Analysis of Motions and Loads on a Catamaran Vessel in Waves

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ANALYSIS OF MOTIONS AND LOADS ON A CATAMARAN VESSEL IN WAVES

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ABSTRACT

A 3D Rankine panel method has been designed to calculate the steady and unsteady velocity potential around a twin hull vessel. Recently, model tests have been performed with a catamaran vessel in head waves. Results from these model experiments will be presented and compared with numerical results.

1 INTRODUCTION

The strip theory is a widely used method to calculate the motions of and loads on a vessel sailing in waves. The method gives in most cases satisfactory results while the calculation effort is minimal. However, since the strip theory is a 2D method the results become less satisfactory if 3D effects will get more pronounced, as can be expected by catamaran vessels. A typical 3D effect is the interaction of waves generated by the two hulls of the catamaran.

It is understood that for high forward speeds these interaction effects vanish since the waves generated by one hull cannot reach the other hull.

In a 3D Rankine panel method the interaction effects are automatically included since each panel will have its influence on all the other panels. Another important point is that a 3D panel method can predict the seascape around the vessel, which gives the possibility to look at for example the midship structure clearance or the wash behind the vessel.

In the next section the mathematical description of the Rankine panel method is presented and in Section 3 the numerical implementation is described. In Section 4 model test results are presented and compared with numerical results of the 3D Rankine panel method (Seascape) and with numerical results of a 2D strip theory program (Asap).

2 THE MATHEMATICAL MODEL

The mathematical model is expressed in a right handed Cartesian coordinate system attached to the vessel. The x-axis is pointing forward in the direction of the forward speed U of the vessel. The y-axis is pointing to port side and the z-axis is pointing upwards.

The flow is assumed to be incompressible and irrotational and can therefore be described by a velocity potential satisfying the Laplace equation $\Delta\Psi(\bar{x},t)=0$ in the whole fluid domain. To solve the flow problem a boundary value method is used, thus flow conditions have to be prescribed on each boundary. The boundaries of the flow domain are the underwater part of the hull surface, the free surface and the sea bottom. If the water depth is assumed to be infinite the sea bottom can be removed from the problem. A normal vector on a boundary surface is pointing into the fluid domain.

2.1 The exact boundary conditions

On the actual hull surface B the boundary condition that no water can penetrate the hull surface must be fulfilled, thus

$$\frac{\partial\Psi(\bar{x},t)}{\partial n}=\frac{\partial\bar{\alpha}}{\partial t} \quad \text{on B}$$

Equation (1)

where $\bar{\alpha}$ is the oscillatory displacement vector of the hull, which is zero if the vessel is sailing in otherwise undisturbed water. On the free surface the dynamic boundary condition has to be satisfied (the pressure on the water surface equals the atmospheric pressure), and the kinematic boundary condition has to be satisfied (the velocity of the water particles is tangential to the wave surface). Satisfying both conditions results in a non linear free surface condition on the yet unknown free surface elevation $z=\zeta(\bar{x},t)$,

$$\Psi_{tt}+2\nabla\Psi\cdot\nabla\Psi_t+\frac{1}{2}\nabla\Psi\cdot\nabla(\nabla\Psi\cdot\nabla\Psi)+g\Psi_z=0$$

Equation (2)

The wave elevation is given by the dynamic boundary condition,

$$\zeta(\bar{x},t)=-\frac{1}{g}(\Psi_t+\frac{1}{2}\nabla\Psi\cdot\nabla\Psi-\frac{1}{2}U^2)$$

Equation (3)

The boundary value problem governed by the Equations (1) and (2) is highly non linear and cannot be solved at once. Seeking a linear set of equations to solve the boundary conditions are linearised. With the assumption that the flow disturbance by the vessel is relatively small, the linearisation is allowed.

2.2 The linearised boundary conditions

To carry out the linearisation process the overall velocity potential is written as a summation of three velocity potentials, that is

$$\Psi(\bar{x},t)=\Phi(\bar{x})+\phi(\bar{x})+\varphi(\bar{x},t)$$

Equation (4)

The base flow $\Phi(\bar{x})$ is the double body flow, about which the problem will be linearised. The steady velocity potential $\phi(\bar{x})$ is related to the ship resistance problem and the unsteady velocity potential $\varphi(\bar{x},t)$ is related to the ship motion problem. These two potentials are assumed to be independent of each other, which makes it possible to solve the steady and unsteady problem separately.

The exact free surface boundary condition is found by substitution of Equation (4) in Equation (2). The result is a non linear equation in ϕ and φ on an unknown free surface. The first step in the linearisation procedure is to remove the non linearity of ϕ and φ leading to a linear equation on $z=\zeta$. The next step is to apply a Taylor expansion to express the boundary condition on $z=0$. The last step is separation of the steady and unsteady terms, leading to a steady and unsteady free surface condition.

The linearied steady free surface boundary condition on z = 0 is,

$$-g\varphi_z = \frac{1}{2}\nabla\phi \cdot \nabla(\nabla\Phi \cdot \nabla\Phi) + \nabla\Phi \cdot \nabla(\nabla\Phi \cdot \nabla\phi) - \Phi_{zz}\nabla\Phi \cdot \nabla\phi +$$
$$\frac{1}{2}\nabla\Phi \cdot \nabla(\nabla\Phi \cdot \nabla\Phi) - \frac{1}{2}(\nabla\Phi \cdot \nabla\Phi - U^2)(\Phi_{zz} + \phi_{zz})$$

Equation (5)

with the steady wave elevation,

$$\zeta(\bar{x}) = -\frac{1}{g}(\nabla\Phi \cdot \nabla\phi + \frac{1}{2}\nabla\Phi \cdot \nabla\Phi - \frac{1}{2}U^2)$$

Equation (6)

The linearised unsteady free surface boundary condition on is,

$$-g\varphi_{kz} = \varphi_{ktt} + 2\nabla\Phi \cdot \nabla\varphi_{kt} + \nabla\Phi \cdot \nabla(\nabla\Phi \cdot \nabla\varphi_k) + \frac{1}{2}\nabla\varphi_k \cdot \nabla(\nabla\Phi \cdot \nabla\Phi) -$$
$$\Phi_{zz}(\varphi_{kt} + \nabla\Phi \cdot \nabla\varphi_k) - \frac{1}{2}(\nabla\Phi \cdot \nabla\Phi - U^2)(g\varphi_{kzz} + \varphi_{kztt})$$

k=1,...,7

Equation (7)

where k=1,...,6 represent the modes of oscillation, the radiation potentials, and where k=7 represents the diffraction potential. The unsteady wave elevation on z = 0 can be written as,

$$\zeta(x,t) = -\frac{1}{g}(\varphi_t + \nabla\Phi \cdot \nabla\varphi)$$

Equation (8)

On the (mean) hull surface $\bar{B}$ the steady flow condition is,

$$\frac{\partial\phi(\bar{x})}{\partial\bar{n}} = 0 \quad \text{on } \bar{B}$$

Equation (9)

This hull surface is known so no linearisations have to be carried out.

In the unsteady problem the hull boundary condition has to be imposed on the actual hull surface B which is only known after the problem has been solved. If the oscillatory displacement vector $\bar{\alpha}$ is used the hull boundary condition, Equation (1), reads as,

$$\frac{\partial\varphi(\bar{x},t)}{\partial\bar{n}} = \frac{\partial\bar{\alpha}}{\partial t} \cdot \bar{n} - \nabla(\Phi + \varphi) \cdot \bar{n} \quad \text{on B}$$

Equation (10)

Equation (10) is linearised using the procedure described by Timman and Newman (1962).

$$\frac{\partial\varphi_a}{\partial n} = i\omega_e n_k + m_k \quad \text{k=1,...,6} \quad \text{on } \bar{B}$$

Equation (11)

The diffraction potential exist by virtue of the incoming wave. The boundary condition is

$$\frac{\partial\varphi_7}{\partial n} = -\frac{\partial\varphi_0}{\partial n} \quad \text{on } \bar{B}$$

Equation (12)

where the incoming wave potential is defined by,

$$\phi_0 = i\frac{g}{\omega_0} e^{-i\frac{\omega_0^2}{g}(x\cos\beta + y\sin\beta)} e^{\frac{\omega_0^2}{g}z} e^{i\omega_e t}$$

Equation (13)

3 THE NUMERICAL MODEL

3.1 Solving the double body flow

The double body flow is solved using an external Neumann formulation. The Neumann condition applied is that the normal component of the ship velocity equals zero.

For any point P on the (external) surface B of the non-lifting hull the integral formulation reads:

$$\frac{\partial\Phi(\bar{x}_P)}{\partial\bar{n}_P} = \frac{1}{4\pi}\iint_B \sigma(\bar{x}_Q)\frac{\partial G(\bar{x}_P,\bar{x}_Q)}{\partial\bar{n}_P}dS + \frac{1}{2}\sigma(\bar{x}_P) = -U_\infty \cdot \bar{n}_P$$

Equation (14)

where U² is the undisturbed free stream velocity infinitely far away from the vessel, and $\sigma(\bar{x}_P)$ represent the source strength in $\bar{x}_P$. No free surface is present since the vessel is mirrored in the still water plane. The Green's function is the Rankine source singularity,

$$G(\bar{x}_P,\bar{x}_Q) = \frac{-1}{r(\bar{x}_P,\bar{x}_Q)}$$

Equation (15)

The influence coefficients concerning the Green's function are calculated using the method described by Newman (1986).

If the strength of each source singularity is known the double body flow velocities can be calculated in any point of the fluid domain.

3.2 Solving the steady and unsteady flow

The steady and the unsteady flow are solved by applying Green's second identity on the fluid domain, resulting in the following integral formulation:

$$\frac{1}{2}\varphi(\bar{x}_P,t) + \frac{1}{4\pi}\iint_{FS,B}[\frac{\partial\varphi(\bar{x}_Q,t)}{\partial\bar{n}_Q}G(\bar{x}_P,\bar{x}_Q) - \varphi(\bar{x}_Q,t)\frac{\partial G(\bar{x}_P,\bar{x}_Q)}{\partial\bar{n}_Q}]dS = 0$$

Equation (16)

in which the Rankine source singularity is used as the Green's function. In Equation (16) the problem is written down for the unsteady potential $\varphi(\bar{x},t)$ but the same equation applies to the steady potential $\phi(\bar{x})$.

In the steady and the unsteady problem the boundaries of the fluid domain are the free surface and the hull surface.

The normal derivative of the velocity potential on the free surface in Equation (16) is expressed in its tangential derivatives using Equations (5) and (7) for the steady and unsteady problem respectively.

3.3 The discretisation scheme

The hull surface and the free surface are discretised using flat quadrilateral panels. An example of a typical catamaran free surface discretisation is given in Figure 1. In each panel a collocation point is selected in which the integral equation is discretised. A constant source and normal dipole singularity strength are distributed over each panel.

To obtain a solution for the steady or unsteady flow it is necessary to express the unknown velocity potential and its first and second derivatives in a common unknown. Sclavounos and Nakos (1988) showed that a bi-quadratic spline collocation scheme of cubic order can be utilised for this purpose.

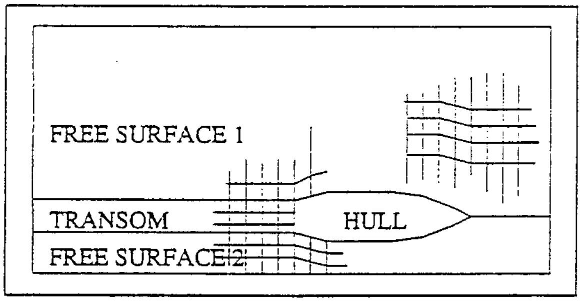

Figure 1: Typical catamaran free surface discretisation

3.4 A transom free surface sheet

Most existing catamaran vessels are fitted with a transom stern to install the waterjet propulsion system. Therefore the implementation of a (limited) transom stern must be possible.

It is understood that a transom stern with some immersion below the free surface introduces a significant non linear effect in the flow. And even if the transom stern has a zero or very limited immersion the stern wave system will be dramatically influenced by it.

The assumption is made that the flow leaves the transom edge tangential to the hull surface. This smooth separation condition is modeled as,

$$\frac{\partial\zeta_{tr}}{\partial x} = \arctan\bar{\alpha}_{tr} \quad \zeta_a = \eta_{tr} + h\arctan\bar{\alpha}_{tr}$$

Equation (17)

where $\bar{\alpha}_{tr}$ is the transom edge angle, η_{tr} is the transom edge elevation, and ζa is the wave elevation in the first collocation point at a distance h aft of the transom. The dynamic boundary condition is used to discretise Equation (17).

The solution of the double body flow for a hull with a small transom immersion is questionable, since the hull surface is not a closed surface any more. However, up till now no problems occured in finding the double body solution for the catamaran under consideration.

3.5 The m-terms

The m-terms as presented in the linearised hull boundary condition, Equation (11), were introduced by Ogilvie and Tuck (1969), and read as,

$$(m_1, m_2, m_3)^T = -(\bar{n}\cdot\nabla)\nabla\Phi$$
$$(m_4, m_5, m_6)^T = -(\bar{n}\cdot\nabla)(\bar{x}\times\nabla\Phi)$$

Equation (18)

In the m-terms second derivatives of the double body flow occur and they must be calculated with some care since they are known to introduce large numerical errors.

In the panel method presented here the second derivatives for a far field collocation point are calculated following the approach given by Newman (1986). For a near field collocation point Stoke's integral theorem is used to rewrite the surface integral over a panel to an integration along the panel edges, see Koning Gans (1994).

3.6 The overall motion equation

In the frequency domain the classical motion equation in six degrees of freedom read,

$$\sum_{j=1}^{j=6}[-\omega_e^2(M_{ij}+A_{ij})+i\omega_e B_{ij}+C_{ij}]\xi_j = F_i \quad \text{I}=1,\ldots,6$$

Equation (19)

where Mij is the mass matrix, $\xi_i = \bar{\xi}_i e^{i\omega_e t}$ is the complex excitation in the i-th mode with $\bar{\xi}_i$ as the motion amplitude, and where F_i is the complex exciting force in the i-th mode, which is a summation of the Froude Kriloff force and the diffraction force,

$$F_i = \rho\iint(i\omega_e(\varphi_0+\varphi_7)+\nabla\Phi\cdot\nabla(\varphi_0+\varphi_7))\bar{n}_i dS$$

Equation (20)

Using the unsteady radiation potential for the i-th mode of oscillation the pressure on the hull surface can be calculated, resulting in the hydrodynamic coefficients,

$$A_{ij} = \frac{\rho g}{\omega_e^2}\Re\iint_B(i\omega_e\varphi_j+\nabla\Phi\cdot\nabla\varphi_j)\bar{n}_i dS$$
$$B_{ij} = -\frac{\rho g}{\omega_e}\Im\iint_B(i\omega_e\varphi_j+\nabla\Phi\cdot\nabla\varphi_j)\bar{n}_i dS$$

Equation (21)

The restoring coefficients are given by,

$$C_{ij} = -\rho\iint_B\nabla(\frac{1}{2}\nabla\Phi\cdot\nabla\Phi+gz)\bar{n}_i dS \qquad j=1,2,3$$
$$= -\rho\iint_B(\bar{x}\times\nabla)(\frac{1}{2}\nabla\Phi\cdot\nabla\Phi+gz)\bar{n}_i dS \qquad j=4,5,6$$

Equation (22)

4 RESULTS

4.1 Model experiments, Catamaran 372

Model experiments have been carried out with a catamaran in the towing tank of Delft University, Van 't Veer (1997). The main particulars of the model are presented in Table 1 and a lines plane is given in Figure 2.

Table 1: Main characteristics of the Catamaran 372 (DUT cat) model

Length over all	3.11 m
Length between perpendiculars	3.00 m
Beam over all, B	0.94 m
Beam demihull, b	0.24 m
Distance between centerline demihulls, H	0.70 m
Draught, T	0.15 m
Displacement	87.07 kg
Trim	0.0 deg
Vertical center of gravity, KG	0.337 m
Longitudinal center of gravity, LCG	1.41 m
Pitch radius of gyration, k_{yy}	0.224 L
Length over beam ratio, L/b	12.5
Length over draught ratio, L/T	20.0
Block coefficient demihull	0.403

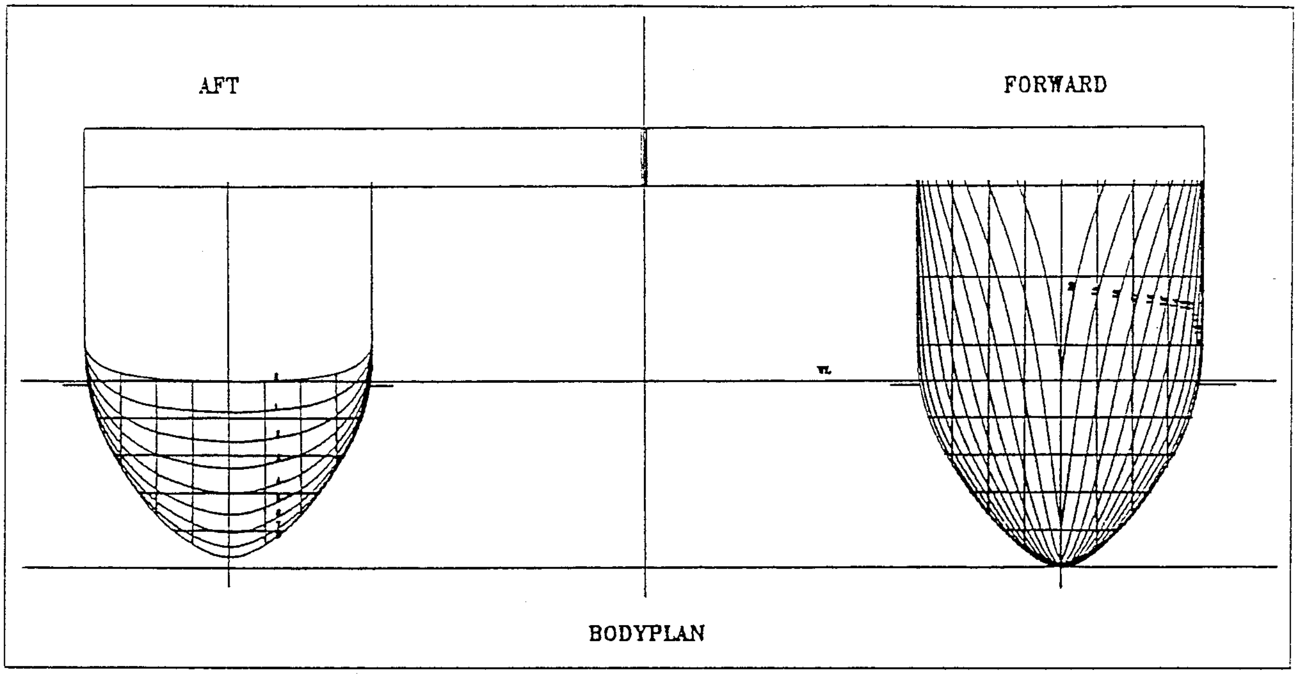

Figure 2: Lines plan catamaran 372 (DUT cat)

The following set of experiments have been carried out: 1) sinkage and trim measurement, Fn = 0.18 to Fn =0.75; 2) wave cut measurements during test series 1; 3) heave and pitch motion response measurements, Fn= 0.30, 0.45, 0.60 and 0.75 and; 4) heave and pitch oscillation test, Fn = 0.30, 0.45, 0.60 and 0.75.

During the still water test runs, a wave cut measurement was carried out at a distance of y=625 mm from the center plane of the model (that is y/(0.5 B) = 1.38). In Figures 3 and 4 the measurements are compared with the steady Seascape calculations for Fn = 0.30 and Fn = 0.60. During the run at Fn = 0.60 the measured trim of the catamaran was 2.1 degrees (bow up) and the sinkage was 7.9mm (down). If these quantities are included in the calculations by rebuilding the hull surface, a better comparison is found with the wave cut measurements.

The steady seascape at Fn = 0.45 is presented in Figure 5. The addition of a wake sheet behind the catamaran vessel, as was proposed by Kring and Sclavounos (1991) to obtain a smooth free surface wave elevation, is not applied in Seascape. Despite this fact, the wave elevation shows a smooth connection between the different calculation grids.

The heave and pitch motions in head waves are presented in Figure 6 for Fn = 0.30 and for Fn = 0.60 in the Figures 7 and 8. The agreement in heave for Fn = 0.30 is excellent but the prediction for pitch is less satisfactory. The comparison

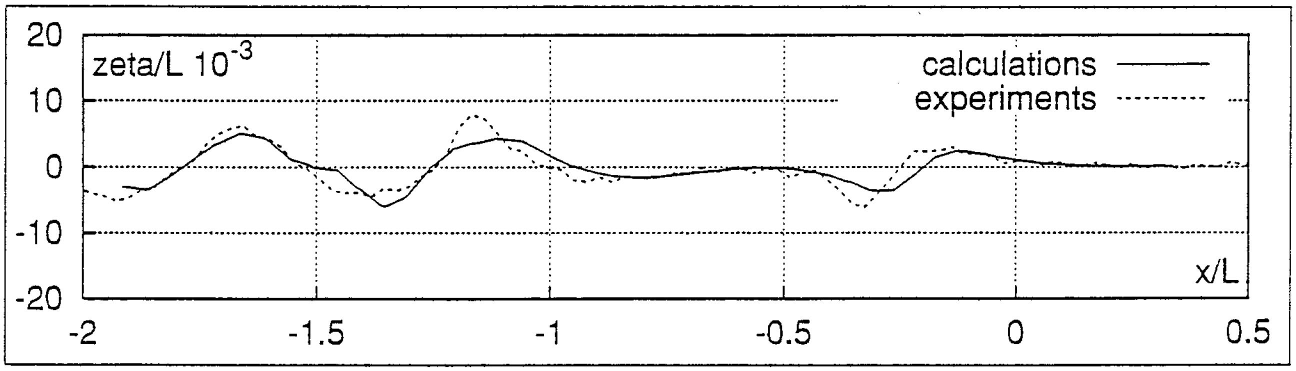

Figure 3: Wavecut measurement and Seascape calculations, DUT Catamaran, Fn = 0.30, y/0.5B = 1.38

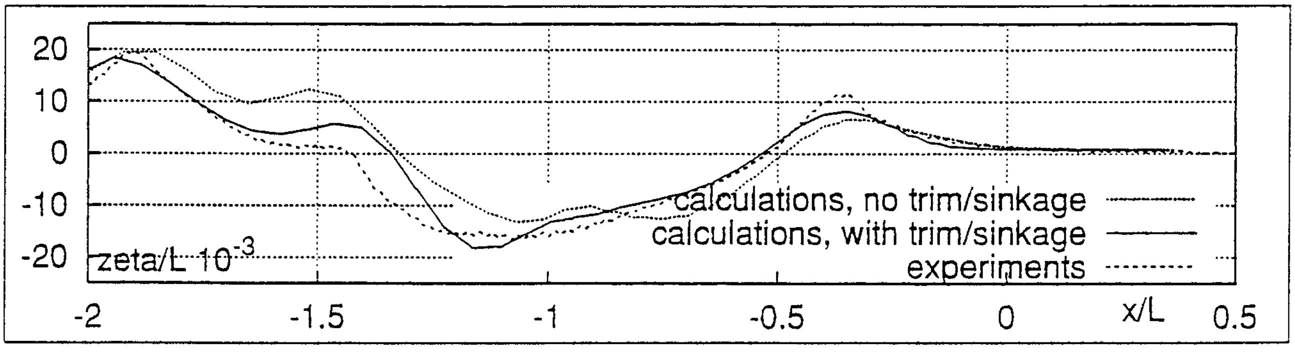

Figure 4: Wavecut measurement and Seascape calculations, DUT Catamaran, Fn = 0.60, y/0.5B = 1.38

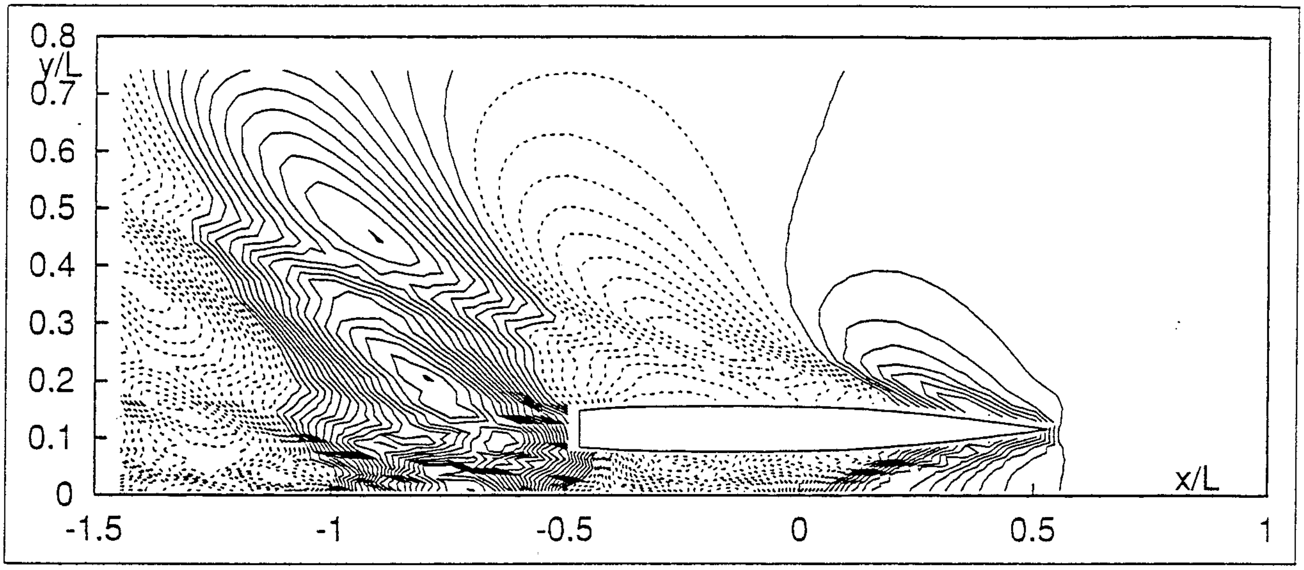

Figure 5: Steady Seascape, DUT Catamaran, Fn = 0.45

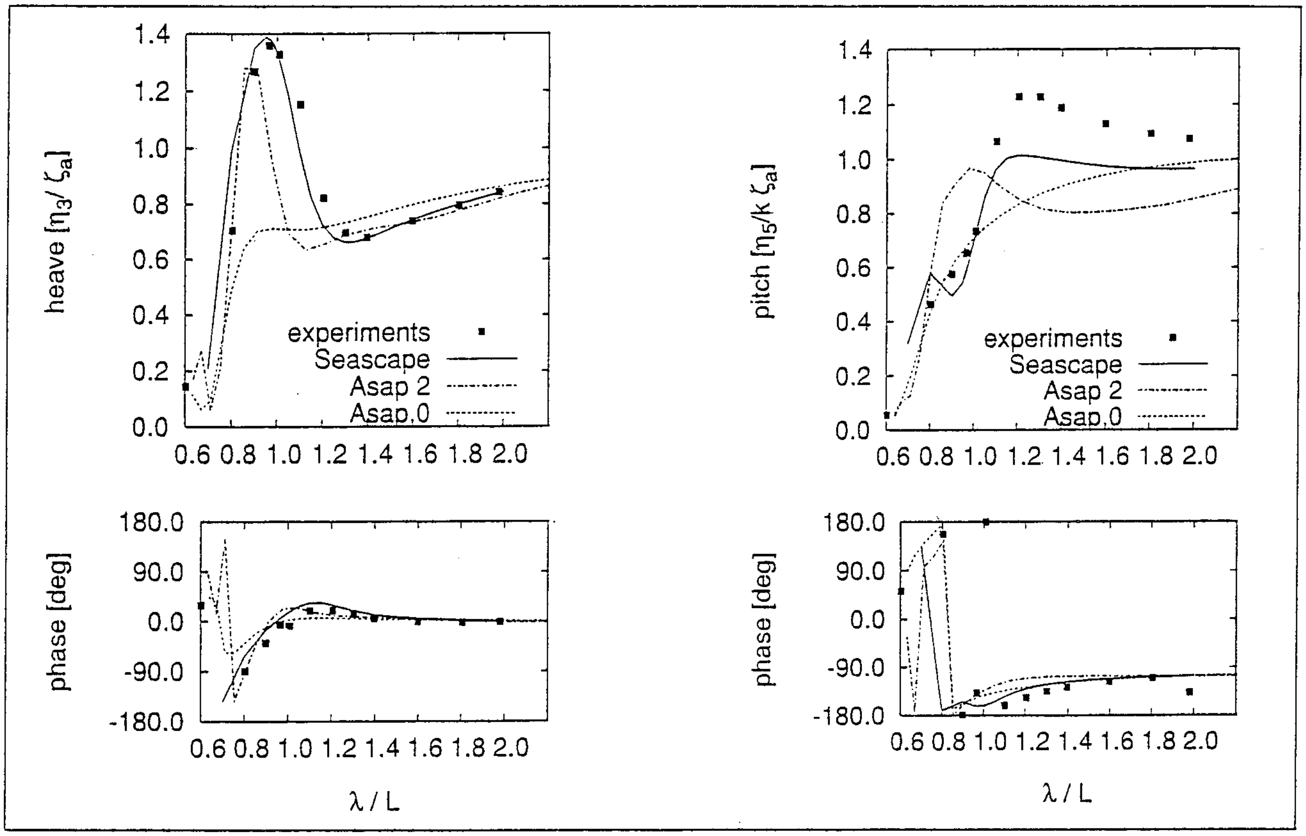

Figure 6: Heave and pitch RAO, DUT catamaran, Fn = 0.30, without trim and sinkage correction

between the calculations and the measurement in Figure 7 is less good than the comparison between calculations and measurements in Figure 8 where the hull grid has been corrected for the measured trim angle and sinkage. Since the trim and sinkage are quite significant at Fn =0.60 the effect in the restoring terms is important and should be taken into account.

A comparison between the hydrodynamic coefficients at Fn = 0.30 is presented in Figure 9. Reasonable agreement has been found.

CONCLUSIONS

With a 3D Rankine panel method it is possible to obtain a good solution for the steady and unsteady wave pattern around twin hull vessel. The method can predict the heave and pitch responses of a catamaran vessel with reasonable accuracy up to high Froude numbers. If the trim and sinkage are significant they should be included in the motion calculations.

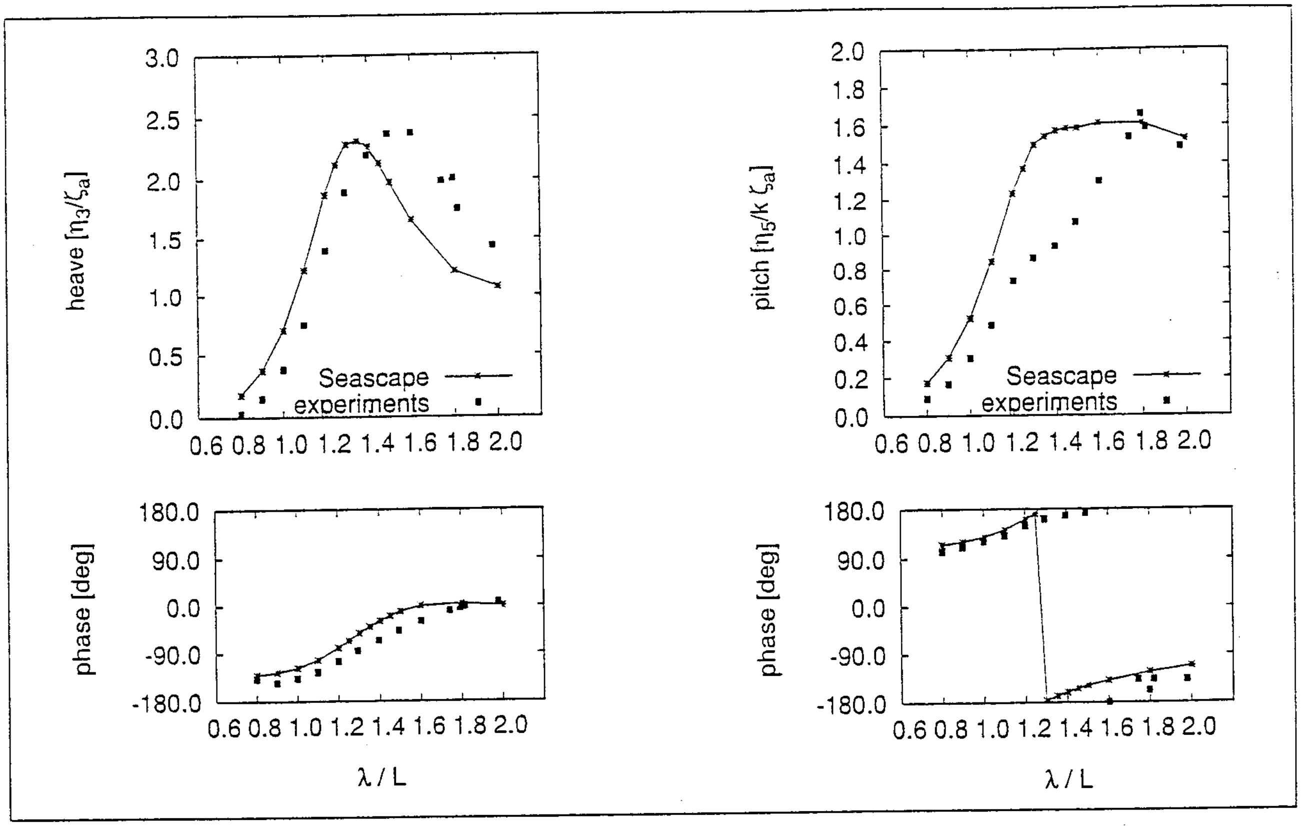

Figure 7: Heave and pitch RAO, DUT catamaran, Fn = 0.60 without trim and sinkage correction

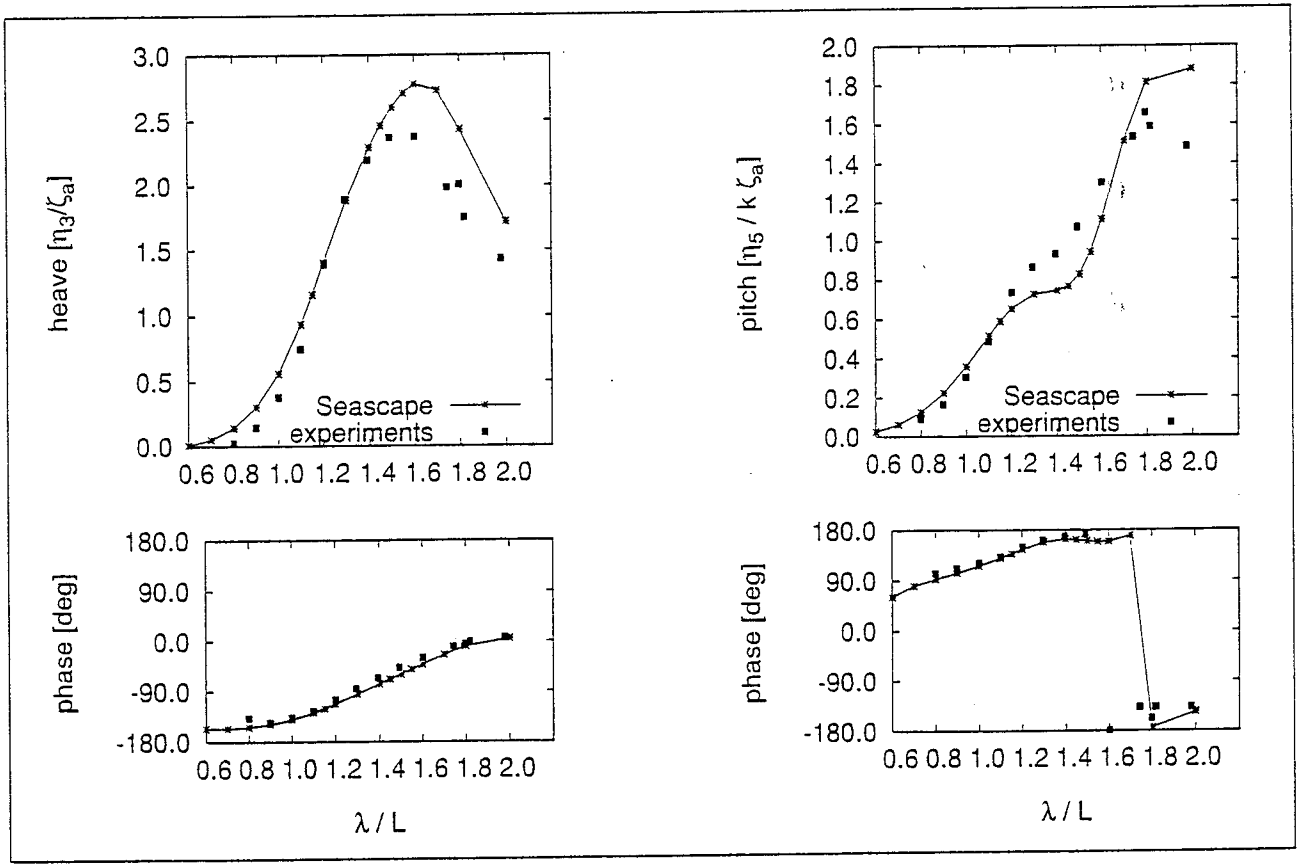

Figure 8: Heave and pitch RAO, Dut catamaran, Fn = 0.60 with trim and sinkage correction

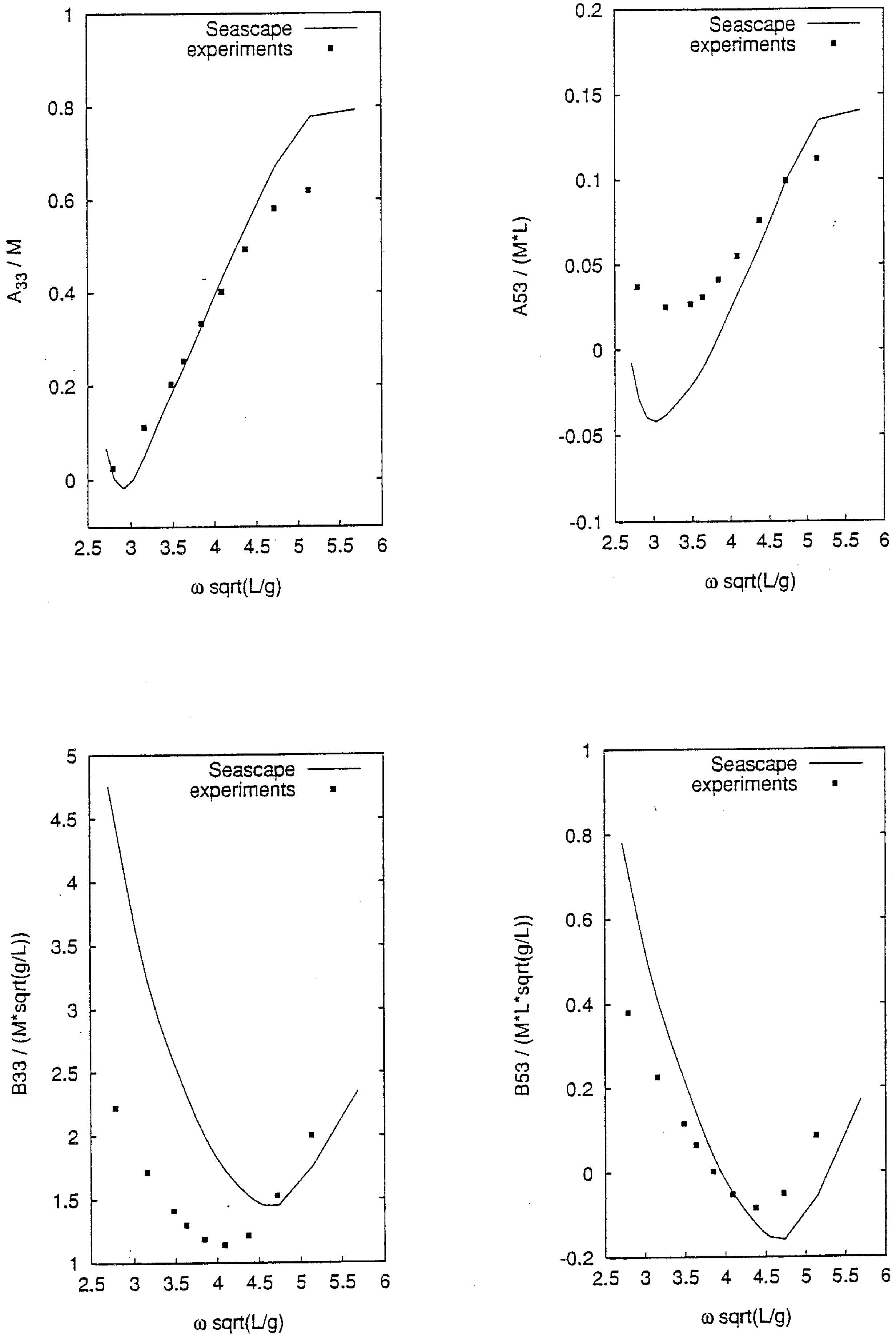

Figure 9: Hydrodynamic coefficients, Fn = 0.30

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