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Towards Real Time Simulation of Ship-Ship Interaction*

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We present recent and preliminary work directed towards the development of a simplified, physics-based model for improved simulation of ship-ship interaction that can be used for both analysis and real-time computing (i.e. with real-time constraints due to visualization). The goal is to implement the model into a large maritime simulator for training of naval officers, in particular tug boat helmsmen. Tug boat simulators are used for training of communication and situation awareness during manoeuvre involved with towing of large vessels. A main objective of the work is to improve and enable more accurate (realistic) and much faster ship-wave and ship-ship simulations than are currently possible. The coupling of simulation with visualization should improve the visual experience such that it can be perceived as more realistic in training. Today the state-of-art in real-time ship-ship interaction is for efficiency reasons and time-constraints in visualization based on model experiments in towing tanks and precomputed force tables. We anticipate that the fast, and highly parallel, algorithm described by Engsig-Karup et al. [2011] for execution on affordable modern high-throughput Graphics Processing Units (GPUs) can provide the basis for efficient simulations in combination with an accurate free-surface model for Ship-Ship simulation. Another area of application is the determination of wave disturbances from a ship in a coastal environment, channels and harbours. The model proposed in the following can in a simple and efficient way calculate the wave field from a ship sailing in a finite depth sea, even with variations in the height of sea bed. The generated wave field can be applied as an input to other models that simulate the marine environment on a larger scale.

Ship-Wave Model

In order to take full advantage of the accuracy and efficiency of the wave model discussed above, we will adopt a rough approximation of the ship geometry based on surface pressure distributions. This will of course limit the accuracy of the geometric description of the hull. The representation of sailing ships by a pressure distribution on the free surface is a classical

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idea that dates back at least to Thomson (Lord Kelvin) [1910]. Many applications of the idea exist in the literature, including *e.g.* recent work by Raven [2010], who used the idea for hull optimization based on wave-making resistance; and Li and Sclavounos [2002] who used surface pressures to study nonlinear solitary waves in shallow water as a model for a ship moving at sub-critical, critical and super-critical speed. To model a ship as a pressure distribution on the free surface, the hull must be approximated by a single-valued function of the horizontal coordinates: $\eta_{ship} = \eta_{ship}(t, x, y)$. Ship appendices like bulbous bows or complex rudder tubes can not be represented and must be suitably smoothed out. The fluid pressure on the ship hull surface is the sum of the dynamic and the hydrostatic components. Clearly an approximation to the stationary ship is obtained by applying the hydrostatic component $p_{ship} = \rho g \eta_{ship}$. As the ship begins to move, the flow induced dynamic components must be balanced by the applied surface pressure in order to maintain a constant hull form. The goal of this project is to find a robust means of predicting and applying this pressure in general, but we present here some preliminary work with constant applied pressures. The model is based on assuming inviscid, incompressible and irrotational potential flow. The free surface of the sea is described by the single-valued function $\eta = \eta(t, x, y)$, where t is time and (x, y) the horizontal coordinates. Mass conservation is satisfied though the Laplace equation for the scalar velocity potential

$$\nabla^2 \phi = 0, \quad z \in [-h, \eta], \tag{1}$$

where z is the vertical coordinate and $h = h(x, y)$ is the distance from the mean sea level to the sea bed. The motion of the free surface is governed by the kinematic free surface boundary condition

$$\frac{\partial \eta}{\partial t} + \boldsymbol{u} \cdot \nabla \eta = w, \quad z = \eta, \tag{2}$$

where $\boldsymbol{u} = \nabla \phi \in \mathbb{R}^2$ is the horizontal velocity vector and w is the vertical free surface velocity. The forces on the free surface are governed by the dynamic free surface condition

$$\frac{\partial \phi}{\partial t} + \frac{1}{2}\boldsymbol{u} \cdot \boldsymbol{u} + \frac{p}{\rho} + g\eta = 0, \quad z = \eta, \tag{3}$$

where p is the pressure, $\rho \approx 1000\text{kg/m}^3$ is the density and $g = 9.81 m/s^2$ is the gravitational acceleration. The equations are solved in a moving reference frame attached to the ship and given by (τ, x_m, y_m), where x_m is forward and y_m is the transverse direction relative to the ship. The ship is assumed not to move in the vertical direction and to be sailing in the the positive x direction. Based on these assumptions the coordinate transform from the fixed to the ship following frame of reference is

$$\tau = t, \quad x_m = x - Vt, \quad y_m = y, \quad z_m = z, \tag{4}$$

where $V = const.$ is the ship velocity in the x direction. The coordinate transform adds a convective term to the kinematic and dynamic free surface boundary conditions

$$\frac{\partial \eta}{\partial \tau} - V\frac{\partial \eta}{\partial x_m} + \boldsymbol{u} \cdot \nabla \eta = w, \quad z = \eta, \tag{5}$$

$$\frac{\partial \phi}{\partial t} - V\frac{\partial \phi}{\partial x_m} + \frac{1}{2}\boldsymbol{u} \cdot \boldsymbol{u} + \frac{p}{\rho} + g\eta = 0, \quad z = \eta. \tag{6}$$

The free surface boundary conditions are are solved in a ship following rectangular domain on the free surface and the Laplace equation is solved in a corresponding domain extending to the seabed, i.e. the solution domain is

$$\Omega = \{[x_m, y_m, z_m]^T \in \mathbb{R}^3 \;:\; x_{m,min} \leq x_m \leq x_{m,max},\; y_{m,min} \leq y_m \leq y_{m,max},\; h \leq z_m \leq \eta\} \tag{7}$$

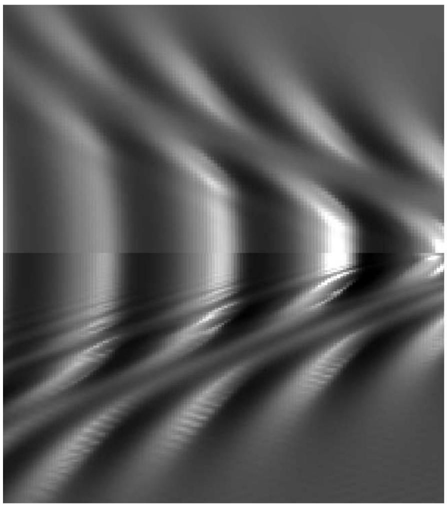

Figure 1: The Kelvin wave system generated by a moving pressure distribution with the parameters $Fn(ship) = 0.30$, $Fn(depth) = 0.47$, $B/L = 0.2$ and $D/L = 0.04$. The semi analytical solution are below the center line and the numerical solutions are above the center line.

The numerical solutions $\eta_h \approx \eta$ and $\phi_h \approx \phi$ are represented by local polynomials on a structured grid over the free surface boundary of Ω. The equations are transformed from the physical domain to a time independent computational domain, where the derivatives are approximated by higher-order finite differences. The temporal derivatives are approximated by the classical explicit fourth-order Runge-Kutta method. Details on the numerical approximations and solution methods are described by Engsig-Karup et al. [2009].

Applications

In this preliminary work, the method has been tested on the double cosine "ship" geometry used in Li and Sclavounos [2002] where the pressure distribution is

$$p(x_m, y_m) = \rho g D \cos^2\left(\frac{\pi x_m}{L}\right)\cos^2\left(\frac{\pi y_m}{B}\right), \quad -\frac{L}{2} \leq x_m \leq \frac{L}{2}, \quad -\frac{B}{2} \leq y_m \leq \frac{B}{2}, \tag{8}$$

with D the draft, L the length and B the width of the "ship". The preliminary simulations have been promising and a snap shot illustrating a generated Kelvin Wave system is presented in Figure 1. The calculation are shown next to the far-field linear as expressed for example by Wehausen and Laitone [1960]. This semi-analytical solution has been used to find the theoretical wave system caused by the double cosine pressure distribution above and we present a qualitative comparison between this and out numerical solution to the linear problem in figure 1. The result is qualitatively in good agreement and we are now working on making a more quantitative comparison. The second application is a typical cargo ship. The ship geometry has been simplified such that the surface of the hull is described by a single valued function of the horizontal coordinates: The bulbous bow has been extended upwards through the free surface, the vertical sides of the hull have been mollified and sharp intersections between the still water level and the hull has been smoothed. The resultant wave system is seen in Figure 2.

Conclusion

The Kelvin wave system has been simulated around a ship propagating at subcritical fixed speed in still water using a potential flow model with linearized free surface boundary conditions.

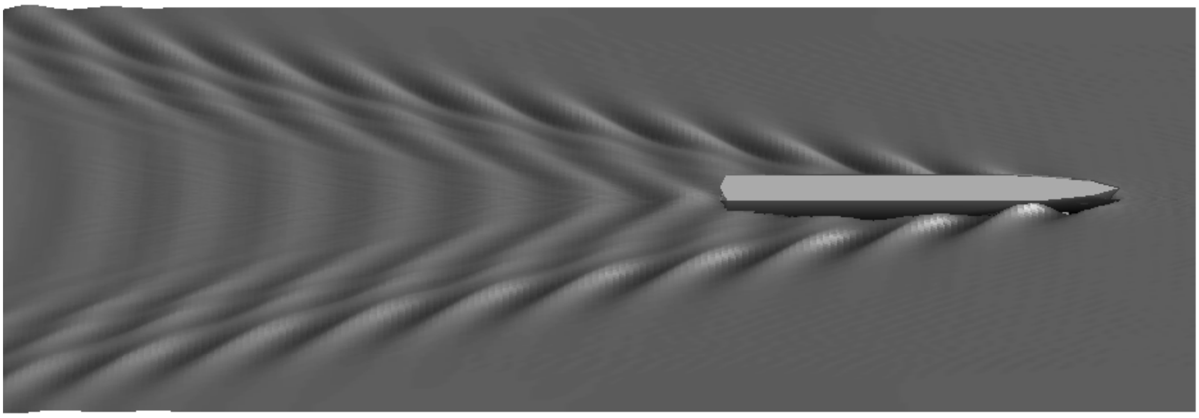

Figure 2: The wave system generated by the hydro static pressure on a typical cargo ship sailing with at Froude numbers $Fn(ship) = 0.20$ and $Fn(depth) = 0.32$. The geometric parameters of the ship are $B/L = 0.13$ and $D/L = 0.04$.

Preliminary results have been presented for a simple pressure patch which show good qualitative agreement with the semi-analytic solution. Future work will focus on including the nonlinear terms in the free-surface boundary conditions, and using the dynamic pressure on the ship hull to achieve a fixed geometry. The model will be implemented for parallel execution on modern high-throughput Graphics Processing Units (GPUs) and implemented in a real marine simulator to predict ship-ship interaction effects in real time.

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