Effective Energy-Saving Device of Eco-Ship by Using Wave Propulsion

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Abstract **— In this work, an effective energy-saving device is proposed to extract wave energy and convert to useful propulsive thrust for a merchant ship travelling in waves. Eco-Ship was internationally introduced and aimed to reduce carbon dioxide emission generated from ships. The energy-saving device equipped underneath the front part of the ship model of general merchant ships that inspired by marine mammals is investigated in this work. An active control of pitch-oscillating bow fin with NACA0016 section is applied as an effective energy-saving device in this work. Free-running model test using a 1/50th scale model of a container ship was conducted for validating the effectiveness of this device. The ship speed, ship motion, angle of bow fin and power consuming are measured and recorded. There are two kinds of wavelength to ship length ratio of regular wave in the experiments with fixed propeller speed. Based on different heave motion, the different pitch angle of bow fin is controlled to obtain the extra energy from wave. The experimental results shows the feasibility of the energy-saving device when the phase lead of the bow fin pitch motion with respect to its heave motion set in a proper range between 60 degree to 200 degree. When the ratios of wavelength to ship length are 1.0 and 1.3, the maximum of power efficiency improving are around 6.5% and 18.9% respectively. The experimental results demonstrated that the proposed device is effective to enhance ship speed and save energy for achieving the goal of Eco-Ship.**

Keywords — active pitch-oscillating fin; wave energy; ocean renewable energy; Eco-ship.

I. INTRODUCTION

Global warming is happening, people are seeking green energy sources for reducing carbon dioxide emission. Taiwan is an island, so ocean renewable energy is the most important resources. Wave energy is one of ocean renewable energy and there are some developed wave energy captured devices or converters. In this work, an effective energy-saving device is proposed to capture wave energy and convert to useful propulsive thrust for augmenting the propulsion of a merchant ship travelling in waves.

There are lots of experimental studies on oscillating foil(s) to generate thrust or/and lift forces [1]. Anderson and Triantafyllou conducted a series of experiments about propulsive performance of a 2D oscillating foil with varied amplitudes and frequency [2]. Active oscillating foil propulsion system that developed by O-foil company was applied on inland shipping [3]. Filippas and Belibassakis further investigated the effects of free surface and waves to a 2D oscillating foil by numerical method [4]. Belibassakis and Politis analyzed the hydrodynamics of flapping wings located beneath a ship hull travelling in waves [5]. The boat SUNTORY mermaid II equipped with a passive wave energy devouring propulsion system has proved its success in a long voyage of 7800 km crossing Pacific Ocean from Honolulu to Japan [6]. Chiu and Li evaluated performance of active oscillating fin that equipped at the bow in full-scale (321 meter length) VLCC by simulation [7,8]. The simulation result shows the feasibility of a pitch-oscillating bow fin applied on a merchant ship to augment propulsion in waves.

The paper is composed of four sections. Section II introduces the characteristics of the free-running model. Section III describes the experiment and results conducted by a 1/50th scale model of a container ship. Then conclusion is given in Section IV.

II. FREE-RUNNING MODEL

A. Scale Model

Figure 1 shows the 1/50th scale model of a container ship with bulbous bow adopted in the present study. In full-scale, the length between perpendiculars (L_{pp}) is 168.8 meter and displacement is 26,200 tons. The principal characteristics of the container ship are shown in Table I.

Fig.1 Side view of scale model with active pitch-oscillating fin

Based on the geometry of model and size of driven mechanism, the NACA 0016 airfoil was applied. The chord length is 10.0 cm and width is 18.0 cm each side. The fin was equipped on the square station 9 and below load water line 9.65cm. The front view of effective energy-saving device of Eco-ship is shown in Fig.2.

TABLE I. THE MAIN CHARACTERISTICS OF CONTAINER SHIP

	Full Scale	Model
Length on the Load Water Line (L_{WL})	168.8 m	3.376 m
Breadth	27.9 m	0.558 m
Draft	8.5 m	0.17 m
Designed Speed	20 knots	1.455 m/s
Water plane Area	3736.8 m^2	1.494 m^2
Volume of Displacement	25552.2 m^3	0.204 m^3
Longitudinal radius of gyration	N/A	26.7% L_{WL}

B. System Architecture

The scale model described before was used in free-running model test. The configuration of scale model is shown in Fig.3. From right to left, one vertical accelerometer at bow, servo motor of pitch-oscillating bow fin, power measurement sensor, a forward laser ranger on a 3D stabilizer, pitch motion sensor, vertical accelerometer at midship, an on-board computer, two lateral laser rangers, encoder of propeller, and indicator of rudder angle.

The range measured by the forward laser ranger is used to calculate the ship speed. The stabilizer keeps laser point unaffected by ship motion. On-board computer served as a controller and data collector for all the sensors. The auto-pilot controller of free-running model is developed on Microsoft Visual Basic 6.0. The lateral laser rangers used to estimate the heading of ship and feedback to control the rudder, so the free running model can keep running along the water tank stably.

Fig.2 The front view of effective energy-saving device of Eco-ship.

Fig.3 The free-running model

C. The Controller of Active Pitch-Oscillating Bow Fin

The active pitch-oscillating fin is controlled by the measurement of vertical accelerometer at the bow. LabVIEW and A/D card are used to capture the signal of vertical accelerometer at the bow and on-line analyzer used to track the wave frequency. The same frequency of control signal was applied on active pitch-oscillating bow fin. The amplitude of oscillating fin was controlled with respect to heave motion of ship. The different inflow angle-of-attack and leading phase was set to find the effective propulsion in different ship motion.

A sample of the control flow of pitch-oscillating bow fin is shown in Fig.4 when the free-running model travels in the regular waves that the ratio of wavelength to ship length is 1.0 and amplitude of pitch-oscillating bow fin set as 6.4 degree. During 35 second to 45 second, the pitch motion of ship was analyzed on-line. The leading phase was set and active pitch-oscillating bow fin was controlled between 48 second to 55 second.

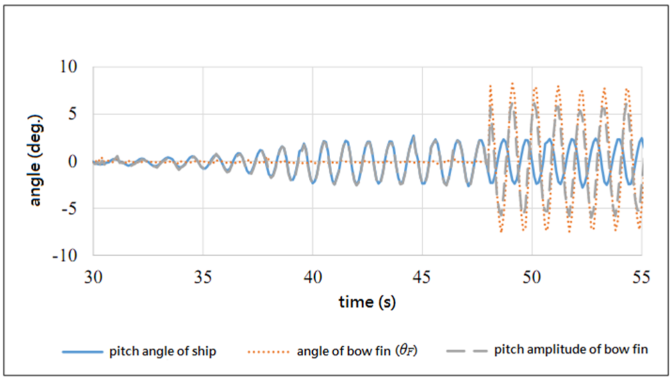

Fig.4 The pitch angle control of oscillating fin.

III. EXPERIMENTS

A. Experimental Conditions

The experiment conducted by fixed propeller speed in the clam water and the speed of ship was measured. When propeller speed is 714RPM and bow fin is fixed, the speed of scale model is 1.205m/s and 16.6 knots in full scale. The following experiments was carried out at 714RPM propeller speed. The ratios of wavelength to ship length set as 1.0 and 1.3 and the ratios of wave height to wavelength are around 1/50 to 1/40. Oscillating modes in coupled motions are described as follows

$$h(t) = h_0 \sin(\omega t) \tag{1}$$

$$\theta(t) = \theta_0 \sin(\omega t + \psi) \tag{2}$$

where h_0 is the heave amplitude, ω is the angular frequency, θ_0 is the pitch amplitude, and ψ is the phase lead of the pitch motion with respect to the heave motion.

Angle-of-attack (α) based on the resulting inflow velocity can be expressed as:

$$\alpha(t) = tan^{-1}[(dh(t)/dt)/U] - \theta(t) \tag{3}$$

where U is the inflow speed. In this work, the amplitude of bow fin set at maximum angle-of-attack, α_{max}=21°. [1] The pitch angle of bow fin is described as (4).

$$\theta(t) = tan^{-1}[dh(t)/Udt] - \alpha(t) \tag{4}$$

Referred to [1], the phase lead of the pitch motion of bow fin with respect to its heave motion set as 90 degree. The amplitude of angle-of-attack can be described as (5). The U set as the average speed of free-running model at 714RPM when free-running model travels in the regular waves with fixed bow fin. Thus, the pitch amplitude of bow fin θ_0 was calculated by the heave amplitude h_0 and the angular frequency ω.

$$\alpha_0 = tan^{-1}[\omega h_0/U] - \theta_0 \quad (5)$$

Fig.5 shows the relationship of bow fin with respect to horizontal plane. θ_S is the pitch angle of ship with respect to horizontal plane, θ is the pitch amplitude of bow fin and the θ_F is the target angle of motor, which is described in (6). The different phase lead of the bow fin pitch motion with respect to heave motion were tested to evaluate the useful leading phase range when free-running model travels in regular waves.

$$\theta_F = \theta - \theta_S \quad (6)$$

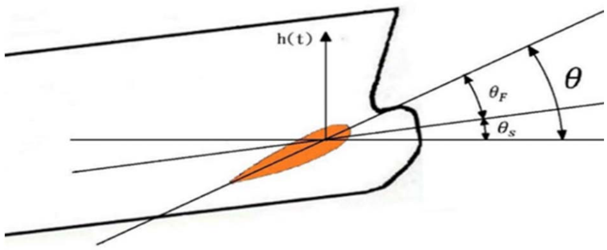

Fig.5 The relationship of bow fin with respect to horizontal plane.

B. Mean Speed with Fixed Bow Fin

Firstly, the scale model was controlled to free run in regular waves with fixed bow fin at 714RPM propeller speed. TABLE II and TABLE III show the results of experiment under the conditions of wavelength to ship length ratio of 1.0 and 1.3 respectively. The mean speed, propeller mean power and ship motions had no significant difference between the two runs.

TABLE II. RESULTS AT WAVELENGTH TO SHIP LENGTH RATIO OF 1.0

Run No.	Wave Height [cm]	Mean Speed [m/s]	Propeller Mean Power [W]	Pitch of Ship RAO	Heave of Bow RAO
1	8.20	0.861	43.671	0.608	2.228
2	8.04	0.867	42.757	0.618	2.275
AVG.	8.12	0.864	43.214	0.613	2.252

TABLE III. RESULTS AT WAVELENGTH TO SHIP LENGTH RATIO OF 1.3.

Run No.	Wave Height [cm]	Mean Speed [m/s]	Propeller Mean Power [W]	Pitch of Ship RAO	Heave of Bow RAO
1	8.11	0.884	46.889	0.712	2.726
2	8.19	0.879	42.866	0.733	2.537
AVG	8.15	0.882	44.878	0.723	2.632

C. Mean Speed improvement with Active Oscillating Bow Fin

Based on the previous experimental results of average mean speed and the angular frequency ω, the target pitch amplitude of bow fin θ_0 at wavelength to ship length ratios of 1.0 and 1.3 are 6.4° and 13.1° respectively.

There are 14 runs in the experiment at wavelength to ship length ratio of 1.0 and the target pitch amplitude of bow fin is 6.4 degree. The results of experiment show that the average of wave height is 8.21cm, maximum and minimum variations are 2.80%, -2.68% respectively. The percentage of ship mean speed improvement due to oscillating bow fin with respected to fixed bow fin (0.864 m/s) and the efficiency of energy-saving at varied leading phases ψ are shown in Fig.6. Both the powers to drive propeller and bow fin are taken into account. In this figure, not only positive ship speed improvement but also positive efficiency of energy-saving due to active pitch-oscillating bow fin in specified range of leading phase can be found. The maximum speed improvement is up to 6.24% at leading phase of 163 degree. The second best of speed improvement is 5.69% at leading phase of 132 degree. On the other hand, the speed decreased 5.39% at leading phase of 355 degree.

There are 16 runs in the experiment at wavelength to ship length ratio of 1.3 and the target pitch amplitude of bow fin is 13.1 degree. The percentage of ship mean speed improvement due to oscillating bow fin with respected to fixed bow fin (0.882 m/s) and the efficiency of energy-saving at varied leading phases ψ are also shown in Fig.6. Similarly, the ship speed and energy saving were enhanced with active pitch-oscillating bow fin in specified range of leading phase. The maximum speed improvement is up to 11.86% at leading phase of 117 degree. The second best of speed improvement is 11.29% at leading phase of 145 degree. The speed decreased 7.34% at leading phase of 330 degree. About the efficiency of energy-saving including its definition is described in next Section *D*.

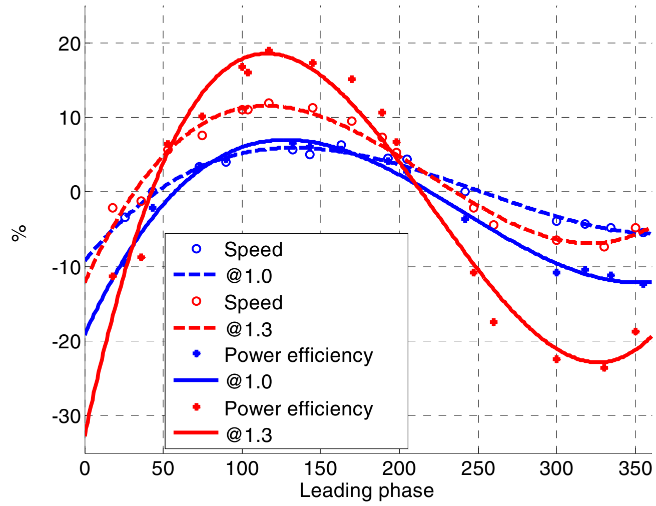

Fig.6 The mean speed improvement and power reduction by oscillating bow fin with respected to fixed bow fin in varied leading phase. Blue and red stand for the conditions of wavelength to ship length ratio of 1.0 and 1.3 respectively.

In order to clarify the effects of angle-of-attack amplitude of oscillating bow fin α_0 to ship mean speed in waves. Fig. 7 shows the relationship between amplitude of angle-of-attack and the leading phase of pitch motion with respect to heave motion of the active oscillating bow fin. Fig.6 and Fig.7 show that the ship speed had significant improvement in the range of leading phase between 60 degree and 180 degree, and corresponding range of angle-of-attack is between 20 degree and 25 degree at wavelength to ship length ratio of 1.0. Stall may occur at higher angle-of-attack to reduce the thrust force. For the case of wavelength to ship length ratio of 1.3, ship speed was improved significantly in the range of leading phase between 78 degree and 200 degree, and corresponding range of angle-of-attack is between 20 degree and 35 degree.

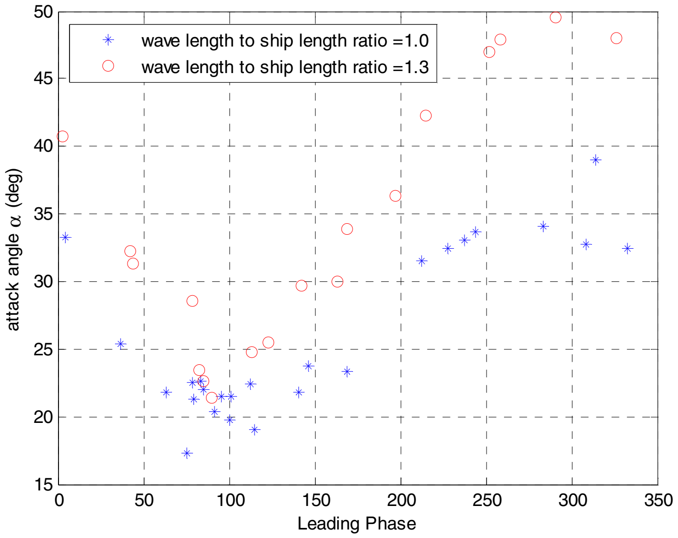

Fig.7 The relationship between angle-of-attack and the leading phase of the pitch motion with respect to the heave motion.

D. Efficiency of Energy-Saving

In order to evaluate the extent of energy-saving by applying the active pitch-oscillating bow fin, the efficiency of energy-saving η is defined as (7).

$$\eta = (W_1 - W_0 - P_{pitch}) / W_1 \quad (7)$$

where W_1 is the mean power of propeller with fixed bow fin at the same mean speed with active pitch-oscillating fin, W_0 is the mean power of propeller with active pitch-oscillating fin and P_{pitch} is the mean power for driving pitch-oscillating fin. The numerator of the right hand side of (7) is the power saved due to the device at the same mean speed in wave. As the base power for analyzing η, the mean power of propeller with fixed bow fin W_1 at varied mean speed in wave is shown in Fig.8 for these two ratios of wavelength to ship length of 1.0 and 1.3.

Combining with speed improvement, the efficiency of energy-saving due to active pitch-oscillating bow fin at varied leading phase is also shown in Fig.6. The maximum efficiency of energy-saving is up to 6.5% at leading phase of 132 degree at wavelength to ship length ratio of 1.0. And for the case of wavelength to ship length ratio of 1.3, the maximum efficiency of energy-saving is up to 18.9% at leading phase of 117 degree. Based on the experimental results shown in Fig.6, the effectiveness of the present energy-saving device for a merchant ship running in waves can be confirmed.

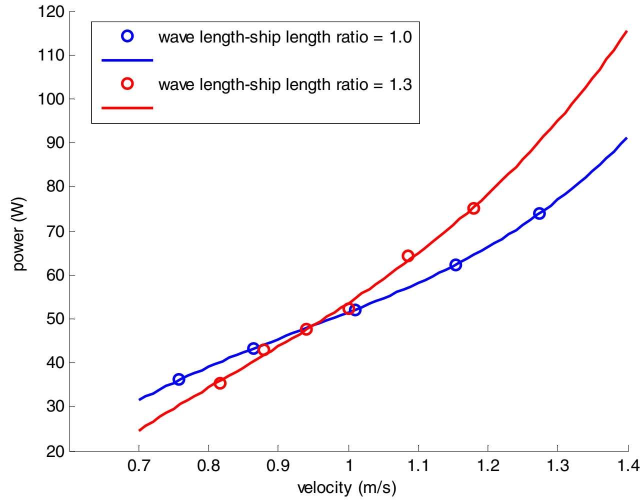

Fig.8 The mean power of propeller with fixed bow fin W_1 at varied mean speed in wave.

IV. CONCLUSION

This work shows the experimental results of effective saving-energy device for a merchant ship by a free-running model running in waves with autopilot. This experimental study shows the feasibility to improve ship speed and save energy by applying active pitch-oscillating bow fin compared to fixed bow fin. A proper range of the leading phase of bow fin pitch motion with respect to its heave motion exists for obtaining positive effects to ship propulsion in waves. As an example, in regular waves of wavelength to ship length ratios of 1.0 and 1.3, the proper range of leading phase is around 60~200 degree, the speed improvement may reach 6.24% for the wavelength to ship length ratio of 1.0, and 11.86% for the wavelength to ship length ratio of 1.3. In addition, the saved energy may reach 6.5% and 18.9% for the wavelength to ship length ratios of 1.0 and 1.3 respectively.

In summary, the experimental results demonstrated that the proposed device is effective to augment ship speed and save energy for achieving the goal of Eco-Ship by extracting wave energy. At the same ship speed, comparing with the power saved to propeller the power needed for driving the pitch-oscillating bow fin is relatively small. In the near feature, the development of control method plays the most important role to implement the energy-saving device proposed in this work on the full scale ship.

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