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IMPROVEMENT OF SEAKEEPING PREDICTION METHODS FOR HIGH SPEED VESSELS WITH A TRANSOM STERN

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ABSTRACT

In the majority of applications of a translating-pulsating source Green's function method for the seakeeping problem, the influences of the steady flow past the vessel and the flow behind the transom are either not accounted for or accounted for in a simplified manner. In this study, the surface of the hollow cavity region behind the dry transom is replaced by a flexible appendage whose shape is derived from the steady flow problem. The final shape of the appendage is determined by means of an iterative numerical scheme of study, concluded when the atmospheric pressure and kinematic conditions are satisfied on the modified flexible appendage. This final shape of the flexible appendage is used in the subsequent calculation of the steady flow potential and its first and second derivatives using a Kelvin wave-making source potential method. The linear body boundary condition for the unsteady motions' problem is then calculated using the full m-terms. The method is applied to predict the heave and pitch motions of the NPL mono-hull irregular head waves for a forward speed corresponding to a Froude number of 0.53.

INTRODUCTION

The development of mono- and, especially, multi-hulled vessels capable of sustaining high speeds in all-weather conditions has been the predominant driving force for progress in analytical seakeeping in the past decade or so. Many of the resultant mono- or multi- hulled forms are characterised by a transom stern because of benefits in housing powerful water jets, reduced resistance compared to hulls with streamlined sterns, position of flow separation etc. Doctors and Day (1997) discussed these benefits and observed that at sufficiently high speeds, the transom runs dry with a three-dimensional hollow cavity shape attached to the stern and a rooster tail plumed wake generated well aft of the stern. This highly non-linear flow region around and off the stern is accompanied by spray, entrained bubbles in the fluid, unsteadiness, etc and to understand and model the inherent complex phenomena involved, simplification is necessary. In general, the flow behind a transom stern leaves tangentially to the hull and on the nearby free surface atmospheric pressure and kinematic conditions hold.

The relatively fast pace of the development of hull types and forms, suitable for high speed operations, created difficulties in obtaining and comparing resistance and seakeeping characteristics through time consuming model tests. This resulted in bringing to the forefront numerical methods capable of accurately predicting such characteristics. Use of the boundary element method (BEM) to solve the three-dimensional potential flow problem for a ship moving in calm water and in waves offers the possibility of a range of efficient numerical methods, as a result of increasing computational power. For example Inglis and Price (1981, 1982) used Green's functions for the pulsating and the translating-pulsating source to predict rigid body motion characteristics in regular waves. These Green's functions satisfy the speed independent and speed dependent mean free surface boundary conditions respectively, thus, requiring source distribution over the mean wetted surface of the hull alone.

An alternative to the ship motion problem with forward speed involves the use of the time domain Green's function (see for example King et al 1988). Another alternative approach is based on the use of the Rankine source, as applied for example by Nakos and Sclavounos (1990). As the Rankine source does not satisfy the free surface condition, this method requires the distribution of singularities on the free surface as well as the hull-wetted surface. The influence of the steady flow, modelled using a double body approximation is included in this work through the so-called m-terms.

Inglis and Price (1981) incorporated the influence of the steady flow in the body boundary condition, through the use of suitable m-terms, using both pulsating and translating-pulsating source distributions. In this work, the steady flow was modelled by a translating source Green's function. Fang and Lin (2000) used the Kelvin wave-making source to incorporate the influence of the steady flow, through the body boundary condition, on the hydrodynamic coefficients of Wigley and Series 60 hull forms. Ahmed et al (2004) investigated the influence of the steady flow on the prediction of the unsteady hydrodynamic coefficients, exciting forces and moments and motions, using pulsating and translating-pulsating source Green's functions. This was done by expressing the complete linear body boundary condition for the unsteady problem, on the mean wetted surface, as a function of the first and second derivatives of the steady potential, through the so-called m-terms. The method was applied to a Series 60 and a NPL hull form and comparisons were made with available experimental measurements.

Several researchers addressed some of the issues relating to the flow behind the transom for the steady (or wave-making resistance) problem. For example, Molland et al (1994) and Couser et al (1998) introduced the concept of a virtual appendage attached to the transom. This encloses the separated flow at low forward speeds and the hollow cavity in the high-speed range. This rigid and prescribed appendage shape is a geometrically smooth addition to the vessel with all longitudinal lines meeting at a single point on the free surface. The length of the appendage is experimentally determined and is a function of Froude number and beam, B to draught, T ratio. Doctors and Day (1997) modified this approach accounting for continuity of hull slope, geometric aspects of the stern, influence of forward speed, sinkage and trim. All reported that this approach produced favourable agreement between numerical predictions and model wave-making resistance results for a wide range of forward speeds. Du et al (2003) presented a practical approach for analysing the transom stern influences on the steady flow hydrodynamic characteristics, based on the hydroelasticity theory. The surface of the hollow cavity region was replaced by a flexible appendage (e.g. a massless thin shell or beam framework) whose final shape is determined by an iterative numerical scheme of study ensuring that the atmospheric pressure and kinematic conditions are satisfied. The method was successfully applied to predict the wave-making resistance of a NPL mono-hull form and comparisons were made with available experimental measurements and other numerical predictions.

This study aims at incorporating the effects of the flow behind the transom stern on the unsteady (i.e. seakeeping) problem by "combining" the methods developed by Du et al (2003) and Ahmed et al (2004). The final shape of the flexible appendage, determined by the method of Du et al (2003), is used as input (hull + flexible appendage) into the Kelvin wave-making source potential method developed by Baar and Price (1988). Through this process the steady flow potential and its first and second derivatives are evaluated for use in the linear body boundary condition, over the mean wetted surface of the hull alone, through the so called m-terms. This "combined" approach is applied to a NPL round bilge, high-speed hull form, travelling in regular head waves at a Froude number of 0.53. Predicted hydrodynamic coefficients and motions for heave and pitch are compared with predictions obtained using a body boundary condition based on neglecting the interaction between the steady and unsteady flows (i.e. the simplified formulation for the m-terms). Comparisons are also made with predictions obtained using a body boundary condition based on incorporating m-terms that are evaluated without the influence of the flexible appendage (Ahmed et al 2004). The influence of the steady flow effects on the vessel's motion is then assessed by comparison with available experimental measurements (Molland et al 2001). Both pulsating and translating-pulsating source distributions are used when solving the unsteady problem.

1. MATHEMATICAL MODEL

A right-handed equilibrium axis system *Oxyz* translating with the forward velocity, U, of the vessel is adopted. The origin *O* lies on the mean free (calm water) surface and the longitudinal plane of symmetry of the vessel. *O* is vertically aligned with the vessel's centre of gravity. *Ox* is positive forward, towards the bow, *Oy* positive to port and *z* positive upwards. Vector quantities are denoted in bold in the subsequent formulation.

In the fluid region behind the transom stern, the fluid motion exhibits a strong non-linear behaviour. In this region, it is assumed that the fluid is homogenous, ideal and incompressible and the flow is irrotational allowing general kinematic and dynamic conditions to define, in non-dimensional form, the non-linear free surface condition (Du et al 2003)

$$\begin{aligned} &\frac{1}{2}\mathbf{W}\cdot\mathbf{W}+a(x,y)-\frac{1}{2}Fn^2=0, \quad (p_a=0), \\ &\mathbf{W}\cdot\mathbf{n}=0, \qquad \text{on } z_0=a(x,y) \end{aligned} \tag{1}$$

where, **W** denotes the steady fluid velocity defined in the *Oxyz* axis system, *a(x,y)* the free surface behind the dry transom stern, and **n** the normal vector to *a(x,y)*. It is assumed that the dynamic atmospheric condition $p_a = 0$ and the non-dimensional variables are based on ship length L and Froude number

$Fn = U/\sqrt{gL}$. The steady velocity potential, $\tilde{\phi}$ is given by

$$\mathbf{W} = Fn\,\nabla(\tilde{\phi} - x)\ . \qquad (2)$$

For the subsequent analysis, used in the evaluation of the steady potential and its derivatives, the following dimensional formulation is adopted (Baar and Price 1988). The velocity vector of the steady flow is given by

$$\mathbf{W} = U\,\nabla(\bar{\phi} - x) \qquad (3)$$

where $\bar{\phi}(x,y,z)$ is the velocity potential due to steady forward motion with speed U.

The unsteady linear velocity potential in regular waves can be expressed as

$$\phi = [\phi_0 + \phi_D + \sum_{j=1}^{6} p_j\phi_j]\exp(i\omega_e t) \qquad (4)$$

where ω_e denotes the encounter frequency of the regular waves, ϕ_0 the incident wave potential, ϕ_D the diffracted wave potential and ϕ_j (j=1,2...,6) the radiation potentials in each of the six rigid body degrees of freedom surge (p_1), sway (p_2), heave (p_3), roll (p_4), pitch (p_5) and yaw (p_6).

The influence of the steady flow is accounted for through the body boundary condition on the mean wetted surface of the hull for the radiation potentials. This may be expressed as

$$\frac{\partial\phi_k}{\partial n} = i\omega_e n_j + Um_j \quad for\ j = 1,2,...6 \qquad (5)$$

where

$$U(m_1, m_2, m_3) = -(\mathbf{n}.\nabla)\mathbf{W}$$

$$U(m_4, m_5, m_6) = -(\mathbf{n}.\nabla)(\mathbf{r}\times\mathbf{W})$$

and **r**= (x,y,z) and **n**=(n_1,n_2,n_3) are the position and normal vectors, respectively. Performing the requisite differentiation, it can easily be seen that the m-terms, for heave and pitch motions only, in equation (5) may be expressed as a function of the first and second derivatives of the steady flow velocity potential as follows, (Ahmed et al 2004):

$$m_3 = -(n_1\bar{\phi}_{zx} + n_2\bar{\phi}_{zy} + n_3\bar{\phi}_{zz}) \qquad (6a)$$

$$m_5 = -xm_3 + zm_1 + n_1\bar{\phi}_z - n_3(\bar{\phi}_x - 1) \qquad (6b)$$

where the indices in the steady velocity potential denote differentiation i.e. $\bar{\phi}_x = \partial\bar{\phi}/\partial x$ etc.

The steady and unsteady effects can be uncoupled by assuming that **W**=($-U$, 0, 0). In this case the m-terms reduce to

$$m_1 = 0 = m_2 = m_3 = m_4\ ;\quad m_5 = n_3\ ;\quad m_6 = -n_2\ . \qquad (7)$$

This corresponds to the case where the interactions between the steady and the unsteady problems are neglected.

The linear equation of motion in regular waves can be written as

$$\left[-\omega_e^{\,2}(m_{jk} + A_{jk}) + i\omega_e B_{jk} + C_{jk}\right]\left[p_k\right] = \left[F_j\right] \qquad (8)$$

where $m_{jk}, A_{jk}, B_{jk}, C_{jk}$ denote mass (or inertia), added mass, hydrodynamic damping and restoring coefficients respectively; F_j, p_k denote the wave exciting forces (or moments) and motions. Details of how the hydrodynamic coefficients and wave excitation terms are evaluated, when the full m-terms are included, are given by Ahmed et al (2004).

2. NUMERICAL RESULTS AND DISCUSSION

The influence of incorporating the steady-state potential in the unsteady problem, taking into account the flexible appendage in modelling the hollow cavity behind the transom, has been examined by applying the method for a NPL round bilge, high-speed hull form, travelling in regular head waves at a Froude number Fn=0.53. The principal characteristics of the model are shown in Table 1, where all symbols have their conventional meanings and S denotes the mean wetted surface area.

Table 1. Details of the NPL model

L(m)	L/B	B/T	$L/\nabla^{1/3}$	C_B	C_P	S(m^2)
1.6	11.0	2.0	8.5	0.397	0.693	0.276

The first stage is the modelling of the steady flow problem with the flexible appendage, depicting the hollow cavity behind the transom. The relevant values of running sinkage and trim are used in the idealisation (Couser et al 1998). The corresponding mean wetted surface of the hull itself is idealised using 312 four-cornered panels in total, as shown in Figure 1(a). 120 panels, in total, are used to describe the wetted surface of the flexible appendage for the hydrodynamic part of the procedure. The grid provided by this panel idealisation is used to construct a beam framework for the FE model of the flexible appendage. That is to say the nodes of the beam elements coincide with the panel vertices. Properties of these beam elements, e.g. Young's modulus, are selected based on accumulated experience (Du et al 2003). To commence the iterative scheme the initial form of the flexible appendage is assumed to be flat-tailed with the initial length set at four times the breadth at the transom. This shape satisfies a continuous structural transition from the transom to the hollow cavity behind it. Its final length is determined through the iterative scheme which continues until a balanced position is reached on the flexible appendage. That is to say, a local non-linear free surface condition with atmospheric pressure acting in the hollow cavity region, given by equation (1), is satisfied. At each iterative step the velocity and pressure distributions on the mean wetted surfaces of the hull and appendage, together, are calculated using the source distribution method. Based on this information the deformation of the appendage is determined, thus forming a new appendage in terms of shape and size. A new mesh, structural and hydrodynamic, is generated for the flexible appendage and the process continues until the aforementioned balance is attained. It should be noted that during this process the mean wetted surface of the hull remains unchanged and so does the number of panels depicting the appendage surface. The number of iterative steps required to obtain the final shape of the flexible appendage are of the order of 15 to 20, although this depends on the idealisation used and, especially, the speed of the vessel. The final shape of the appendage, for the NPL hull travelling at Fn=0.53, is shown in Figure 1(b). Several idealisations were used during this stage of the calculations to assess the influence of mesh refinement on the final appendage shape. It was concluded that the mesh with 120 panels on the appendage was good enough. One of these more refined meshes is shown in Figure 1(b). One final point to be made about stage one calculations concerns the boundary conditions at the connection between the appendage and the transom stern. This is important, as discussed by Du et al (2003), and based on this experience a nearly fixed (98%) boundary condition gives the best deformation results in terms of a stable and convergent iterative process.

The panel data describing the mean wetted surface of the NPL hull (312 panels) and the final shape of the flexible appendage surface (120 panels) obtained from the first stage are, subsequently, used for the modelling of the steady flow. In this second stage the Kelvin wave-making source distribution is used on the "combined" hull and appendage mean wetted surface. This stage of the calculations provides the requisite information for the calculation of the m-terms, described by equation (6), on the hull mean wetted surface alone. These are used in the body boundary condition, defined by equation (5), in the third and final stage of the analysis. It should be noted that in this stage the NPL hull form, whose mean wetted surface is idealised by 312 panels, is used. Both pulsating and translating-pulsating source distribution methods are used. Subsequently the hydrodynamic coefficients, exciting forces and moments and responses of equation (8) are calculated. The current application focuses on heave and pitch motions only, for the NPL hull travelling in regular head waves at Fn=0.53.

It is interesting to examine first the behaviour of some intermediate variables and assess the influence of the steady flow, with and without the effects of the flexible appendage. The terms m_3 and m_5 are shown in Figure 2, calculated at panel centres located at the stern and at amidships. The panel centres are identified by the z-coordinate only, which is referenced to the vertical position of the centre of gravity. That is to say 0.04m approximately corresponds to the mean waterline. It should also be noted that the simplified formulation, described by equation (7), is also provided for the m_5 term. As can be seen from this figure the inclusion of the flexible appendage, when accounting for the effects of the steady flow, has some influence in the vicinity of the transom, but this influence decreases away from the transom. The imaginary and real parts of the heave and pitch (radiation) velocity potentials on panels at the stern and amidships are shown in Figure 3, for ω_e=12 rad/s, when using the pulsating source distribution. In these figures there are three sets of curves per panel region, namely when using the simplified and full m-terms, with and without the influence of the flexible appendage for the latter. As can be seen the influence of the flexible appendage is very small at the stern panels and diminishes with distance from the transom region. One can clearly see from Figure 3 the influence of the steady flow on the velocity potentials.

The non-dimensional added mass and hydrodynamic damping coefficients are shown in Figure 4, using both pulsating and translating-pulsating source distributions. $[\rho\ (L/2)^n]$ and $[\rho\ (L/2)^n\ \omega_e]$ are used for the non-dimensionalisation of the added mass and hydrodynamic damping coefficients, respectively, where ρ denotes water density and n=3 for j=3=k, n=4 for j=3 or 5 and k=5 or 3, and n=5 for j=5=k. Based on the intermediate results shown in Figures 2 and 3, it is not surprising to see that the influence of including the flexible appendage when modelling the steady flow has negligible effects. The behaviour of A_{53} at very low frequencies appears to be the exception. This requires further investigation; nevertheless, this may be due to the lack of stability in the numerical procedures at such low frequencies. One can note, however, that the influence of the steady flow accounted for by the full m-terms is important. The non-dimensional total wave exciting heave force and pitch moment, shown in Figure 5, display some small influence due to the inclusion of the flexible appendage in the steady flow calculations, especially for the latter. $[\rho\ g\ a\ (L/2)^n]$ is used for the non-dimensionalisation, where a denotes the wave amplitude and n=2 and 3 for the heave force and pitch moment, respectively. Consequently in the heave (p_3/a) and pitch (p_5/ka, where k:wave number) RAOs, shown in Figure 6, the main differences are due to accounting for the influence of the steady flow, rather than the effects of the additional inclusion of the flexible appendage. Nevertheless, the appendage has some influence in the resonance region for both RAOs. This is especially notable in the heave RAO predicted by the pulsating source method, where the inclusion of the flexible appendage results in a prediction closer to that when the simplified form of the m-terms is used.

CONCLUSIONS

The flexible appendage concept was previously used successfully to model the hollow cavity behind the transom in the steady flow problem and better predictions for the wave-making resistance were obtained. The expectations, thus, were that by allowing for its effects in the steady flow when accounting for the steady flow influence in the unsteady (seakeeping) problem, better predictions of motions can be achieved. This indirect or uncoupled manner of taking into account the flow characteristics behind a dry transom resulted only in small differences in the hydrodynamic characteristics and motions of the NPL hull travelling at Fn=0.53 in regular head waves. Preliminary calculations with more refined idealisations confirm this conclusion. As the final shape of the flexible appendage varies with forward speed, further calculations will be carried out at higher Froude numbers to confirm these findings. A fully coupled approach for solving the unsteady problem of the hull with flexible appendage is not considered feasible at the moment.

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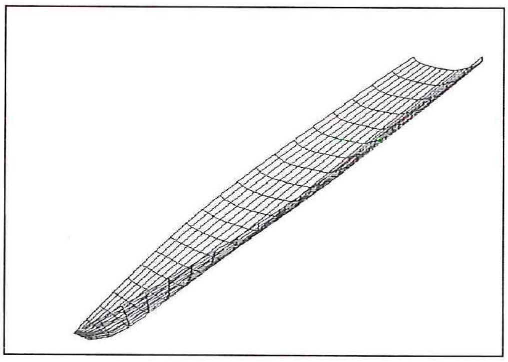

Fig.(1a). Idealization of the mean wetted surface of the NPL hull form (312 panels).

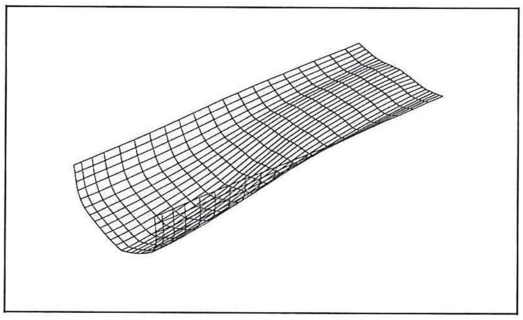

Fig.(1b). Final shape of the flexible appendage, depicting the hollow transom cavity for the NPL hull form traveling at Fn=0.53 (Refined idealisation).

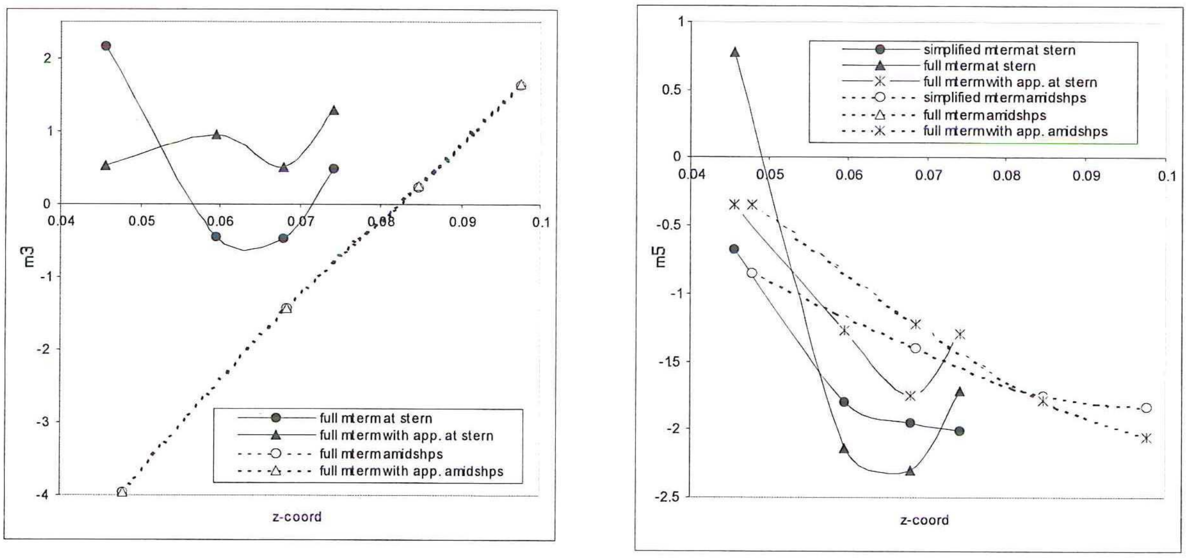

Fig.2. Comparison of the values of the m-terms for a NPL hull form travelling in regular head waves at Fn=0.53.

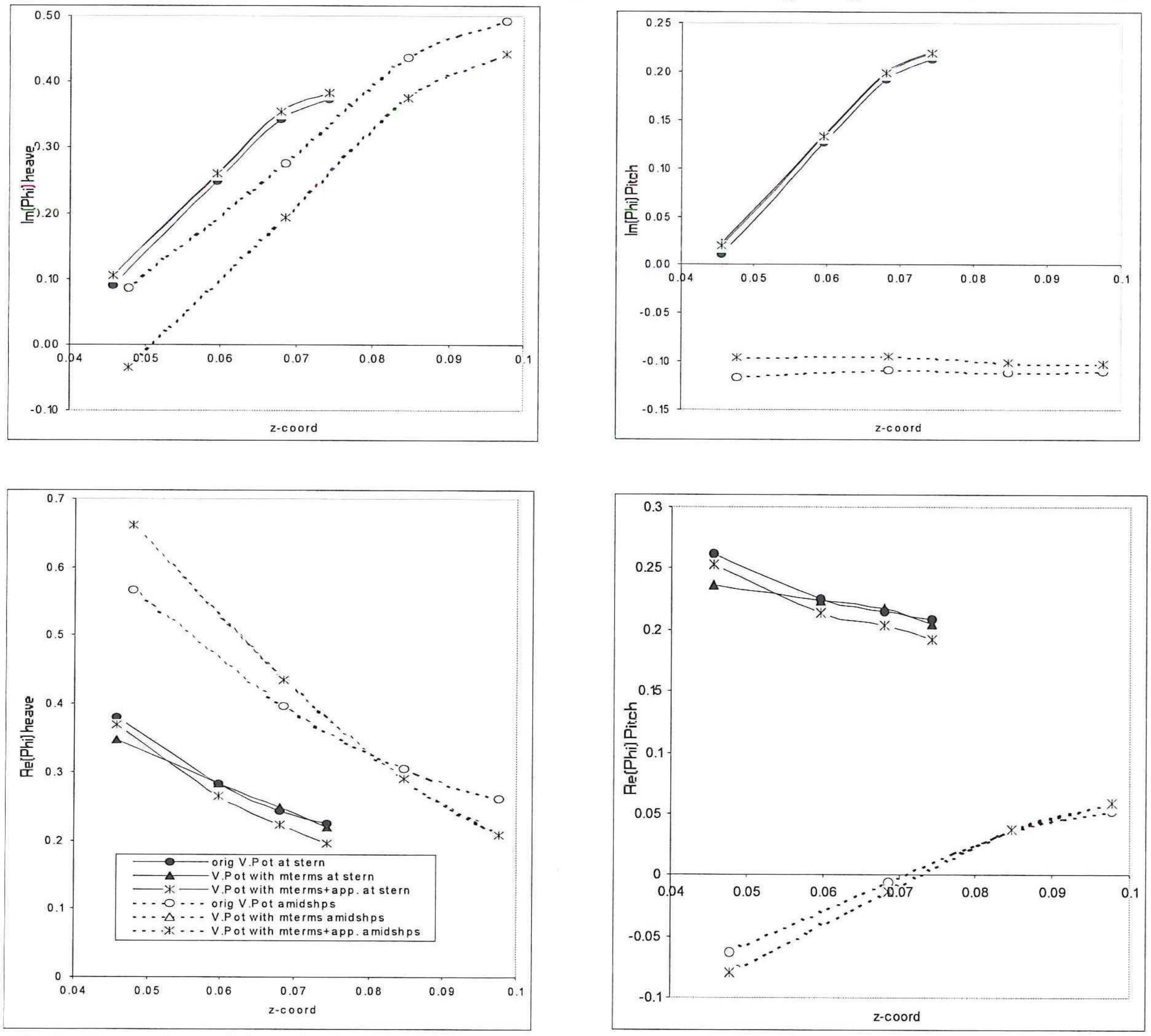

Fig.3. Comparison of the velocity potential (pulsating, ω_e=12 rad/s) for a NPL hull form travelling in regular head waves at Fn=0.53.

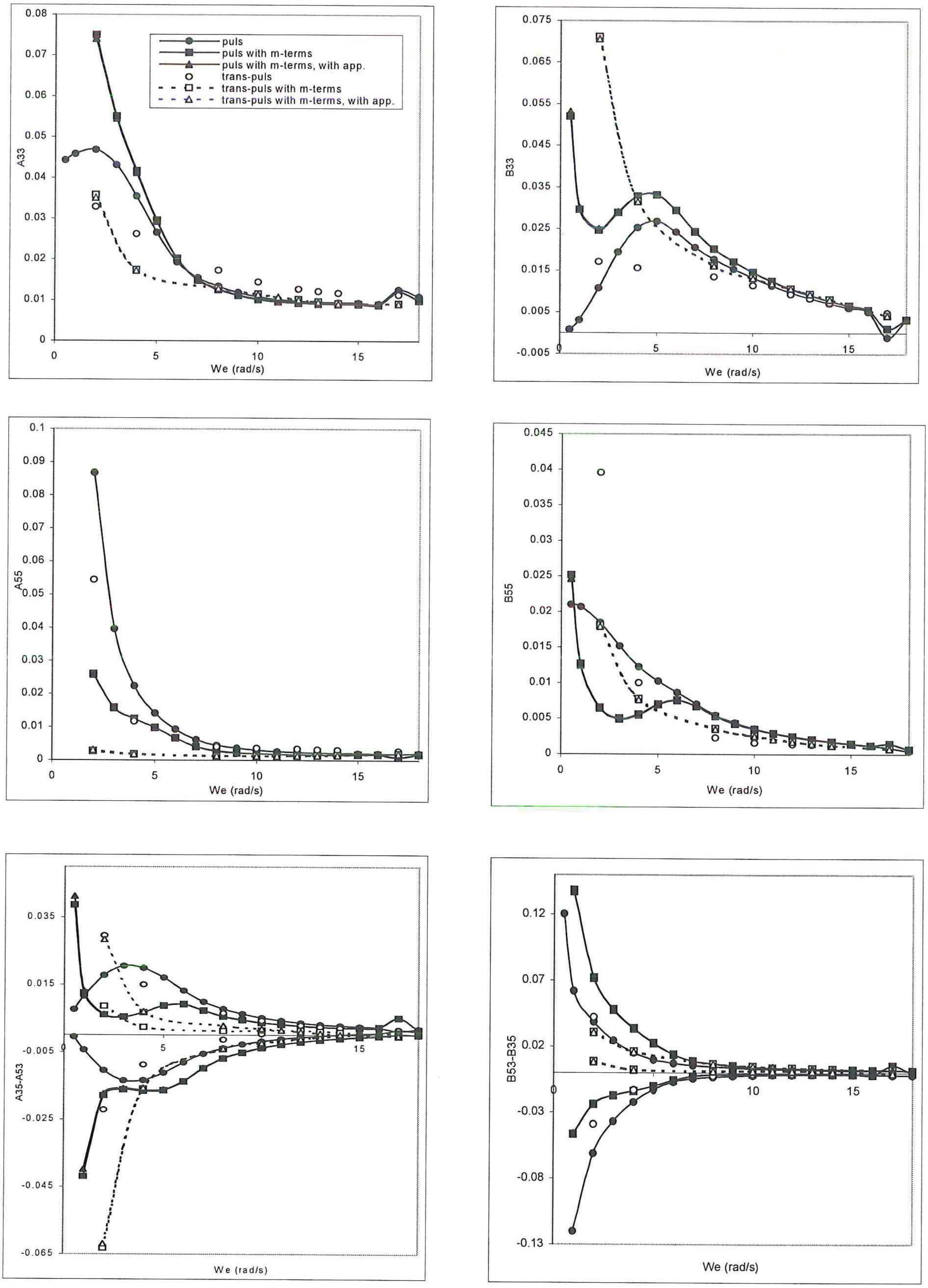

Fig.4. Influence of the steady flow, with and without the flexible appendage, on the non-dimensional hydrodynamic coefficients of heave and pitch for a NPL hull form travelling in regular head waves at Fn=0.53.

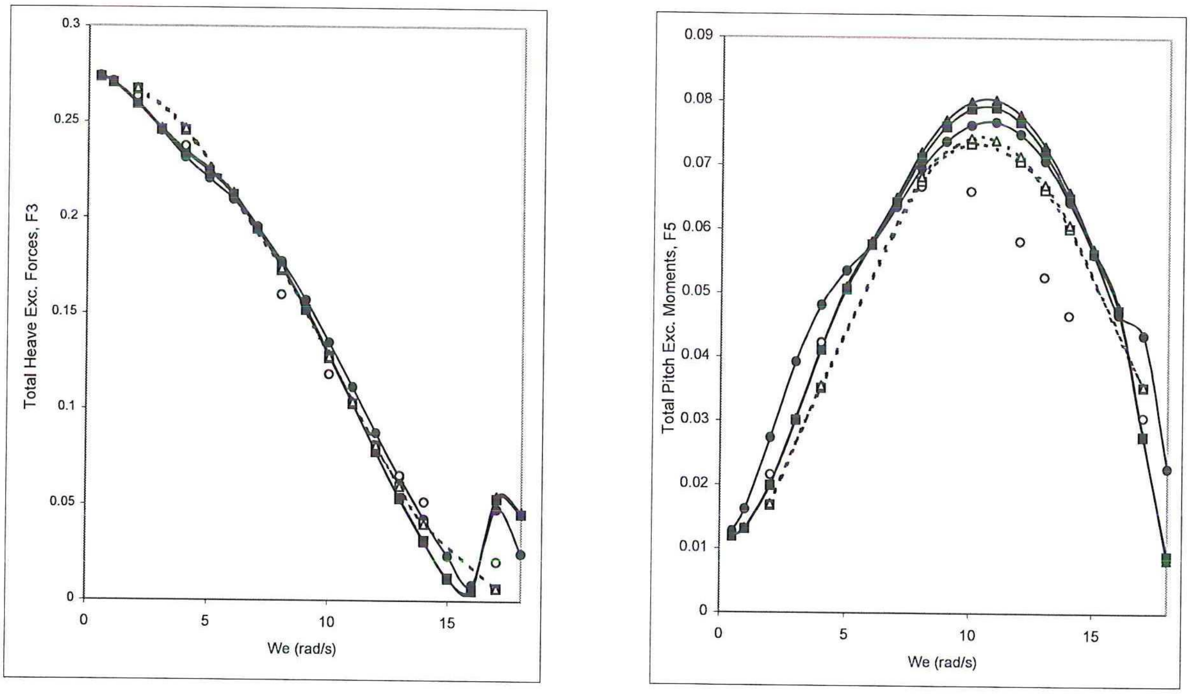

Fig.5. Influence of the steady flow, with and without the flexible appendage, on the non-dimensional total wave exciting heave force and pitch moment for a NPL hull form travelling in regular head waves at Fn=0.53.

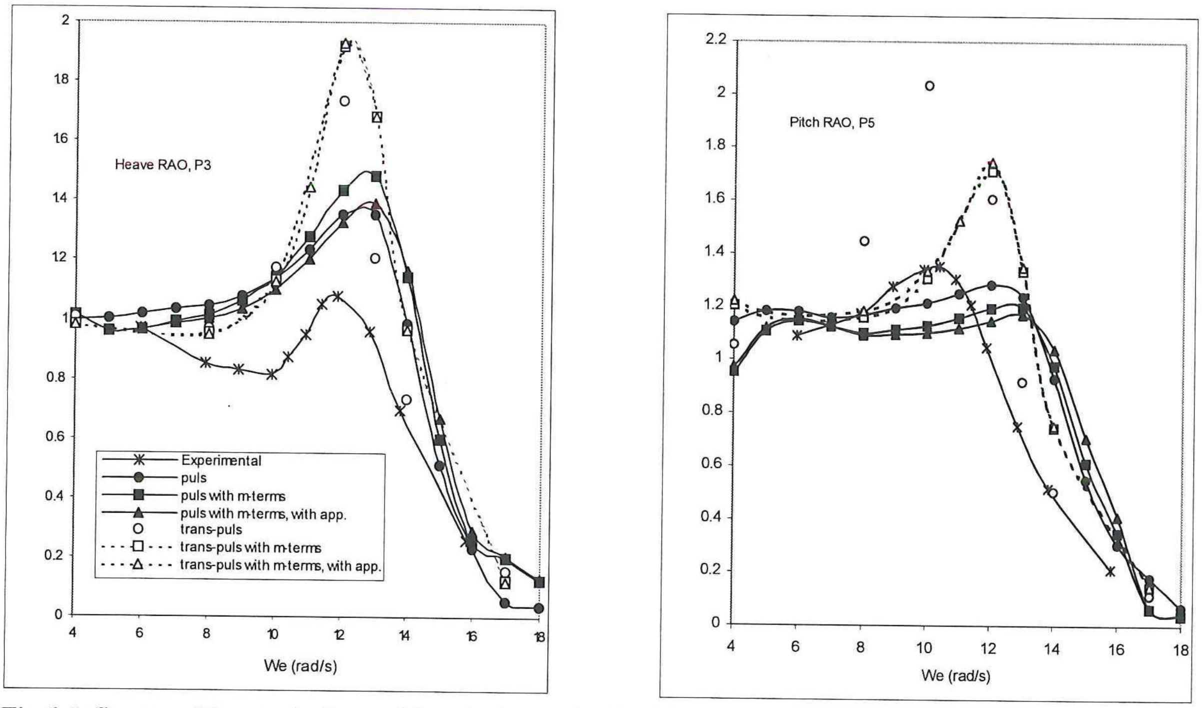

Fig.6. Influence of the steady flow, with and without the flexible appendage, on the heave and pitch RAOs for a NPL hull form travelling in regular head waves at Fn=0.53.