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A Consistent Theory for Oscillating Slender Ships at Arbitrary Forward Speed

By Masashi KASHIWAGI*

A consistent linear theory is presented for the radiation problem of heave and pitch modes of a slender ship advancing at forward speed. The theory has no restrictions on the order of forward speed and oscillation frequency. The inner velocity potential includes a particular solution which is the same as that of the high-speed strip theory, plus a homogeneous component which is constructed by the superposition of the real-flow potential and the reverse-flow reverse-time potential. The unknown coefficient of the homogeneous component is determined from the matching with the outer solution, which makes the present theory essentially different from Yeung & Kim's, developed with the same objective as the present paper.

Key words : Slender-ship theory, Radiation problem, Forward-speed effect, Free-surface effect

1. Introduction

The strip theory has been used as a practical method for ship-motion predictions. However the idea of the strip theory is rather intuitive, and thus to establish a more rational theory a large number of investigations based on the slender-ship theory began in 1960s.

The first attempt was an application of the slender-body theory devised in the field of aerodynamics, but ship hydrodynamics is distinctive in that not only the geometrical lengthscale but also the wavelength of ship-generated waves must be taken into account. In particular, when a ship is moving at forward speed while oscillating, two different kinds of wave pattern must be considered : one originating from the ring wave due to harmonic oscillation and the other from the Kelvin wave due to steady translation. This complicates the analysis, and actually several theories emerged with different assumptions on the order of oscillation frequency and forward speed.

However, as a matter of course, assuming the order of frequency and speed restricts the range of these parameters in which developed theories are valid. Therefore it is desirable for a general slender-ship theory to avoid restrictive assumptions concerning the frequency and forward speed ; in other words these should be assumed arbitrary.

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The unified theory, proposed by Newman[1)2)], is remarkable in that it can be applied irrespective of the order of oscillation frequency. However, since the free-surface condition in the inner problem is independent of the forward speed, the unified theory implicitly assumes the order of forward speed to be less than O (1).

On the other hand, the high-speed strip theory, initiated by Chapman[3)4)], satisfies the speed-dependent free-surface condition in the inner problem. The resulting inner solution includes only the downstream influences and thus the frequency must be high, but the forward speed can be arbitrary. We need not consider the matching in the high-speed strip theory, because the inner solution satisfies the extraneous radiation condition.

The present paper is intended to develop a new theory which embraces both of the unified theory and the high-speed strip theory. The inner solution is given in the form of the high-speed strip-theory solution plus a homogeneous solution. The unknown coefficient of the homogeneous solution is determined from the matching requirement with the outer solution represented by a line distribution of translating and pulsating 3-D sources along the ship's length.

Yeung & Kim[5)] also developed a forward-speed slender-ship theory with the intention of generalizing the unified theory and the high-speed strip theory. They introduced a "generalized" inner Green function, which was used in the boundary integral-equation method as an alternative to the 3-D Green function. Therefore Yeung & Kim's theory seems different in the analytical procedure from conventional slender-ship theories, and hence apparently different from the theory in this paper.

Computationally, the present theory is necessarily more complicated than existing slender-ship theories, but it stands out as a consistent theory with no restrictions on the frequency of oscillation and the forward speed of the ship.

2. Formulation

Consider a ship advancing with constant speed U and undergoing small-amplitude motions of circular frequency ω in deep water. For simplicity, only the radiation problem of heave and pitch are considered. Fig. 1 shows an adopted steady reference frame, with the x-axis positive in the direction of the forward motion and the z-axis positive downward.

Assuming the flow inviscid with irrotational motion, we introduce the velocity potential which is expressed as

$$\Phi = U\Big[-x+\varphi_s(x,\ y,\ z)\Big]+\mathrm{Re}\Big[i\omega\sum_{j=3,5}X_j\phi_j(x,\ y,\ z)e^{i\omega t}\Big] \tag{1}$$

Here φ_s denotes the steady-state disturbance potential, ϕ_j the unsteady potential of the j-th mode with unit velocity, where j is the mode index ; $j=3$ for heave and $j=5$ for pitch, and X_j is the complex amplitude of oscillation.

The unsteady potentials, $\phi_j\,(j = 3,\ 5)$, are governed by the 3-D Laplace

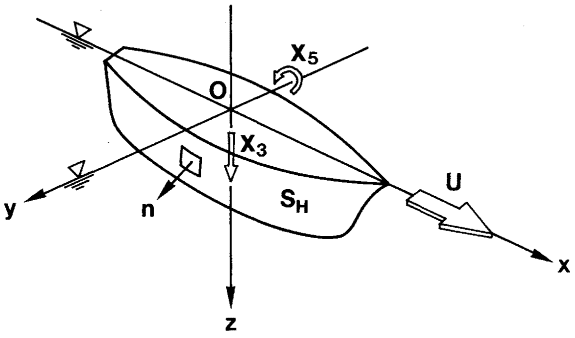

Fig. 1 Coordinate system

equation

$$\frac{\partial^2\phi_j}{\partial x^2}+\frac{\partial^2\phi_j}{\partial y^2}+\frac{\partial^2\phi_j}{\partial z^2}=0 \tag{2}$$

and subject to the linearized free-surface boundary condition

$$\left(i\omega-U\frac{\partial}{\partial x}\right)^2\phi_j-g\frac{\partial\phi_j}{\partial z}+\mu\left(i\omega-U\frac{\partial}{\partial x}\right)\phi_j=0 \quad \text{on } z=0 \tag{3}$$

Here μ is Rayleigh's artificial viscosity coefficient ensuring the radiation condition be satisfied far from the ship, and g is the gravitational acceleration.

The linearized body boundary condition can be written as follows:

$$\frac{\partial\phi_j}{\partial n}=n_j+\frac{U}{i\omega}m_j \quad \text{on } S_H \tag{4}$$

where

$$\left.\begin{aligned} m_3 &= -(\boldsymbol{n}\cdot\nabla)W_3,\ m_5=-(\boldsymbol{n}\cdot\nabla)(\boldsymbol{r}\times\boldsymbol{W})_2 \\ \boldsymbol{r} &= (x,\ y,\ z),\ \boldsymbol{W}=\nabla[-x+\varphi_s(x,\ y,\ z)] \end{aligned}\right\} \tag{5}$$

and $\boldsymbol{n}$ denotes the unit normal vector pointing out of the ship hull (S_H), and n_5 is defined as $z\,n_1-x\,n_3$. (The subscripts 1, 2, 3 correspond respectively to x, y, z.)

Although several simplifications are employed in the above formulation, it is still troublesome to obtain an "exact" solution, even with recent computer power. Instead here we apply the slender-ship theory.

In the context of slender-ship theories, the transverse dimensions of the ship are assumed to be of $O(\varepsilon)$ relative to the ship length, where ε is a small quantity, and the flow field is analysed separately after being divided into the inner and outer regions.

In the inner region close to the ship hull, the longitudinal flow gradient is small compared to the transverse ones; this simplifies the governing equation and boundary conditions. However no restrictions should be placed on the order of forward speed U and circular frequency ω, because it is the intent of the present paper to treat U and ω as arbitrary parameters. Moreover the radiation condition need not be imposed in the inner region, since the inner observer is not concerned about the far-field asymptotic behavior of the flow.

With all of the above taken into account, the inner problem is defined in the present study as follows:

$$\frac{\partial^2 \phi_j}{\partial y^2}+\frac{\partial^2 \phi_j}{\partial z^2}=0 \tag{6}$$

$$\left(i\omega-U\frac{\partial}{\partial x}\right)^2\phi_j-g\frac{\partial \phi_j}{\partial z}=0 \quad \text{on } z=0 \tag{7}$$

$$\frac{\partial \phi_j}{\partial N}=N_j+\frac{U}{i\omega}M_j \quad \text{on } S_H \tag{8}$$

where N is the 2-D unit normal vector on the contour of transverse sections, N_j is its component, and M_j is the slender-body approximation of m_j discarding longitudinal derivatives in (5).

When viewed from the outer region, the ship looks like a line on the x-axis. Therefore the body boundary condition can not be applied, and the flow field is governed by (2) and (3).

3. 2-D Green function

In order to construct the inner solution, let us consider the Green function associated with the inner problem (6)-(8), satisfying the followings:

$$\left(\frac{\partial^2}{\partial y^2}+\frac{\partial^2}{\partial z^2}\right)G^{\pm}=\delta(x-\xi)\delta(y-\eta)\delta(z-\zeta) \tag{9}$$

$$\left(i\omega-U\frac{\partial}{\partial x}\right)^2G^{\pm}-g\frac{\partial G^{\pm}}{\partial z}\pm\mu\left(i\omega-U\frac{\partial}{\partial x}\right)G^{\pm}=0 \quad \text{on } z=0 \tag{10}$$

where δ is Dirac's delta function, and the superscripts '$\pm$' are taken according to the sign in front of μ in (10).

As is clear from (3), the real-flow solution satisfying the proper radiation condition should be the '$+$' case. However in the inner problem, the '$-$' case is also allowed owing to the absence of the radiation condition. Physically this '$-$' case corresponds to a reverse-flow and reverse-time problem.

The present Green function may easily be obtained by means of the Fourier transform with respect to x; the definition of which is as follows:

$$f^*(k)=\int_{-\infty}^{\infty}f(x)e^{ikx}dx, \quad f(x)=\frac{1}{2\pi}\int_{-\infty}^{\infty}f^*(k)e^{-ikx}dk \tag{11}$$

The final result can be expressed in the form

$$G^{\pm}(x-\xi\,;P,\,Q)=\frac{\delta(x-\xi)}{2\pi}\ln\frac{r}{r_1}+G_P^{\pm}(x-\xi\,;|y-\eta|,\,z+\zeta) \tag{12}$$

$$\begin{aligned} G_P^{\pm *}(k\,;y,\,z) &= -\frac{1}{2\pi}\lim_{\mu\to 0}\int_{-\infty}^{\infty}\frac{e^{-z|m|-imy}}{|m|-\dfrac{1}{g}(\omega+kU-i\mu)^2}dm \\ &= -\frac{1}{\pi}\mathrm{Re}\left[e^{-\nu(z+i|y|)}E_1\{-\nu(z+i|y|)\}\right]\pm i\epsilon_k e^{-\nu(z\pm i\epsilon_k|y|)} \end{aligned} \tag{13}$$

where

$$P=(y,\ z),\ Q=(\eta,\ \zeta),\ \left.\begin{array}{c} r \\ r_1 \end{array}\right\} = \sqrt{(y-\eta)^2+(z\mp\zeta)^2} \tag{14}$$

$$\nu=(\omega+kU)^2/g,\quad \epsilon_k=\mathrm{sgn}(\omega+kU) \tag{15}$$

and $E_1(u)$ in (13) is the exponential integral with complex argument.

By using known expansions of the exponential integral, the asymptotic properties of the Green function can be readily obtained for large and small values of νR, with the result

$$G_P^{\pm*}(k\,;y,\ z)=\frac{\cos\theta}{\pi\nu R}\pm i\epsilon_k e^{-\nu(z\pm i\epsilon_k|y|)}+O((\nu R)^{-2}) \text{ for } \nu R\gg 1 \tag{16}$$

$$G_P^{\pm*}(k\,;y,\ z)=\frac{1}{\pi}(1-\nu z)\Big(\ln\nu R+\gamma\pm\pi i\epsilon_k\Big)+\frac{1}{\pi}\nu R(\cos\theta+\theta\sin\theta) + O(\nu^2R^2) \quad \text{for } \nu R\ll 1 \tag{17}$$

where $z=R\cos\theta$, $|y|=R\sin\theta$, and γ is Euler's constant.

It is noteworthy that the present 2-D Green function actually includes the variable x through the convective term in the free-surface condition, and thus may be called the pseudo 3-D Green function.

We can see from (13) that the following relation holds:

$$G_P^{-*}(k\,;y,\ z)=G_P^{+*}(k\,;y,\ z)-2i\epsilon_k e^{-\nu z}\cos(\nu y) \tag{18}$$

4. 3-D Green function

As will be shown in the next section, the outer solution will be constructed in terms of the 3-D Green function satisfying the free-surface condition (3). This function is well studied in the past slender-ship theories; its Fourier transform can be written in the form

$$G_{3D}^*(k\,;y,\ z)=-\frac{1}{2\pi}\lim_{\mu\to 0}\int_{-\infty}^{\infty}\frac{e^{-z\sqrt{k^2+m^2}-imy}}{\sqrt{k^2+m^2}-\frac{1}{g}(\omega+kU-i\mu)^2}dm \tag{19}$$

$$=-\frac{1}{\pi}K_0(|k|R)+\frac{\nu}{\pi}\int_0^{\infty}e^{-\nu\zeta}K_0\Big\{|k|\sqrt{y^2+(z-\zeta)^2}\Big\}d\zeta + \begin{bmatrix} \dfrac{i\epsilon_k}{\sqrt{1-k^2/\nu^2}}e^{-\nu z-i\epsilon_k\nu|y|\sqrt{1-k^2/\nu^2}} \\ \dfrac{-1}{\sqrt{k^2/\nu^2-1}}e^{-\nu z-\nu|y|\sqrt{k^2/\nu^2-1}} \end{bmatrix} \tag{20}$$

Here the top and bottom expression in brackets corresponds to $\nu>|k|$ and $\nu<|k|$ respectively, and $K_0(x)$ is the zeroth order modified Bessel function of the second kind.

For later purpose, the expansions appropriate for large and small values of νR are needed, for which the analysis of Newman[1)] or Yeung & Kim[5)] can be used. The result can be expressed as

$$G_{3D}^{*}(k\,;y,\,z)=\frac{\cos\theta}{\pi\nu R}+i\epsilon_k e^{-\nu(z+i\epsilon_k|y|)}+O((\nu R)^{-2},\,k^2/\nu^2,\,k^2y/\nu)\ \text{for}\ \nu R\gg 1 \tag{21}$$

$$G_{3D}^{*}(k\,;y,\,z)=\frac{1}{\pi}(1-\nu z)\Big(\ln\frac{|k|R}{2}+\gamma\Big)+\frac{1}{\pi}\nu R(\cos\theta+\theta\sin\theta)$$
$$+\frac{1}{\pi}(1-\nu z)\left[\begin{array}{c}\dfrac{1}{\sqrt{1-k^2/\nu^2}}\Big\{\pi i\epsilon_k+\cosh^{-1}\Big(\dfrac{\nu}{|k|}\Big)\Big\}\\ \dfrac{1}{\sqrt{k^2/\nu^2-1}}\Big\{-\pi+\cos^{-1}\Big(\dfrac{\nu}{|k|}\Big)\Big\}\end{array}\right]+O(\nu^2R^2,\,k^2R^2)\ \text{for}\ \nu R\ll 1 \tag{22}$$

Comparison of (21) with (16) tells us that, for $\nu R\gg 1$, the 2-D Green function for the real flow, G_P^{+*}, is compatible with the 3-D Green function, G_{3D}^{*}. Another comparison between (22) and (17) gives the relation

$$G_{3D}^{*}(k\,;y,\,z)=G_P^{+*}(k\,;y,\,z)-\frac{1}{\pi}(1-\nu z)g^*(k)+O(\nu^2R^2,\,k^2R^2) \tag{23}$$

where

$$g^*(k)=\ln\frac{2\nu}{|k|}+\pi i\epsilon_k-\left[\begin{array}{c}\dfrac{1}{\sqrt{1-k^2/\nu^2}}\Big\{\pi i\epsilon_k+\cosh^{-1}\Big(\dfrac{\nu}{|k|}\Big)\Big\}\\ \dfrac{1}{\sqrt{k^2/\nu^2-1}}\Big\{-\pi+\cos^{-1}\Big(\dfrac{\nu}{|k|}\Big)\Big\}\end{array}\right] \tag{24}$$

It should be noted that $g^*(k)$ tends to zero for $\nu\gg|k|$, meaning that (23) is a general expression for arbitrary values of νR. Since it is known that the 2-D Green function G_P^{+} represents only the divergent wave system, $g^*(k)$ is a correction term associated with the transverse wave system in the genuine 3-D wave field.

5. Inner and outer solutions

Let us consider the inner solution first. According to the concept of Newman's unified theory[1)2)], the inner solution must be of the form of a particular solution plus a homegeneous component.

Since the appropriate Green function is given by (12), the particular solution may be easily obtained by means of the boundary intergral-equation method.

With the real-flow Green function, G^+, satisfying the extraneous radiation condition, the velocity potential can be given in the form

$$\begin{aligned}\phi_j^+(x;P)=&\frac{1}{2\pi}\int_{B(x)}\Big\{\frac{\partial\phi_j^+(x;Q)}{\partial n}-\phi_j^+(x;Q)\frac{\partial}{\partial n}\Big\}\ln\frac{r}{r_1}d\ell(\eta,\zeta)\\&+\int_x^{L/2}d\xi\int_{B(\xi)}\Big\{\frac{\partial\phi_j^+(\xi;Q)}{\partial n}-\phi_j^+(\xi;Q)\frac{\partial}{\partial n}\Big\}G_P^+(x-\xi;P,Q)d\ell(\eta,\zeta)\\&+\frac{U^2}{g}\int_x^{L/2}\Big\{\phi_j^+(\xi;Q)\frac{\partial}{\partial\xi}-\frac{\partial\phi_j^+(\xi;Q)}{\partial\xi}+i2\frac{\omega}{U}\phi_j^+(\xi;Q)\Big\}\\&\times\Big[G_P^+(x-\xi;|y+b(\xi)|,z)-G_P^+(x-\xi;|y-b(\xi)|,z)\Big]\frac{db(\xi)}{d\xi}d\xi\end{aligned} \tag{25}$$

Here the superscript '+' is attached to the velocity potential to mean the 'real-flow' problem and, in the line integral expressed by the last term, $b(\xi)$ denotes the half breadth at station $x=\xi$ and thus Q should be interpreted as

$(b(\xi), 0)$. We note that there are no influences from the downstream and thus the integration range for ξ is reduced to $\xi=[x, L/2]$.

The solution (25) is the same as that in the high-speed strip theory. This solution is not general as the inner solution, because we can add homogeneous solutions to (25), because of no necessity of satisfying the radiation condition.

In order to construct a homogeneous solution, we consider the reverse-flow and reverse-time problem where the signs of U and ω are reversed. Let the velocity potential in this reverse problem be expressed by ϕ_j^-. Then in view of (6)-(8), we can take the following as a homogeneous solution

$$\phi_H(x;y,z)=\phi_3^+(x;y,z)-\phi_3^-(x;y,z) \tag{26}$$

With this component, the general inner solution can be written in the form

$$\phi_j^{(i)}(x;y,z)=\phi_j^+(x;y,z)+\int_{-\infty}^{\infty}C_j(\xi)\phi_H(x-\xi;y,z)d\xi \tag{27}$$

where $C_j(\xi)$ is the unknown coefficient, representing physically 3-D interactions among transverse sections along the ship's length. Since we have no information which can specify the integration range, we have written the limits as in (27).

Next we turn to the outer solution; which is the same as that having been studied in the past slender-ship theories. In the outer field, the ship may be viewed as a line disturbance along the x-axis. Therefore we can write as

$$\phi_j^{(o)}(x,y,z)=\int_{-\infty}^{\infty}q_j(\xi)G_{3D}(x-\xi,y,z)d\xi \tag{28}$$

Here $G_{3D}(x,y,z)$ is the 3-D Green function studied in § 4, equivalent physically to the velocity potential of a translating and pulsating source, and $q_j(\xi)$ is its unknown strength along the ship's length.

6. Matching

In the inner solution the coefficient of the homogeneous component is unknown, and likewise in the outer solution the strength of source distribution along the x-axis is unknown. These unknowns will be determined by the method of matched asymptotic expansions.

For that purpose, we need the outer expansion of (27) and the inner expansion of (28). It may be easier to consider those in the Fourier domain.

Applying to (25) the Fourier transform with respect to x and then considering its asymptotic expansion for large y and z, we have

$$\phi_j^{+*}(k;y,z)\sim H_j^+(k)G_P^{+*}(k;y,z) \tag{29}$$

where

$$H_j^+(k)=\int_{-L/2}^{L/2}e^{ik\xi}d\xi\int_{B(\xi)}\left\{\frac{\partial\phi_j^+(\xi;Q)}{\partial n}-\phi_j^+(\xi;Q)\frac{\partial}{\partial n}\right\}e^{-\nu\zeta}\cos(\nu\eta)d\ell(\eta,\ \zeta) \tag{30}$$

Here (30) is called the Kochin function, the definition of which must include the contribution from the line-integral term, but here that contribution is omitted for simplicity of the expression. $G_P^{+*}(k;y,z)$ in (29) is the Fourier transform of the pseudo 3-D Green function given by (13).

Similarly the outer expansion of ϕ_j^- can be written in the form

$$\phi_j^{-*}(k;y,z) \sim H_j^-(k) G_P^{-*}(k;y,z)$$
$$= H_j^-(k)\left\{ G_P^{+*}(k;y,z) - 2i\epsilon_k e^{-\nu} \cos(\nu y) \right\} \tag{31}$$

Here the relation (18) has been substituted. The Kochin function $H_j^-(k)$ may be defined in a form analogous to (30).

Using the convolution theorem to transform (27) and then substituting (29) and (31), the desired result of the outer expansion can be expressed in the form

$$\phi_j^{(i)*}(k;y,z) \sim \left[H_j^+(k) + C_j^*(k)\left\{ H_3^+(k) - H_3^-(k) \right\} \right] G_P^{+*}(k;y,z)$$
$$+ 2i\epsilon_k\, e^{-\nu} \cos(\nu y) C_j^*(k) H_3^-(k) \tag{32}$$

Turning to the inner expansion of the outer solution, it can be obtained from (28) by using the convolution theorem and substituting the relation (23) for the Fourier transform of $G_{3D}(x,y,z)$, with the result

$$\phi_j^{(o)*}(k;y,z) = q_j^*(k) G_{3D}^*(k;y,z)$$
$$\sim q_j^*(k)\left\{ G_P^{+*}(k;y,z) - \frac{1}{\pi}(1-\nu z) g^*(k) \right\} \tag{33}$$

Requiring (32) and (33) to be compatible in an overlap region gives the following two equations:

$$q_j^*(k) = H_j^+(k) + C_j^*(k)\left\{ H_3^+(k) - H_3^-(k) \right\} \tag{34}$$

$$2i\epsilon_k C_j^*(k) H_3^-(k) = -\frac{1}{\pi} q_j^*(k) g^*(k) \tag{35}$$

Eliminating $q_j^*(k)$ from these two equations, one can obtain

$$C_j^*(k) = \frac{-g^*(k) H_j^+(k)}{2\pi i\epsilon_k H_3^-(k) + g^*(k)\left\{ H_3^+(k) - H_3^-(k) \right\}} \tag{36}$$

With numerical results of $C_j^*(k)$, the outer source strength, $q_j^*(k)$, can be readily computed from (34) or (35).

As described before, the correction function $g^*(k)$ reduces to zero for $\nu \gg |k|$, implying that $C_j^*(k)=0$ and $q_j^*(k)=H_j^+(k)$ in this limiting case. We note that this limiting case holds for arbitrary forward speeds only if the frequency is high ($\omega \gg 1$), because $\nu=(\omega+kU)^2/g$.

The complete inner solution can be given either by transforming inversely (36) and then evaluating the convolution integral in (27), or by using the Fourier transform of the convolution integral in (27) and then substituting (36). The latter idea gives the following expression equivalent to (27):

$$\phi_j^{(i)}(x;y,z) = \phi_j^+(x;y,z) + \frac{1}{2\pi}\int_{-\infty}^{\infty} C_j^*(k) \phi_H^*(k;y,z) e^{-ikx} dk \tag{37}$$

Equation (27) or (37) is one of the principal results of the present paper.

7. Discussions

In the context of forward-speed slender-ship theories, the unified theory proposed by Newman[1] and the high-speed strip theory initiated by Chapman[3] may be two theories of practical utility which can give reasonable predictions for relatively wide range of U and ω.

However, as shown analytically by Yeung & Kim[5], the unified theory is applicable only for small forward speeds and the high-speed strip theory is appropriate for $\omega \gg 1$. The present theory generalizes these two theories, thus being valid for arbitrary speed and frequency parameters. In order to demonstrate this, let us derive the unified-theory expression as a special case of the present theory.

In the inner problem of the unified theory, the free-surface condition does not include forward speed. Therefore homogeneous solutions can be constructed just in the transverse y-z plane, which enables us to write

$$\phi_H(x;y,z)=\delta(x)\left\{\phi_3(y,z)-\overline{\phi_3(y,z)}\right\} \tag{38}$$

where the overbar denotes the conjugate of the complex potential ϕ_3, i.e. the reverse-time velocity potential.

Substituting (38) into (27), we have an expression of the inner solution based on the unified theory:

$$\phi_j^{(i)}(x;y,z)=\phi_j(y,z)+C_j(x)\left\{\phi_3(y,z)-\overline{\phi_3(y,z)}\right\} \tag{39}$$

Here the first term on the right-hand side, which is the particular solution, can be computed using the zero-speed 2-D Green function, and the calculation of $C_j(x)$ can be much easier than that in the present theory. (But the calculation procedure is essentially the same.)

On the other hand, for high frequencies and nonzero forward speed, the 3-D interaction function $g^*(k)$ becomes very small and thus the coefficient of homogeneous component $C_j^*(k)$ reduces automatically to zero as can be seen from (36). This means that the inner solution in the present theory becomes identical to the high-speed strip-theory solution.

Computationally the present theory may be more involved than existing forward-speed slender-ship theories. However, it is clear from the above discussions that the present theory is a generalization of existing theories and can be applied for arbitrary parameters of forward speed and oscillation frequency.

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