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Development of a time domain strip theory approach for maneuvering in a seaway

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Introduction

Ship maneuvering and seakeeping have traditionally been dealt with as separate sub problems. Maneuvering is done in calm waters dealing with the low frequency characteristics and seakeeping with the high frequency at wave periods. These give very important information to the Naval Architect during preliminary design. But in reality they are coupled problems and the presence of waves are known to affect the course keeping and maneuvering performance of the ship. On the other hand maintaining a given course can induce severe ship motions, increase the resistance and decrease propulsive efficiency and speed.

The maneuvering of ships in a seaway has been investigated by several authors. One popular method is the use of linear convolution integrals of Cummins [4] which accounts for the unsteady wave memory effects. Fossen [5] and Bailey [1] have developed unified models for maneuvering in a seaway. Although basically linear, these models compute some of the 2nd order effects because the forces are integrated on time dependent body geometry. Recently Skejic and Faltinsen [8] have developed a unified 4 dof maneuvering model in which the mean 2nd order wave loads were added using a direct pressure integration scheme. In their method, a two time scale problem was solved in which the wave frequency problem was separated from the low frequency maneuvering problem. Seo and Kim [7] have developed a unified model based on three-dimensional potential based methods, where a 4-DOF maneuvering model is used and 2nd order seakeeping forces are computed and taken into account.

The present research proposes to address the combined problem of seakeeping and maneuvering in an attempt to bring about coupling between the two. The idea is to develop a methodology which is fast, robust and captures the important physics of the problem with reasonable accuracy.

A 2-D body exact strip theory method is used to solve the unified seakeeping and maneuvering problem in the time domain using direct pressure integration to compute forces. A frame following the instantaneous position of the ship by translating and rotating in the horizontal plane is used to solve the BVP (Boundary value problem). This has the advantage that the speed or heading need not be predetermined. A nonlinear 6-DOF Euler equation of motion solver is used to find the new body position and velocities. The use of the time dependent body wetted surface to integrate the forces and the use of 2nd order terms in the Bernoulli equation make sure that vital nonlinearities are captured. Thus both the high frequency seakeeping and low frequency maneuvering is captured without resorting to two separate time scales.

DEFINITION SKETCH

The problem definition is as shown in fig.1 where a freely floating rigid body such as a ship with a certain speed is moving in the presence of external waves. The objective is to predict the forces and resultant motions of such a body.

Three different axis systems are used; an earth fixed inertial axis (x_e,y_e,z_e) is used to keep track of the position of the centre of gravity and rotations of the ship. A hydrodynamic frame (x,y,z) translates in the horizontal x-y plane with translational velocities U, V and rotational yaw rate $\dot{\psi}$. It thus follows the ship with its origin O_h in a vertical line with O_b ,the origin of the body frame. This is the frame in which the boundary value problem is solved. A frame fixed to the body (x_b,y_b,z_b) rotates and translates in all 6-DOF with the body. This frame is used to compute the forces acting on the vessel and to solve the equations of motion.

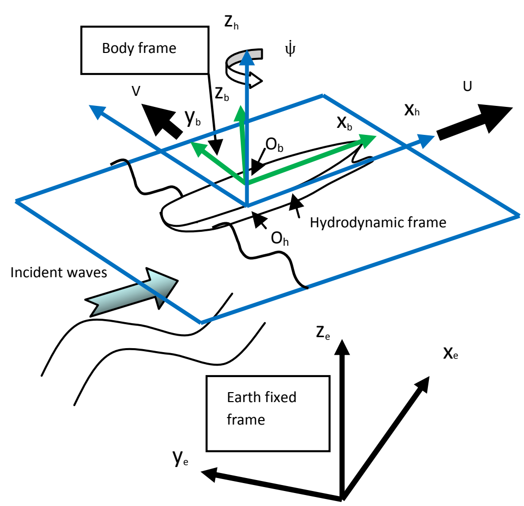

Fig.1 Schematic showing different coordinate frames used

FORMULATION

The fluid flow is considered to be inviscid, irrotational, incompressible and unsteady. For such a flow a potential ϕ can be defined such that the velocity field $\vec{v}$ can be represented as:

$$\vec{v} = \nabla\phi \qquad (1)$$

The governing partial differential equation (PDE) is the Laplace equation:

$$\nabla^2\phi\ (x, y, z, t) = 0 \qquad (2)$$

Here ϕ represents the perturbation potential for the absolute fluid velocity in the hydrodynamic frame.

If it is assumed that the ship is slender such that the length is much greater than the breadth and draft, then the gradients in the longitudinal direction (along the length) are much smaller than the derivatives in the transverse direction.

This forms the basis for the strip theory formulation where the three-dimensional problem is solved as a series of individual two-dimensional problems. The ship is divided into stations where the BVP is solved. Under these assumptions the BVP becomes:

$$\nabla^2\varphi(y, z, t) = 0 \qquad (3)$$

Here φ(y, z, t) represents the two-dimensional velocity potential in the cross flow plane. The linearized free surface boundary conditions written in the hydrodynamic frame are:

$$\frac{\partial\eta}{\partial t} = \frac{\partial\varphi}{\partial z} + V\frac{\partial\eta}{\partial y} + x\dot{\psi}\frac{\partial\eta}{\partial y} \quad \text{on } z=0 \qquad (4)$$

$$\frac{\partial\varphi}{\partial t} = -g\eta + V\frac{\partial\varphi}{\partial y} + x\dot{\psi}\frac{\partial\varphi}{\partial y} \quad \text{on } z=0 \qquad (5)$$

The body boundary conditions become $\nabla\varphi.\vec{N} = \vec{v}.\vec{N}$, which can be written separately in terms of the of diffraction and radiation components as:

$$\nabla\varphi_D.\vec{N} = -\nabla\varphi_I.\vec{N} \quad \text{on } S_B \qquad (6)$$

$$\nabla\varphi_R.\vec{N} = \vec{v}.\vec{N} \quad \text{on } S_B \qquad (7)$$

$\vec{N}$ is the two-dimensional unit normal including a two-dimensional approximation to N1, the longitudinal component of the unit normal. The details are given in Bandyk [2]. $\vec{v}$ is the absolute velocity of a node on the body wrt the earth fixed frame including velocities due to rotational motions and S_B is the exact wetted body surface.

At each time step, a mixed BVP is solved for the perturbation potentials φ_D and φ_R. By applying Green's theorem the potential can be written as:

$$\varphi = \int G(\vec{x}, \vec{\varsigma})\sigma(\vec{\varsigma})dl \qquad (8)$$

where the integration is done over the body and the free surface.

Desingularised sources are placed above the free surface nodes and constant strength panels are used on the body surface.

At a given time, the potentials on the free surface are obtained by time marching the free surface equations and the body normal velocities are determined by solving the rigid body equations of motion. The free surface is integrated in time using a 4th order Adams Bashforth scheme. The free surface also uses a beach to damp out the perturbed waves in the far field to satisfy the radiation boundary condition. This is vital to carry out long time simulations.

The pressure equation in the rotating and translating hydrodynamic frame is:

$$\frac{p}{\rho}+\frac{1}{2}\nabla\varphi.\nabla\varphi+\frac{\partial\varphi}{\partial t}-U\frac{\partial\varphi}{\partial x}-V\frac{\partial\varphi}{\partial y}+y\dot{\psi}\frac{\partial\varphi}{\partial x}-x\dot{\psi}\frac{\partial\varphi}{\partial y}+gz=0 \quad (9)$$

The pressure is integrated over the instantaneous submerged body surface to get the forces and moments due to the hydrodynamic and hydrostatic terms.

To obtain the quantity $\frac{\partial\varphi}{\partial t}$, a separate BVP is set up and solved for in the same manner as for the potential [3]. To compute the $\frac{\partial\varphi}{\partial x}$ term, radial basis functions are used to interpolate from the given values of φ on each strip [2].

Once the hydrodynamic forces are obtained, the accelerations $[\ddot{\xi}]$ of the floating body are obtained by solving the nonlinear 6 degree of freedom Euler equations of motion:

$$[M+M^*][\ddot{\xi}] = [F(t)] \quad (10)$$

Here M is the generalized rigid body mass matrix and M* denotes the impulsive added mass. The details are given in Bandyk and Beck [3]. F(t) is the generalized hydrodynamic force vector. This would include forces due to propeller thrust, ship resistance, control systems and viscous effects arising due to maneuvering and ship motions (roll damping).

A 4th Order Adams Bashforth scheme is used to integrate the body accelerations to obtain the new velocities and the position of the body for the next time step.

RESULTS AND DISCUSSION

The seakeeping prediction capability of the present code has been tested by computing the RAOs of the Wigley-I and S175 in head seas, and comparing them with available model tests and other seakeeping programs. The results compare favorably but will not be presented here due to space constraints.

In order to perform controlled maneuvers in a seaway, a steady thrust force was applied in the body x component, along with a resistance model. Linear maneuvering forces in sway and yaw (Y_v, Y_r, N_v and N_r) were also applied by empirical formulas as used by Bailey [1]. 90 degree turn tests were performed for the containership S175 both in calm water and in the presence of external waves. After performing some convergence studies, the free surface domain size was set to two wavelengths with another two wavelengths for the beach. The free surface node spacing was set to λ/30 and time step size of T/200 was used.

Fig.2 shows the comparison of the tracks for the 90 degree turning tests between calm water and in the presence of waves. A constant rudder angle of 35 degrees was applied after the ship reached a steady speed of about 6.2 m/s (Fn. = 0.15), to turn to starboard. Waves are incident along the x_e direction. The wavelength to ship length ratio λ/L was set to 1.0 and wave amplitude of 1.5 m was used. The ship is able to enter and execute the turn after which the rudder is brought back to neutral. In order to maintain straight line course before and after the maneuver, a 4-DOF nonlinear controller developed by Li et al. [6] was implemented.

Fig.3 shows the comparison of the time history of the forward speed during the maneuvers; between the calm water test and in the presence of waves. The interesting feature to note is that in the presence of waves, in addition to the low frequency maneuvering effects on forward speed, the high frequency seakeeping responses are also captured thus providing direct feedback and interaction between the two problems.

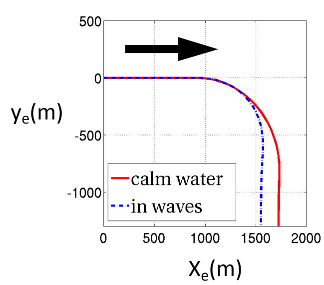

Fig.2 90 deg. turning trajectory of S175 in calm water and in waves. Arrow indicates wave direction.

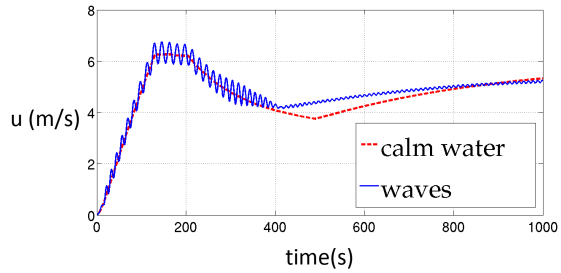

Fig.3 Time histories of forward speed during the 90 degree turn in calm water and in regular waves.

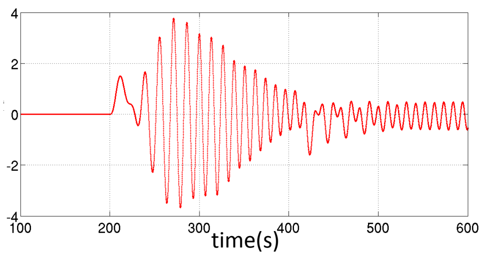

Fig.4 The roll motion of S175 during the 90 degree turning maneuver in the presence of regular waves.

CONCLUSION

In this short paper, a time domain strip theory approach for predicting the maneuvering of a vessel in a seaway has been introduced. Preliminary results for the 90 deg. turning trajectory of S175 in calm waters and in the presence of waves have been introduced. The hydrodynamic axis system is shown to be stable and effective in capturing the qualitative aspects of the maneuver. The key advantage is that since the axis follows the instantaneous position of the vessel, the forward speed and path need not be prescribed in advance. The simulations were performed for long times. However, the accuracy of the maneuvering results need to be verified. At the time of writing, only linear maneuvering forces have been modeled. This assumption may be erroneous since nonlinear coefficients could play a vital role during tight turns. These issues would be addressed and the progress reported at the workshop.

TABLE 1. HULL PARTICULARS

	S-175
LBP [m]	175.0
B[m]	25.4
T[m]	9.5
C_W	0.7080
C_B	0.5714

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