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 Wave Devouring Propulsion System (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
\[
\phi = \frac{gA}{\omega} e^{-kz} \sin( ky - \omega t) \tag{1}
\]
\[
k = \frac{\omega^2}{g} \tag{2}
\]
\[
\frac{\partial \phi}{\partial z} = -A \omega e^{-kz} \sin( ky - \omega t) = v_w \tag{3}
\]

Therefore the wave profile is as follow.
\[
\eta = A \cos( ky - \omega t) \bigg|_{y = 0} \tag{4}
\]

Fig.1 shows the hydrofoil with forward speed U and flow angle is \( \alpha \).

At first, we set both foil angles to zero. \( L_w \) is the lift, which is generated in the wave orbital flow field, and \( \alpha_w \) 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
\[
L_w = \frac{1}{2} \rho S C_L (\alpha_w) U^2 \tag{5}
\]
\[
\alpha_w = \frac{v_w}{U} \tag{6}
\]

Lift is expressed as
\[
L_w = \frac{1}{2} \rho S \frac{\partial C_L}{\partial \alpha} v_w U \tag{7}
\]

If we do not take into count the leading edge suction force, the foil thrust \( T_w \) is as shown in the following equation,
\[
T_w = L_w \sin \alpha = L_w \frac{v_w}{U} = \frac{1}{2} \rho S \frac{\partial C_L}{\partial \alpha} v_w \tag{8}
\]

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 \( \lambda \). After the integration of \( T_w \), we can obtain the following equations as after mathematical manipulation.
The maximum expected encounter wave period around the Japanese coastal sea is nearly 3 seconds; thus we can estimate that the optimum foil depth is as shown in Table 1 and is a realistic value.

<table>
<thead>
<tr>
<th>T (sec)</th>
<th>k</th>
<th>z (m)</th>
<th>(m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>2.094</td>
<td>0.447</td>
<td>1.117</td>
</tr>
</tbody>
</table>

Table 1. Optimum foil depth vs. wave period
\[ v_R = s \dot{\alpha} \]  
\[ \alpha_R = \frac{v_R}{U} \]  
\[ T_L = \frac{1}{2} \rho S \frac{dC_L}{d\alpha} v_R U \]  
\[ T_W = L \sin(\alpha_w) \]  
\[ = \frac{1}{2} \rho S \frac{dC_L}{d\alpha} \left( \frac{\partial \phi}{\partial z} + \alpha_{\text{Foil}} \right) U \left( \frac{\partial \phi}{\partial z} \right) \]

The lift force generated by this roll motion is

\[ L_R = \frac{1}{2} \rho S \frac{dC_L}{d\alpha} v_R U \]

\[ D_R = \rho S \frac{dC_L}{d\alpha} (A \mu \omega) U \sin(\text{ks}) \sqrt{s^2 + 1} \]

The thrust force generated by the roll motion \( T_R \) is

\[ T_R = L \sin \alpha = \frac{v_R}{U} \]

\[ = \frac{1}{2} \rho S \frac{dC_L}{d\alpha} v_R^2 \]

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

\[ T_R = \frac{1}{2} \rho S \frac{dC_L}{d\alpha} \int_0^1 (v_R \sin(\text{ks}) \sqrt{s^2 + 1}) \text{d}y \text{d}t \]

\[ = \frac{1}{2} \rho S \frac{dC_L}{d\alpha} \int_0^1 v_R \text{d}y \text{d}t \]

\[ = \frac{1}{2} \rho S \frac{dC_L}{d\alpha} \left[ (A \mu \omega)^2 \right] \]

\[ = \frac{1}{6} \rho S (A \mu \omega)^2 \text{Cs}^3 \]

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 \( \alpha_{\text{Foil}} \) is foil attack angle.

\[ \alpha_{\text{All}} = \alpha_w + \alpha_{\text{Foil}} \]

where

\[ L = \frac{1}{2} \rho S \frac{dC_L}{d\alpha} \alpha_{\text{All}} U^2 \]

Thus the generated thrust \( T_{WF} \) is

\[ T_{WF} = \frac{1}{2} \rho S \frac{dC_L}{d\alpha} \left( \frac{\partial \phi}{\partial z} + \alpha_{\text{Foil}} \right) U \left( \frac{\partial \phi}{\partial z} \right) \]

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.

\[ I_{WF} = \frac{1}{2} \rho S \frac{dC_L}{d\alpha} \int_0^1 (v_w + v_F)(v_w) \text{d}y \text{d}t \]

\[ = \frac{1}{2} \rho S \frac{dC_L}{d\alpha} \int_0^1 (v_w^2 + v_F v_w) \text{d}y \text{d}t \]

\[ = \frac{1}{2} \rho S \frac{dC_L}{d\alpha} \left( \int_0^1 (-A \omega e^{-2\text{ks}}) \text{d}y + \int_0^1 (v_F v_w) \text{d}y \right) \]

\[ = s A^2 \omega^2 e^{-2\text{ks}} + I_{FV1} \]

where

\[ I_0 = C_1 \sin(e_1 - \omega t) \cdot C_2 \sin(e_2 - \omega t) \]

\[ C_1 = -A \omega e^{-2\text{ks}} \]

\[ C_2 = U \cdot \alpha_{\text{Foil}} \]

\[ e_1 = ky \]

\[ e_2 = ky_F + \varepsilon_a \]

\[ C_{12} = C_1 \cdot C_2 \]

Thus, \( I_0 \) is rewritten in the form of

\[ I_0 = -\frac{C_{12}}{2} \{ \cos(e_1 + e_2 - 2\omega t) - \cos(e_1 - e_2) \} \]

The main term of the foil pitching motion and wave orbital velocity effect is
\[ I_{FV1} = \frac{1}{2} \frac{C_{12}}{k} \cos(e_1 - e_2) dy \]  
\[ e_1 \text{ and } e_2 \text{ replaced by former expression, we can}
\text{obtain the following expression.} \]
\[ I_{FV1} = \int C_{12} \cos(k(y - ky_f - e_a)) dy \]
\[ = \frac{C_{12}}{2k} \left[ \sin(ky - ky_f - e_a) \right]_s \]
\[ = \frac{C_{12}}{2k} \left[ \sin(ky - ky_f - e_a) \right]_v \]
\[ = \frac{C_{12}}{2k} \left[ \sin(ky - ky_f - e_a) \right]_e \]
\[ = \frac{C_{12}}{2k} \left[ \sin(-ky_f - e_a) - \sin(-sk - ky_f - e_a) \right] \]
\[ + \frac{C_{12}}{2k} \left[ \sin(sk - ky_f - e_a) - \sin(-ky_f - e_a) \right] \]
\[ = \frac{C_{12}}{k} \left[ \sin(ky_f + e_a) \sin(ks) \right] (35) \]

We assumed both foil motion separately, but if those foil amplitudes are the same like this, \( C_{12L} = C_{12R} \)  
\[ \text{(36)} \]

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.
\[ e_{2R} = ky_f + e_a \]  
\[ e_{2L} = e_{2R} \]
\[ I_{FV1, sym} = \frac{2C_{12}}{k} \left[ \cos(ky_f + e_a) \sin(ks) \right] \]
\[ \text{(39)} \]

(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
\[ e_{2R} = ky_f + e_a \]  
\[ e_{2L} = -e_{2R} \]
\[ I_{FV1, asym} = \frac{2C_{12}}{k} \left[ \sin(sk - ky_f - e_a) + \sin(ky_f + e_a) \right] \]
\[ = \frac{2C_{12}}{k} \left[ \cos(ky_f + e_a) \sin(ks) \right] \]
\[ + \frac{2C_{12}}{k} \left[ \sin(ky_f + e_a)(1 - \cos(ks)) \right] \]
\[ \text{(42)} \]

\[ \cos(\delta_{sk}) = \frac{\sin sk}{\sqrt{1 - \sin^2 sk}} \]
\[ \sin(\delta_{sk}) = \frac{\sin sk}{\sqrt{2 \sqrt{1 - \sin^2 sk}}} \]  
\[ \text{(44)} \]

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
\[ e_2 = e_1 + \pi \]  
\[ \text{(45)} \]

The integration term is simplified and the theoretical maximum value of \( I_{WF} \) is rewritten in the form of
\[ \frac{1}{T_e} \int_0^{T_e} (v_f v_w) dy dt \equiv -C_{12s} \]
\[ \therefore I_{FV1} = -C_{12s} \]
\[ \therefore I_{WF} = sa^2 \omega e^{-2zk} + sa\omega e^{-zk} \alpha_{F0} \]  
\[ \text{(46)} \]

If all foil motions are considered and the wave effect is taken into consideration, the foil attack angle is derived as below
\[ \alpha_{All} = \alpha_{W} + \alpha_{R} + \alpha_{Foil} + \alpha_{H} \]  
\[ \text{(47)} \]

Lift and drag is rewritten as
\[ L = \frac{1}{2} \rho S \frac{\partial C_L}{\partial \alpha} \alpha_{All} U^2 \]  
\[ D = L \]  
\[ \text{(48)} \]

The thrust force is
\[ T = L \sin(\alpha_{W} + \alpha_{R} + \alpha_{H}) \]
\[ = \frac{1}{2} \rho S \frac{\partial C_L}{\partial \alpha} (s \phi + \phi_z + \alpha_{Foil} \cdot \alpha) \]
\[ \cdot (s \phi + \frac{\partial \phi}{\partial z} + \phi_z) \]
\[ \text{(50)} \]

The mean thrust is
The integration part of the mean thrust is shown as
\[ I = \frac{1}{Te} \int Pdtdy \]
\[ = \frac{S}{2} V_{wr}^2 \int dy \]  
(69)

Using a new variable \( \Gamma \)
\[ \Gamma = \psi + \delta \]
\[ \Gamma + \tau = \psi + \epsilon_a \]  
(70)

and
\[ \tau = \epsilon_a - \delta \]
\[ = \epsilon_a - \tan^{-1}\left(\frac{-V_w - V_R \sin \epsilon_R}{V_R \cos \epsilon_R}\right) \]  
(71)

when
\[ V_R(y) = V_R : \Psi(y, t) = \Psi(t) \]  
(72)

The integrated result is simplified as
\[ I = V_{wr}^2 S \]
\[ \delta = \tan^{-1}\left(\frac{-V_w - V_R \sin \epsilon_R}{V_R \cos \epsilon_R}\right) \]  
(73)

\[ V_{wr}^2 = V_w^2 + 2V_w V_R \sin \epsilon_R + V_R^2 \]

These equations show that if \( \epsilon_R = \frac{\pi}{2} \) and
\[ \delta = \epsilon_a \]  
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

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

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

<p>| | |</p>
<table>
<thead>
<tr>
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<tbody>
<tr>
<td>1</td>
<td>Roll gyro</td>
</tr>
<tr>
<td>2</td>
<td>Relative wave probe</td>
</tr>
<tr>
<td>3</td>
<td>Roll-pitch angle sensor</td>
</tr>
<tr>
<td>4</td>
<td>2-directional force meter</td>
</tr>
<tr>
<td>5</td>
<td>Foil angle sensor</td>
</tr>
</tbody>
</table>

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.

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, Fig.17 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 7. Schematic view of model testing
Figure 8. Mono-hull with foil  $T_w=0.88$ (sec)

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

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

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

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

Figure 13. Mono-hull without foil  $T_w=0.62$ (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.

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.
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 for a motion stabilizer and another is for a thruster.

5. REFERENCES

