Article history:
Received 14 January 2015
Accepted 3 February 2016

Keywords:
Boat rolling energy
Kinetic energy conversion
Hula-hoop motion
Approximate solution
Stability analysis
Green energy

ABSTRACT

This study developed an energy converter composed of an eccentric rotor and a circular Halbach-array magnetic disk to convert the energy created by the rolling motion of a sailing boat into electrical energy. The proposed eccentric rotor was expected to be capable of converting reciprocating rolling motion into a rotational hula-hoop motion when equipped with an appropriate weighted block. The eccentric rotor revolving in a hula-hoop motion enhances power generation because the angular velocity is higher than that provided by small-amplitude oscillation. The rolling frequencies and angles for hula-hoop motion occurrence correspond with the main frequencies and amplitudes obtained from the spectrum analysis of the rolling-motion signal of a 700-ton sailing boat. Comprehensive dynamic analysis of the proposed energy converter was conducted to characterize the relationships between the various parameters and the probability of hula-hoop motion occurrence. An approximate solution was derived according to the numerical results, and the corresponding stability analysis was evaluated using the homotopy perturbation method and the Floquet theory to create an occurrence criteria map for hula-hoop motion. The magnetic flux density and electromagnetic damping of the circular Halbach-array magnetic disk were evaluated using magnetic field strength simulation and Faraday's law of induction. A rolling motion emulator was constructed to verify the performance of the energy converter. The output power of a 6.25-kg prototype connected to an external load of 300 Ω in series was 1.37 mW at a rolling frequency of 0.30 Hz and a rolling angle of 10°. A large version of the proposed energy converter can be applied as a backup power source for a sailing boat, and a small version can be used as a power source for self-powered sensors installed on a boat.

1. Introduction

A backup power source for a sailing boat or ship is necessary, particularly for emergency uses, such as satellite phone calls or emergency lighting. Converting ambient energy into electricity to maintain fully charged batteries is one method for creating a backup power source. Wind and solar energy are two widely recognized renewable energy sources. However, microwind turbines installed on a sailing boat to generate wind power reduce the energy from the propulsion generated by a boat, and solar energy is dependent upon weather conditions and inefficient at night. For a boat sailing on the ocean, kinetic energy is another continuously renewable energy source. Researchers have converted kinetic energy by using three types of transducers: electromagnetic (Arnold, 2007; Wang et al., 2010; Bouendeu et al., 2011), piezoelectric (Anton and Sodano, 2007; Khaligh et al., 2010; Platt et al., 2005), and electrostatic (Paradiso and Starner, 2005; Roundy et al., 2003) transducers. Electromagnetic and piezoelectric conversion mechanisms provide higher energy storage density than do electrostatic conversion mechanisms (Roundy et al., 2005). For energy converters with rotational motion, electromagnetic conversion mechanisms are suitable for large angular displacement (Wang et al., 2013). Moreover, electromagnetic generators can successfully integrate with electronic circuits for self-powered sensors (Chao, 2011).

Two main fields represent the kinetic energy of ocean waves converting into electrical energy. The first field is wave energy conversion, which uses the buoyancy force from rising waves and the gravitational force from sinking waves to power the generator (Ummaneni et al., 2008; Langhamer et al., 2010; Elwood et al., 2010; Okada et al., 2011; Huang et al., 2012; Babarit et al., 2012; Ahn et al., 2012). Wave-energy converters efficiently convert energy through buoys situated near the coast. The second field, used for sailing vehicles, is converting kinetic energy from ambient vibrations (El-hami et al., 2001; Toh et al., 2011; Rastegar et al.,

* Corresponding author. Tel.: +886 7 5252000 4212; fax: +886 7 5254299.
E-mail address: yjwang@mail.nsysu.edu.tw (Y.-J. Wang).

http://dx.doi.org/10.1016/j.oceaneng.2016.02.008
0029-8018/

2006; Morais et al., 2011; Foisal et al., 2012). Toh et al. (2011) developed an energy converter for converting the kinetic energy of an unmanned vehicle in open water. Storing the energy in a battery enabled the device to achieve an average useful power output of 0.30 mW. Foisal et al. (2012) demonstrated a four-generator array with a power density of 52.02 μW/cm^3 at a 7–10-Hz vibration frequency.

Sailing boats have six degrees of freedom: heave (vertical motion on the *z*-axis), surge (sailing direction on the *x*-axis), and sway (lateral motion on the *y*-axis), as well as yaw, pitch, and roll (i.e., swinging around the *z*-, *y*-, and *x*-axes, respectively). According to Guizzi et al. (2014), the main kinetic energy of a sailing boat is attributed to the heave, roll, and pitch. According to the conversion of kinetic energy using a single degree-of-freedom rotor, the dominant motion of a boat is roll.

This paper proposes a novel energy converter composed of an eccentric rotor to convert the rolling energy of a boat. “Hula-hoop motion” refers to the revolution of a ring around a moving body; an eccentric rotor with suitable parameters revolves in a manner similar to that of a hula-hoop to enlarge the angular speed of the rotor and power generation. Section 2 presents a dynamic analysis of the sailing boat and the energy converter. In Sections 3 and 4, the parameters related to hula-hoop motion are addressed, and approximate solutions for hula-hoop motion are derived. The hula-hoop motion of irregular boat rolling is analyzed in Section 5. Section 6 describes magnets arranged in a circular Halbach array and mounted on the eccentric rotor to convert kinetic energy into electric energy. In Section 7, the experimental setup, prototype, and experimental results are presented, and finally, in Section 8, several conclusions and comparisons between the simulation and experiments are provided.

2. Dynamic analysis of energy converter

2.1. Motion of sailing boats

In previous studies (Neves and Rodriguez, 2006; Surendran and Reddy, 2003; Neves et al., 1999, 2003), dynamic analyses of specific boats (length from boat bottom to metacenter ranging from 2.20 to 2.85 m) have been performed. According to the results, the peak of the rolling frequency spectrum ranged from 0.17 to 0.30 Hz, and the maximal rolling angle ranged from $\pm 5°$ to $\pm 20°$. The dynamic behavior of a sailing boat varies depending on the geometries and sea states. In this study, the time-domain responses of a 700-ton fishing boat, the *Nan-Fone*, sailing near Anping off the coast of Taiwan was measured using a three-axis accelerometer and a gyroscope. Table 1 shows the main characteristics of *Nan-Fone*. The sailing speed of the boat was 13 knots when departing from the coast. According to the noise filtered measurement data shown in Fig. 1(a), the maximal rolling angle was approximately $\pm 10°$. According to the spectrum analysis of the rolling motion, conducting using a fast Fourier transform (FFT), the main frequency of the roll was distributed between 0.18 and 0.25 Hz, as shown in Fig. 1(b). Both the angle and frequency of the roll were larger than those of the pitch. The statistical results of

Table 1
Main characteristics of *Nan-Fone*.

Boat length	59.2 m
Boat width	9 m
Boat depth	3.95 m
Designed draft	2.45 m
Metacentric height	1.7 m
Boat bottom to metacenter	3.98 m

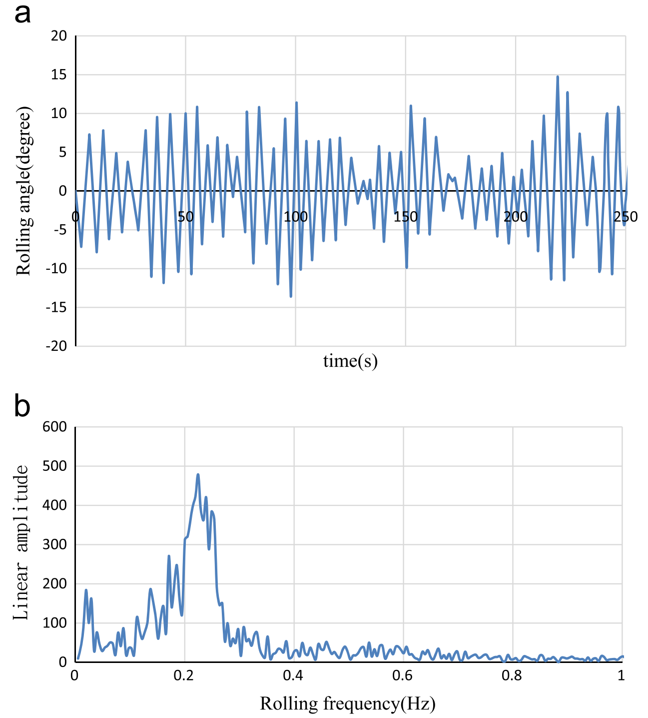

Fig. 1. Measurement of rolling motion of *Nan-Fone*; (a) time-domain response of rolling motion, (b) spectrum analysis results for rolling frequency.

the rolling motion of *Nan-Fone* were similar to those of prior studies. Therefore, the rolling motion information shown in Fig. 1 was considered during the design of the proposed energy converter.

2.2. Kinetic model of the eccentric rotor

To capture the kinetic energy from the rolling motion of a boat, an eccentric rotor equipped with magnets was mounted in the boat cabin (Fig. 2(a)). The distance between the mass center and the pivot point of the eccentric rotor was *H*, and the rolling angle of the boat with respect to the coordinate (x, y) was τ. The angular velocity and acceleration of the rolling motion of the boat were $\dot{\tau}$ and $\ddot{\tau}$, respectively. A schematic diagram of the eccentric rotor is shown in Fig. 2(b). A local coordinate $(\bar{x}, \bar{y})$ was located at the pivot of the eccentric rotor (Fig. 2(b)). The location of the pivot is defined as

$$\begin{cases} X_1 = H \sin \tau \\ Y_1 = H \cos \tau \end{cases} \tag{1}$$

with respect to coordinate (x, y). The position of an infinitesimal element *dm* on the eccentric rotor is defined according to the distance *r* and an angle ϕ (Fig. 2(b)). Variable θ is the swing angle of the eccentric rotor. In this study, the angle φ was further defined as follows:

$$\phi + \theta + \varphi - \tau = \frac{\pi}{2} \tag{2}$$

For an arbitrary swing angle θ, the location of *dm* with respect to $(\bar{x}, \bar{y})$ is

$$\begin{cases} x_2 = H \sin \tau + r \sin \varphi \\ y_2 = H \cos \tau + r \cos \varphi \end{cases} \tag{3}$$