A Theory of Wave Devouring Propulsion

(1st Report)

—Thrust Generation by a Linear Wells Turbine—

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Summary

In the present paper, two aspects of wave energy utilization for ship propulsion or so-called "Wave Devouring Propulsion"*** are clarified.

(1) From a general viewpoint of conversion of the wave energy into the thrust, the possibility of the wave devouring propulsion is proved by considering the property of the ideal thrust generated by incoming waves and that of the drag required to propel a ship.

(2) As a realization of the wave devouring propulsion, the thrust generation by an oscillating hydrofoil advancing in waves is discussed. This problem has already been discussed by Wu^{15),16)}, but the free surface effect is not included in his theory. When the conversion of the wave power into the propulsive power is aimed at through interaction between a wave and a converter, for example, a hydrofoil, it seems to the author that the free surface effect should not be neglected, since the thrust increase due to the wave power absorption and the wave resistance increase are both proportional to the square of the wave amplitude. In the present paper, Wu's theory is improved by including the free surface effect approximately, and some numerical results are given for a non-oscillating hydrofoil advancing in waves or "A Linear Wells Turbine".

1. Introduction

The conversion of wave power into propulsive power may be one of the most interesting problems for naval architects. Although the increase of ship speed in following seas is well-known, the ship speed, in general, decreases in head seas. This phenomenon is explained as "Resistance Increase", and is too well-known to naval architects. Hence, the possibility of thrust increase in head seas has long been ignored by naval architects.

According to the author's survey, some inventions, observations and investigations related to the wave devouring propulsion have been reported as described in the following.

Descriptions about the first attempt by Herman F. L. Linden on boats propelled by wave motion at the end of the last century are found in refs. 11) and 17). He used flexible fins as shown in Fig. 1, and 13 and 24 ft boats named Autonaut are reported to reach a speed of 3

Fig. 1a Drawing from Linden's British patent specification, 1895. (From ref. 17))

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** According to Prof. M. Bessho of National Defense Academy of Japan, this terminology was proposed by Prof. T. Y. Wu of California Institute of Technology, when they discussed privately on the subject on the occasion of the 13th ONR Symposium held in Tokyo in 1980.

Fig. 1b A drawing of the Autonaut showing the arrangement of fins and steering flag. (From ref. 17))

and 4 knots respectively against wind and sea. But this invention seems to have not been paid much attention by naval architects.

In ref. 7), Longuet-Higgins gives an example of a submerged body like a sand-bar which moves against short and steep waves at a mean speed of 1.2 cm/s when wave breaking takes place behind the body. According to his description, this phenomenon is qualitatively similar to "the well-known behavior of offshore sand-bars", and a theory is proposed on the basis of the energy and momentum balance when wave breaking takes place.

In refs. 15) and 16), Wu describes that sea gulls and pelicans are seen to skim ocean waves over a long distance without making noticeable flapping of their wings as in ordinary flight. He also refers to a study on migrating salmon by M. F. M. Osborne. And Wu explores theoretically the possibility to improve propulsive efficiency of a body moving through waves by using oscillating foil propulsors. The theory is based on previous researches by Lighthill⁶⁾ and Wu^{13),14)}.

Huse reports in his paper⁴⁾ that, for certain platforms and sea states, model tests have shown the towing resistance in head seas to be smaller than in calm water, and he explains the phenomenon by introducing a viscous drag force.

Recently, Terao¹²⁾ succeeded to make a model or "Terao Model" which moved at a fairly high speed against waves without any power supply. His model is made of a plate, called "deck", floating on water surface and two hydrofoils placed under the deck. The details of his model and the experimental results are reported in his paper. The Mechanism of the thrust generation of Terao model has not yet been fully clarified. Its theoretical explanation is one of the motives of the author's present study, though he has not yet succeeded in it.

Terao has also succeeded to make a model similar to the above mentioned model by Herman F. L. Linden.

The author has long been interested in the oscillating foil propulsion of a ship³⁾, since he

was ordered to investigate the subject by his superiors of his company about 5 years ago. In the present paper, the author proposes the possibility of the wave devouring propulsion through a general viewpoint of energy conversion. And as a realization of the wave devouring propulsion, the thrust generation by an oscillating hydrofoils in waves is discussed on the basis of Wu's theory^{15),16)}. Wu's theory is developed by introducing the free surface effect on the basis of Maruo's theory⁹⁾ for resistance increase of a ship in waves. Some numerical results are given for the thrust generation by a linear Wells turbine, or a non-oscillating plate foil, advancing in waves.

2. A discussion of the wave devouring propulsion from a general viewpoint of the wave energy conversion⁵⁾

In this section, the possibility of the wave devouring propulsion is proved through a discussion which is based on a general viewpoint of the wave energy conversion and does not specify the type of the energy converter.

For the sake of simplicity, a two-dimensional problem is discussed instead of the actual three dimensional one, and the resistance increase or the wave drifting force is estimated by assuming the advance velocity to be equal to zero.

Furthermore, if the complete absorption of the incoming wave with the amplitude a is assumed, the wave drifting force ΔR is given as^{1),8)}

$$\Delta R = \frac{\rho g}{4} |a|^2 B, \quad (1)$$

where ρ , g and B are the density of water, acceleration of gravity and breadth of the two-dimensional body or ship respectively. On the other hand, the wave power $\bar{P}_w^+$ absorbed in this case is given as

$$\bar{P}_w^+ = \Delta R c, \quad (2)$$

where c is the phase velocity of the wave. Hence, the thrust $\bar{T}_E$ obtained by converting the absorbed wave power into the thrust may be written as

$$\bar{T}_E = \eta_E \frac{\bar{P}_w^+}{U} = \eta_E \Delta R \frac{c}{U}, \quad (3)$$

where η_E and U are the efficiency of conversion and the advance velocity of the ship respectively. Therefore, the actual thrust $\bar{T}_a$ is obtained by subtracting ΔR from $\bar{T}_E$, that is,

$$\bar{T}_a = \bar{T}_E - \Delta R = \Delta R \left(\eta_E \frac{c}{U} - 1 \right). \quad (4)$$

It must be noticed that $\bar{T}_a$ is proportional to $1/U$.

From eq. (4), a critical speed U_{cr} may be

defined by a condition $T_a=0$ as

$$U_{cr} = \eta_E c = \eta_E \sqrt{\frac{\lambda g}{2\pi}}, \quad (5)$$

where λ is the wave length. According to eq. (5), U_{cr} is proportional to $\sqrt{\lambda}$ and takes pretty large value when λ is large. For example, it becomes as large as about 25 kt when λ is equal to 100 m. This property of U_{cr} may be important, since $\bar{T}_a$ becomes positive for $U < U_{cr}$.

The resistance R of the ship may be written as

$$R = \frac{\rho}{2} U^2 B d C_D, \quad (6)$$

where d and C_D are the draft and the drag coefficient of the ship. Hence, the velocity U_s of the self-propulsion speed U_s is the solution of the equation:

$$\bar{T}_a = R \quad (7)$$

or

$$\Delta R \left(\eta_E \frac{c}{U_s} - 1 \right) = \frac{\rho}{2} U_s^2 B d C_D. \quad (8)$$

Since $\bar{T}_a$ is proportional to $1/U$ and R to U^2 , the solution U_s of eq. (7) or eq. (8) dose always exist as shown in Fig. 2.

Fig. 2 Self-propulsion velocity U_s and critical velocity U_{cr} .

In conclusion, the absorbed wave power must be converted into the thrust by some device such as screw propeller, linear propeller^{(6), (13)~(16)}, wave radiation propeller^{(1), (7)}, etc. And when the thrust, which has, in principle, the property of being inversely proportional to the advance speed, is larger than the wave resistance increase, the positive thrust is obtained from the wave. Furthermore, it may be said that there can exist a velocity at which the ship moves against waves without any power supply.

3. Thrust generation by an oscillating hydrofoil in waves

In this section, the thrust generation by an oscillating two-dimensional hydrofoil in waves

is discussed on the basis of Wu's theory^{(13)~(16)}, and the two-dimensional version of Maruo's theory for the wave drifting force^{(8), (9)} is introduced to include the free surface effect approximately.

3.1 Wu's theory for an oscillating two-dimensional hydrofoil in waves

A two-dimensional hydrofoil of chord $2l$ and submerged at a mean depth h_1 moves horizontally with velocity U in a sinusoidal gravity wave of amplitude a and wave length λ . In terms of the body coordinate system (x, z) as shown in Fig. 3, the wave profile ζ_0 , the velocity potential $\phi_0 + \phi_1(x, z, t)$ and the pressure $p_0(x, z, t)$ of the undisturbed wave may be written as

$$\zeta_0 = a \exp[i(\omega_0 t \langle \mp \rangle kx)] \quad (9a)$$

$$\phi_0 = \frac{iga}{\sqrt{gk}} \exp[i(\omega_0 t \langle \mp \rangle kx) + kz] \quad (9b)$$

$$p_0 = \rho ga \exp[i(\omega_0 t \langle \mp \rangle kx) + kz] - \rho gz \quad (9c)$$

where $i = \sqrt{-1}$

$$k = \text{wave number} = 2\pi/\lambda \quad (10a)$$

$$\omega_0 = \text{encounter frequency} = \sqrt{gk} \langle \pm \rangle kU \quad (10b)$$

and the upper and lower signs in $\langle \rangle$ correspond to the heading and following seas respectively. The wave amplitude a is assumed small such that $ka \ll 1$. The z -component of the wave velocity at $z = -h_1$ (which coincides with the mean position of the hydrofoil) is given as

$$\begin{aligned} v_0(x, -h_1, t) &\equiv V_0(x, t) = \frac{\partial \phi_0}{\partial z} \\ &= iA_0 \exp[i(\omega_0 t \langle \mp \rangle kx)] \end{aligned} \quad (11)$$

where

$$A_0 = \sqrt{gk} a \exp(-kh_1). \quad (12)$$

As a simplifying assumption, the ratio $\epsilon = A_0/U$ of the orbital wave velocity to the mean free stream velocity is taken to be small so that the x -component orbital velocity $u_0 = \partial \phi_0 / \partial x$ may be neglected in comparison with U in formulating the present linear theory.

Fig. 3 Body coordinate system for a two-dimensional hydrofoil oscillating in a regular wave.

Although a ship model with a hydrofoil attached to the model with flexible rods can start moving against oncoming waves according to experiments of Prof. Y. Terao of Tokai University, this phenomenon may not be explained by the present linearized theory.

In the following, Wu's theory is summarized and supplemented a little. In Wu's theory, the foil-thickness effect is neglected, since the effect is secondary from the viewpoint of potential theory. But, in practical applications, enough attentions to the effect, especially to the shape of the leading edge, should be paid to avoid the flow separation.

The unsteady motion of the hydrofoil assumes the form

$$z = h(x, t) = \hat{h}(x) \exp(i\omega t) \quad (-l < x < l), \quad (13)$$

where the circular frequency ω is arbitrary. With the resultant flow velocity denoted by $(U + u_0 + u_1, v_0 + v_1)$, the linearized kinematical boundary condition on the foil may be written as

$$v_1(x, \pm 0, t) \equiv V_1(x, t) = V(x, t) - V_0(x, t) \quad (|x| < l) \quad (14a)$$

$$V(x, t) = Dh(x, t) \quad (14b)$$

$$D \equiv \partial/\partial t + U \partial/\partial x, \quad (14c)$$

where $V_0(x, t)$ is given by eq. (11). When the pressure p is taken to be the sum of the undisturbed pressure p_0 given by eq. (9c) and its perturbation p_1^* , the perturbation pressure p_1 satisfies the equations of motion

$$Du_1 = -\frac{1}{\rho} \frac{\partial p_1}{\partial x}, \quad Dv_1 = -\frac{1}{\rho} \frac{\partial p_1}{\partial z}. \quad (15)$$

Eliminating u_1 and v_1 from eq. (15) by using the equation of continuity, the governing equation for p_1 is given as

$$\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial z^2} \right) p_1 = 0 \quad \text{in fluid.} \quad (16)$$

The pressure component p_0 gives no hydrodynamic force or moment on the hydrofoil, since it is continuous across the foil of the zero thickness.

The problem to obtain p_1 is specified by the boundary conditions

$$-\frac{1}{\rho} \frac{\partial p_1}{\partial z} = DV_1(x, t) \quad (|x| < l, z = \pm 0) \quad (17a)$$

$$p_1 = 0 \quad (|x| > l, z = \pm 0) \quad (17b)$$

$$p_1 = 0 \quad (x = l, z = \pm 0) \dots \text{Kutta condition} \quad (17c)$$

$$p_1 \rightarrow 0 \quad \text{as } |x^2 + z^2| \rightarrow \infty \quad (17d)$$

and the free surface condition

$$\left(D^2 + g \frac{\partial}{\partial z} + \nu D \right) p_1 = 0, \quad (18)$$

where $\nu (= +0)$ is Rayleigh's fictitious viscosity.

For the first order approximation, the free surface condition (18) may be neglected, and the solution which satisfies the above mentioned boundary conditions (17) is known (see eqs. (35), (37), (38), (61) and (62) in ref. 13)). In particular, the value of $p_1(x, \pm 0, t)$ at the foil is given by

$$-\frac{1}{\rho} p_1(x, \pm 0, t) = \pm \frac{U}{2} a_0 \left(\frac{l-x}{l+x} \right)^{1/2} \pm \frac{1}{\pi} \oint_{-l}^l \left(\frac{l^2 - x^2}{l^2 - \xi^2} \right)^{1/2} \frac{\psi_1(\xi, t)}{\xi - x} d\xi, \quad (19)$$

where

$$\psi_1(x, t) = -D \int_{-l}^x V_1(\xi, t) d\xi \quad (20a)$$

$$a_0 = [b_1 - (b_0 + b_1)\Theta(\sigma)] - [b_1' - (b_0' + b_1')\Theta(\sigma_0)] \quad (20b)$$

$$b_n = \frac{2}{\pi} \int_0^\pi V(l \cos \theta, x) \cos n\theta d\theta \quad (x = l \cos \theta, n = 0, 1, 2, \dots) \quad (20c)$$

$$b_n' = \frac{2}{\pi} \int_0^\pi V_0(l \cos \theta, x) \cos n\theta d\theta = \frac{2}{\pi} \int_0^\pi i A_0 \exp[i(\omega t \langle \mp \rangle h l \cos \theta)] \cos n\theta d\theta = \langle \pm \rangle 2 A_0 \langle \mp \rangle i^{n-1} J_n(hl) \exp(i\omega t) \quad (20d)$$

$$\Theta(\sigma) = \frac{K_1(j\sigma)}{K_0(j\sigma) + K_1(j\sigma)} = \frac{H_1^{(2)}(\sigma)}{H_1^{(2)}(\sigma) + iH_0^{(2)}(\sigma)} = \mathcal{F}(\sigma) + i\mathcal{Q}(\sigma) \quad (20e)$$

$$\sigma_0 = \omega l / U \quad (20f)$$

$$\sigma = \omega l / U. \quad (20g)$$

Here, the integral in eq. (19) assumes its Cauchy principal value; $J_n(hl)$ is the Bessel function of the first kind; $\Theta(\sigma)$ is the Theodorsen function¹⁰⁾, $\mathcal{F}$ and $\mathcal{Q}$ being its real and imaginary parts; $K_n(\sigma)$ is the modified Bessel function of the second kind; $H_n^{(2)}(\sigma)$ is the Hankel function of the second kind; σ and σ_0 are the reduced frequencies of the foil and wave motions respectively. There exists a relation between σ_0 and hl as

$$\sigma_0 = (\delta kl)^{1/2} \langle \pm \rangle hl, \quad \delta = gl / U^2, \quad (21)$$

$(1/\delta)^{1/2}$ being the Froude number.

The differential lift distribution $\mathcal{L}$ along the chord is clearly

$$\mathcal{L}(x, t) = p(x, -0, t) - p(x, +0, t) = -2p_1(x, +0, t) \quad (|x| < l). \quad (22)$$

The integral representation of the lift $L(t)$ and the moment $M(t)$ (about the mid-chord; positive in the nose up sense) are

$$L(t) = \int_{-l}^l \mathcal{L}(x, t) dx \quad (23)$$

* The pressure p_1 is related to Prandtl's acceleration potential ϕ_1 in Wu's paper¹⁵⁾ by $p_1 = -\rho\phi_1$.

$$M(t) = - \int_{-l}^l \mathcal{L}(x, t) x dx. \quad (24)$$

When eqs. (19) and (22) are substituted into eqs. (23) and (24), the lift $L(t)$ and the moment $M(t)$ can be written as

$$L(t) = \pi \rho U l \left\{ - \left[(b_0 + b_1) \Theta(\sigma) + \frac{i\sigma}{2} (b_0 - b_2) \right] + \left[(b_0' + b_1') \Theta(\sigma_0) + \frac{i\sigma_0}{2} (b_0' - b_2') \right] \right\} \quad (25)$$

$$M(t) = \frac{\pi \rho U l^2}{2} \left\{ [b_1 - (b_0 + b_1) \Theta(\sigma) + b_2] + \frac{i\sigma}{4} (b_1 - b_3) - [b_1' - (b_0' + b_1')] \times \Theta(\sigma_0) + b_2'] - \frac{i\sigma_0}{4} (b_1' - b_3') \right\}. \quad (26)$$

In order to obtain eqs. (25) and (26), eqs. (40) and (41) in ref. 13) are used respectively. The substitutions of eqs. (20d) into eqs. (25) and (26) gives

$$\frac{L(t)}{\pi \rho U^2 l} = - \frac{1}{U} \left[(b_0 + b_1) \Theta(\sigma) + \frac{i\sigma}{2} (b_0 - b_2) \right] - 2 \frac{A_0}{U} \left[W_1(\sigma_0) - i W_2(\sigma_0) + \left(\langle \mp \rangle + 1 + \frac{\sigma_0}{kl} \right) J_1(kl) \right] \exp(i\omega_0 t) \quad (27)$$

$$\frac{M(t)}{(1/2)\pi \rho U^2 l^2} = - \frac{1}{U} \left[(b_0 + b_1) \Theta(\sigma) - b_1 - b_2 - \frac{i\sigma}{4} (b_1 - b_3) \right] - 2 \frac{A_0}{U} \left[W_1(\sigma_0) - i W_2(\sigma_0) - i \left(1 + \langle \mp \rangle + \frac{\sigma_0}{kl} \right) \times J_2(kl) \right] \exp(i\omega_0 t), \quad (28)$$

where

$$W_1(\sigma) = [\langle \pm \rangle + 1 + \langle \mp \rangle \mathcal{F}(\sigma)] J_1(kl) + \mathcal{G}(\sigma) J_0(kl) \quad (29a)$$

$$W_2(\sigma) = \mathcal{F}(\sigma) J_0(kl) + \langle \pm \rangle \mathcal{G}(\sigma) J_1(kl). \quad (29b)$$

The formulas for calculating the thrust T , the power required for maintaining the motion P and the kinetic energy imparted to the fluid E may be given as

$$T = \int_{-l}^l \mathcal{L}(x, t) \frac{\partial h}{\partial x} dx + S \quad (30)$$

$$P = - \int_{-l}^l \mathcal{L}(x, t) \frac{\partial h}{\partial t} dx \quad (31)$$

$$E = - \int_{-l}^l \mathcal{L}(x, t) D h dx - S U, \quad (32)$$

where S is the leading edge suction and is given as (see eq. (43) in ref. 13))

$$S = \frac{1}{2} \pi \rho (Re[a_0])^2. \quad (33)^*$$

* Eq. (18) in ref. 16) seems to be incorrect. The coefficient 1/8 should be 1/2 as given in eq. (21) in ref. 15).

From the above expressions of T , P and E , it is easily shown that there exists the energy relation, that is,

$$P = T U + E. \quad (34)$$

In the following, discussions are limited to the heaving and pitching oscillations of the flat-plate hydrofoil. The motion of the foil may be described as

$$h(x, t) = \left[\frac{1}{2} (\xi_1 + i \xi_2) + (\xi_3 + i \xi_4) x \right] \exp(i\omega t), \quad (35)$$

where $\xi_1, \dots, \xi_4$ are real coefficients. (ξ_1, ξ_2) and (ξ_3, ξ_4) represents a heaving and a pitching-about-mid-chord with their amplitudes

$$\xi_h = (\xi_1^2 + \xi_2^2)^{1/2}, \quad \xi_p = (\xi_3^2 + \xi_4^2)^{1/2} \quad (36a)$$

and their phase angles

$$\alpha_h = \tan^{-1} \xi_2 / \xi_1, \quad \alpha_p = \tan^{-1} \xi_4 / \xi_3 \quad (36b)$$

respectively. When the expression (35) is substituted into (14b), $V(x, t)$ is now given as

$$V(x, t) = \left[\frac{i\omega}{2} (\xi_1 + i \xi_2) + U (\xi_3 + i \xi_4) \right] \exp(i\omega t) + [i\omega (\xi_3 + i \xi_4) x] \exp(i\omega t). \quad (37)$$

The substitution of eq. (37) into eq. (20c) gives

$$b_0 = U [i\sigma (\xi_1 + i \xi_2) + 2(\xi_3 + i \xi_4)] \exp(i\omega t) \quad (38a)$$

$$b_1 = U i\sigma (\xi_3 + i \xi_4) \exp(i\omega t) \quad (38b)$$

$$b_n = 0 \quad \text{for } n \geq 2. \quad (38c)$$

The simple geometry of the flat plate foil leads to simplifications in the calculation for thrust and power. In fact, the substitution of eq. (25) into eqs. (30) and (31) yields

$$T = Re[L] \cdot Re[\partial h / \partial x] + S \quad (39)$$

$$P = - Re \left[\frac{1}{2} i\omega (\xi_1 + i \xi_2) \exp(i\omega t) \right] Re[L] + Re [i\omega (\xi_3 + i \xi_4) \exp(i\omega t)] Re[M]. \quad (40)$$

Furthermore, if ω is assumed to be equal to ω_0 , the mean value of thrust $\bar{T}$, leading edge suction $\bar{S}$, power $\bar{P}$ and energy loss $\bar{E}$ are obtained as

$$\bar{T} = \frac{1}{2} Re \left[L \cdot \left(\frac{\partial h}{\partial x} \right)^* \right] + \bar{S} \quad (41)$$

$$\bar{S} = \frac{1}{4} \pi \rho |a_0|^2 \quad (42)$$

$$\bar{P} = - \frac{1}{4} Re [i\omega_0 (\xi_1 + i \xi_2) \exp(i\omega_0 t) L^*] + \frac{1}{2} Re [i\omega_0 (\xi_3 + i \xi_4) \exp(i\omega_0 t) M^*] \quad (43)$$

$$\bar{E} = \bar{P} - \bar{T} U, \quad (44)$$

where the asterisk means to take the complex conjugate of the corresponding quantities.

3.2 Wave drifting force acting on an oscillating hydrofoil in waves

In the following, the two-dimensional version

of Maruo's theory for the wave drifting force^{3),8),9)} is applied to estimate approximately the wave drifting force or resistance increase in head seas and "thrust increase" in following seas.

For simplicity, the wave drifting force is estimated by using the amplitudes of the radiated waves which is generated by the concentrated singularities expressing the lift L and the moment M , whose values are calculated without including the free surface effect, that is, according to eqs. (27) and (28).

In the first place, the hydrodynamic pressure $P_L \exp(i\omega_0 t)$ and $P_M \exp(i\omega_0 t)$ of the singularities at (x_1, z_1) expressing the lift $L = L_0 \exp(i\omega_0 t)$ and the moment $M = M_0 \exp(i\omega_0 t)$ are summarized. P_L and P_M are obtained as

$$P_L = L_0 \frac{\partial P_F}{\partial z_1} \quad (45)$$

$$P_M = -M_0 \frac{\partial [P_L]_{L_0=1}}{\partial x_1}, \quad (46)$$

where P_F is the fundamental singularity²⁾ defined by

$$\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial z^2} \right) P_F = \delta(x - x_1) \delta(z - z_1) \quad \text{in fluid} \quad (47a)$$

$$\left[\left(i\omega_0 + U \frac{\partial}{\partial x} \right)^2 + g \frac{\partial}{\partial z} + \nu \left(i\omega_0 + U \frac{\partial}{\partial x} \right) \right] P_F = 0 \quad \text{at } z=0 \quad (47b)$$

$$P_F \rightarrow 0 \quad \text{as } z \rightarrow -\infty, \quad (47c)$$

since the hydrodynamic pressure $p(x, z, t)$ generated by the source distribution $m(x, z, t)$ and the external force distribution $(f_x(x, z, t), f_z(x, z, t))$ is the solution of the following problem

$$\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial z^2} \right) p = -\rho \left(\frac{\partial}{\partial t} + U \frac{\partial}{\partial x} + \nu \right) m + \left(\frac{\partial f_x}{\partial x} + \frac{\partial f_z}{\partial z} \right) \quad \text{in fluid} \quad (48a)$$

$$\left[\left(\frac{\partial}{\partial t} + U \frac{\partial}{\partial x} \right)^2 + g \frac{\partial}{\partial z} + \nu \left(\frac{\partial}{\partial t} + U \frac{\partial}{\partial x} \right) \right] p = 0 \quad \text{at } z=0 \quad (48b)$$

$$p \rightarrow 0 \quad \text{as } z \rightarrow -\infty. \quad (48c)$$

By solving the problem defined by eq. (47), the fundamental singularity P_F is obtained as

$$P_F = \frac{1}{2\pi} \{ \ln \sqrt{(x-x_1)^2 + (z-z_1)^2} - \ln \sqrt{(x-x_1)^2 + (z+z_1)^2} - \frac{g}{2\pi} \int_0^\infty \frac{\exp[ik(x-x_1) + k(z+z_1)]}{\{-(\omega_0 + kU)^2 + gk + i\nu(\omega_0 + kU)\}} dk - \frac{g}{2\pi} \int_0^\infty \frac{\exp[-ik(x-x_1) + k(z+z_1)]}{\{-(\omega_0 - kU)^2 + gk + i\nu(\omega_0 - kU)\}} dk \}, \quad (49)$$

and P_F has the following asymptotic forms

$$P_F \sim E \left(\frac{1}{4} - \Omega \right) \frac{i}{\sqrt{1-4\Omega}} \exp[ik_2^-(x-x_1) + k_2^-(z+z_1)] \quad \text{when } x \rightarrow -\infty \quad (50a)$$

$$P_F \sim E \left(\frac{1}{4} - \Omega \right) \frac{i}{\sqrt{1-4\Omega}} \exp[ik_1^-(x-x_1) + k_1^-(z+z_1)] - \frac{i}{\sqrt{1+4\Omega}} \exp[-ik_1^+(x-x_1) + k_1^+(z+z_1)] + \frac{i}{\sqrt{1+4\Omega}} \exp[-ik_2^+(x-x_1) + k_2^+(z+z_1)] \quad \text{when } x \rightarrow \infty, \quad (50b)$$

where

$$E(x) = \begin{cases} 0 & \text{when } x < 0 \\ 1 & \text{when } x > 0 \end{cases} \quad (51a)$$

$$\frac{k_1^+}{k_2^+} = \frac{\kappa_0}{2} (1 + 2\Omega \pm \sqrt{1+4\Omega}) \quad (51b)$$

$$\frac{k_1^-}{k_2^-} = \frac{\kappa_0}{2} (1 - 2\Omega \pm \sqrt{1-4\Omega}) \quad (51c)$$

$$\kappa_0 = g/U^2 \quad (51d)$$

$$\Omega = U\omega_0/g. \quad (51e)$$

The asymptotic forms of P_L and P_M may easily be derived from eqs. (45), (46), and (50).

Since the velocity potential $Ux + \Phi(x, z) \exp(i\omega_0 t)$ is obtained by solving the Bernoulli equation

$$p = -\rho \left(\frac{\partial}{\partial t} + U \frac{\partial}{\partial x} \right) \Phi \exp(i\omega_0 t), \quad (52)$$

where $p(x, z, t)$ is the hydrodynamic pressure, the wave terms in the asymptotic forms of the velocity potential $Ux + \Phi \exp(i\omega_0 t)$ which expresses the uniform stream, the incoming wave and the lift and moment singularities at (x_1, z_1) may be obtained as

$$\Phi \sim \frac{iga}{\omega_0 \langle \mp \rangle k U} \exp[\langle \mp \rangle ikx + kz] - E \left(\frac{1}{4} - \Omega \right) \frac{(L_0 + iM_0 k_2^-) k_2^-}{\rho(\omega_0 + U k_2^-) \sqrt{1-4\Omega}} \times \exp[ik_2^-(x-x_1) + k_2^-(z+z_1)] \quad \text{when } x \rightarrow -\infty \quad (53a)$$

$$\Phi \sim \frac{iga}{\omega_0 \langle \mp \rangle k U} \exp[\langle \mp \rangle ikx + kz] - E \left(\frac{1}{4} - \Omega \right) \frac{(L_0 + iM_0 k_1^-) k_1^-}{\rho(\omega_0 + k_1^- U) \sqrt{1-4\Omega}} \times \exp[ik_1^-(x-x_1) + k_1^-(z+z_1)] + \frac{(L_0 - iM_0 k_1^+) k_1^+}{\rho(\omega_0 - k_1^+ U) \sqrt{1+4\Omega}} \times \exp[-ik_1^+(x-x_1) + k_1^+(z+z_1)] - \frac{(L_0 - iM_0 k_2^+) k_2^+}{\rho(\omega_0 - k_2^+ U) \sqrt{1+4\Omega}} \times \exp[-ik_2^+(x-x_1) + k_2^+(z+z_1)] \quad \text{when } x \rightarrow \infty. \quad (53b)$$

Subsequently, the two-dimensional version

of Maruo's formula for the wave drifting force, that is eq. (5.74) in ref. 9), is derived. In the first place, the two-dimensional form of the oscillatory part $\Phi_1(x, y, z) \exp(i\omega_0 t)$ of the velocity potential:

$$\begin{aligned} \Phi_1 = & -2i \left[\int_{-\pi/2}^{\theta-\pi/2} - \int_{\pi/2}^{\theta+\pi/2} \right] H_1(\kappa_1, \alpha) \\ & \times \frac{\kappa_1 \exp[\kappa_1 z - i\kappa_1 R \cos(\alpha - \theta)]}{\sqrt{1 - 4\Omega \cos \alpha}} d\alpha \\ & - 2i \int_{\theta-\pi/2}^{\theta+\pi/2} H_1(\kappa_2, \alpha) \\ & \times \frac{\kappa_2 \exp[\kappa_2 z - i\kappa_2 R \cos(\alpha - \theta)]}{\sqrt{1 - 4\Omega \cos \alpha}} d\alpha \\ & + 0(R^{-1}) \quad \text{for large } R \end{aligned} \quad (54)$$

is obtained (see eq. (5.63) in ref. 9)). In the above expression,

$$R = \sqrt{x^2 + y^2}, \quad \theta = \tan^{-1}(y/x) + \pi \quad (55a)$$

$$\begin{aligned} H_1(\kappa, \alpha) = & \iint_S \sigma_1(x', y', z') \\ & \times \exp(\kappa z' - i\kappa x' \cos \alpha - i\kappa y' \sin \alpha) \\ & \times dS(x', y', z') \end{aligned} \quad (55b)$$

$$\sigma_1 = \text{strength of the source distributed on the ship surface} \quad (55c)$$

$$\left. \begin{matrix} \kappa_1 \\ \kappa_2 \end{matrix} \right\} = \kappa_0 \frac{1 - 2\Omega \cos \alpha \pm \sqrt{1 - 4\Omega \cos \alpha}}{2 \cos^2 \alpha} \quad (55d)$$

The coordinate system is adjusted to coincide with the one adapted in the present paper: the variables x and y are replaced by $-x$ and $-y$ respectively; the uniform stream of the velocity U flows from $x = -\infty$ to $x = +\infty$; the angles α and θ are measured in counter-clockwise sense from the negative x -axis.

In the two-dimensional case, σ_1 is independent of y' , that is,

$$\sigma_1 = \sigma_1(x', z'). \quad (56)$$

Substituting eq. (56) into eq. (55b), $H_1(\kappa, \alpha)$ can now be written as

$$\begin{aligned} H_1(\kappa, \alpha) = & \int_S \sigma_1(x', z') \\ & \times \exp(\kappa z' - i\kappa x' \cos \alpha) \\ & \times dS(x', z') \delta(\kappa \sin \alpha) \\ = & H_1'(\kappa, \alpha) \delta(\kappa \sin \alpha), \end{aligned} \quad (57)$$

where δ is Dirac's delta function and the following expression of the delta function is used

$$\delta(\kappa) = \frac{1}{2\pi} \int_{-\infty}^{\infty} e^{-i\kappa x} dx. \quad (58)$$

Substituting eq. (57) into eq. (54) and putting $\theta = 0$, the asymptotic expression of the two-dimensional velocity potential Φ_1 when $x \rightarrow -\infty$ is obtained as

$$\begin{aligned} \Phi_1 \sim & -2i \int_{-\pi/2}^{\pi/2} H_1'(\kappa_2, \alpha) \delta(\kappa_2 \sin \alpha) \\ & \times \frac{\kappa_2 \exp[\kappa_2 z + i\kappa_2 x \cos \alpha]}{\sqrt{1 - 4\Omega \cos \alpha}} d\alpha \\ = & -2i \int_{-\kappa_2(0)4\alpha}^{\kappa_2(0)4\alpha} H_1'(\kappa_2, \alpha) \delta(t) \\ & \times \frac{\kappa_2 \exp[\kappa_2 z + i\kappa_2 x \cos \alpha]}{\sqrt{1 - 4\Omega \cos \alpha}} \\ & \times \frac{dt}{\kappa_2'(\alpha) \sin \alpha + \kappa_2(\alpha) \cos \alpha} \\ = & -2i H_1'(\kappa_2(0), 0) \frac{\exp[\kappa_2(0)z + i\kappa_2(0)x]}{\sqrt{1 - 4\Omega}}. \end{aligned} \quad (59a)$$

Similarly, the asymptotic expression when $x \rightarrow +\infty$ is obtained as

$$\begin{aligned} \Phi_1 \sim & -2i H_1'(\kappa_1(0), 0) \frac{\exp[\kappa_1(0)z + i\kappa_1(0)x]}{\sqrt{1 - 4\Omega}} \\ & + 2i H_1'(\kappa_1(\pi), \pi) \frac{\exp[\kappa_1(\pi)z - i\kappa_1(\pi)x]}{\sqrt{1 + 4\Omega}} \\ & - 2i H_1'(\kappa_2(\pi), \pi) \frac{\exp[\kappa_2(\pi)z - i\kappa_2(\pi)x]}{\sqrt{1 + 4\Omega}}. \end{aligned} \quad (59b)$$

From eqs. (51b), (51c) and (55d), $\kappa_j(\alpha)$ ($j=1, 2$; $\alpha=0, \pi$) and $k_j^\pm$ ($j=1, 2$) are related as

$$\left. \begin{matrix} \kappa_j(0) = k_j^- \\ \kappa_j(\pi) = k_j^+ \end{matrix} \right\} \quad \text{for } j=1, 2. \quad (60)$$

Now, the two-dimensional form of Maruo's formula for the resistance increase ΔR in waves (see eq. (5.74) in ref. 9):

$$\begin{aligned} \Delta R = & 2\pi\rho \left[\int_{-\pi/2}^{-\alpha_0} + \int_{\alpha_0}^{\pi/2} - \int_{\pi/2}^{3\pi/2} \right] \\ & \times |H_1(\kappa_1, \alpha)|^2 \frac{\kappa_1^2 \cos \alpha}{\sqrt{1 - 4\Omega \cos \alpha}} d\alpha \\ & + 2\pi\rho \int_{\alpha_0}^{2\pi-\alpha_0} |H_1(\kappa_2, \alpha)|^2 \frac{\kappa_2^2 \cos \alpha}{\sqrt{1 - 4\Omega \cos \alpha}} d\alpha \\ & - i\pi\rho c r k [H_1(k, \chi) - H_1^*(k, \chi)] \cos \chi \end{aligned} \quad (61)$$

is derived as follows. In the expression (61), α_0 is

$$\alpha_0 = \begin{cases} 0 & \text{for } \Omega \leq 1/4 \\ \cos^{-1}(1/4\Omega) & \text{for } \Omega > 1/4, \end{cases} \quad (62)$$

and χ is the direction of the incident wave Φ_0 :

$$\Phi_0 = c r \exp[kz + ik(x \cos \chi + y \sin \chi)]. \quad (63)$$

Substitution of eq. (57) into eq. (61) then leads the form of ΔR for an infinite cylinder moving in a heading ($\chi = \pi$) or following ($\chi = 0$) seas

$$\Delta R = 2\pi\rho \left[E(1 - 4\Omega) |H_1'(\kappa_1(0), 0)|^2 \right]$$

$$\begin{aligned}
& \times \frac{\kappa_1(0)}{\sqrt{1-4\Omega}} + |H_1'(\kappa_1(\pi), \pi)|^2 \frac{\kappa_1(\pi)}{\sqrt{1+4\Omega}} \\
& + E(1-4\Omega) |H_1'(\kappa_2(0), 0)|^2 \frac{\kappa_2(0)}{\sqrt{1-4\Omega}} \\
& - |H_1'(\kappa_2(\pi), \pi)|^2 \frac{\kappa_2(\pi)}{\sqrt{1+4\Omega}} + \frac{1}{2} icrk \\
& \times \{H_1'(k, \chi) - H_1'^*(k, \chi)\} \cos \chi \} \delta(0). \quad (64)
\end{aligned}$$

Comparing eq. (64) with eq. (17) in ref. 8) for zero advance velocity, $2\pi\delta(0)$ in eq. (64) is replaced by 1, and the two-dimensional value ΔR_2 corresponding to ΔR is obtained as

$$\begin{aligned}
\Delta R_2 = & \rho \left[E(1-4\Omega) |H_1'(\kappa_1(0), 0)|^2 \right. \\
& \times \frac{\kappa_1(0)}{\sqrt{1-4\Omega}} + |H_1'(\kappa_1(\pi), \pi)|^2 \frac{\kappa_1(\pi)}{\sqrt{1+4\Omega}} \\
& + E(1-4\Omega) |H_1'(\kappa_2(0), 0)|^2 \frac{\kappa_2(0)}{\sqrt{1-4\Omega}} \\
& - |H_1'(\kappa_2(\pi), \pi)|^2 \frac{\kappa_2(\pi)}{\sqrt{1+4\Omega}} - \frac{1}{2} icrk \\
& \left. \times \{H_1'(k, \chi) - H_1'^*(k, \chi)\} \cos \chi \right]. \quad (65)
\end{aligned}$$

From the comparison of eq. (53) with eqs. (59) and (63), cr , $H_1'(\kappa_j(0), 0)$ and $H_1'(\kappa_j(\pi), \pi)$ ($j=1, 2$) is calculated by

$$cr = \frac{ga}{|\omega_0 \langle \mp \rangle k U|} \quad (66a)$$

$$\begin{aligned}
H_1'(\kappa_j(0), 0) = & \frac{-i(L_0 + iM_0 k_j^-) k_j^-}{2\rho(\omega_0 + U k_j^-)} \exp \left[-k_j^- h \right. \\
& \left. - i \left(\frac{\pi}{2} - \arg(\omega_0 \langle \mp \rangle k U) \right) \right] \quad (66b)
\end{aligned}$$

$$\begin{aligned}
H_1'(\kappa_j(\pi), \pi) = & \frac{-i(L_0 - iM_0 k_j^+) k_j^+}{2\rho(\omega_0 - k_j^+ U)} \exp \left[-k_j^+ h_1 \right. \\
& \left. - i \left(\frac{\pi}{2} - \arg(\omega_0 \langle \mp \rangle k U) \right) \right]. \quad (66c)
\end{aligned}$$

4. Some numerical results for a linear Wells turbine

In order to clarify the effect of oscillations of a hydrofoil, the details of the oscillations must be specified by solving any optimum problems as pointed by Wu^{(15), (16)}. A solution of an optimum problem has already been given by Wu, but the author wants to treat problems of optimization in future.

In the present paper, some numerical calculations are conducted for a non-oscillating foil advancing in waves or "linear Wells turbine". The mechanism of thrust generation by a linear Wells turbine is illustrated in Fig. 4.

In Fig. 5, the performance results for a linear Wells turbine of chord $2l=0.328$ m advancing in head seas with a velocity of $U=1$ m/s are shown.

Fig. 4 Thrust generation by a linear Wells turbine.

In Figs. 5~9, $\bar{T}_a$, $\bar{P}_{\mp}$ and $\eta_{\mp D}$ are as follows

$$\begin{aligned}
\bar{T}_a & = \text{actual mean thrust} \\
& = \bar{T} - \Delta R_2 \quad (67a)
\end{aligned}$$

$$\begin{aligned}
\bar{P}_{\mp} & = \text{wave power} \\
& = \frac{\rho g}{2} |a|^2 (c_g \pm U) \quad (67b)
\end{aligned}$$

$$\begin{aligned}
\eta_{\mp D} & = \text{wave devouring efficiency} \\
& = \bar{T}_a U / \bar{P}_{\mp} \quad (67c)
\end{aligned}$$

where the upper and lower signs in $\pm$ refer to heading and following seas respectively, and

c_g = group velocity of the wave

$$= \frac{1}{2} \sqrt{\frac{\lambda g}{2\pi}} \quad (68)$$

In Fig. 5, when the wave length λ tends to $15+0$ m, the resistance increase ΔR_2 tends to infinity. This wave length corresponds to the critical wave length, that is, $\Omega = \omega_0 U / g = 1/4$. For $\lambda < 15$ m, the diffracted wave does not exist in front of the foil.

For the critical value and small values of λ , ΔR_2 becomes larger than $\bar{T}$, and $\bar{T}_a$ becomes negative. Hence, for these values of λ , the linear Wells turbine can not produce thrust.

In Fig. 6, the lift L and the moment M acting on the same linear Wells turbine as in Fig. 5 are shown, where $\text{Amp}(\)$ and $\text{Arg}(\)$ refer to the amplitude and the argument of the quantity in the parentheses respectively. When λ tends to infinity, the reduced frequency tends to zero, and $\text{Arg}(L)$ and $\text{Arg}(M)$ tends to 90 deg.

In Fig. 7, the performance of a linear Wells turbine of chord $2l=0.328$ m advancing with various speeds in a wave of wave length $\lambda=8$ m is shown. In this case, $U=0.73$ m/s is the critical speed where $\Omega=1/4$.

It must be noted that $\bar{T}_a$ becomes negative for $U > 2.47$ m/s. The existence of the speed limit can be found only by introducing the free surface effect and is not mentioned in Wu's papers^{(15), (16)}.

In Figs. 8 and 9, results for following seas are shown. In following seas, ΔR_2 is always negative

Fig. 5 Performance of a linear Wells turbine in head seas.
($U=1$ m/s, $h_1=0.492$ m, $l=0.164$ m, $a=\lambda/40$)

Fig. 6 Lift L and moment M acting on a linear Wells turbine in head seas.
($U=1$ m/s, $h_1=0.492$ m, $l=0.164$ m, $a=\lambda/40$)

Fig. 7 Performance of a linear Wells turbine in a head sea.
($\lambda=8$ m, $h_1=0.492$ m, $l=0.164$ m, $a=0.2$ m)

Fig. 8 Performance of a linear Wells turbine in following seas.
($U = 1$ m/s, $h_1 = 0.492$ m, $l = 0.164$ m, $a = \lambda/40$)

Fig. 9 Performance of a linear Wells turbine in a following sea.
($\lambda = 8$ m, $h_1 = 0.492$ m, $l = 0.164$ m, $a = 0.2$ m)

and makes $\bar{T}_a$ larger than $\bar{T}$ calculated by Wu's theory. Hence, applications of linear Wells turbine in following seas may have some practicability.

In Fig. 8, $\lambda = 2.5$ m is the critical wave length. Hence, for $\lambda < 2.5$ m, the group velocity of the wave c_g becomes smaller than the advance speed of the foil, and the foil can not produce thrust by absorbing wave power.

In Fig. 9, $U = 1.76$ m/s is the critical speed, and, for $U > 1.76$ m/s, c_g of the wave of $\lambda = 8$ m becomes smaller than U . Hence, the foil can not produce thrust. But when U tends to $1.76 - 0$ m/s, ΔR_2 tends to infinity. This is clearly the error due to the approximate procedure adapted in the present paper to estimate the resistance increase.

The ideal thrust $\bar{T}_i$:

$$\bar{T}_i = \bar{P}_w / U \quad (69)$$

is shown in Fig. 9. If a more refined theory is

used to estimate $\bar{T}_a$, $\bar{T}_a$ may tends to zero when U tends to the critical value as shown by a dotted line in Fig. 9.

5. Conclusions

In the present paper, the following items are discussed.

(1) The possibility of the wave devouring propulsion in head seas is shown from a general viewpoint of conversion of wave power into thrust.

(2) Wu's theory^{15),16)} for oscillating foil propulsors in waves is developed by including approximately the free surface effect. For the purpose, the two-dimensional version of Maruo's theory for resistance increase in waves⁹⁾ is applied.

(3) Some numerical results are given for non-oscillating foils in waves or linear Wells turbines are given, and the importance of introducing the free surface effect is shown.

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