TECHNICAL REPORT 503-2

SINGULARITIES ON THE FREE SURFACE AND HIGHER ORDER WAVE HEIGHT FAR BEHIND A PARABOLIC SHIP

By

B. Yim

October 1966

HYDRONAUTICS, incorporated
research in hydrodynamics

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TABLE OF CONTENTS

LIST OF FIGURES

INTRODUCTION

Since the linear solutions for the problems of free surface waves were found by Kelvin (1887) and Michell (1898), theoretical and experimental research on the improvement of ship forms by the application of the linear theory has been conducted by many naval hydrodynamicists, and many fruitful results have been obtained. However, the linear theory, particularly for surface ship problems, seems to have severe limitations. Yet, the higher order wave theory of surface ships, being inherently difficult, has developed at an extremely slow pace. Recently, because of the easier availability and improvement of the computing speed of high speed computing machines, this complicated by highly necessary theory has become more and more attractive. Wehausen (1963) considered the systematic development of higher order ship wave theory. Sesov (1961) formulated the second order wave resistance. Yim (1966), considering the free surface condition more carefully, investigated the higher order potential and the wave resistance. This author also investigated the effect of the line integral on the free surface, among many other higher order effects (Yim, 1964), unfortunately with some computational error.

In this report another attempt on the investigation of the line integral on the free surface is now made, with a parabolic ship form and by a much simpler method of computation. As before, the influence of the line integral on the asymptotic wave height is calculated.

It has long been known that a pressure point moving on the free surface produces a peculiar flow field along its path, Lamb (1945), Ursell (1960). Although a pressure point is known to be equivalent to a doublet point, not much information is available about the properties of general singularities on the free surface. However, due to the recent development of slender ship theory, Vossers (1962), Tuck (1963), Maruo (1962), Joosen (1963), and the higher order ship wave theory, the importance of the singularity on the free surface increased rapidly. Thus the author has devoted his attention to obtain as much information as possible about the behavior of singularities on the free surface - before calculating the line integral due to a singularity distribution along a line on the free surface.

SINGULARITIES ON THE FREE SURFACE

We locate an origin of the rectangular right-handed coordinate system on the undisturbed free surface (or a mean free surface) with the directions of three axes as shown in Figure 1. If we consider a pressure point at the origin moving with constant velocity $-\overline{V}$ on the free surface, the flow field satisfies Laplaces equation

$$\nabla^2\phi = 0 \qquad [1]$$

with the free surface boundary condition

$$\phi_{xx} + k_o\phi_x + \mu\phi = 0$$

$$(k_o = g/V^2) \qquad [2]$$

on $z = 0$, except at the singularity, and with the proper boundary conditions at infinity. The solution is well known (Wehausen, 1960; Peters, 1948; Ursell, 1960).

$$\varphi(x,y,z) = -\frac{k_o P_o}{\pi \rho V}\int_0^{\pi/2} d\theta \, \sec^3\theta \, e^{zk_o \sec^2\theta} \cos(k_o x \sec\theta)$$

$$\times \cos(k_o y \sec^2\theta \sin\theta)$$

$$+ \frac{P_o}{\pi^2 \rho V}\int_0^{1/2\pi} d\theta \sec\theta \int_0^{\infty} dk \frac{k\, e^{kz}}{k - k_o \sec^2\theta} \sin(kx\cos\theta)\cos(ky\sin\theta) \qquad [3]$$

This is exactly the same as the limiting case of zero submergence of the potential due to a point doublet with its direction $-\bar{V}$.

The pressure point being naturally the limiting case of zero submergence of the lift element, this fact can be seen easily from the free surfac boundary condition outside the singularity,

$$\varphi_{xx} + k_o \varphi_z = 0 \quad \text{on } z = 0 \qquad [4]$$

If we consider a point singularity at a point $(x_1, y_1, 0)$ and the flow which satisfies [4] at a point $(x, y, 0)$ we can rewrite [4]

$$\varphi_{x_1 x_1}(x_1, y_1, 0; x, y, 0) + k_o \varphi_{z_1}(x_1, y_1, 0; x, y, 0) = 0 \qquad [5]$$

since

$$\varphi_{x_1} = -\varphi_x, \quad \varphi_{y_1} = -\varphi_y, \quad \varphi_{z_1} = +\varphi_z \qquad [6]$$

referring to the Green's function (see, e.g., Lunde (1951)) which represents a potential due to a point source. Then from [5]

$$\varphi_{x_1}(0, y_1, 0; x, y, 0) = k_o \int_0^\infty \varphi_{z_1}(x_1, y_1, 0; x, y, 0) dx_1 \qquad [7]$$

This means that the flow on $z = 0$ due to a point doublet located on the free surface is the same everywhere on $z = 0$ as that due to a vortex element on the free surface. Thus the two flows are identical everywhere in the fluid.

A point source located on the free surface can also be considered in a similar manner as the point doublet on the free surface. Since a point source at the origin may be considered as a line distribution of doublets on the positive x axis, a point source on the free surface can be interpreted as the uniform pressure distribution along the x axis.

The wave height ζ due to the pressure point is, according to the dynamic relation,

$$\zeta = \frac{\varphi_x}{k_o} \qquad [8]$$

and Equation [3] with some changes of variables, can be expressed (see Ursell (1960)) as,

$$\zeta(x,y) = \zeta_1(x,y) + \zeta_2(x,y)$$

$$= \frac{1}{\pi^2 \rho V^2} \int_0^\infty dk\ k^2 e^{-k|x|} \int_0^{1/2} dm\ \frac{\sin^2 m \cos(ky \cos m)}{k_o^2 + k \sin^2 m}$$

$$- \frac{P_o k_o}{\pi \rho g} \operatorname{sign}(x) \lim_{z \to 0} \int_{-\infty}^{\infty} (1+u^2) \exp\left[ik_o(x-uy)\sqrt{1+u^2}\right]$$

$$\times \exp\{-k_o z(1+u^2)\}\ du \qquad [9]$$

where ζ_1 is the local disturbance which decays rapidly with increasing $|x|$, and ζ_2 is the regular wave. The regular wave ζ_2 far behind the pressure point can be decomposed into two parts: the transverse wave and the divergent wave.

If the pressure is distributed on a finite area, there exists no singularity in the velocity field (Stoker, 1957, or Ursell, 1960). However, Equation [9] has an innate singularity at the pressure point and near its path such that the wavelength is infinitely decreasing and the wave height is infinitely increasing as $y \to 0$ (Lamb, 1945; Ursell, 1960), although the wave height on $y = 0$ or the flow in $z < 0$ is finite. The singularity near the path arises from only the divergent wave, while the transverse wave has a finite amplitude except at the origin. The wave resistance due to the pressure point also blows up. If we follow exactly the same procedure as in Ursell's paper (1960), it is obvious that the flow field due to a point source on the free surface has exactly the same kind of singular phenomena with a slightly weaker singularity. In general, a line doublet distribution on the free surface also has the same kind of singular phenomena. If the distribution of doublet strength near the end points smooths sufficiently to zero, the flow field behaves nicely. The source distribution along a straight line parallelto $\overline{V}$, in general has neither finite wave resistance nor finite wave height on the path, unless the end distribution is smooth enough. However, if the line where the sources are distributed is smooth and not parallel to $\overline{V}$, the flow may behave well. These results mentioned above can be easily obtained, if we apply the method of steepest descents to each expression using the result in the case of the pressure point in Ursell's paper (1960) and having Havelock's formula for the wave resistance (Havelock, 1934) in mind.

The singular behavior in the actual flow never arises. Even if we just consider the surface tension (Wehausen, 1963), the divergent wave heights have no singular behavior anywhere. Thus, in the case of point singularities on the free surface considered above, the wave height near the path of singularities may well be considered as smooth to the finite theoretical value at $y = 0$.

FLOW FIELD DUE TO A SHIP AND THE LINE INTEGRAL

From the Green's formula, the potential φ can be written using the Green's function $G(\xi,\eta,\zeta;x,y,z)$ which satisfies

$$G_\zeta = -\frac{1}{k_o} G_{\xi\xi} \qquad \text{on } \zeta = 0 \qquad [10]$$

Outside the ship,

$$\Delta\left(G - \frac{1}{r}\right) = 0 \qquad \text{in } z \leq 0 \qquad [11]$$

where

$$r^2 = (x - \xi)^2 + (y - \eta)^2 + (z - \zeta)^2$$

and

$$G \to 0 \qquad \text{for} \quad |r| \to \infty \text{ in } z < 0$$

$$\varphi = \frac{1}{4\pi}\iint_S [\varphi(\xi,\eta,\zeta)G_n(\xi,\eta,\zeta,x,y,z) - \varphi_n G]\, dS \qquad [12]$$

where n is the normal into the fluid, and S consists of the ship surface S_s and the free surface S_F since the integral from infinity is null.

From the free surface integral,

$$I \equiv \iint_F [\varphi G_n - \varphi_n G]dS = -\iint_{z=0} [\varphi G_\zeta - G\varphi_\zeta]\, d\xi d\eta$$

$$= \frac{1}{k_o}\iint_{z=0} \left\{\frac{\partial}{\partial\xi}(\varphi G_\xi) - \frac{\partial}{\partial\xi}(\varphi_\xi G)\right\} d\xi d\eta$$

$$= -\frac{1}{k_o}\oint_{\ell} (\varphi G_\xi - \varphi_\xi G)d\eta \qquad [13]$$

where ℓ is the intersection of the ship surface and the z = 0 plane. This line integral on the free surface has been unusually neglected in Michell's ship theory. A numerical computation of the effect from this line integral to the bow wave on the centerplane far behind the wedge ship was considered (Yim, 1964). Now we consider a parabolic forebody with a parallel midsection represented by a source distribution on $y = 0$, $z \le 0$

$$\left.\begin{aligned} m &= a_o(1 - x) && \text{in} \quad 0 < x < 1 \\ m &= 0 && \text{in} \quad 1 < x < a_1 \\ m &= a_o(a_1 - x) && \text{in} \quad a_1 < x < a_1 + 1 \end{aligned}\right\} \qquad [14]$$

By Michell's approximation

$$\frac{1}{2\pi}\frac{dy}{dx} = \frac{m}{V} \qquad [15]$$

so that the corresponding waterline can be represented by

$$\left.\begin{aligned} y &= 2\pi a_o\left(x - \frac{x^2}{2}\right) && \text{in} \quad 0 < x < 1 \\ &= \pi a_o && \quad 1 < x < a_1 \\ &= 2\pi a_o\left(a_1 x - \frac{x^2}{2}\right) + \pi a_o(1 - a_1^2) && \text{in} \quad a_1 < x < a_1 + 1 \end{aligned}\right\} [16]$$

For simplicity, the case of infinite draft is considered here, since the wave height on the ship hull and the perturbation potential which is zero at infinity can be calculated easily in that case.

To evaluate the effect of the line integral I on the wave height we write

$$I_x = \frac{1}{2\pi k_o}\int_0^1 (\varphi G_{\xi x} - \varphi_\xi G_x)\,\frac{df}{d\xi}\,d\xi \qquad [17]$$

Since

$$f = a_o \xi - \frac{\xi^2}{2} \qquad \text{in} \qquad 0 < \xi < 1$$

$$G_\xi = - G_x$$

we have

$$I_x = \frac{1}{2\pi k_o} \left[\varphi G_x \frac{df}{d\xi}\right]_o^1 - 2 \int_o^1 G_x \varphi_\xi \frac{df}{d\xi} + \int_o^1 G_\xi \varphi \frac{d^2 f}{d\xi^2} d\xi$$

$$= \frac{a_o}{2\pi k_o} \Bigg[- \varphi(0) G_x(x,0) - 2 \int_o^1 G_x \varphi_\xi (1 - \xi)\, d\xi$$

$$- G(x,1)\varphi(1) + G(x,0)\varphi(0) + \int_o^1 G\varphi_\xi d_\xi \Bigg] \qquad [18]$$

neglecting the higher order terms. The first term represents the wave height due to a point source. This is singular as we have seen in our previous section. This phenomenon is familiar to hydrodynamicists especially concerned with higher order problems. The singularity usually becomes more severe when the order becomes higher. Thus, the reliability of the higher order theory in most problems in hydrodynamics may be judged through experiments only.

We consider here the wave height on $y = 0$ far behind the ship where the theoretical wave height has a definite value if we consider that the divergent waves are continuous everywhere because of surface tension or for other reasons.

Using Wigley's notations (1931) and Havelock's example (1932), we can write the total wave height in $0 < x < 1$

$$\zeta = -\frac{2a_o}{k_o}\Bigg(Q_o(k_o x) + Q_o(k_o \overline{a_1 - x + 1}) - \frac{1}{k_o}\Big\{Q_1(k_o x) + Q_1(k_o \overline{1 - x}) - Q_1(k_o \overline{a_1 - x}) + Q_1(k_o \overline{a_1 - x + 1})\Big\} - 4\left[P_o(k_o x) - \frac{1}{k_o} P_o^{-1}(k_o x)\right]\Bigg) \qquad [19]$$

where

$$Q_o(a) = \frac{\pi}{2}\int_0^a \{H_o(t) - Y_o(t)\}\, dt$$

$H_o(t)$: Struve function of order zero

$Y_o(t)$: Neumann function of order zero

$$Q_1(a) = \int_0^a Q_o(u)\, du$$

$$P_o(a) = -\frac{\pi}{2}\int_0^a Y_o(t)\, dt$$

$$P_o^{-1}(a) = \int_0^a P_o(t)\, dt \qquad [20]$$

This value of ζ is plotted in Figure 2. In $x < 0$

$$\zeta = -\frac{2a_o}{k_o}\left[Q_o(k_o x') + \frac{1}{k_o}\left\{Q_1(k_o x') - Q_1(k_o \overline{x' + 1})\right\}\right.$$

$$\left. + Q_o(k_o \overline{a_1 - x + 1}) + \frac{1}{k_o}\left\{Q_1(k_o \overline{a_1 - x}) - Q_1(k_o \overline{a_1 - x + 1})\right\}\right] \tag{21}$$

where $x' = -x$

The potential is unique with the condition at infinity $\varphi \to 0$ which is necessary to get the Green's formula (see, e.g., Kellog, 1953), and at the origin

$$\varphi(0) = \int_{-\infty}^{0} \varphi_\xi d\xi = k_o \int_{-\infty}^{0} \zeta \, d\xi$$

$$= \frac{2a_o}{k_o}\left[Q_1(k_o \overline{a_1 + 1}) + \frac{1}{k_o}\int_{k_o}^{0} Q_1(u)du + \frac{1}{k_o}\int_{k_o \overline{a_1 + 1}}^{k_o a_1} Q_1(u)du\right] \tag{22}$$

Similarly

$$\varphi(1) = \varphi(0) + \int_0^1 \varphi_\xi d\xi \quad \text{on } z = 0 \tag{23}$$

can be obtained.

Considering the asymptotic value of the Green's function on $y = 0$

$$\left.\begin{aligned}
G_x &\sim -4\pi k_o^2 \frac{d}{dt} Y_1(t) \Big|_{t = k_o(x - \xi)} \\
G &\sim -4\pi k_o Y_1\{k_o(x - \xi)\} \\
&\sim -4\pi k_o \sqrt{\frac{2}{\pi k_o(x - \xi)}} \sin\left\{k_o(x - \xi) - \frac{3}{4}\pi\right\} \\
G_x &\sim -4\pi k_o^2 \sqrt{\frac{2}{\pi k_o(x - \xi)}} \cos\left\{k_o(x - \xi) - \frac{3}{4}\pi\right\}
\end{aligned}\right\} \qquad [24]$$

we can now evaluate I_x in [18] on $y = 0$ $x \gg 1$, substituting Equations [19] - [24], and [8] in [18], than integrating numerically. We obtain

$$\begin{aligned}
\zeta_\epsilon = \frac{I_x}{k_o} = a_o^2 \sqrt{\frac{2}{\pi k_o x}} &\left\{A(k_o) \cos\left(k_o x - \frac{3}{4}\pi\right)\right. \\
&\left. + B(k_o) \sin\left(k_o x - \frac{3}{4}\pi\right)\right\} \\
&= A_\epsilon \sin\left(k_o x + \frac{\pi}{4} + \beta\right) \qquad [25]
\end{aligned}$$

with the numerical values $A(k_o)$, $B(k_o)$ or A_ϵ, β as functions of k_o. The wave height in $x > 1$ due to the front source distributed in $0 < x < 1$ is

$$\zeta_1 = \frac{8a_o}{k_o}\left[P_o(k_ox) - \frac{1}{k_o}\left\{P_o^{-1}(k_ox) - P_o^{-1}(k_o\overline{x-1})\right\}\right.$$

$$\left. - \frac{2a_o}{k_o}\left[Q_o(k_ox) - \frac{1}{k_o}\left\{Q_1(k_ox) - Q_1(k_o\overline{x-1})\right\}\right]\right] \qquad [26]$$

By application of the method of stationary phase and neglecting the local disturbance

$$\zeta_1 \sim \frac{8a_o}{k_o}\frac{\pi}{2}\sqrt{\frac{2}{\pi k_ox}}\left\{\sin\left(k_ox + \frac{\pi}{4}\right) + \frac{1}{k_o}\cos\left(k_ox + \frac{\pi}{4}\right)\right.$$

$$\left. - \frac{1}{k_o}\cos\left(k_ox - 1 + \frac{\pi}{4}\right)\right\}$$

$$= \frac{4\pi a_o}{k_o}\sqrt{\frac{2}{\pi k_ox}}\left\{\left(1 - \frac{\sin k_o}{k_o}\right)\sin\left(k_ox + \frac{\pi}{4}\right)\right.$$

$$\left. + \left(\frac{1}{k_o} - \frac{\cos k_o}{k_o}\right)\cos\left(k_ox + \frac{\pi}{4}\right)\right\}$$

$$= A_1 \sin\left(k_ox + \frac{\pi}{4} + \theta\right)$$

$$\text{for } x >> 1 \qquad [27]$$

Then the total wave height ζ_t will be

$$\zeta_t = \zeta_1 + \zeta_\epsilon$$

$$= A_1 \sin\left(k_o x + \frac{\pi}{4} + \theta\right) + A_2 \sin\left(k_o x + \frac{\pi}{4} + \beta\right)$$

$$= A_3 \sin\left(k_o x + \frac{\pi}{4} + \theta + \delta\right)$$

where

$$\delta = \tan^{-1} \frac{A_2 \sin (\beta - \theta)}{A_1 + A_2 \cos (\beta - \theta)}$$

$$A_3 = \{A_1^2 + A_2^2 + 2 A_1 A_2 \cos (\beta - \theta)\}^{\frac{1}{2}}$$

A_3 and δ are plotted in Figures 3 - 5.

DISCUSSION

The calculated result shows that the line integral effect on the wave height due to the fore body of the parabolic ship with parallel mid body appears as an increment of the amplitude and a forward shift of the wave phase. The percentage is more in lower Froude numbers. Thus, the discrepancy between the experiment and theory may be ascribed to higher order effects and especially to this line integral effect. The importance of this effect can also be shown by the following approach.

We consider a double model ship with uniform speed $-\overline{V}$ in the infinite medium, where $z < 0$ correspond to the case of zero Froude number. Then the pressure P_1 on $z = 0$ will be

$$P_1 = \rho f(\varphi_1) \sim V\rho\varphi_{1x}$$

where ρ is the density of water and φ_1 is the potential due to the double model ship. Here we consider on $z = 0$, Kelvin's pressure source distribution $-P_1$ which satisfies

$$\varphi_{2xx} + k_o\varphi_{2z} = -\frac{P_{1x}}{\rho U} \quad \text{on} \quad z = 0$$

where φ_2 is the potential in $z \leq 0$ due to Kelvin's pressure distribution. If we consider the ship is symmetric with respect to $y = 0$ plane, P_1 is also symmetric with respect to x axis. Thus

$$\varphi_y = 0 \quad \text{on} \quad y = 0$$

If we superpose the two flows

$$\varphi = \varphi_1 + \varphi_2$$

will exactly satisfy Laplace's Equation [1], the free surface condition on $z = 0$ and the linear boundary condition of the thin ship surface on $y = 0$. Thus φ will be exactly the same as the Michell's solution.

If we want to consider the problem more accurately, we have to first notice the fact that the free surface is limited to the region outside of the ship. The pressure inside the double model ship on $z = 0$ is most strong, and the effect on the ship surface due to the Kelvin's pressures located outside of the ship is not too large because of the symmetry of the pressure distribution with respect to $y = 0$. Thus, Michell's theory which neglects the strong extra pressure inside the ship can be expected to lead to a sizable error on that account.

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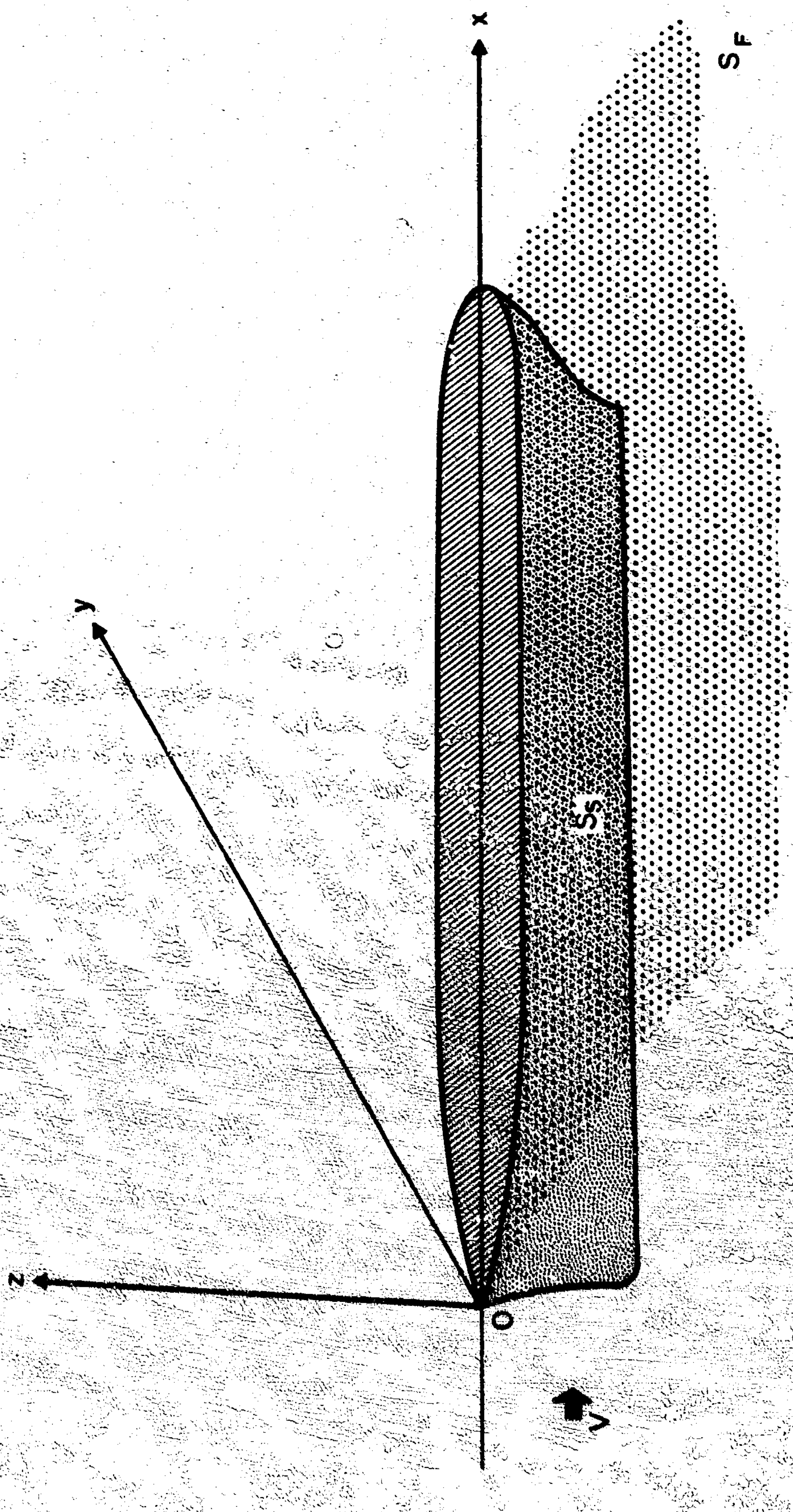

FIGURE 1- COORDINATE SYSTEM

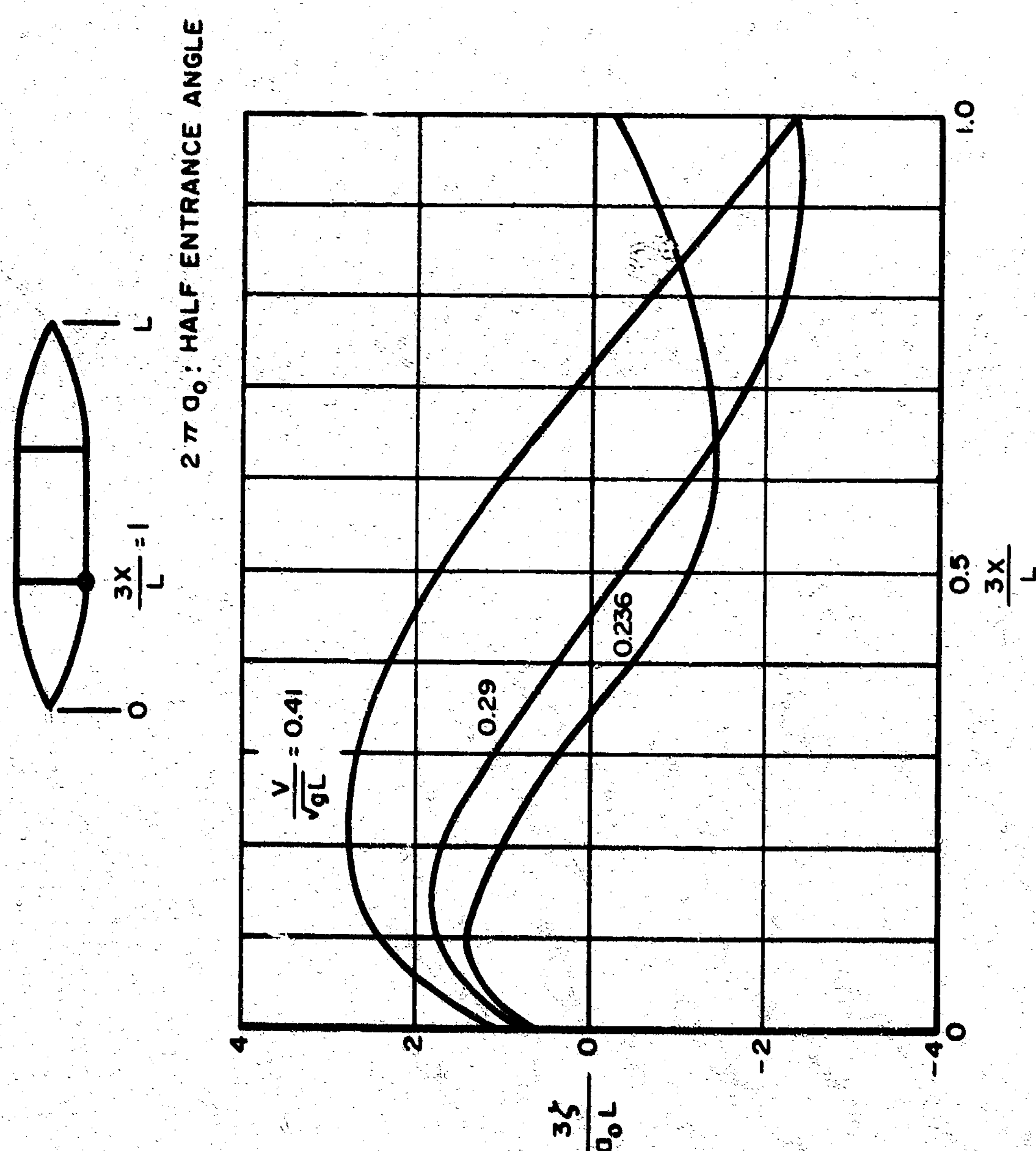

FIGURE 2– FIRST ORDER WAVE HEIGHT OF PARABOLIC SHIP WITH PARALLEL MIDDLE BODY

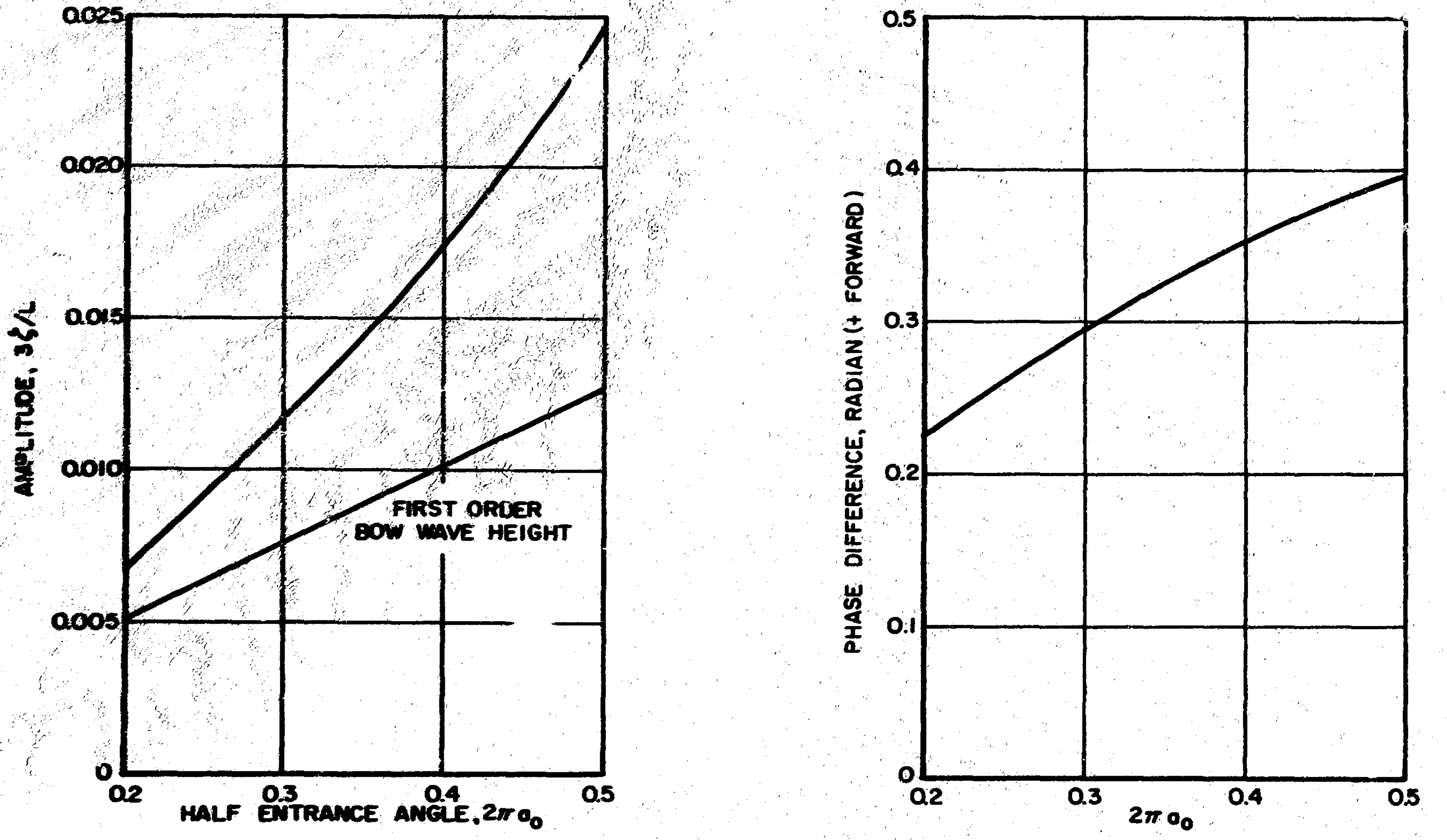

FIGURE 3– INFLUENCE OF HIGHER ORDER WAVE ON THE FIRST ORDER WAVE FAR AFT OF PARABOLIC SHIP. $V/\sqrt{gL} = 0.258$, $x/L = 15$.

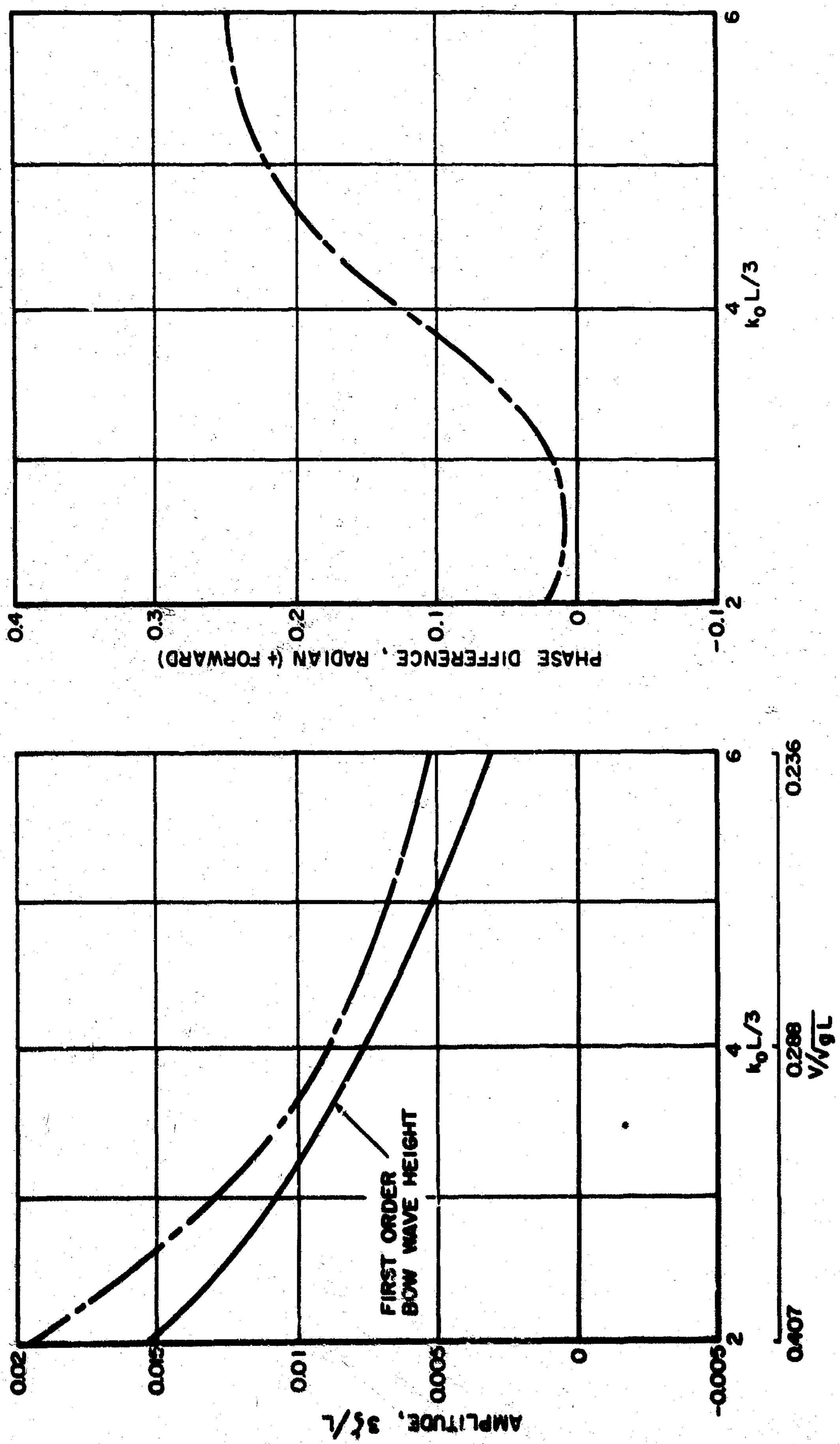

FIGURE 4– INFLUENCE OF HIGHER ORDER WAVE ON THE FIRST ORDER WAVE FAR AFT OF PARABOLIC SHIP $2\pi a_0 = 0.2$, $x/L = 15$.

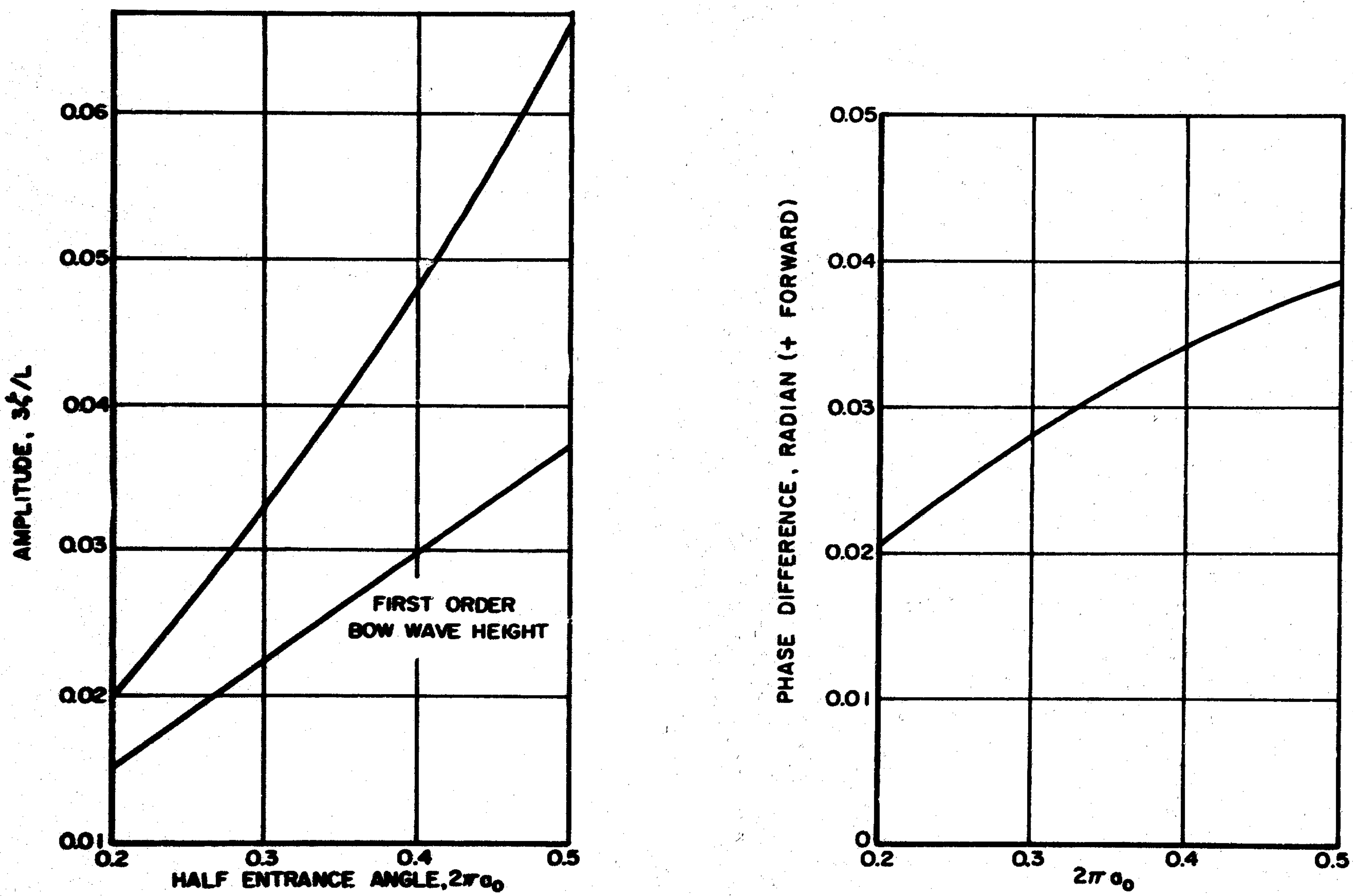

FIGURE 5– INFLUENCE OF HIGHER ORDER WAVE ON THE FIRST ORDER WAVE FAR AFT OF PARABOLIC SHIP. $V/\sqrt{gL} = 0.408$, $x/L = 15$.

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13. ABSTRACT

A theoretical investigation is made of one aspect of non-linear ship wave making theory; the line integral of the free surface is computed by a simple method. It is shown that the discrepancy between experimental and linearized theory can be partially ascribed to the neglect of this important non-linear term.

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