

DYNAMIC STABILITY ANALYSIS OF A SHIP AT HIGH FORWARD SPEED IN CALM WATER

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1. INTRODUCTION

The dynamic stability of a ship can become more and more of an issue as the ship speed increases. While many different forms of dynamic instability are known, often very little is known about their cause and only a limited amount of research exists [1]. Therefore, an incident of dynamic instability observed during model tests of a semi-displacement vessel in calm water [2] is investigated. The incident occurred at a very high Froude number of $Fn = 0.9$, see Fig. 1. Despite of the restraint by the gimbal yaw and sway motions develop followed by a roll motion in the end.

First the approach used here is outlined. The numerical method and its extensions to consider sway, roll and yaw motions are introduced briefly. Then the computations carried out are described. Afterwards, the obtained results are presented and discussed.

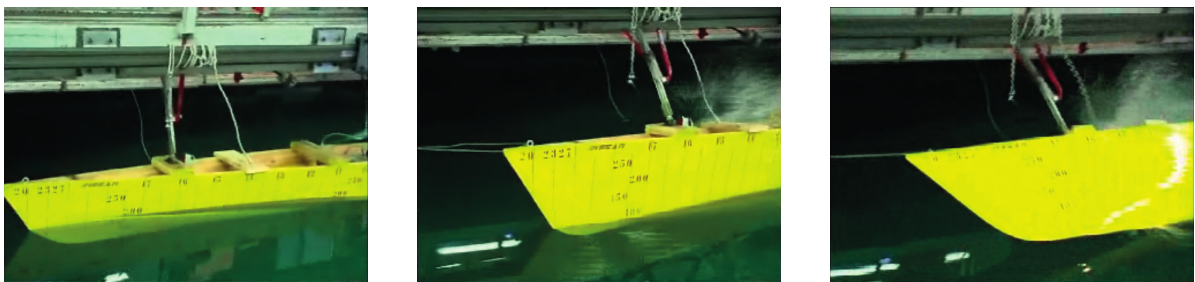


Figure 1 - Calm water broaching incident observed during experiments by Lugni et al. [2].

2. APPROACH

A nonlinear 2D+t method is extended and used to compute free sway, roll and yaw motions of the vessel. In such a method the three dimensional flow around the ship is replaced by several two-dimensional flows in earth-fixed transverse cross planes, see Fig. 2. The time development of the two dimensional flows caused by the ship advancing through these transverse cross planes is computed. This approach simplifies the computations significantly and is appropriate for fast and slender ships. The two-dimensional flows are treated as fully nonlinear potential flows. This means that viscous effects are neglected and that boundary conditions are kept in their nonlinear form and fulfilled on the instantaneous wetted hull and free surface. Therefore, most of the nonlinear effects can be taken into account. A boundary element method (BEM) is used to calculate the flow in each cross plane numerically. Using a BEM only the boundaries of each cross plane have to be discretised. This is done using linear elements.

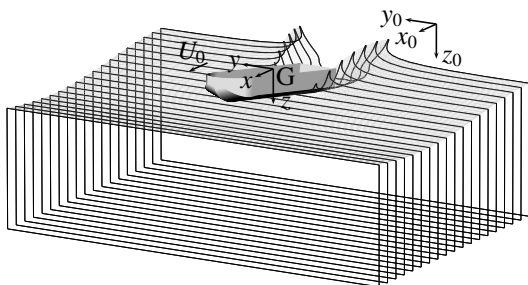


Figure 2 - Principle of the employed 2D+t method.

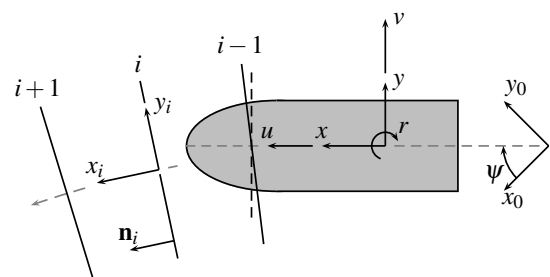


Figure 3 - Used coordinate systems.

A linear system of equations can then be set up and solved. Afterwards, the boundary conditions, which apply at the free surface, can be evaluated and used to step the free surface forward in time. This approach is called Mixed Euler-Lagrange (MEL) approach. Furthermore, the forces acting on the vessel can be computed from the flow solution and used to calculate the motions of the vessel. Simonis et al. [4] provide a more detailed description of the method and use it to analyse the heave and pitch motions of a fast semi-displacement vessel in head waves.

Here, the method is extended in such a way that also sway, roll and yaw motions can be considered. An earth-fixed coordinate system $x_0y_0z_0$ is used in the following, see Fig. 2. This can be related to a ship-fixed coordinate system $x_0'y_0'z_0'$ by the Euler angles φ (roll), θ (pitch) and ψ (yaw). Furthermore, a coordinate system xyz is used, which has its origin at the ship's center of gravity G and follows its yaw motion but not its pitch and roll motions, see Fig. 3. While quantities used in manoeuvring theory often refer to a ship-fixed system, they will be referring to the xyz coordinate system used here in the following. Furthermore, sometimes simplifications will be made in the following, because only small transverse velocities are dealt with.

As the ship moves forward, cross planes are constantly added in front of the ship and discarded behind it. In order to also consider yaw motions, the sections are added in such a way that they are perpendicular to the instantaneous orientation of the ship's longitudinal axis, which correlates with the unit vector \mathbf{i} in the x -direction. Their current yaw velocity is also considered, so that the angle between the normal vector \mathbf{n}_i of the section and \mathbf{i} remains small while the ship advances through the section. The flow in that section is solved in a local (earth-fixed) $x_iy_iz_i$ coordinate system, where the index i denotes the section number. Afterwards the pressures can be computed and the sectional forces are obtained by first projecting the section to a plane at a certain longitudinal location x which is perpendicular to \mathbf{i} (see section $i - 1$ and the corresponding projected section denoted by a dashed black line in Fig. 3) and integrating the pressure afterwards. The total forces are then computed by integrating the sectional forces in the x direction.

In the analysis presented here, constant sway and yaw velocities are considered first and the results for transverse forces are compared to numerical results computed using a RANS method. Then the 2D+t method is used to calculate the free sway and yaw motions, which develop from a small initial disturbance in terms of an initial sway velocity, while the vessel is advancing at constant forward speed in calm water. Additionally, the 2D+t method is used to compute linear force coefficients in sway and yaw. These are used to solve the linearised equations of motion in sway and yaw. Furthermore, the computed coefficients are used to evaluate a yaw stability criterion. The influence of roll is also touched upon.

3. RESULTS

The main dimensions and most important properties of the model used in the experiments by Lugni et al. [2] are listed in Table 1. The values marked by a * were not provided by Lugni et al. [2] and are taken from Ommani [3], who also investigated the dynamic stability of this model using a linear 3D BEM. In Fig. 4 its body plan is shown. The model is actually a demi-hull of a catamaran, which may explain its quite small beam-to-draft ratio B/D . Since the interaction of the demi-hulls was one of the aspects studied by Lugni et al. [2], they were also tested as monohulls. They also obtained values for running trim and sinkage, which are used in the computations presented here to prescribe the equilibrium running attitude. All computations are carried out in model scale.

First, the ability of the method to compute transverse forces resulting from small sway and yaw motions is studied. Fig. 6 shows the non-dimensional sectional transverse forces dY'/dx' for steady sway and yaw for two different Froude numbers $F_n = U_0/\sqrt{gL}$, where U_0 denotes the constant forward speed in the x -direction. Furthermore, $Y' = Y/(\rho U_0^2 LD/2)$ is the total non-dimensional transverse force in the y -direction and $x' = x/L$. The

Length L [m]	25
Beam B [m]	2
Draft D [m]	1.75
Displaced volume ∇ [m ³]	40.48
Roll gyradius k_{xx} [m]	0.6125*
Yaw gyradius k_{zz} [m]	6.5*
Longitudinal COG LCG [m]	10.8
Vertical COG VCG [m]	1.35*
Model scale factor λ [-]	6.25

Table 1 - Vessel properties.

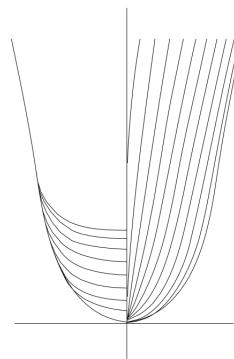


Figure 4 - Body plan of the vessel.

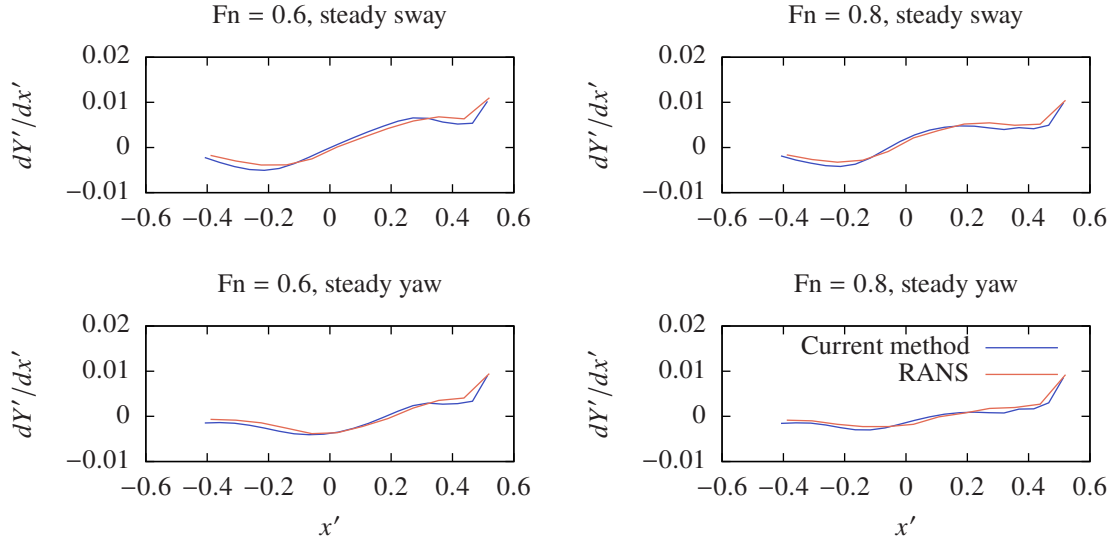


Figure 6 - Sway force distribution for steady sway and yaw motions and two different forward speeds.

non-dimensional sway velocity is chosen according to $v/U_0 = -0.0087$ corresponding to a drift angle of $\beta = 0.5^\circ$ and the non-dimensional yaw velocity is chosen as $rL/U_0 = -0.0080$, leading to similar transverse velocities observed at the bow. The convergence with respect to element size and time step size was checked.

The results of the method presented here are compared to results obtained using the RANSE solver STAR-CCM+. This solver employs a finite-volume method to solve the Reynolds-averaged Navier-Stokes (RANS) equations. In the simulations carried out here, turbulence is modeled using the $k\omega$ -SST turbulence model with wall function treatment. This was considered acceptable due to the small transverse velocities dealt with here. The grid for the simulations is adjusted iteratively, so that the dimensionless wall distance y^+ takes values between 40 and 100 on boundaries on which friction is considered (no-slip walls), i.e. the hull. To capture the free surface a Volume of Fluid (VoF) method is utilised. The time marching procedure is selected to be first-order accurate. Convective and viscous fluxes are handled with second-order accuracy in space.

The distribution of the transverse force is similar for both sway and yaw motions and the two considered Froude numbers. The agreement between the current method and the RANS method appears satisfactory. Deviations mainly seem to occur where the local minima near the bow and in the aft half of the model are. In both cases the current method underestimates the forces. Separation effects are known to influence the force distribution in such a way that most of the transverse momentum is retained in the fluid in the aft half of the vessel, which leads to smaller negative forces. If the transverse forces are computed using slender body theory, the aft half is therefore often excluded from the integration of the sectional forces to some extent [6]. However, the agreement seems to improve for the higher Froude number, which could indicate the importance of accounting for the elevation of the free surface along the hull due to the steady flow caused by the forward speed. This is generally better captured by the current method the higher the Froude number is [1]. Söding [5] recommends accounting for the steady wave field for higher Froude numbers if transverse forces are computed using slender body theory. Fig. 5 shows a screenshot of the simulation at $Fn = 0.6$ considering a constant sway velocity. It can be seen that the sectional drafts are influenced by the flow around the hull.

Next, the method is used to compute linear hydrodynamic coefficients Y'_v , Y'_r , N'_v and N'_r , where N refers to the yaw moment. As indicated above, the non-dimensional forms are obtained by dividing the transverse forces by $\rho U_0^2 L D / 2$ and the yaw moment by $\rho U_0^2 L^2 D / 2$. The coefficients are obtained from simulations of either an

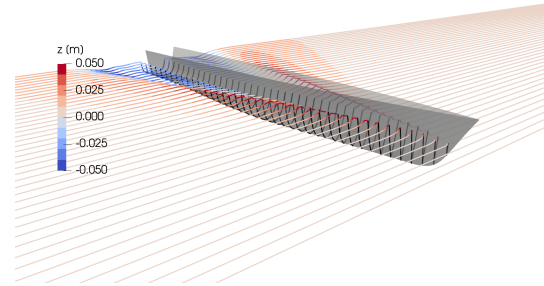


Figure 5 - Simulation of the model at $Fn = 0.6$ having a constant sway velocity using the presented 2D+t method.

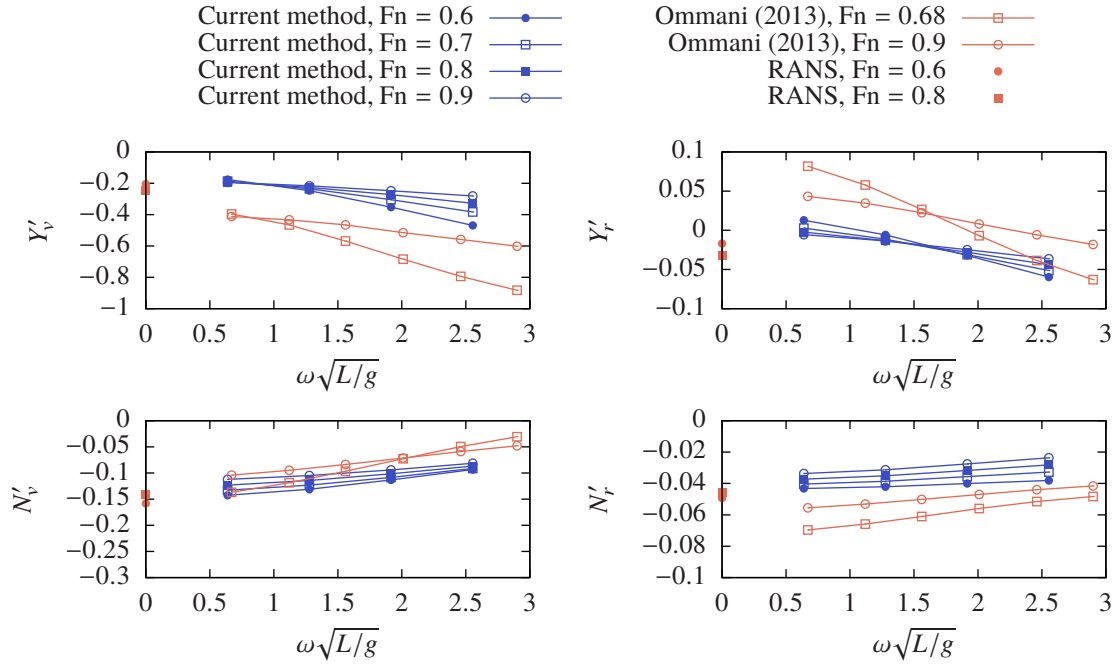


Figure 7 - Computed damping coefficients for sway and yaw.

oscillatory sway motion or an oscillatory yaw motion. Afterwards, Y and N can be expanded into a Fourier series and Y_v , Y_r , N_v and N_r and also $Y_{\dot{v}}$, $Y_{\dot{r}}$, $N_{\dot{v}}$ and $N_{\dot{r}}$ may be computed from the first-order Fourier coefficients. The results are presented in Fig. 7 together with the results obtained by Ommani [3] and the results from RANS computations discussed before. Ommani [3] used a linear 3D BEM and simplified the shape of the vessel to that of a surface piercing flat plate. Although the absolute values differ, the two methods show a very similar dependence regarding frequency ω and speed U . The 2D+t method seems to agree better with the results obtained using the RANS method. This could indicate that accounting for the steady flow and the actual shape is of importance, as also noted by Ommani [3].

The hydrodynamic coefficients appear in the linearised equations of motion in sway and yaw. They may be written as

$$m\dot{v} + mUr = Y = Y_v v + Y_r r + Y_{\dot{v}} \dot{v} + Y_{\dot{r}} \dot{r} \quad (1)$$

$$I_{zz} \dot{r} = N = N_v v + N_r r + N_{\dot{v}} \dot{v} + N_{\dot{r}} \dot{r} \quad (2)$$

or using matrix vector notation as

$$\mathbf{M}\dot{\nu} + \mathbf{D}\nu = \mathbf{0}, \quad (3)$$

where

$$\mathbf{M} = \begin{bmatrix} -Y_{\dot{v}} + m & -Y_{\dot{r}} \\ -N_{\dot{v}} & -N_{\dot{r}} + I_{zz} \end{bmatrix} \quad \mathbf{D} = \begin{bmatrix} -Y_v & -Y_r + mU \\ -N_v & -N_r \end{bmatrix} \quad \nu = \begin{bmatrix} v \\ r \end{bmatrix}.$$

Eq. (3) is solved by assuming

$$\nu = \hat{\nu} e^{\lambda t}, \quad (4)$$

which leads to an eigenvalue problem. After inserting Eq. (4) into Eq. (3) the eigenvalues λ can be determined from

$$\det(\lambda \mathbf{M} + \mathbf{D}) = A\lambda^2 + B\lambda + C = 0. \quad (5)$$

Generally,

$$\lambda = \delta + i\omega. \quad (6)$$

The general solution is then given by

$$\nu = \sum_j c_j \hat{\nu}_j e^{\lambda_j t}, \quad (7)$$

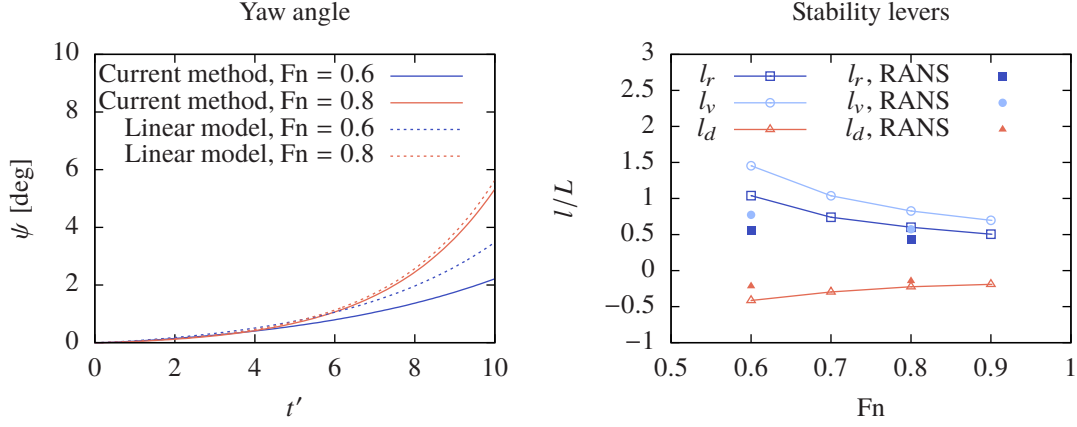


Figure 8 - Computed yaw angle ψ using nonlinear time domain simulations and the linear coefficient based model (left) and yaw stability levers computed from the linear hydrodynamic coefficients (right).

where the eigenvectors $\hat{\nu}_j$ corresponding to an eigenvalue λ_j can be determined from

$$[\lambda_j \mathbf{M} + \mathbf{D}] \hat{\nu}_j = \mathbf{0}. \quad (8)$$

The constants c_j are determined from the initial values, i.e. $\nu(t=0) = \nu_0$. According to this linear analysis, the real parts δ of the eigenvalues λ have to be negative for stability, meaning that sway and yaw motions decay if no additional forces are present. A further study of the characteristic polynomial according to Eq. (5) reveals that in practical cases the vessel will be directionally stable if

$$C = Y_v N_r - N_v (Y_r - mU) > 0, \quad (9)$$

or

$$l_d = l_r - l_v = \frac{N_r}{Y_r - mU} - \frac{N_v}{Y_v} > 0, \quad (10)$$

where l_d is the dynamic stability lever, l_r is the yaw damping lever and l_v is the static stability lever.

In Fig. 8 yaw motions developing from a small disturbance in terms of an initial sway velocity $v_0 = 0.001$ m/s are shown. Results from free coupled sway-yaw simulations using the presented method are compared to results obtained using the linear model described above, i.e using Eq. (7). The agreement for $F_n = 0.8$ is better than for $F_n = 0.6$. However, in both cases the same behavior is observed. The yaw angle changes increasingly faster and no new steady course can be reached, i.e. the vessel is unstable for all tested Froude numbers based on the numerical results. As is also shown in Fig. 8, this result is recovered from the evaluation of the dynamic stability levers, i.e. the dynamic stability lever l_d is negative for all tested Froude numbers. The results obtained using the RANS method also indicate directional instability. As before, the results obtained using the 2D+t method agree better with those using the RANS method at higher Froude numbers.

As instability of semi-displacement vessels at high speed may also be initiated by a loss of transverse stability, the influence of the roll motion is also investigated. Fig. 9 shows the distribution of the sway force and roll moment due to a small steady heel angle of $\varphi = -2^\circ$. Good agreement is found between RANS and the 2D+t method, indicating that the roll motion might be reasonably predicted. Wakeling et al. [7] investigated the transverse stability of semi-displacement vessels at high speed and found a loss of righting moment in the aft part of the hull. The same is found here, while the total righting moment does not seem to be influenced significantly, as an increase of righting moment can be observed in the forward sections. Fig. 10 shows results from free coupled sway-roll-yaw simulations using the presented method. Here, an additional disturbance in terms of an initial roll angle $\varphi_0 = -0.5^\circ$ has been used. It can be seen that including the roll motion does not change the observed yaw motion significantly. The model is stable in roll, i.e. a decaying oscillatory roll motion can be observed.

4. CONCLUSIONS

From the results it may be concluded that the presented 2D+t method can be used to compute efficiently the sway and yaw motions and associated hydrodynamic forces considering the nonlinear steady flow around the vessel. Neglecting viscous effects seems to be possible as long as the motions remain small as is the case if linear dynamic stability is considered. Judging from the obtained results yaw instability could be the cause of the observed

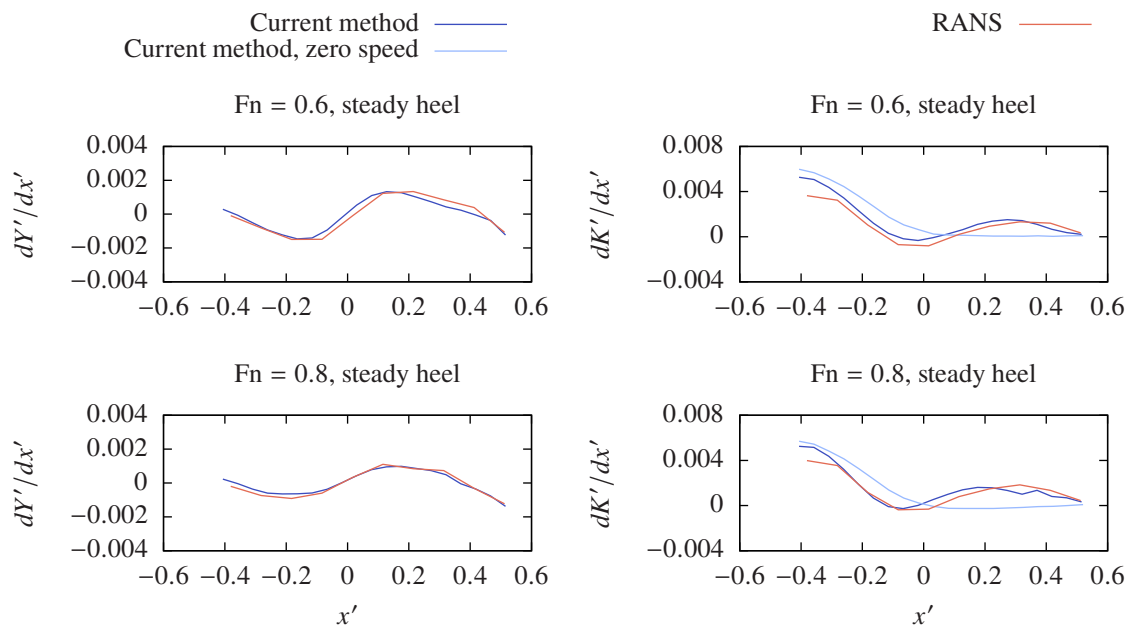


Figure 9 - Computed sway force and roll moment distribution due to steady heel.

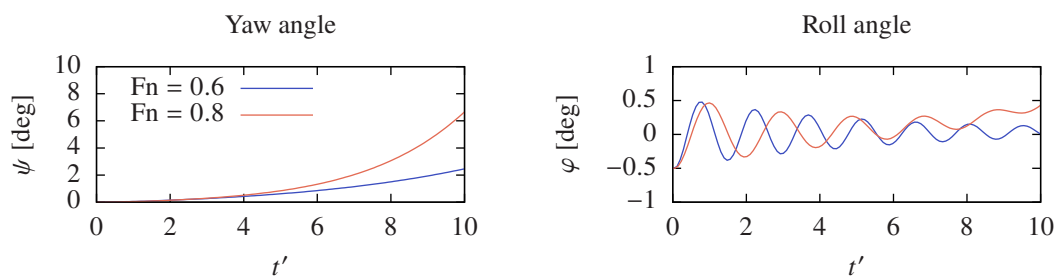


Figure 10 - Computed yaw and roll angles using the presented method.

instability. The restrains might be the reason why this instability was observed only at the highest Froude numbers during towing tank tests. According to the obtained results, including the roll motion in the analysis does not change dynamic behaviour of the model considerably. However, further studies are necessary in that respect.

5. REFERENCES

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