WAVE DRIFT CURRENT INTERACTION ON A TANKER IN OBLIQUE WAVES

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ABSTRACT

In this paper the strong interaction between the wave drift force and sailing speed or current on a LNG tanker is demonstrated. To compute the speed dependency of the second order wave drift force a new theory is developed for a tanker sailing at low forward speed. Some computed results of the wave drift forces with forward speed both in head and bow quartering waves are discussed with results of model tests.

INTRODUCTION

The quadratic transfer function of the wave drift force on a vessel may increase considerably when sailing at low speed or moored in a current field. In fact the quadratic transfer function of the wave drift force is velocity dependent. In the zero-current condition the speed dependency of the wave drift force due to the slowly oscillating moored vessel will be present also. This speed dependency of the wave drift force can be distinguished by the quadratic transfer function of the wave drift damping. In case the vessel is moored in waves combined with current the wave drift force can be described by the current speed dependent quadratic transfer function. The slowly oscillating motions of the vessel in the current field are governed by the current speed associated quadratic transfer of the wave drift damping. The procedures are described by Wichers in Ref. [1].

The formulation for the computations of the speed dependent wave drift forces on a tanker sailing at low speed in head waves has been extensively described in Refs. [1], [2], [3] and [4]. In this method the introduction of the forward speed consists of a steady and an unsteady part. In the steady potential the unperturbed velocity potential was applied. Further it was assumed that the steady part does not contribute to the unsteady part directly. It plays a role in the free surface condition. Because of the considered very low Froude number the effect of the free surface was not taken into account and the contribution of the steady potential was completely neglected. The time dependent oscillatory potential can be written as a source distribution along the hull and the waterline and will be expanded with respect to small values of the forward speed. By solving the potential, the part linear with speed will lead to the speed effects in the ship motions and using the direct integration method, see Pinkster (Ref. [5]), the speed dependent wave drift forces or wave drift damping can then be determined.

The influence of the steady perturbation potential resulting from the stationary fluid flow around the ship can be taken into account. In case the vessel is sailing at a certain drift angle, this effect appears to be of considerable influence as shown in Ref. [3]. One of the extensions of the former method is that the perturbation around the streamlines of the stationary double body potential solution will be taken into account. This enables the inclusion of the influence of the stationary potential solution into the unsteady first order potentials. Furthermore, applied to the direct pressure integration method the derivatives of the fluid velocities along the hull lead to numerically inaccurate results. Pending on the choice of the method to compute the potential along the hull also leads to a method that is inconsistent mathematically. Therefore for the calculation of the drift forces the present method is based on the conservation of impulse. For the conservation of impulse an alternative formulation of Maruo's expression was used (Refs. [6], [7] and [8]). Details of the theory have recently been published by Hermans (Ref. [9]). Similar descriptions are given by Grue and Palm (Ref. [10]) and Nossen et al. (Ref. [11]).

In the present computations the stationary potential has been calculated using a Hess and Smith type of procedure. For the computations a fast iterative solver is used to obtain the first order wave potential. The computations are applied to an LNG carrier. The results of the computations will be discussed in this paper. For the discussion use is made of model test results for the vessel sailing with forward speed in head and bow quartering waves.

MATHEMATICAL FORMULATION

We first derive the equations for the potential function $\Phi(x,t)$, such that the fluid velocity $u(x,t)$ is defined as $u(x,t) = \nabla(\Phi(x,t))$. The total potential function will be split up in a steady and a non-steady part in a well-known way:

$$\Phi(x,t) = Ux + \bar{\phi}(x;U) + \tilde{\Phi}(x,t;U) \tag{1}$$

In this formulation U is the incoming unperturbed velocity field, obtained by considering a coordinate system fixed to the ship moving under a drift angle α. In our approach this angle need not be small. The time dependent part of the potential consists of an incoming, diffracted and radiated wave at frequency $\omega = \omega_0 + k_0 U\cos\beta$, where ω_0 and $k_0 = \omega_0^2/g$ are the frequency and wave number in the earth-fixed coordinate system, while ω is the frequency in the coordinate system fixed to the ship. The waves are incoming under an angle β, with respect to the vessel. To compute the wave drift forces all these components will be taken into account. The system of axis is given in Fig. 1.

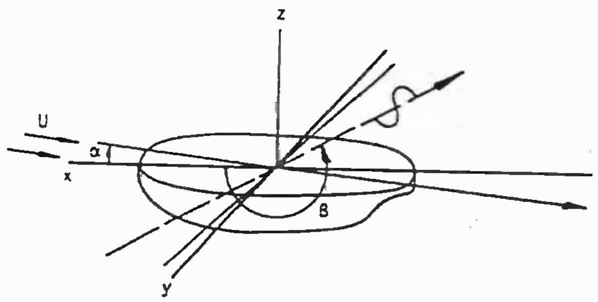

Fig. 1 System of axis

The equations for the potential Φ can be written as:

$$\Delta\Phi = 0 \text{ in the fluid domain } D_e \tag{2}$$

To compute the first order wave potential the free surface has to be linearized first. We assume $\tilde{\phi}(x,t;U) = \phi(x;U)\exp(-i\omega t)$, then the free surface condition at z=0 can be written as [12]:

$$-\omega^2\phi - 2i\omega U\phi_x + U^2\phi_{xx} + g\phi_z = D(U;\bar{\phi})\{\phi\} \quad \text{at } z=0 \tag{3}$$

where $D(U;\bar{\phi})$ is a linear differential operator acting on ϕ defined in Ref. [12]. The quadratic terms in $\bar{\phi}$ are neglected.

The linear problem is solved by means of a source distribution along the ship hull, its waterline and the free surface z = 0. We write:

$$4\pi\phi(x) = -\iint_S \sigma(\xi)G(x,\xi)dS_\xi + \frac{U^2}{g}\int_{WL} \alpha_n\sigma(\xi)G(x,\xi)ds_\xi + \frac{i\omega}{g}\iint_{FS} G(x,\xi)D\{\phi\}dS_\xi \quad \text{for } x \in D_e \tag{4}$$

where $D\{\phi\} = 2\nabla\bar{\phi}.\nabla\phi$. The function $G(x,\xi)$ is the Green's function that obeys the free surface condition (3) where D equals zero. In general the boundary conditions on the ship are given in the form:

$$\nabla\phi.n = V(x) \quad \text{for } x \in S \tag{5}$$

This leads to an equation for the source strength:

$$-2\pi\sigma(x) - \iint_S \sigma(\xi)\frac{\partial}{\partial n_x}G(x,\xi)dS_\xi + \frac{U^2}{g}\int_{WL}\alpha_n\sigma(\xi)\frac{\partial}{\partial n_x}G(x,\xi)ds_\xi + \frac{i\omega}{g}\iint_{FS}\frac{\partial}{\partial n_x}G(x,\xi)D\{\phi\}dS_\xi = 4\pi V(x) \quad \text{for } x \in S \tag{6}$$

This equation can be solved iteratively in principle, however, the numerical evaluation of the Green's function is rather time consuming. Therefore we make use of the fact that U is small, keeping in mind that there are two dimensionless parameters that play a role, namely:

$$\tau = \frac{\omega U}{g} << 1 \text{ and } \nu = \frac{gL}{U^2} >> 1$$

The source strength and the potential function can be evaluated as follows:

$$\sigma(\xi) = \sigma_0(\xi) + \tau\sigma_1(\xi) + \dot{\sigma}(\xi;U) \tag{7}$$

$$\phi(x) = \phi_0(x) + \tau\phi_1(x) + \dot{\phi}(x;U) \tag{8}$$

where $\dot{\sigma}$ and $\dot{\phi}$ are $O(\tau^2)$ as $\tau \to 0$, while the expansion of G is less trivial, see [4]. Computations can be carried out by means of a modification of the existing fast code.

WAVE DRIFT FORCES

In [4] we described a way to compute the first order forces and the second order mean drift forces. The method we used there was based on a direct pressure integration of the first and second order pressures respectively. It has been shown before [5] that this method works well and is even necessary in order to compute the slowly varying drift forces in irregular waves.

At this moment we are mainly interested in the constant component of the drift force. In this section we apply a method that leads to results that are more accurate numerically. This method is the one that in the past led to the first results of the drift forces [6, 7]. Maruo [6] and later Newman [7] have derived an expression for the wave drift forces and moments in still water.

The mean drift forces and moments may be expressed as [7]:

$$\bar{F}_x = -\overline{\iint_{S_\infty} [p\cos\theta+\rho V_R(V_R \cos\theta-V_\theta\sin\theta)]Rd\theta dz} \quad (9)$$

$$\bar{F}_y = -\overline{\iint_{S_\infty} [p\sin\theta+\rho V_R(V_R \sin\theta-V_\theta\cos\theta)]Rd\theta dz} \quad (10)$$

$$\bar{M}_z = -\rho\iint_{S_\infty} \overline{V_R V_\theta R^2 d\theta dz} \quad (11)$$

where p is the first order hydrodynamic pressure, V is the fluid velocity with radial and tangential components V_r, V_θ and S_∞ is a large cylindrical control surface with radius R in the ship-fixed coordinate system. Faltinsen and Michelsen [8] derived from these formulas expressions in terms of the source densities of the first order potentials in the case of zero speed at finite depth. We follow a similar approach from:

$$\sigma = \sigma^{(7)} + \sum_{j=1}^{6} \sigma^{(j)}\bar{\alpha}_j \quad (12)$$

where $\alpha_j = \bar{\alpha}_j e^{-i\omega t}$, $j = 1(1)6$ are the six modes of motion and the superscript 7 refers to the diffracted component of the source strength. However in our case, the velocity potential has the form:

$$\Phi(x,t) = Ux + \bar{\phi}(x;U) + \phi(x;U)e^{-i\omega t}$$

$$= Ux + \bar{\phi}(x;U) + \{\phi^{(0)}(x;U) + \phi^{(7)}(x;U)$$

$$+ \sum_{j=1}^{6} \phi^{(j)}(x;U)\bar{\alpha}_j\}e^{-i\omega t} \quad (13)$$

where the potentials $\phi^{(j)}(x;U)$, $j = 1,7$ have the form (4) and are the potentials due to the motions and the diffraction. We assume that they are all determined by means of the source distributions $\sigma^{(j)} = \sigma_0^{(j)}+\tau\sigma_1^{(j)}$.

We find the following expression for the drift force $\bar{F}_x$ after some lengthy manipulations (see Hermans [9]):

$$\bar{F}_x = F_x^{(1)} + F_x^{(2)} \quad (14)$$

with $\bar{F}_y$ defined accordingly and with

$$F_x^{(1)} \simeq A\sqrt{\frac{2\pi}{\bar{k}}}\, F(\beta^*)\cos(S(\beta^*) + \tfrac{\pi}{4})(\cos\beta) + O(\tau^2) \quad (15)$$

where

$$A = -\frac{\rho\omega^2}{2\omega_0}\zeta_a \quad \text{and} \quad \beta^* = \beta - 2\tau\sin\beta \quad (16)$$

and $\bar{k} = \omega_0^2/g$.

The second part of the wave drift force may be analyzed in the same way. We obtain:

$$F_x^{(2)} \simeq -\frac{\rho}{4}\bar{k}\int_0^{2\pi} F^2(\theta)\{\cos\theta - 2\tau\sin\theta^2\}d\theta + $$

$$+ O(\tau^2) \quad (17)$$

and for $F_y^{(1)}$ and $F_y^{(2)}$:

$$F_y^{(1)} \simeq A\sqrt{\frac{2\pi}{\bar{k}}}\, F(\beta^*)\cos(S(\beta^*) + \tfrac{\pi}{4})\sin\beta + O(\tau^2) \quad (18)$$

and

$$F_y^{(2)} \simeq -\frac{\rho}{4}\bar{k}\int_0^{2\pi} F^2(\theta)\{\sin\theta(1 + 2\tau\cos\theta)\}d\theta + $$

$$+ O(\tau^2) \quad (19)$$

The function $F(\theta)$ is the Kochin function which describes the behaviour of the potential for large distances (see Huijsmans [13]).

RESULTS OF COMPUTATIONS AND MODEL TESTS

In order to apply the above described method computations have been carried out on an LNG tanker. The particulars of the LNG tanker are given in Table 1, while the small body plan is given in Fig. 2.

For the computations the tanker was schematized by means of a panel distribution. The number of facets that were used amounts to 1024 on the whole body surface. The panel description of the tanker is given in Fig. 3.

In order to incorporate the influence of the stationary potential solution into the unsteady motion potential the stationary double body potential has been computed. Use is made of the Hess and Smith procedure. For this purpose the free surface was extended to a maximum of two ship lengths and three ship breadths. Fig. 4 shows the free surface surge velocities around the sailing vessel (or the vessel in head current). In this condition the deviation from the unit velocity is relatively small. More deviation can be expected when the vessel is moored in a cross current. In Fig. 5 the free surface surge and sway velocities around the tanker in a cross current are shown. Taking into account the velocity profile in the free surface the developed theory for the wave drift forces were carried out for a set of regular waves. The computations were carried out for head waves only.

The results of the computations in terms of the quadratic transfer function of the wave drift force for zero and 1.5 m/s forward speed are presented in Fig. 7. In the same figure the quadratic transfer function of the surge wave drift damping is given. The result of the wave drift damping is approximated according to Ref. [1]:

Table 1 Particulars of the LNG tanker

Designation	Symbol	Unit	Magnitude
Length between perpendiculars	L_{pp}	m	273.0
Breadth	B	m	42.0
Draft	T	m	11.5
Displacement volume	∇	m^3	98,740
Centre of gravity above keel	KG	m	13.70
Centre of buoyancy forward of section 10	FB	m	2.16
Metacentric height	GM	m	4.0
Longitudinal radius of gyration in air	k_{yy}	m	62.52
Natural pitch period	T_ϕ	s	8.8
Waterplane coefficient	C_W	-	0.805
Midship section coefficient	C_M	-	0.991
Block coefficient	C_B	-	0.75

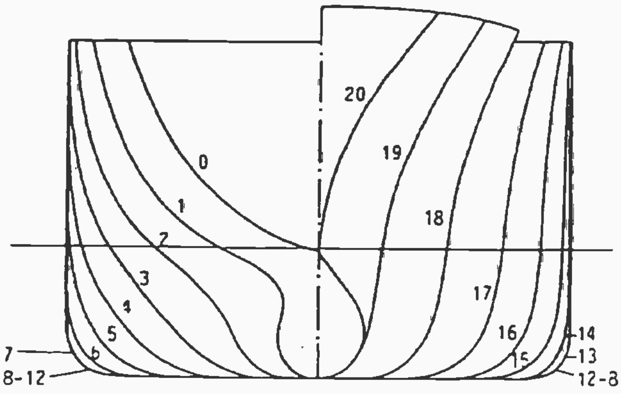

Fig. 2 Small body plan of the LNG tanker

$$B_x(\omega)/\zeta_a^2 = (\bar{F}_x(U,\omega)/\zeta_a^2 - \bar{F}_x(0,\omega)/\zeta_a^2)/U \qquad (20)$$

in which:

U = undisturbed sailing or current speed

ω = earth-bound wave frequency for sailing speed or current bound for current condition.

From the results it can be concluded that with regard to the quadratic transfer function of the wave drift force at zero speed the transfer function for 1.5 m/s increases considerably between ω = 0.55 and 0.75 rad/s. As a result the wave drift damping will be large in this frequency range also. The measured wave drift damping values as derived from decay tests in waves (Ref. [1]) corresponds well with the computed curve.

In order to study the speed dependency of the wave drift forces model tests with a sailing LNG tanker were carried out. The tanker was exposed to a set of regular waves incoming from ahead and the bow quarter. The tests were carried out in the Seakeeping Laboratory of MARIN measuring 100 x 24.5 x 2.5 m. The scale was 1:70. The mean wave drift forces in surge direction were measured (added resistance) for Froude numbers Fn = 0.14, 0.17 and 0.2. For full scale the sailing speeds correspond to 7.2, 8.74 and 10.29 m/s respectively. The results of the measurements are given in Fig. 6. In the same figure the results of the computed mean wave drift force in head waves for Fn = 0.0 and 0.029 (1.5 m/s) are indicated, while for bow quartering waves the computed mean wave drift force for Fn = 0.0 is given. Fig. 6 clearly shows the important effects of small forwards speed (current speed) on the wave drift forces.

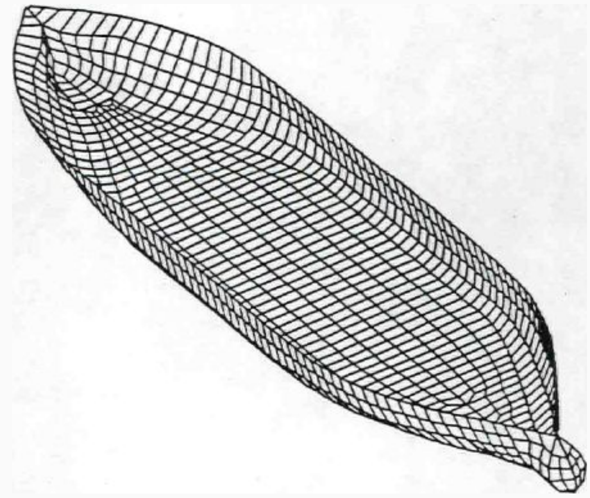

Fig. 3 Facetization of the LNG tanker

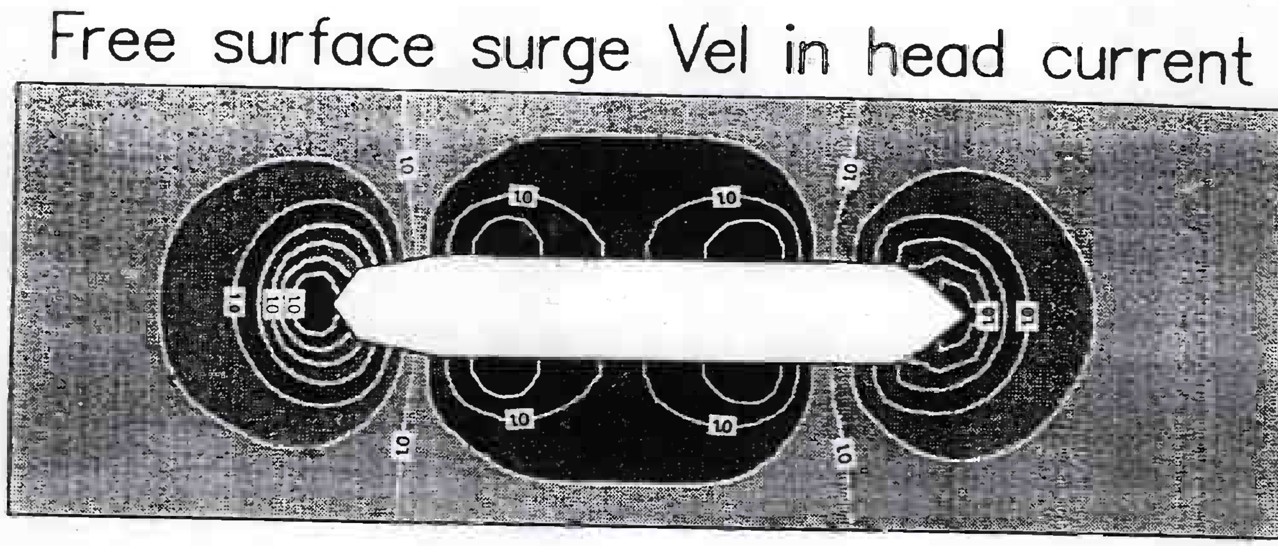

Fig. 4. Profile in head-on current

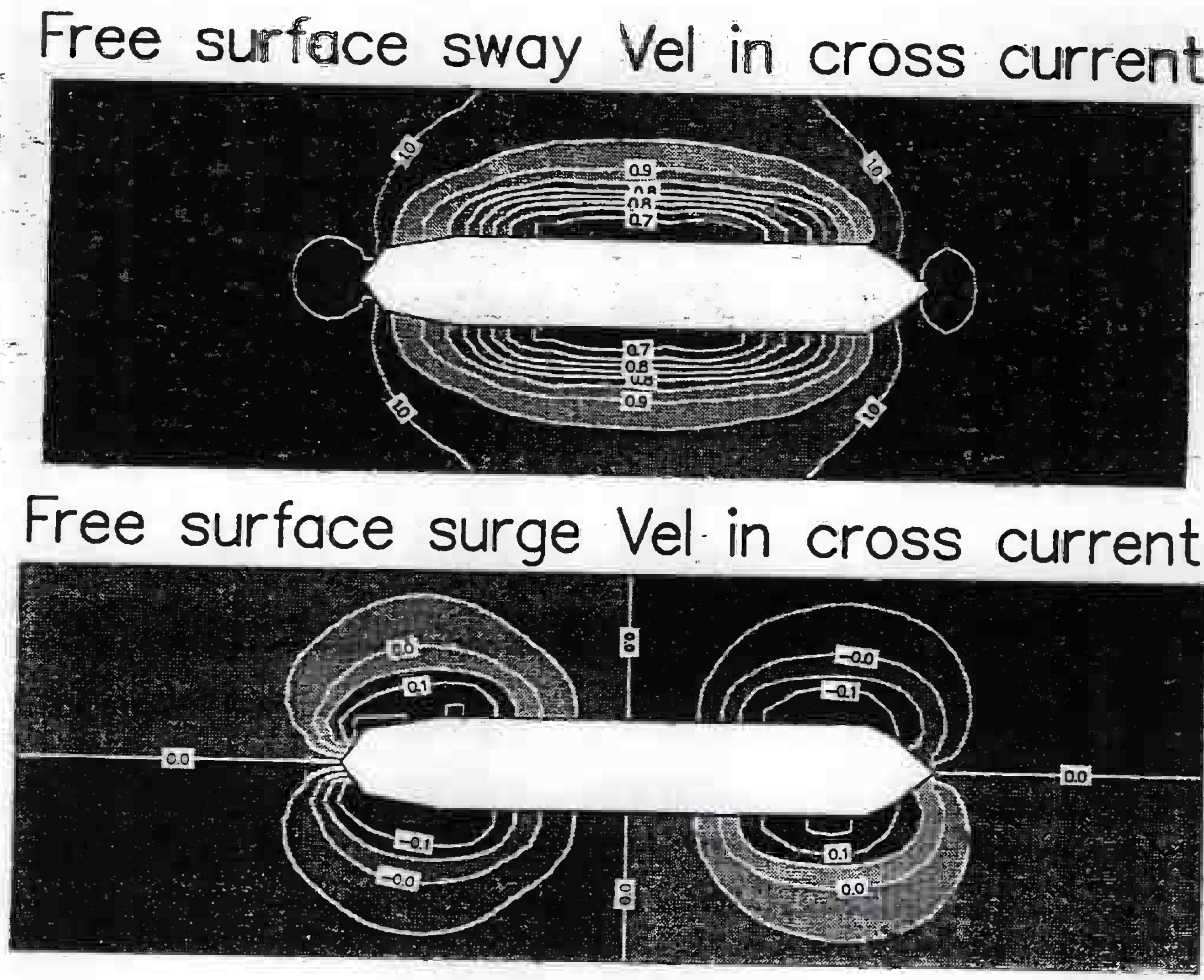

Fig. 5. Profile in cross current.

For the LNG tanker sailing in bow quartering waves the effect of the speed (current) on the wave drift force seems to be even larger. Interpolation between the computed data (Fn = 0.0) and measured points (Fn = 0.14, 0.17 and 0.2) shows that the magnitudes of the quadratic transfer function of the wave drift force for small forward speed may be relatively large, see Fig. 8. As a consequence the wave drift damping may be large too.

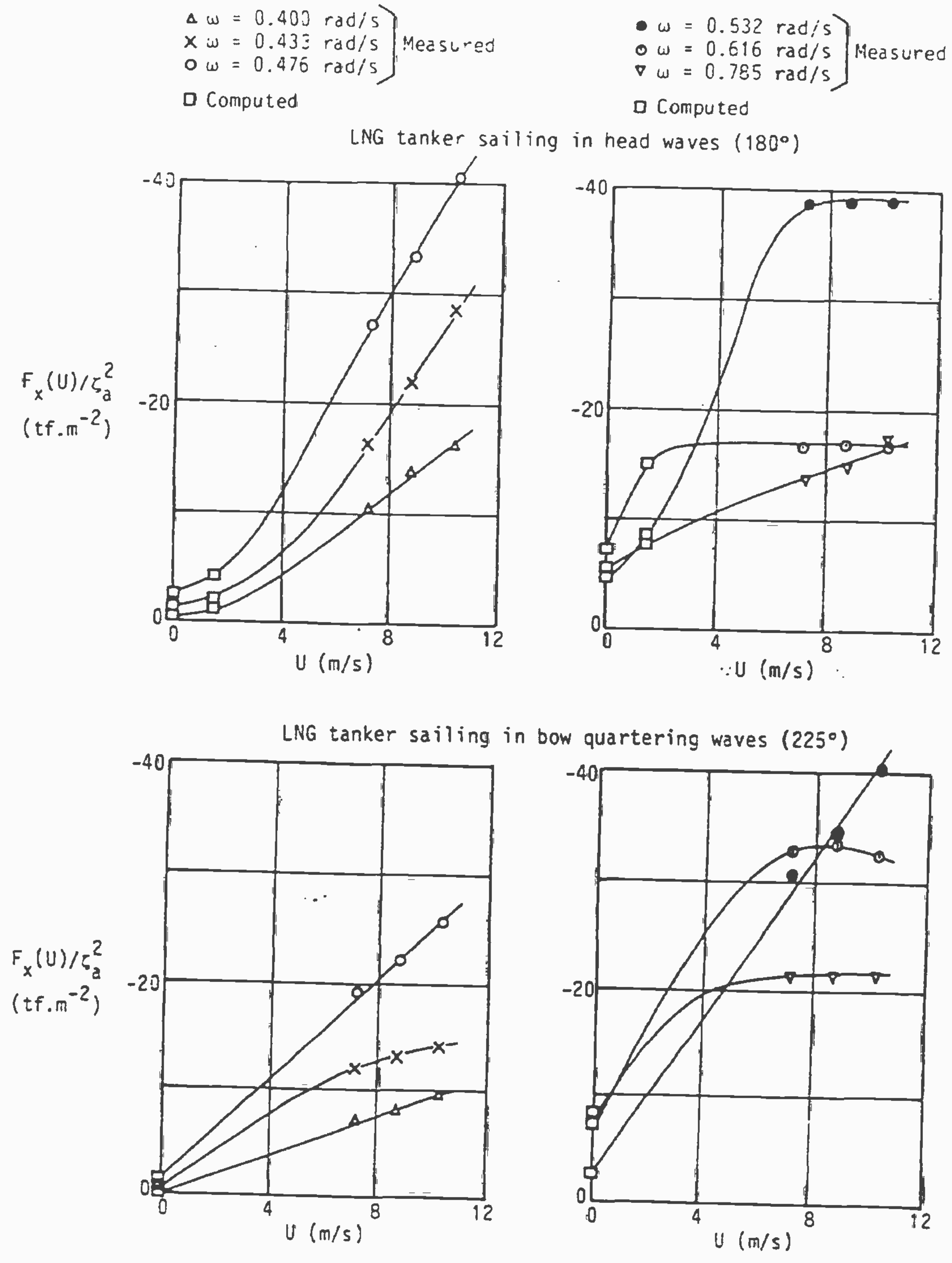

Fig. 6. Measured and computed quadratic transfer function of the wave drift force as function of forward speed in head and bow quartering waves (earth-bound frequencies)

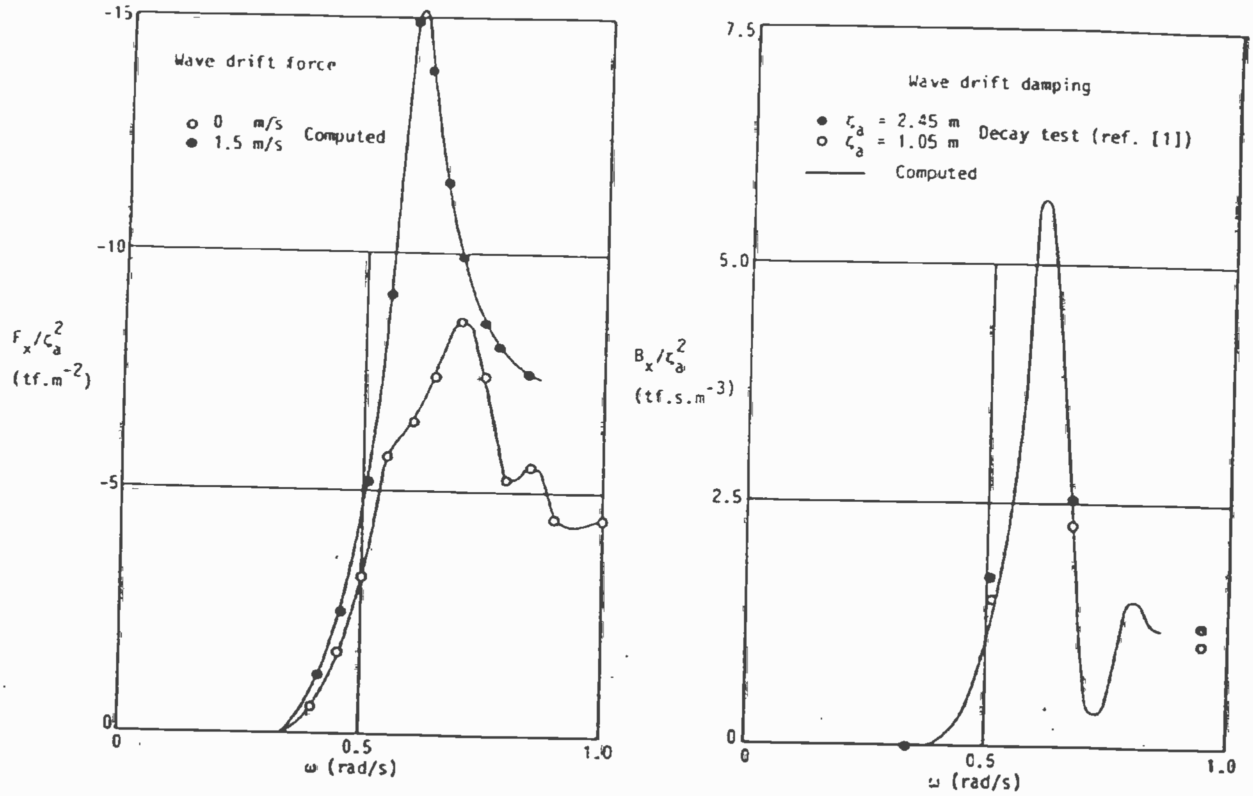

Fig. 7. Quadratic transfer function of wave drift force and wave drift damping for an LNG tanker sailing in head waves (earth-bound wave frequencies)

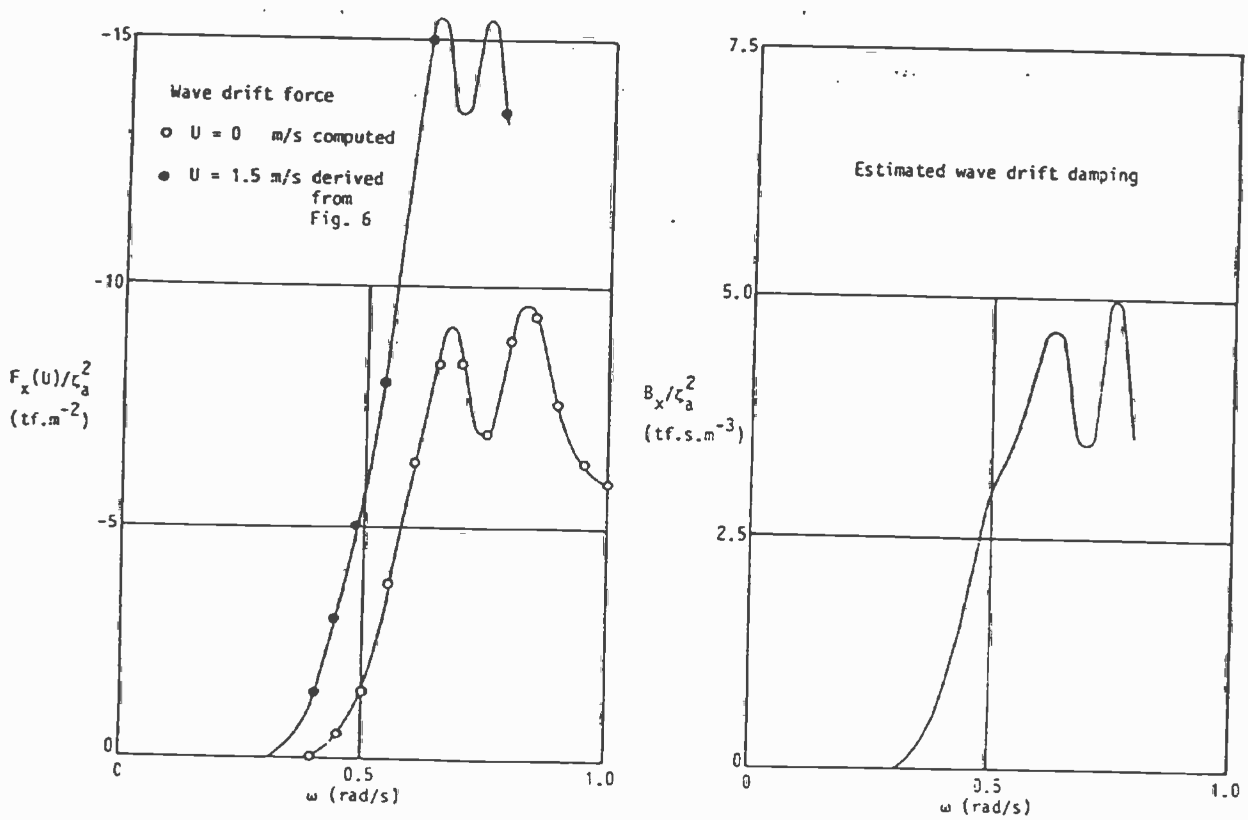

Fig. 8. Quadratic transfer function of wave drift force and wave drift damping in bow quartering waves (earth-bound wave frequencies)

CONCLUSION

The interaction of current and waves can lead to a strong increase of the values of the transfer function of the wave drift force. In this paper the speed dependency of the drift forces is restricted to the surge direction for a vessel sailing in head and bow quartering seas.

In this paper a new theory is presented where the current profile is taken into account for the computation of the unsteady first order potential and an alternative of Maruo's expression for the conservation of impulse is used to compute the wave drift forces. By means of this theory the speed dependency of the wave drift forces and the associated wave drift damping for arbitrary wave and current direction may be computed more precisely.

The computed results for the tanker in head waves are encouraging. In the future the results for arbitrary wave and current direction will published.

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