The 2012 World Congress on
Advances in Civil, Environmental, and Materials Research (ACEM' 12)
Seoul, Korea, August 26-30, 2012

Application of Wave Devouring Propulsion System for Ocean Engineering

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ABSTRACT

A Wave Devouring Propulsion System (WDPS) is a device that generates thrust directly from wave power while simultaneously generating significant damping force. A relatively simple WDPS design consists of hydrofoils mounted below the bow of a vessel. If a WDPS is integrated with the hull of a vessel, it can power the vessel forward, even against the wave direction itself. One example of a successful WDPS was installed on the vessel named Mermaid II that successfully completed a trans-Pacific voyage in 2008, traveling approximately 7,800 km from Hawaii to Japan using wave power alone. This success indicates that WDPS has potential for use in the field of ocean engineering. In this paper, we will explore two possible applications. The first of the two WDPS applications we will discuss is a small autonomous controlled WDPS design and its associated sea trial. The second is an application of basic research into active type WDPS design. This active system improves WDPS performance in waves and acts as a new energy absorber.

Fig. 1 WDPS vessel Mermaid II beginning its historical trans-Pacific voyage from Hawaii to Japan

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1. INTRODUCTION

In Japan, the study of Wave Devouring Propulsion systems (WDPS) began in 1980 as a negative wave drifting force device (Terao 1980). That WDPS design was envisioned as an auxiliary propulsion system for a conventionally powered vessel, as shown in Figs. 2 and 3.

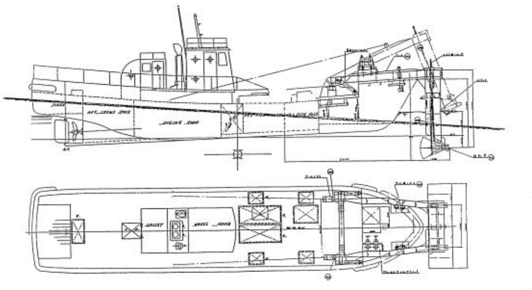

Fig. 2 Single fin type WDPS designed for actual sea trials (Terao 1990)

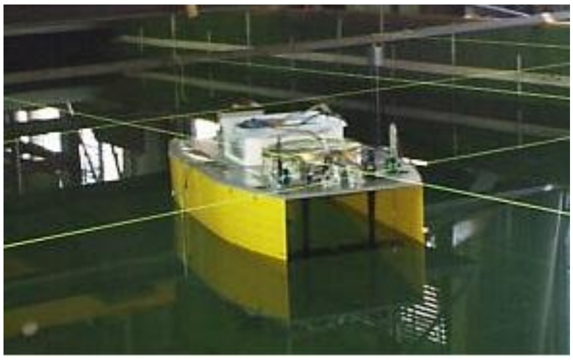

Fig. 3 Dual fin type WDPS testing in a wave tank (Terao 2000)

After various research efforts (Isshiki 1984, Terao 2000) into pure wave power devices, the Mermaid II was developed and dispatched on its successful trans-Pacific voyage from Hawaii to Japan in 2008 using the wave power alone (Terao 2009).

Various other wave-powered systems have also been proposed and developed. These include a seawater desalination system (Hicks 1988), a small-scale power generation system (Brown 2006), an autonomous underwater vehicle (AUV) (Ageev 2000), a marine vehicle (Hine 2009), and an oceanographic profiler (Su-hua 2009).

In this paper, we will begin by exploring the potential application of a WDPS system for ocean measurements. It is believed that if autonomous WDPS vessels could be developed, they could provide potentially useful tools for use in long-term oceanographic environment observations, marine and mineral resource observations, and port or waterway coastal security observations. Such vessels would not require operators to navigate and/or control them, nor would they require any power other than ocean waves.

With those missions in mind, we developed small, lightweight catamaran type WDPS vessels equipped with dual fin type WDPSs that transform wave force into propulsive thrust. As part of this project, we also developed a measurement system and an autonomous control system. Those developed systems consist primarily of a micro-controller unit, multiple sensors and communication devices to permit coordination between the vessels and their operators ashore. The navigation system consists of a global positioning system (GPS) receiver and a digital magnetic compass. The other installed sensors were used for data acquisition related to motion analysis of the hull and other forces acting on the WDPS system.

The outline of this paper is as follows:

The specifications and performance of the experimental WDPS vessels themselves will be presented briefly in Section 2. The autonomous control and the measurement systems of those vessels are described in Sections 3 and 4. In Section 5, we present a monitoring system that allows operators ashore to observe the vessel's state in real-time. Sections 6 and 7 describe preliminary experiments that were conducted ashore and at sea to test the effectiveness of the developed systems.

In Sections 8 and 9, our research into the development of a new active WDPS vessel is described. This research focused on determining the optimum hydrofoil motion control conditions necessary to absorb wave energy, as well as optimizing WDPS functions such as thrust production and increasing wave damping force.

2. NEWLY DESIGNED WDPS BOAT

We developed a small, lightweight WDPS vessel that is versatile, transportable, and easy to use. The principal dimensions of this vessel are given in Table 1 below:

Table 1 Principal dimensions

Dry weight	5.2 kgf (50.96 N)
Full	7.6 kgf (74.48 N)
Length	1.3 m
Beam	0.98 m
Height	0.70 m
Hydrofoil section	NACA0012 × 2
Span	0.31 m
Chord	0.12 m
Foil Depth	0.15 m

Fig. 4 Small newly designed dual fin type WDPS model. The upper cover is removed.

The hull of the vessel is fabricated from NC catted polyurethane foam covered with thin glass-fiber reinforced plastic. Dual fins are installed under the bow, as shown in Figure 4. Each fin has a pitch restoring spring and travels along a pivot axis, as shown in Figure 5. The maximum pitch amplitude angle is set at 45 degrees. As seen in Figure 6, two balanced steering rudders, driven by two servomotors, are installed at the vessel's stern.

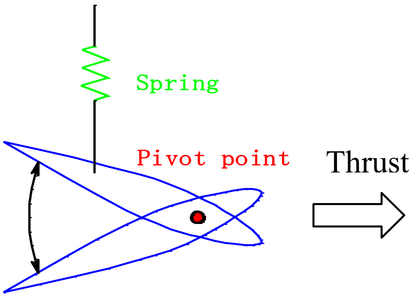

Fig. 5 Pitch restoring spring and fin pivot position. Hydrofoil oscillation generates thrust.

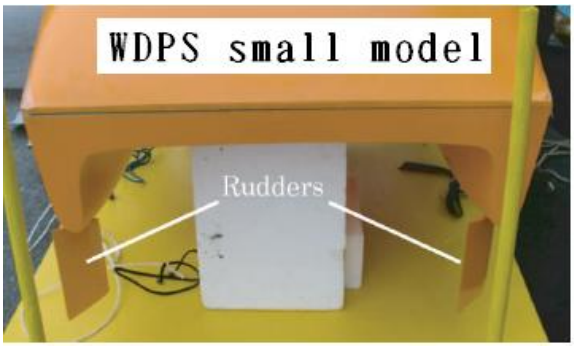

Fig. 6 Two rudders are installed to steer the WDPS vessel.

Figure 7 shows an example of a model WDPS performance test conducted in a wave tank. The new WDPS vessels are designed for actual sea conditions and the model used was somewhat larger than practical for our wave tank test setup. In the test shown in the figure, the model was allowed to drift freely with its forward speed set to zero. Regular wave action was then applied. When the incident waves reached the hull, the WDPS vessel began moving against the wave action, accelerating as necessary to maintain its intended position.

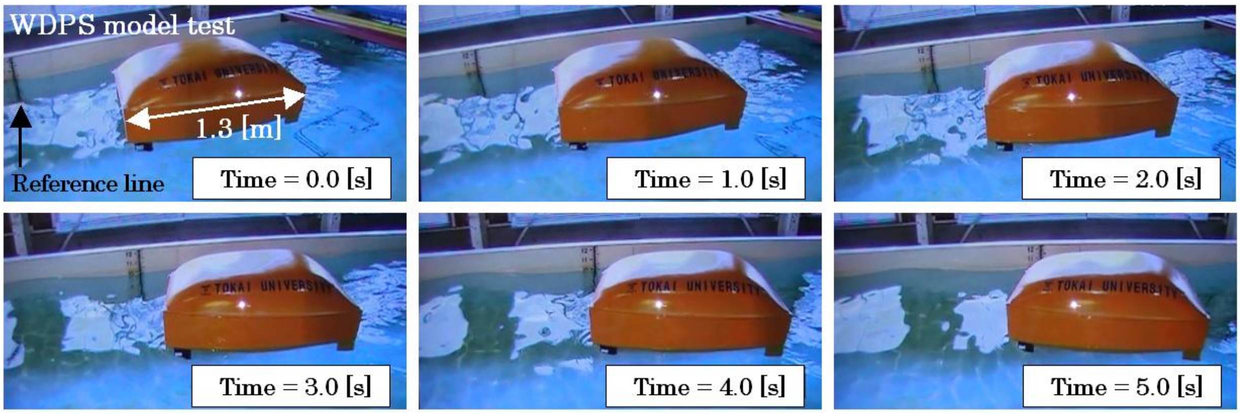

Fig. 7 WDPS wave tank test. Regular wave height is 0.1 [m]; wave length is 1.5 [m]. Advance speed against the waves is 0.16 [m/sec].

3. MEASUREMENT SYSTEM

The WDPS vessel performance is affected by ocean conditions. These include wave height, wave length, tidal current, wind speed, and other factors. Therefore, we investigated the vessel's hull performance using a variety of sensors. Figure 8 provides an overview of the measurement system configuration, which is based on a 16 MHz micro-controller unit and is equipped with a triple axis accelerometer, strain-gauge force and moment sensors (to measure the horizontal and vertical force and pitching moment acting on the foil system), along with potentiometers to measure foil pitch angles. A micro SD card logger is used for data logging. These measured signals pass through a 10-bit A/D converter and are stored on a micro SD card. Rechargeable batteries (7.2 [V] 5200 [mAh] NiMH-Pack ×2) supply power to these electric devices. The total system weight (including batteries, controller and navigation components) is approximately 2.4 [kgf].

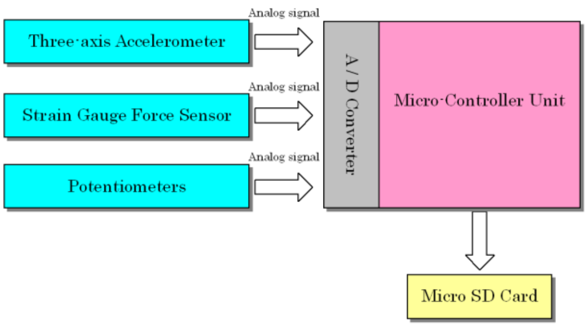

Fig. 8 Measurement system for the WDPS vessel

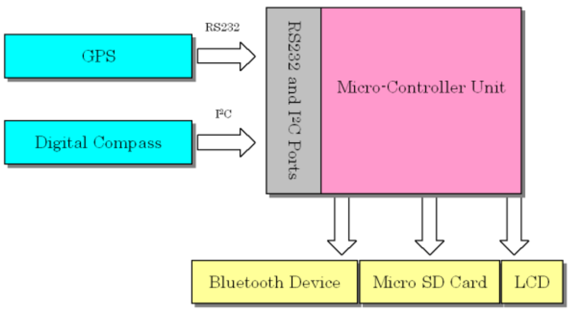

Fig. 9 Autonomous control system for the WDPS vessel

4. AUTONOMOUS CONTROL AND MONITORING SYSTEM

For the navigation system, a GPS receiver and a digital magnetic compass are used. Two servomotors control the vessel's twin rudders, as shown in Figure 6. The navigation system configuration is shown in Figure 9. The vessel's position is determined by GPS readings taken once each second, while the micro-controller calculates the absolute hull velocity. The magnetic compass with tilt compensation accurately detects the heading of the vessel in the seaway. The operation of the navigation is achieved as follows:

1) The desired waypoints and the radius of a circle around them (that represents an error range) are set as shown in Figure 10.

2) The micro-controller calculates the distance and heading error from the present position to a desired waypoint, and then adjusts the rudder angles so that the vessel

moves toward the desired waypoint. This part is executed in the normal sailing loop of the micro-controller.

3) When the vessel reaches a point that falls within the error range of the destination waypoint, the micro-controller selects the next waypoint, changes the vessel's heading, and then executes the next sailing loop. The flow chart of the autonomous control is illustrated in Figure 11.
4) The current position and compass-heading angle are displayed on a personal computer LCD and are stored on a micro SD card.

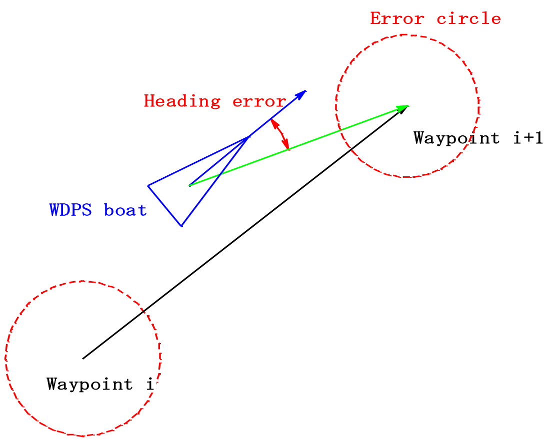

Fig. 10 Schematic view of waypoint and error circle

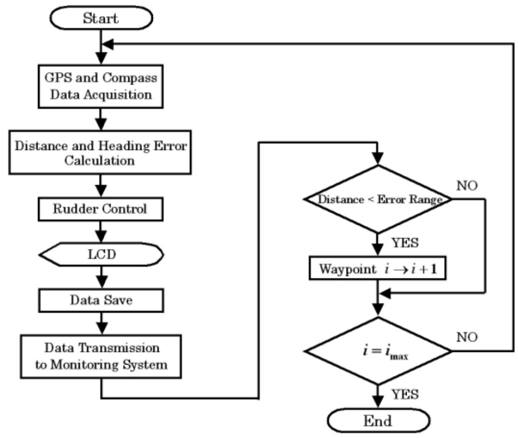

Fig. 11 Flow chart of the autonomous navigation control system.

Navigation data is transmitted to an onshore monitoring system via a Bluetooth device. This allows navigation data such as vessel position, heading angle and the waypoint number to be available in the monitoring computer in real-time. The Bluetooth module data transfer range was found to be approximately 100 [m] in the open-sea testing area.

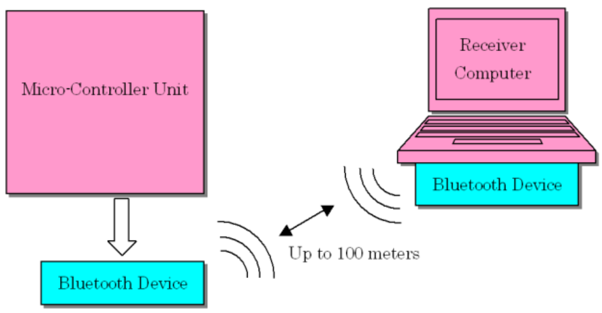

Fig. 12 Monitoring system for WDPS vessel and onshore PC

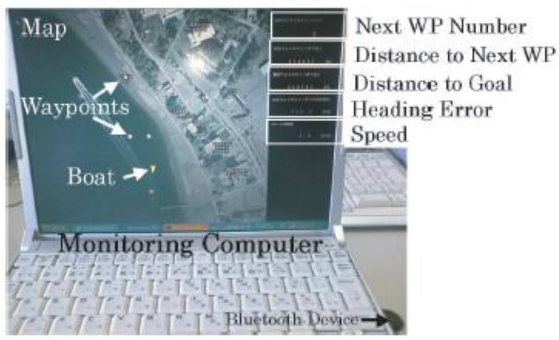

Fig. 13 Computer monitor displaying vessel progress and state

The monitoring system consists of a data transmission device and a PC receiving station located onshore, as shown in Figure 13. Using this system, operators can monitor the state vessel in real time. The information set is updated once each second.

5. PRELIMINARY EXPERIMENTS

We first tested the performance of the measurement, autonomous control and monitoring systems onshore, as shown in Figure 14, where GPS data tracking trajectory is shown.

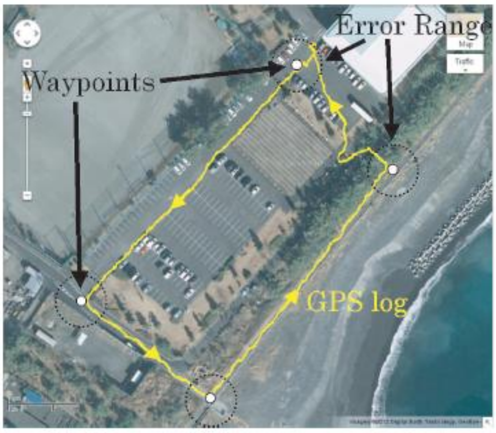

Fig. 14 Preliminary experiment in a coastal location (Image via Google Maps)

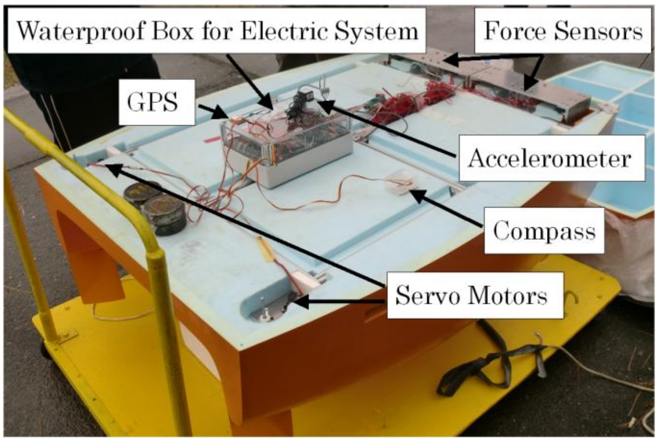

Fig. 15 Experimental setup for WDPS vessel sea trials.

5.1 Measurement System

The multi-sensor measurement system control software was developed in the C/C++ language. During the test program, acceleration along three axes, strain gauge forces, and fin pitch angles were all properly measured and stored on the micro SD card at 5 [Hz].

5.2 Autonomous Control System

Control system testing was conducted separately from the experimental vessel at a coastal location onshore. More specifically, we tested the GPS and digital compass accuracy, as well as the control logic and motion of the rudder servomotors, using the using the procedure described below.

We first set the desired waypoints and the radius of the error range circles as shown in Figure 13. In this test, the radius of the circles was set at 15 [m]. After making these settings, we started the control system in the vicinity of the first waypoint. The micro-controller assumed control and calculated the distance from its present position to the desired waypoint, then adjusted the servomotors so that the "boat" heading was oriented toward the desired waypoint. A simple proportional derivative (PD) feedback control law was applied to control the servomotors that actuate the rudders (i = 1, 2) as follows:

$$\alpha_i = K_p \Delta\theta - K_v \dot{\theta} \quad i = 1,2 \quad (1)$$

Where

α_i	: the servo motor angle for the rudders control;
K_p=38.0	: the proportional gain;
Kv=0.012	: the derivative gain;
$\Delta\theta$	: the heading error as shown in Figure 10.
θ	: the heading angle of the test bed vessel.

When the control system determined that it had reached the designated target area, the micro-controller properly switched to the next waypoint operation. In every sequence, the GPS position and compass heading data were measured and stored on the micro SD card at 1 [Hz].

5.3 Monitoring System

The monitoring system was designed to transmit measurement data and autonomous control systems data between the vessel and its monitoring computer via Bluetooth modules. The monitoring software was developed based on Processing, which is an open source programming language and environment. In our tests, when the micro-controller was started, the Bluetooth module began transmitting navigation data (such as GPS position, compass heading, and waypoint number) once each second. These data were received by the monitoring computer, which then displayed them for the operators.

6. SEA TRIALS

The complete system was mounted on the experimental WDPS vessel and tested in Orido bay off the coast of Shizuoka Prefecture, Japan. Figure 15 shows an overview of the experimental setup.

Two waypoints were selected for the first sea trial, a starting waypoint and a second position at sea. The error range was set at 15 [m]. Using the same procedure as in the preliminary experiment, the system was started near the first waypoint. During this experiment, the WDPS vessel proceeded toward the waypoint as expected and the monitoring system kept the operators informed of its state in real-time.

Figure 16 shows a screenshot of the monitoring display in which the vessel appears as a triangle with the longest axis point indicating the heading angle. The trajectory of the vessel was updated on the display at one-minute intervals. All systems worked properly in this trial and the experimental WDPS vessel advanced toward the set waypoints at an estimated speed of 0.18 [m/s].

Figure 17 shows a view of fine pitch angle data captured during the experiment. This result indicates that the fins moved in the waves and generated thrust as expected.

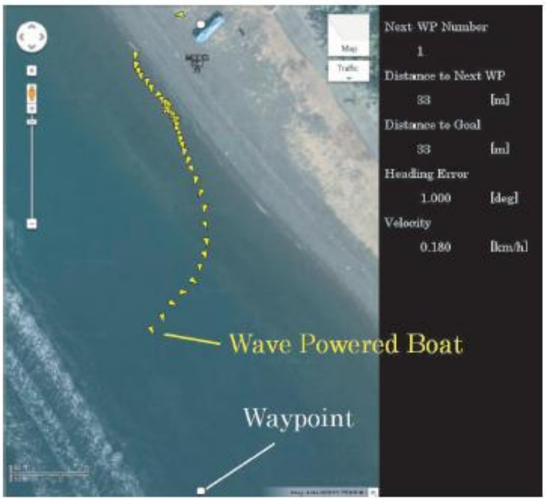

Fig. 16 Screenshot of monitoring display captured during the experiment
(Image via Google Maps)

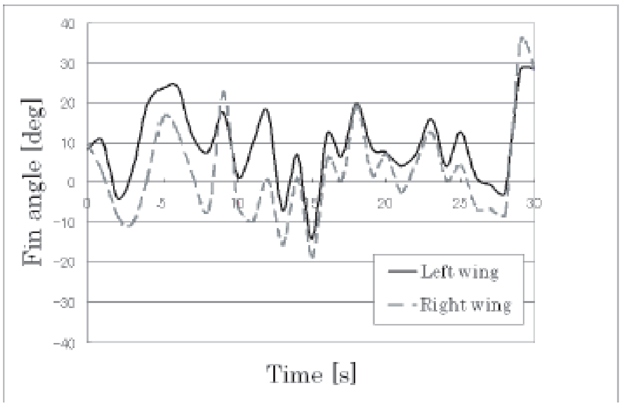

Fig. 17 Screen capture of fin pitch angles

7. AUTONOMOUS WDPS FUTURE WORK

Future work related to autonomous WDPS vessels will include investigating long-distance and long-duration navigation at sea, as well as further study of autonomous cooperative research operations. We have already built and outfitted two vessels with the system, as shown in Figure 18.

Fig. 18 Two WDPS vessels constructed for cooperative research operations

8. BASIC STUDY OF ACTIVE WDPS FOR FUTURE PROGRAM

The present WDPS can be considered passive in that the hydrofoil pitch motion is restricted solely by a simple spring system that provides the pitch restoring force. However, despite the simple and robust nature of this system, it is subject to efficiency limitations in the frequency domain. More specifically, the higher performance frequency band is somewhat narrow due to the simple resonance phenomena and, especially for small vessels, the procedure used to match the hull motion resonance point with the peak point frequency across the ocean wave spectrum is quite difficult.

In contrast, our new WDPS design is based on an active control system in which vertical hydrofoil motions are controlled by the actuator system using a novel hydrofoil motion phase control logic. Figure 19 shows the forced oscillator setup while Figure 20 shows the dimensions of the forced oscillator.

Following collection of incident wave information such as frequency and wave height, the oscillator controls the vertical motions of the hydrofoils separately. More specifically, the incident wave information is collected by the wave probe located just beside of the foil pitch pivot point, and is fed to the microprocessor using a 16 bit 8 CH PCI card A/D and a 16 bit 2 CH D/A converter operating at 100 Hz.

The microprocessor then calculates the continuous foil motions at each zero cross timing of the incident wave height. Simultaneously, the calculated 2 CH heave and pitch control signals are sent to the servomotor controller through the D/A converter. Through continuous repetition of this procedure, the hydrofoil motions are synchronized with the forecasted phase lag or lead of incoming wave configurations.

This hydrofoil motion control process provides another advantage to the WDPS, which is the simultaneous wave energy absorption of the normal WDPS. More specifically, the weather and lee side of the hydrofoil forced oscillator, along with the reflected and transmitted wave height are measured via wave probes. Forces acting on the foil, heave and surge, and pitching moment, are also measured. The wave energy absorption rate, damping coefficients of the hydrofoil motion, and the heaving and pitching of the vessel itself, are then used to estimate the energy absorption and expenditure.

A simple equation of model hydrofoil motion makes it easy to calculate these WDPS effects using a newly developed GUI-based Fourier’s coefficient analysis program. Zero and first order coefficient analysis are sufficient to estimate these relations. If an energy absorption condition occurs, the motion damping coefficients will be negative.

Fig. 19 Newly developed hydrofoil forced oscillator undergoing wave tank testing.

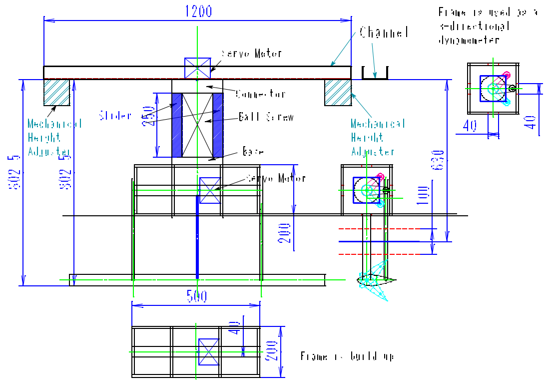

Fig. 20 Newly designed hydrofoil forced oscillator.

9. ENERGY ABSORPTION ANALYSIS

Because our system has no restoring force, we started with an analysis of one degree of freedom and heave motion of the hydrofoil. We assume one hydrofoil is oscillating with or without wave conditions. In equation (2) below, f is a periodic force acting on the hydrofoil and Z is the heave displacement, M is the total mass and C is the heave-damping coefficient.

$$f = M\ddot{Z} + C\dot{Z} \qquad (2)$$

Under the assumption of the periodic heave motion with a period T, taking one period, the mean energy absorption is estimated as follows:

$$\bar{E} \equiv \frac{1}{T}\left\{\int_0^T M\ddot{Z}\dot{Z}dt + \int_0^T C\dot{Z}\dot{Z}dt\right\} \qquad (3)$$

$$= \frac{1}{T}\int_0^T f\dot{Z}dt \qquad (4)$$

The mean energy associated with heave motion is

$$\bar{E} = \frac{C}{T}\int_0^T (\dot{Z})^2 dt \qquad (5)$$

If we use this expression of heave motion,

$$Z = Z_0 \sin\omega t \qquad (6)$$

$$\overline{\mathrm{E}} = \frac{\mathrm{C}(Z_0\,\omega)^2}{2} \qquad (7)$$

This is a very simple formula, and we can easily calculate energy relations using a Fourier coefficient analysis. We will now expand this relation to two degrees of freedom, with pitch and heave combined motion with hydrofoil energy absorption.

The vertical hydrofoil motion equations are shown below. The combined foil motion heaving force is fz, θ is the pitch displacement, I is the hydrofoil moment of inertia, J is the pitch damping coefficient, and l is the length of the forced rotating pitching lever.

$$\mathrm{fz} = \mathrm{M}\ddot{\mathrm{Z}} + C\dot{Z} + \frac{1}{l}\left(\mathrm{I}\ddot{\theta} + \mathrm{J}\dot{\theta}\right) \qquad (8)$$

$$\mathrm{M} = \mathrm{I}\ddot{\theta} + \mathrm{J}\theta^{\cdot} \qquad (9)$$

From (7), the energy contributions from the acting moment and the heave energy can be separated.

$$\overline{\mathrm{E}}_{\mathrm{M}} = \frac{\mathrm{J}(\theta_0\,\omega)^2}{2} \qquad (10)$$

$$\overline{\mathrm{E}_{\mathrm{Fz}}} = \frac{\mathrm{C}(Z_0\,\omega)^2}{2} + \frac{\overline{\mathrm{E}}_{\mathrm{M}}}{l} \qquad (11)$$

These energy terms are comparable to the experimental results obtained with and without wave conditions.

In the next stage of our research, experiments were carried out in a wave tank. The phase of the foil heave motion was fixed to coincide with the phase of the incident wave, and the phase lag of the pitch motion was variable. The experimental data for C and J is shown in Figure 21. The foil section used was NACA0015, span 1000 [mm], chord 500 [mm], made of NC cutting hard plastic. The pitch phase lag against the incident wave was taken as the horizontal axis in degree. We can see negative C and J values in the figure, which indicates direct energy absorption from the incident wave.

In Figure 22, the non-dimensionalized steady surge force, divided by the zero transmitting wave condition's drifting force, is also shown. The negative value indicates thrust. Thus, we can expect the WDPS effect to occur in the negative coefficient value area.

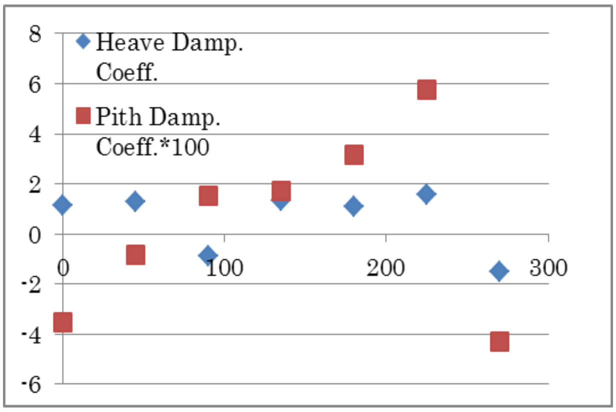

Fig. 21 Nondimensionalized heave and pitch damping coefficient of the foil combined motion. The foil section is NACA0015, depth / Chord = 0.33, λ / Chord = 2.6.

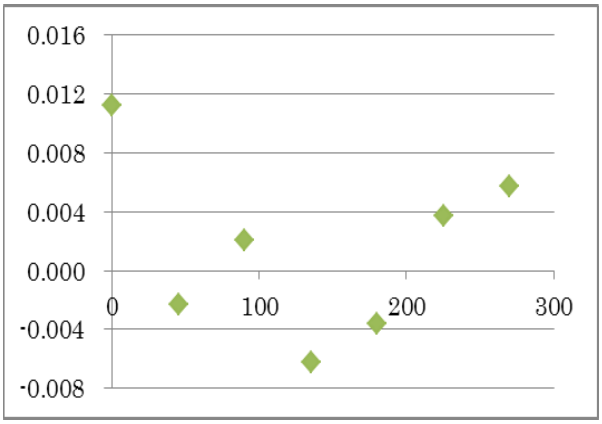

Fig. 22 Nondimensionalized steady surge force under the foil combined motion. The foil section is NACA0015, depth / Chord = 0.33, λ / Chord = 2.6.

CONCLUSIONS

From the autonomous WDPS sea trial, we were able to conclude the following:

(1) Measurement and autonomous control systems for small WDPS vessels have been developed successfully.

(2) The real-time monitoring system for small WDPS vessels worked properly.

(3) The navigation system was tested in actual sea trials and the autonomous control system, consisting of a GPS receiver and a digital magnetic compass, performed as expected.

From the tank test of the new active controlled WDPS, we could conclude the following:

(4) The model experiment probes confirmed that is it possible to decrease the wave drifting force acting on floating structures during WDPS operation.

(5) The WDPS has high damping performance.

(6) An active type WDPS can absorb wave energy.

REFERENCES

Terao, Y.(1982), A Floating Structure Which Moves towards Waves, *Journal of the Kansai Society of Naval Architects*, **184**, 51-54.

Terao, Y., Isshiki, H,(1990), Wave Devouring Propulsion Sea Trial, 1*8th Symposium on Naval Hydrodynamics*, 287-296.

Isshiki, H., Murakami, M. and Terao, Y.,(1984), Utilization of Wave Energy into Propulsion of Ship - Wave Devouring Propulsion, *15th Symposium on Naval Hydrodynamics.*

Terao, Y,(2000), Experimental Study of a Dual Fin Type Wave Devouring Propulsion System, *Fourth Osaka Colloquium on Sea Keeping Performance of Ships*, 469-478,

Terao, Y.(2009), Wave Devouring Propulsion System from Concept to Trans-Pacific Voyage, *OMAE2009,OMAE2009-79223*, 1-8.

Hicks, D., Pleass, C., and Mitcheson, G: DELBUOY, (2006), wave-powered seawater desalination system, *Proceedings of the OCEANS '88 IEEE*, **3**, 1049-1054.

Brown, P., Hardisty, D., and Molteno, T., (2006), Wave-powered small-scale generation systems for ocean exploration, *Proceedings of the OCEANS '06 Asia Pacific IEEE*, 1-6.

Ageev, M.,(2000), Solar and wave powered AUV concept, *Proceedings of Underwater Technology*, 136-139.

Hine, R., Willcox S., Hine, G. and Richardson, T.,(2009), The Wave Glider: A Wave-Powered autonomous marine vehicle, *Proceedings of the OCEANS '09 IEEE*,1-6.

Su-hua, L., De-jun, G. and Yong-ping, X.,(2009), A Moored Wave-Powered Oceanographic Profiler for Vertical Section Acquisition System, *Proceedings of Computer Science and Information Technology*, 388-391.