A STUDY OF THE PERFORMANCE OF WDP IN THE BEAM SEA AS A ROLL-DAMPING DEVICE

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Abstract

The wave Devouring Propulsion System (WDPS) is one of the devices which converts wave energy directly into thrust. The system consists of a hull and underwater foil. The damping force generated by the foil expects hull motion reduction in the head sea. Moreover, WDPS reduced resistance increases in the head sea and the foil thrust can be used in waves and overcome the resistance increase in the waves. In 2002, a new WDPS model with two foils was designed and tested in a newly designed wave tank. Model test was carried out using two types of models, mono-hull and catamaran. The characteristics of the WDPS in the beam sea were studied theoretically and roll-damping characteristics were discussed. From these experiments, the advancement speed in the beam sea condition becomes faster than in the head sea condition, nearly the roll resonance period.

1.INTRODUCTION

The basic concept of a **W**ave **D**evouring **P**ropulsion **S**ystem (**WDPS**) was proposed in Japan (Terao 1982), Actual sea trials of single fin type WDPS was carried out in 1989 (Isshiki et al. 1989). In 2000, a dual fin type WDPS was tested by Terao (Terao 2000) and it was found that this type achieved fastest speed even though the free running in the beam sea condition.
In this paper, simple theoretical analysis of the thrust and damping forces of a hydrofoil and the results of a dual fin type WDPS model test in the beam sea are shown.

WDPS is a natural wave energy utilization system and consists of the hull and the hydrofoil installed in the hull. The WDPS converts wave energy directly into thrust and has an expected motion stabilization effect. The generated thrust reaches enough magnitude to drive the hull against the waves. Measured damping performance in pitch motion is up to 50% in the head sea. (Isshiki et al. 1989).

2. THEORETICAL ANALYSIS OF WDPS IN THE BEAM SEA.

Using the linear lifting surface theory, quasi-steady analytical study of the hydrofoil in the beam sea is discussed, and because of our experimental condition, the reduced frequency is nearly 0.1.

2.1 Fixed Foil with advanced Speed

Using the following incident wave potential

$$\phi = \frac{gA}{\omega} e^{-kz} \sin(ky - \omega t) \qquad (1)$$

$$k = \frac{\omega^2}{g} \qquad (2)$$

$$\frac{\partial \phi}{\partial z} = -A\omega e^{-kz} \sin(ky - \omega t) \equiv v_w \qquad (3)$$

Therefore the wave profile is as follow.

$$\eta = A \cos(ky - \omega t)|_{y=0} \qquad (4)$$

Fig.1 shows the hydrofoil with forward speed U and flow angle is α.

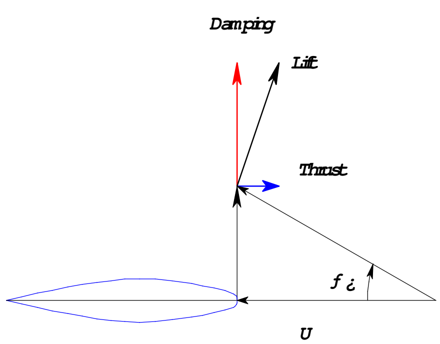


Figure 1. Schematic view of thrust generation of a foil in the flow

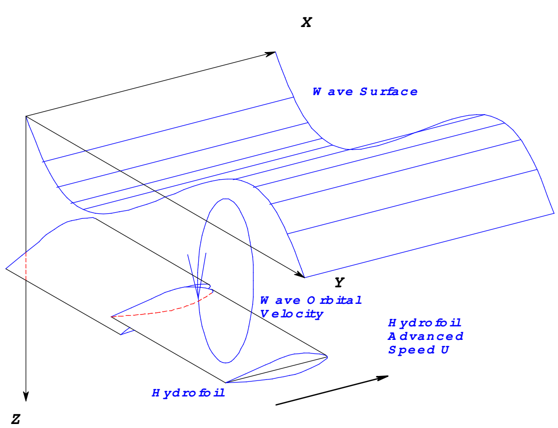


Figure 2. Foil in the beam sea condition

Thrust is generated as the horizontal component of the lift force and the larger damping force is the vertical component of the lift. Fig.2 shows the schematic view of the foil with advance speed U and located in the beam sea condition. The order of the foil span is treated as nearly the wavelength. The attack angle of the two foil is controlled separately. We will consider the thrust and damping of these foil systems.

At first, we set both foil angles to zero. L_w is the lift, which is generated in the wave orbital flow field, and α_w is the apparent attack angle of the foil. If we consider a small vertical flow velocity acting on the foil, the attack angle can be rewritten in the next form

$$L_w = \frac{1}{2}\rho S C_L(\alpha_w) U^2 \qquad (5)$$

$$\alpha_w = \frac{v_w}{U} \qquad (6)$$

Lift is expressed as

$$L_w = \frac{1}{2}\rho S \frac{\partial C_L}{\partial \alpha} v_w U \qquad (7)$$

If we do not take into count the leading edge suction force, the foil thrust T_w is as shown in the following equation,

$$T_w = L_w \sin \alpha = L_w \frac{v_w}{U}$$
$$= \frac{1}{2}\rho S \frac{\partial C_L}{\partial \alpha} v_w^2 \bullet @ \qquad (8)$$

Integrating T_w with respect to the foil surface and over wave one period, we can get the mean thrust. 2S is the foil's span; C is the chord and is assumed to be shorter than the wavelength λ. After the integration of T_w, we can obtain the following equations as after mathematical manipulation.

$$T_w = \frac{1}{T_e}\int_0^{Te}\int_{-s}^{s}\frac{1}{2}\rho C\frac{\partial C_L}{\partial\alpha}v_w{}^2 dydt$$
$$= \frac{1}{2T_e}\rho C\frac{\partial C_L}{\partial\alpha}\int_0^{Te}\int_{-s}^{s}v_w{}^2 dydt$$
$$= C_1\int_0^{Te}\int_{-s}^{s}\{1-\cos(2ky-2\omega t)\}dydt$$
$$(C_1 = \frac{1}{4T_e}\rho C\frac{\partial C_L}{\partial\alpha}A^2\omega^2 e^{-2kz})$$
$$= \frac{1}{2}\rho\frac{\partial C_L}{\partial\alpha}A^2\omega^2 e^{-2kz}Cs$$
$$= \frac{1}{2}\rho\frac{\partial C_L}{\partial\alpha}gA^2CS\bullet E_1(k) \quad (9)$$
$$E_1(k) \equiv ke^{-2kz} \quad (10)$$

$E_1(k)$ has a maximum value when k=1/2Z, that is led as

$$Tw|_{max} = Tw\bullet i\frac{1}{2z}\bullet j$$
$$= \frac{1}{4ze}\rho\frac{\partial C_L}{\partial\alpha}gA^2CS \quad (11)$$

This fact shows that the optimum foil depth exists and depends on some given k.

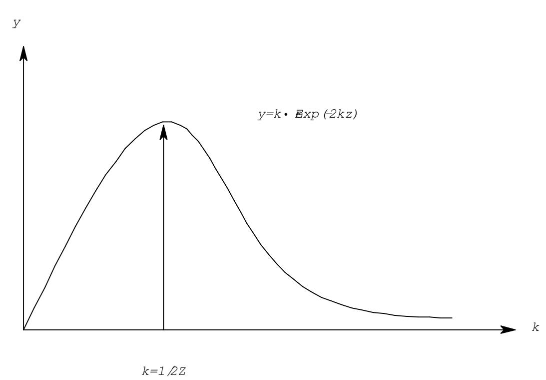


Figure 3. Frequency influence function $E_1(k)$

The maximum expected encounter wave period around the Japanese costal sea is nearly 3 seconds; thus we can estimate that the optimum foil depth is as shown in Table1 and is a realistic value.

Table 1. Optimum foil depth vs. wave period

T (sec)	•	k	z (m)	• (m)
3	2.094	0.447	1.117	14.037

Damping force action on the foil is D_w and treated as nearly equal to the L_w, therefore

$$D_W = L_W\cos\alpha$$
$$\approx L_w$$
$$= \frac{1}{2}\rho S\frac{\partial C_L}{\partial\alpha}v_w U \quad (12)$$

The amplitude of the total damping force can be written

$$Dw_{Foil} = \int_{-s}^{s}\frac{1}{2}\rho C\frac{\partial C_L}{\partial\alpha}v_w U dy$$
$$= \frac{1}{k}\rho C\frac{\partial C_L}{\partial\alpha}UA\omega e^{-kz}\sin(ks)\sin(-\omega t) \quad (13)$$
$$|Dw_{Foil}| = \frac{1}{k}\rho C\frac{\partial C_L}{\partial\alpha}UA\omega e^{-kz}\sin(ks) \quad (14)$$

If (ks) is small, then sin(ks) is rewritten as a Taylor series expansion,

$$\sin(ks) = ks - \frac{1}{3!}(ks)^3 + \frac{1}{5!}(ks)^5 - ... \quad (15)$$

Therefore if (ks) is small, the damping force is proportional to the foil area but larger (ks), so we must expect a strong non-linear effect of k. Moreover the damping force of WDPS in the beam sea is not proportional to the foil area and it is quite different from in the head sea case. A single foil does not always stabilize the roll motion.

2.2 Thrust of a pitch-fixed rolling foil

Now we consider the effect of the fixed-foil roll motion. We treated this case as a roll forced oscillation mode with forward speed U. The foil roll angle is θ and s is the distance from the centerline to a given point on the foil. Foil roll motion generates vertical apparent flow of the foil v_R, and this vertical velocity component induced an apparent attack angle α_R,

ε : Phase

$$\theta = -A\mu k\sin(ky-\omega t+\varepsilon) \quad (16)$$
$$\dot{\theta} = A\mu k\omega\cos(ky-\omega t+\varepsilon) \quad (17)$$

where

$$v_R = s\dot{\theta} \quad (18)$$

$$\alpha_R = \frac{v_R}{U} \quad (19)$$

The lift force generated by this roll motion is

$$L_R = \frac{1}{2}\rho S\frac{\partial C_L}{\partial\alpha} v_R U \quad (20)$$
$$\approx D_R$$

$$|D_R| = \rho S\frac{\partial C_L}{\partial\alpha}(A\mu\omega)U\sin(ks)\sqrt{s^2+\frac{1}{k^2}} \quad (21)$$

The thrust force generated by the roll motion T_R is

$$T_R = L\sin\alpha = L\frac{v_R}{U}$$
$$= \frac{1}{2}\rho S\frac{\partial C_L}{\partial\alpha} v_R{}^2 \quad (22)$$

The total mean thrust generated by the roll motion is written as

$$\bar{T}_R = \frac{1}{T_e}\int_0^{Te}\int_{-s}^{s}\frac{1}{2}\rho C\frac{\partial C_L}{\partial\alpha} v_R{}^2 dydt$$
$$= \frac{1}{2T_e}\rho C\frac{\partial C_L}{\partial\alpha}\int_0^{Te}\int_{-s}^{s} v_R{}^2 dydt$$
$$= C_1\int_0^{Te}\int_{-s}^{s} y^2\{1+\cos(2ky-2\omega t+2\varepsilon)\}dydt \bullet @$$
$$(C_1 = \frac{1}{4T_e}\rho C\frac{\partial C_L}{\partial\alpha}(A\mu k\omega)^2)$$
$$= \frac{1}{6}\rho\frac{\partial C_L}{\partial\alpha}(A\mu k\omega)^2 CS^3 \quad (23)$$

2.3 Thrust of a pitch-free foil in waves

We can easily expand the former equation of the foil attack angle, when the foils are freely pitching in waves, where α_{Foil} is foil attack angle,

$$\alpha_{All} = \alpha_W + \alpha_{Foil} \quad (24)$$

where

$$L = \frac{1}{2}\rho S\frac{\partial C_L}{\partial\alpha}\alpha_{All} U^2 \quad (25)$$

Thus the generated thrust T_{WF} is

$$T_{WF} = L\sin(\alpha_W)$$
$$= \frac{1}{2}\rho S\frac{\partial C_L}{\partial\alpha}(\frac{\partial\phi}{\partial z}+\alpha_{Foil}\bullet U)\bullet(\frac{\partial\phi}{\partial z}) \quad (26)$$

The mean thrust acting on the foil is written as follows:

$$\bar{T}_{WF} = \frac{1}{T_e}\int_0^{Te}\int_{-s}^{s}\frac{1}{2}\rho C\frac{\partial C_L}{\partial\alpha}(\frac{\partial\phi}{\partial z}+\alpha_{Foil}\bullet U)\bullet(\frac{\partial\phi}{\partial z})dydt$$
$$= \frac{1}{2T_e}\rho C\frac{\partial C_L}{\partial\alpha}\int_0^{Te}\int_{-s}^{s}(v_w+v_F)(v_w)dydt \quad (27)$$

$$v_w = -A\omega e^{-kz}\sin(ky-\omega t) \quad (28)$$

$$v_F = U\bullet\alpha_{Fo}\sin(ky-\omega t+\varepsilon_\alpha) \quad (29)$$

2.4 Thrust of a Dual Fin type WDP

In this section, we will consider the thrust of foils with pitching motion. To simplify the equation, we introduce new functions as follows.

$$I_{WF} = \frac{1}{T_e}\int_0^{Te}\int_{-s}^{s}(v_w+v_F)(v_w)dydt$$
$$= \frac{1}{T_e}\int_0^{Te}\int_{-s}^{s}(v_w{}^2+v_F v_w)dydt$$
$$= \frac{1}{2}\int_{-s}^{s}(-A\omega e^{-kz})^2 dy + \frac{1}{T_e}\int_0^{Te}\int_{-s}^{s}(v_F v_w)dydt$$
$$= sA^2\omega^2 e^{-2kz} + I_{FV1} \quad (30)$$

where

$$I_0 = C_1\sin(e_1-\omega t)\bullet C_2\sin(e_2-\omega t) \quad (31)$$

$$C_1 = -A\omega e^{-kz} \qquad C_2 = U\bullet\alpha_{Fo}$$
$$e_1 = ky \qquad e_2 = ky_F + \varepsilon_\alpha \quad (32)$$
$$C_{12} = C_1\bullet C_2$$

Thus, I_0 is rewritten in the form of

$$I_0 = -\frac{C_{12}}{2}\{\cos(e_1+e_2-2\omega t)-\cos(e_1-e_2)\} \quad (33)$$

The main term of the foil pitching motion and wave orbital velocity effect is

$$I_{FV1} = \int_{-s}^{s} \frac{C_{12}}{2} \cos(e_1 - e_2) dy \qquad (34)$$

e_1 and e_2 replaced by former expression, we can obtain the following expression.

$$\begin{aligned}
I_{FV1} &= \int_{-s}^{s} \frac{C_{12}}{2} \cos(ky - ky_F - \varepsilon_\alpha) dy \\
&= \frac{C_{12}}{2k} \left[\sin(ky - ky_F - \varepsilon_\alpha)\right]_{-s}^{s} \\
&= \frac{C_{12L}}{2k} \left[\sin(ky - ky_{FL} - \varepsilon_{\alpha L})\right]_{-s}^{0} \\
&\quad + \frac{C_{12R}}{2k} \left[\sin(ky - ky_{FR} - \varepsilon_{\alpha R})\right]_{0}^{s} \\
&= \frac{C_{12L}}{2k} \left[\sin(-ky_{FL} - \varepsilon_{\alpha L}) - \sin(-sk - ky_{FL} - \varepsilon_{\alpha L})\right] \\
&\quad + \frac{C_{12R}}{2k} \left[\sin(sk - ky_{FR} - \varepsilon_{\alpha R}) - \sin(-ky_{FR} - \varepsilon_{\alpha R})\right]
\end{aligned} \qquad (35)$$

We assumed both foil motion separately, but if those foil amplitudes are the same like this,

$$C_{12L} = C_{12R} \qquad (36)$$

We must consider two cases.

(1) Same phase mode
This is thought of as a single foil mode, and that it uses the former type of WDPS.

$$e_{2R} = ky_F + \varepsilon_\alpha \qquad (37)$$

$$e_{2L} = e_{2R} \qquad (38)$$

$$I_{FV1}\,|_{sym} = \frac{2C_{12}}{k} \{\cos(ky_F + \varepsilon_\alpha)\sin(ks)\} \qquad (39)$$

(2) Anti symmetric phase mode
The two-foil two-phase mode is thought of as the core mechanism of the Dual Fin Type WDPS. We experienced the fastest speed in the model test even in the beam sea. The phase is

$$e_{2R} = ky_F + \varepsilon_\alpha \qquad (40)$$

$$e_{2L} = -e_{2R} \qquad (41)$$

$$\begin{aligned}
I_{FV1}\,|_{asym} &= \frac{2C_{12}}{k} \{\sin(sk - ky_F - \varepsilon_\alpha) + \sin(ky_F + \varepsilon_\alpha)\} \\
&= \frac{2C_{12}}{k} \{\cos(ky_F + \varepsilon_\alpha)\sin(ks)\} \\
&+ \frac{2C_{12}}{k} \{\sin(ky_F + \varepsilon_\alpha)(1 - \cos(ks))\} \qquad (42) \\
&= \frac{2\sqrt{2}C_{12}}{k} \sqrt{1 - \sin sk}\, \sin(ky_F + \varepsilon_\alpha + \delta_{sk}) \qquad (43)
\end{aligned}$$

$$\cos(\delta_{sk}) = \frac{\sqrt{1 - \sin sk}}{\sqrt{2}} \quad ;$$

$$\sin(\delta_{sk}) = \frac{\sin sk}{\sqrt{2}\sqrt{1 - \sin sk}} \qquad (44)$$

From this formulation, we can expect, in some cases, $\sqrt{2}$ times greater thrust compared to the single fin type WDPS.

In this formula, we may have some question about the limit of performance of the multi-fin type WDPS. This will be something like the flexible caudate fin of fish or sea mammals.

If we can control the phase of the foil pitch motion like this

$$e_2 = e_1 + \pi \qquad (45)$$

The integration term is simplified and the theoretical maximum value of I_{WF} is rewritten in the form of

$$\frac{1}{T_e} \int_0^{Te} \int_{-s}^{s} (v_F v_w) dy dt \equiv -C_{12} s$$

$$\therefore I_{FV1} = -C_{12} s$$

$$\therefore I_{WF} == sA^2\omega^2 e^{-2kz} + sA\omega e^{-kz} U \bullet \alpha_{Fo} \qquad (46)$$

If all foil motions are considered and the wave effect is taken into consideration, the foil attack angle is derived as below

$$\alpha_{All} = \alpha_W + \alpha_R + \alpha_{Foil} + \alpha_H \qquad (47)$$

Lift and drag is rewritten as

$$L = \frac{1}{2} \rho S \frac{\partial C_L}{\partial \alpha} \alpha_{All} U^2 \qquad (48)$$

$$D \approx L \qquad (49)$$

The thrust force is

$$\begin{aligned}
T &= L \sin(\alpha_W + \alpha_R + \alpha_H) \\
&= \frac{1}{2} \rho S \frac{\partial C_L}{\partial \alpha} (s\dot{\theta} + \frac{\partial \phi}{\partial z} + \dot{z} + \alpha_{Foil} \bullet U) \\
&\bullet (s\dot{\theta} + \frac{\partial \phi}{\partial z} + \dot{z})
\end{aligned} \qquad (50)$$

The mean thrust is

$$\bar{T} = \frac{1}{T_e}\int_0^{Te}\int_{-s}^{s}\frac{1}{2}\rho C\frac{\partial C_L}{\partial \alpha}(s\dot{\theta} + \frac{\partial \phi}{\partial z} + \dot{z} + \alpha_{Foil} \bullet U)$$

$$\bullet (s\dot{\theta} + \frac{\partial \phi}{\partial z} + \dot{z})dydt$$

$$= \frac{1}{2T_e}\rho C\frac{\partial C_L}{\partial \alpha}\int_0^{Te}\int_{-s}^{s} V_{sqr}dydt \qquad (51)$$

$$V_{sqr} = (v_w + v_R + v_H + v_F)(v_w + v_R + v_H) \quad (52)$$

where

$$v_w = -A\omega e^{-kz}\sin(ky - \omega t)$$
$$v_R = (yA\mu k\omega)\cos(ky - \omega t + \varepsilon_R)$$
$$v_F = U \bullet \alpha_{Fo}\sin(ky_F - \omega t + \varepsilon_\alpha)$$
$$v_H = A\gamma\cos(-\omega t + \varepsilon_H) \qquad (53)$$

Using a new variable Ψ

$$\Psi \equiv ky - \omega t \qquad (54)$$

$$v_w = -V_w\sin(\psi)$$
$$v_R = V_R\cos(\psi + \varepsilon_R)$$
$$v_F = V_F\sin(-\omega t + \delta_\alpha)$$
$$v_H = V_H\cos(-\omega t + \varepsilon_H)$$

(55)

If we assume

$$V_F = V_H = 0 \qquad (56)$$

That means the foil and heave are fixed and V_R and Ψ are assumed to be a function of y and t, $V_R(y), \Psi(y,t)$ etc., therefore

$$v_w + v_R = V_{wR}\sin(\psi + \delta) \qquad (57)$$

where

$$V_{wR}(y) = \sqrt{(V_w + V_R\sin\varepsilon_R)^2 + (V_R\cos\varepsilon_R)^2}$$
$$= \sqrt{V_w^2 + 2V_wV_R\sin\varepsilon_R + V_R^2}$$
$$\delta(y) = \tan^{-1}(\frac{-V_w - V_R\sin\varepsilon_R}{V_R\cos\varepsilon_R}) \qquad (58)$$

$$(V_{wR}\sin(\psi + \delta))^2 \equiv P \qquad (59)$$

The integration part of the mean thrust is shown as

$$I = \frac{1}{Te}\int_0^{Te}\int_{-S}^{S} Pdtdy$$
$$= \int_{-S}^{S}\frac{1}{2}V_{wR}^{\ \ 2}dy \qquad (69)$$

Using a new variable Γ

$$\Gamma = \psi + \delta$$
$$\Gamma + \tau = \psi + \varepsilon_\alpha$$

(70)

and

$$\tau = \varepsilon_\alpha - \delta$$
$$= \varepsilon_\alpha - \tan^{-1}(\frac{-V_w - V_R\sin\varepsilon_R}{V_R\cos\varepsilon_R}) \qquad (71)$$

when

$$V_R(y) = V_R : \Psi(y,t) = \Psi(t) \qquad (72)$$

The integrated result is simplified as

$$I = V_{wR}^{\ \ 2}S$$
$$\delta = \tan^{-1}(\frac{-v_w - v_R\sin\varepsilon_R}{v_R\cos\varepsilon_R}) \qquad (73)$$
$$V_{wR}^{\ \ 2} = V_w^{\ 2} + 2V_wV_R\sin\varepsilon_R + V_R^{\ 2}$$

These equations show that if $\varepsilon_R = \frac{\pi}{2}$ and $\delta = \varepsilon_\alpha$ then we can obtain the maximum mean thrust.

3.MODEL EXPERIMENTS

A model test was carried out in our wave tank. Before this experiment, a new wave maker system and control system were introduced. A lightweight model equipped measurement system was developed based on the one chip microprocessors PIC16F87 and PIC16F873.

3.1 Model and experiment

We prepared two models, a mono-hull and catamaran model. Tab. 3 shows the principal dimensions, Fig.5, 6 show the model lines. The mono-hull model in Fig.5 is a newly designed one to study the mono-hull model performance in the beam sea. It has a round bottom with strong flare, and slender bow and stern form.

Table.3 Principal Dimensions of Models

	Mono-hull	Catamaran
Lpp	1605mm	1200mm
B	377mm	600mm
D	100mm	156mm
Foil depth	162mm	127mm
Displacement	14.3kg	15.5kg
Roll Natural Period	1.34sec	0.85sec
Pitch Natural Period	0.73sec	1.00sec
Foil Section	NACA0012	
Chord	80mm	
Span	250mm	

Fig.4 shows the tested wave period and wave height that was decided for our wave tank performance. Tab.4 shows the equipped sensors, which is the same as ref.4.

Table 4. Equipped sensors

1	Roll gyro
2	Relative wave probe
3	Roll-pitch angle sensor
4	2-directional force meter
5	Foil angle sensor

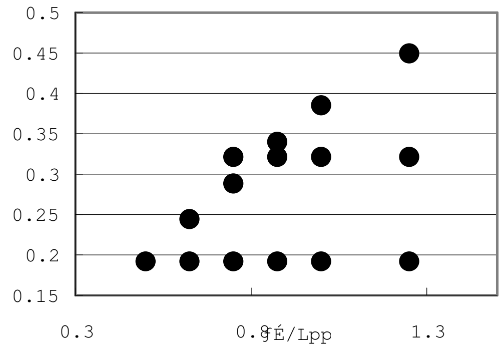


Figure 4. Used wave height and period. (d=0.12m)

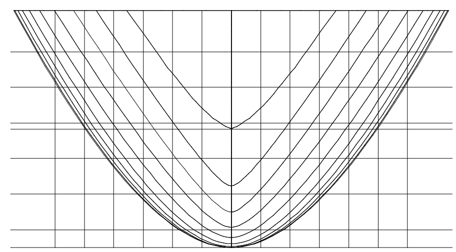


Figure 5. Mono-hull body plan

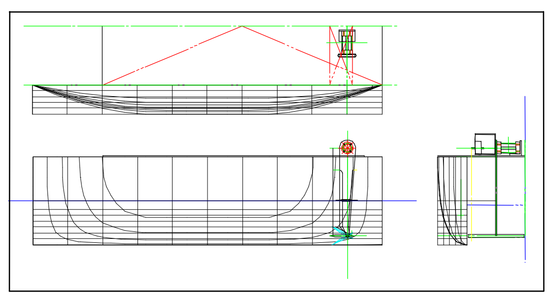


Figure 6. Catamaran model lines

To measure the WDPS planar motion and advance speed, a lattice is set over the wave tank surface and the warp is set parallel to the wave direction that is shown in Fig.7. The model is set completely free, and the steering devices to maintain the course are not installed. With arriving incident waves, the model at rest starts drifting and reaches a constant advancing speed, which is measured by the crossing times of the lattice sections. Without WDPS, hulls only drift with the incident waves.

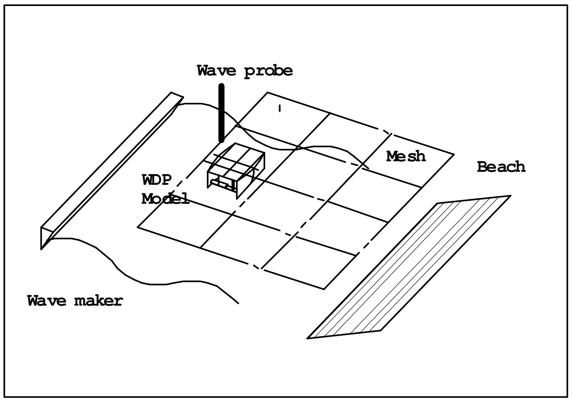


Figure 7. Schematic view of model testing

3.2 Test results

Time histories of the experimental results, incident wave height and roll angle, are shown from Fig.8 to Fig.19. Fig.8 to 10 are a mono-hull with dual foil. Fig.11 to 13 are a mono-hull without foil. Fig.14 to 16 are a catamaran with a dual foil, Fig17 to 19 are a catamaran without a foil. The incident wave height is measured with a fixed probe, and the roll angle is measured with a hull equipped roll sensor.

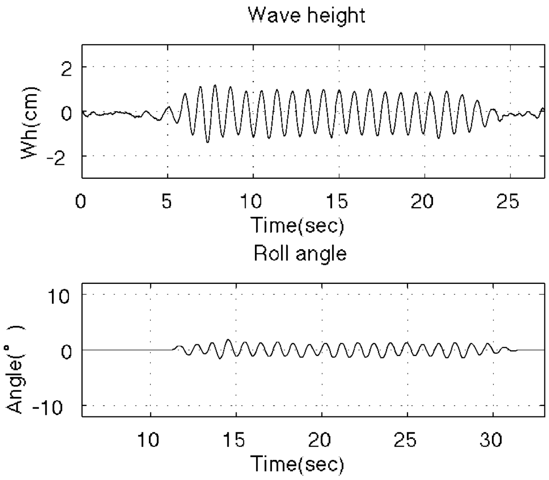


Figure 8. Mono-hull with foil Tw=0.88(sec)

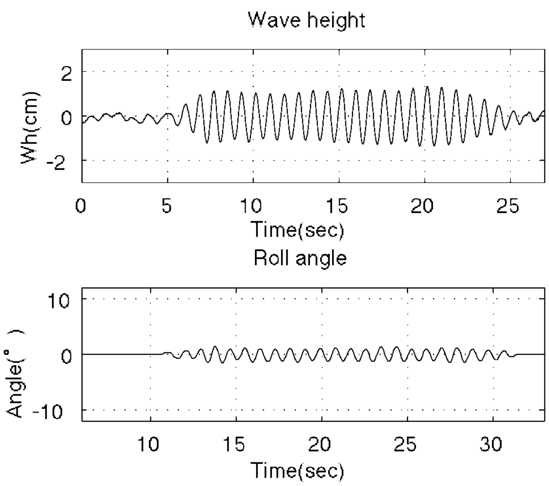


Figure 9. Mono-hull with foil Tw=0.82(sec)

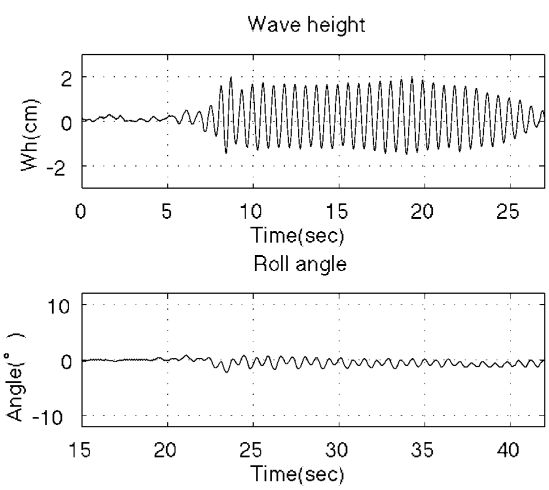


Figure 10. Mono-hull with foil Tw=0.62(sec)

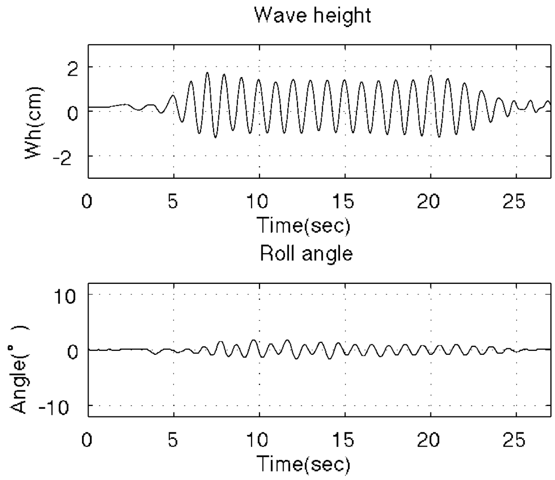


Figure 11. Mono-hull without foil Tw=0.88(sec)

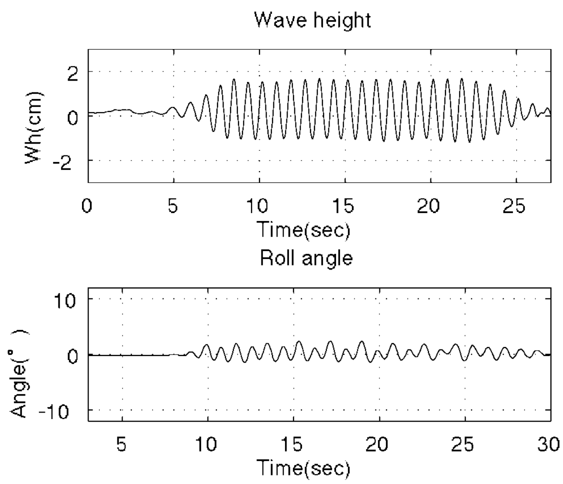


Figure 12. Mono-hull without foil Tw=0.82(sec)

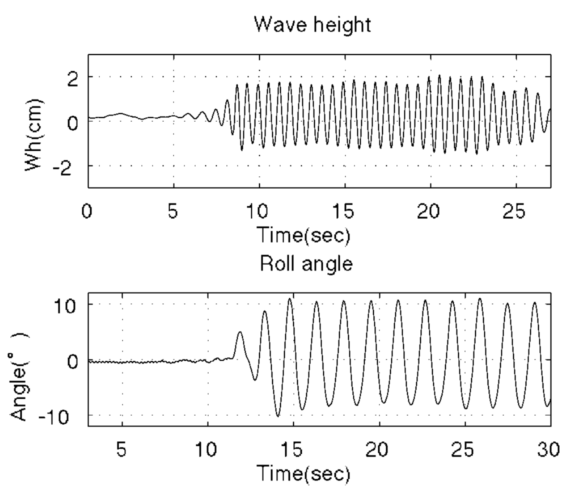


Figure 13. Mono-hull without foil Tw=0.62(sec)

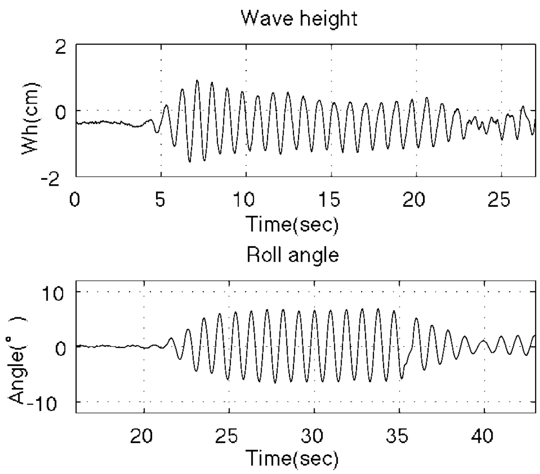


Figure 14. Catamaran with foil Tw=0.88(sec)

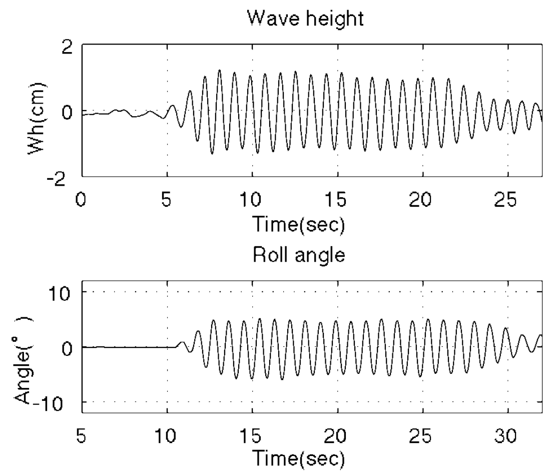


Figure 17. Catamaran without foil Tw=0.88(sec)

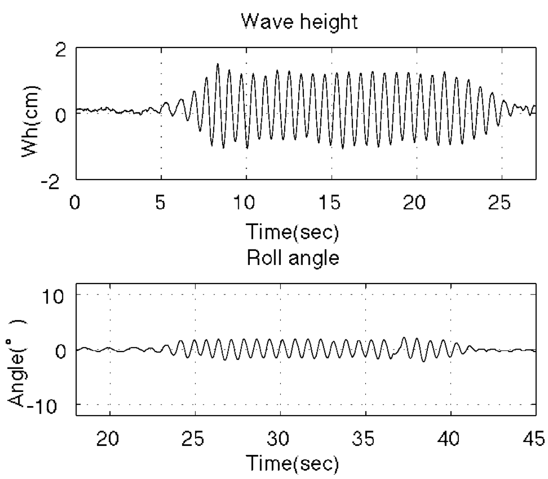


Figure 15. Catamaran with foil Tw=0.69(sec)

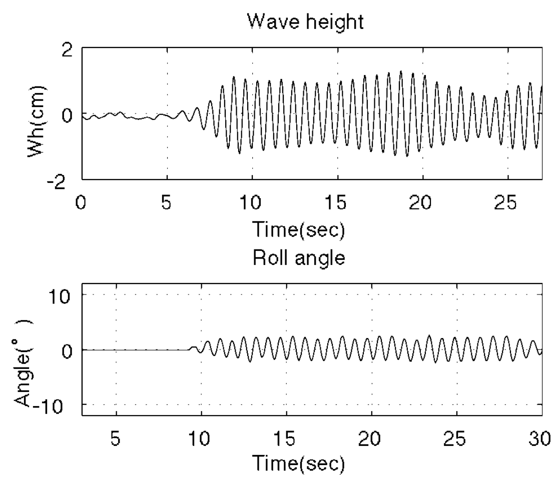


Figure 18. Catamaran without foil Tw=0.69(sec)

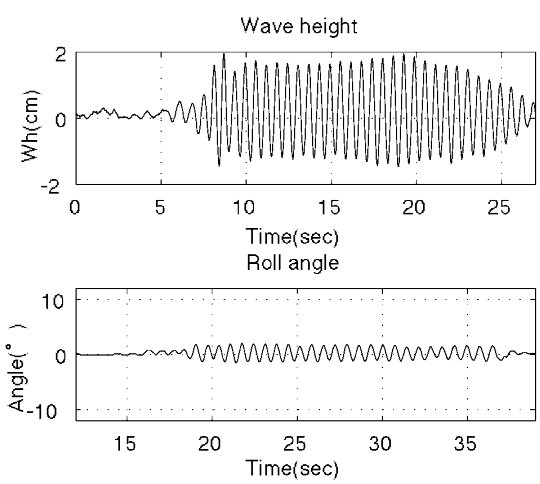


Figure 16. Catamaran with foil Tw=0.62(sec)

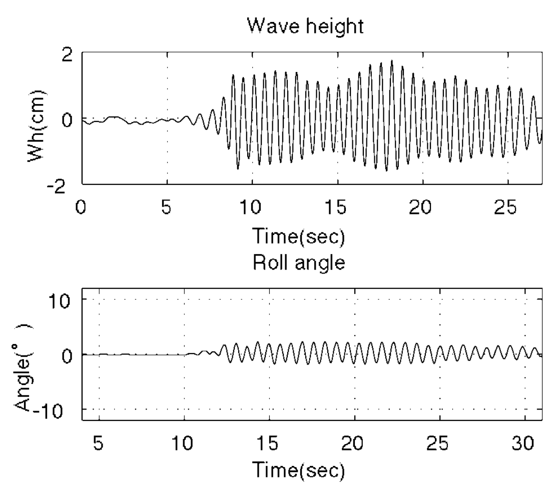
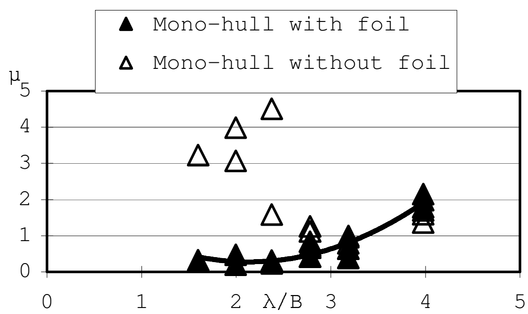


Figure 19. Catamaran without foil Tw=0.62(sec)

From these results, we could not succeed in controlling wave height constant even in the experimental wave frequency range; therefore our experimental results may include some errors. But in the mono-hull case, self-exciting roll motion is obviously observed as shown in Fig.13. But the dual fin type WDPS reduced the hull roll angle up to 20%, and moreover generated thrust that makes forward speed. In another words, WDPS effectively reduced the roll motion even in this critical situation. This self-exciting roll motion is not the expected phenomena. As it is well known about e normal hull rolling motion in the beam sea, self-exciting roll motion is quite rare. Therefore we should use a normal hull form, however we wanted to know new hull form performance, so



we continued to use this hull form experiments.

Figure 20. Results of the roll magnification factor for mono-hull model with and without foil

Fig.20 and 21 shows the results of the magnification factor of the roll angle by the wave slope based on the wavelength by the hull breadth.

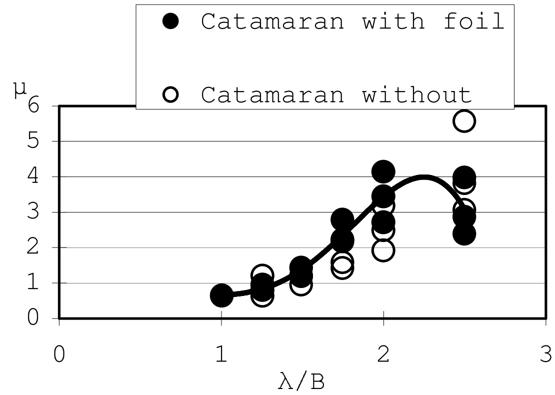


Figure 21. Roll angle magnification factor of a catamaran hull in the beam sea with and without foil

Fig.20 is a mono-hull model and Fig.21 is a catamaran model. The mono-hull with foil results show that the roll motion stabilized effectively, but for the catamaran hull even with foils, we cannot distinguish the stabilization effect. It is assumed that the reason is the higher damping effect for the demi-hull in the case of roll motion, and the phase difference of the hull and foils that are still waiting further research.

Fig. 22 is a mono-hull, Fig.23 is a catamaran hull where the free running advance speed based on wavelength divided by 2S. S is the foil span. Comparing the two figures, the catamaran advance speed exceeds the mono-hull case. If we increase the wave height, the advance speed of the WDPS increased. We measured the theoretical wave breaking height because the breaking wave causes a complex hydrodynamic effect.

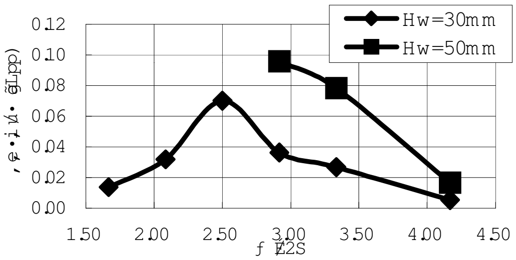


Figure 22. Catamaran hull free running advanced speed in the beam sea with foil

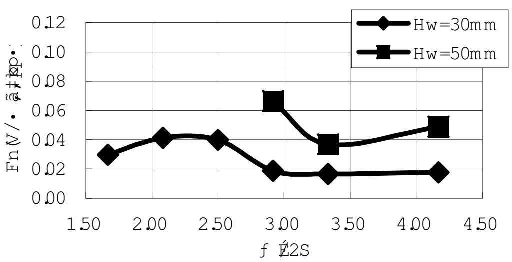


Figure 23. Mono-hull free running advance speed in the beam sea with foil

But at the present time, we cannot conclude that the catamaran hull is superior for WDPS, because we have no information about hull resistance performance.

We must note that the advance speed is only achieved without any energy supply except wave energy, and the first speed is achieved with a simple passive control system. From the observation of the free drifting model test, with a longer free water length, we may achieve a faster record.

4.CONCLUSIONS

Simple theoretical analysis shows the Dual Fin type WDPS roll damping effect and mean thrust performance. We found that an optimum depth for a fixed foils exist at a given wave period and given damping characteristics.

Two-types of hull form models were tested with the dual fin passive type WDPS in the beam sea condition. The mono-hull with a dual fin model exceeded in the roll motion suppressing effect and the catamaran hull type was inferior. However, results for the advance speed were the opposite.

We could not conclude which hull type is superior for the WDPS, because the WDPS has two characteristics. One is that for a motion stabilizer and another is that for a thruster.

5. REFERENCES

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