Rapid Ship Motion Simulations for Investigating Rare Stability Failures in Irregular Seas

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ABSTRACT

The use of time-domain numerical simulations for the investigation of stability failures and other rare events in random, irregular seas requires a challenging combination of speed and accuracy. Simulations must be fast enough to observe a statistically significant number of failure or near failure events in order to build a reliable stochastic model of the event or conditions leading up to the event, while also being accurate and complete enough to capture the physical behavior that drives the event. Of particular importance are the body-nonlinear hydrostatic and Froude-Krylov forces, which are critical for large-amplitude roll motion and may also play a significant role in the surge and sway forces involved in surf-riding and broaching.

This paper presents a volume-based evaluation of the body-linear Froude-Krylov and hydrostatic pressure forces, which retains the inseparability of hydrostatic and Froude-Krylov forces and the effects of large-amplitude relative motion along the length of a ship. Implementation of the method requires a minimum number of evaluations of the incident wave, so it can run at a fraction of the computational cost for traditional surface pressure integration schemes. The calculation has been implemented in a hybrid numerical method that incorporates ordinary different equation (ODE) like models for wave-body perturbation forces. The hybrid method has been used to produce a very large number of realizations of irregular sea responses, including a statistically significant number of stability failures, for validating schemes for the extrapolation of extreme motion responses.

Keywords: *Seakeeping, Nonlinear Restoring, Froude-Krylov Forces*

1. INTRODUCTION

The use of time-domain numerical simulations for the investigation of stability failures and other rare events in random, irregular seas requires a challenging combination of speed and accuracy. The rarity of such events requires an extremely long set of simulations in order to observe a statistically significant number of events, while the complexity of the physics precludes the use of excessively simple models.

Of particular importance are the body-nonlinear restoring (hydrostatic) and incident wave (Froude-Krylov) forces, which are critical for large-amplitude roll motions and may also play a significant role in the surge and sway forces involved in surf-riding and broaching. France *et al.* (2003) described how these forces were key to describing parametric roll, while Spyrou *et al.* (2014) and others have linked the change of roll stability in waves to large roll events and capsizing in pure loss-of-stability events.

Hybrid time-domain simulation codes, which generally combine a body-nonlinear calculation of the hydrostatic and Froude-Krylov forces with a potential-flow solution of the wave-body hydrodynamic disturbance forces (radiation, diffraction, etc.) and theoretical or semi-empirical models of viscous and lift forces, have become the principal tool for simulating non-linear ship motion in irregular waves. These tools provide a reasonable compromise between accuracy and speed, and they can readily generate hundreds or thousands of hours of motion data for different realizations of ocean waves.

This, of course, is not nearly enough simulation time to observe a statistically significant number of failure or near failure events; building a reliable stochastic model of the event or conditions leading up to the event may require millions of hours of simulation for a single wave and operating condition. This has led to the development of extrapolation methods that attempt to characterize the probability of rare events from limited motion data (see, for example, Belenky et al. 2015 and Campbell et al. 2015). However, the development, testing, and validation of such methods still require extremely large simulation data sets of motions in extreme conditions.

Faster methods, therefore, are needed. For the development and validation (or at least testing) of extrapolation methods, they need not be quantitatively accurate to a high degree, but they do need to be qualitatively accurate in that they capture the key physics of the large-amplitude roll motion (Smith and Zuzick 2015). As mentioned above, a key part of such a calculation is the body-nonlinear hydrostatic and Froude-Kyrlov forces. While it is relatively straightforward to calculate these forces via direct pressure integration, they can be computationally expensive: they require a very large number of evaluations of the incident wave, and a very large number of component frequencies are required for a statistically valid representation of the irregular wave field for long simulations (Belenky 2011).

To provide a fast but complete calculation of the body-nonlinear Froude-Krylov and hydrostatic pressure forces, a sectional, volume-based evaluation has been developed that retains the inseparability of hydrostatic and Froude-Krylov forces and the effects of large-amplitude relative motion along a ship's length. Implementing the method requires a minimum number of evaluations of the incident wave, so it can run at a fraction of the computational cost of traditional surface pressure integration schemes. The calculation has been implemented in a hybrid numerical method that incorporates ordinary differential equation (ODE) like models for wave-body perturbation forces. The hybrid method has been used to produce a very large number of realizations of irregular sea responses, including a statistically significant number of stability failures, for validating schemes to extrapolate extreme motion responses (Weems and Wundrow 2013).

In this initial implementation, the simplified model of wave-body hydrodynamics prevents this simulation from being considered as quantitatively accurate. In the future, however, rapid, quantitatively accurate simulations may be possible by combining volume-based restoring and wave forces with a more complex but still fast model of the wave-body hydrodynamics, perhaps based on impulse response potentials or a more sophisticated coefficient representation.

2. FORMULATION OF VOLUME-BASED CALCULATIONS

The non-linear wave forcing and restoring forces can generally be computed by integrating the incident wave and hydrostatic pressure over the instantaneous wetted hull surface (in the Earth-fixed frame):

$$\mathbf{F}_{FK+HS}(t) = -\rho\iint_{S_B(t)}\left(\frac{\partial\phi_0(x,y,z,t)}{\partial t} + gz\right)\hat{\mathbf{n}}\, ds \quad (1)$$

$\partial\phi_0(x,y,z,t)/\partial t$ is the pressure of the undisturbed incident wave field (Froude-Krylov pressure) and $S_B(t)$ is the instantaneous wetted portion of the hull surface up to the incident wave waterline $\eta(x,y,t)$. The key element of this expression is that it captures the geometric non-linearity due to large vertical motion relative to the wave surface, ranging from the effect of bow flare to full emergence or submergence of the bow and stern.

It should be noted that this expression can be used with linear or nonlinear incident wave models as long as the incident wave model expresses a pressure and velocity field in the body-nonlinear domain, that is up to $z=\eta(x,y,t)$. For the typical linear wave model – in which the wave is represented by a superposition of sinusoidal components – this can be accomplished by applying the Wheeler stretching technique, in which the exponential decay term in the expressions for pressure, velocity, and their derivatives is expressed as $e^{k(\eta-z)}$.

As noted above, this expression is relatively straightforward to evaluate but can be expensive to generate, as it generally involves a large number of evaluations of the incident wave. To provide a much faster calculation, a volume-based calculation scheme is considered, using the submerged volume at each instant in time, which can be calculated with a minimal number of incident wave evaluations. It is, however, imperative that the scheme capture the effect of the longitudinal variation of the relative motion, as this is a principle driver in dynamic stability phenomena such as parametric roll and pure loss of stability in waves. To do so, Equation (1) is expressed as the sum of incremental forces calculated on a set of incremental sections distributed along the ship's length:

$$\mathbf{F}_{FK+HS}(t) = \sum \delta\mathbf{F}_{FK+HS}(x_i,t) \quad (2)$$

$\delta\mathbf{F}_{FK+HS}(x_i,t)$ is the force *computed* over the incremental submerged portion of the hull's surface running from x_i-$\Delta x/2$ to x_i+$\Delta x/2$, which is designated $\delta S_B(x_i,t)$:

$$\delta\mathbf{F}_{FK+HS}(x_i,t) = -\rho\iint_{\delta S_B(x_i,t)}\left(\frac{\partial\phi_0(x,y,z,t)}{\partial t} + gz\right)\hat{\mathbf{n}}\, ds \quad (3)$$

Note that the incremental hull surface $\delta S_B(x_i,t)$ is *considered* to include the wetted portion of the hull for that section as well as the wetted (below the incident wave) portions of the planes (cross-sections) separating this section from adjacent sections.

Within each section, a Taylor series expansion (neglecting higher-order derivatives) can be used to approximate the distribution of the incident wave pressure over an incremental hull section in terms of the value and derivatives of the pressure at a nominal point (x_0,y_0,z_0) on the section:

$$\begin{aligned}\frac{\partial\phi_0(x,y,z,t)}{\partial t} \cong \frac{\partial\phi_0(x_0,y_0,z_0,t)}{\partial t} &+ \\ \frac{\partial^2\phi_0(x_0,y_0,z_0,t)}{\partial t\partial x}(x-x_0) &+ \\ \frac{\partial^2\phi_0(x_0,y_0,z_0,t)}{\partial t\partial y}(y-y_0) &+ \\ \frac{\partial^2\phi_0(x_0,y_0,z_0,t)}{\partial t\partial z}(z-z_0)&\end{aligned} \quad (4)$$

The dynamic free surface *boundary* condition can be used to relate the Froude-Krylov pressure at the free surface to the incident wave elevation:

$$\frac{\partial\phi_0(x,y,\eta,t)}{\partial t} = -g\eta(x,y,t) \quad (5)$$

If the *evaluation* point is chosen to be on the incident wave surface, $z_0=\eta$, Equation (4) can be written as:

$$\begin{aligned}\frac{\partial\phi_0(x,y,z,t)}{\partial t} &\cong -g\eta(x_0,y_0,t)\\ &-g\frac{\partial\eta(x_0,y_0,t)}{\partial x}(x-x_0)\\ &-g\frac{\partial\eta(x_0,y_0,t)}{\partial y}(y-y_0)\\ &+\frac{\partial^2\phi_0(x_0,y_0,\eta,t)}{\partial t\partial z}(z-\eta)\end{aligned} \tag{6}$$

Using an overbar to *designate* the mean or nominal value of the elevation, etc. for a section, the sectional force can be written as:

$$\begin{aligned}\delta\mathbf{F}_{FK+HS}(x_{i,}t) &\cong \rho\iint_{\delta S_B(t)}(g\bar{\eta}-gz\\ &+g\overline{\frac{\partial\eta}{\partial x}}(x-x_0)+g\overline{\frac{\partial\eta}{\partial y}}(y-y_0)\\ &+\overline{\frac{\partial^2\phi_0}{\partial z\partial t}}(z-z_0))\hat{\mathbf{n}}\,ds\end{aligned} \tag{7}$$

Since the incremental surface $\delta S_B(x_i,t)$ includes x=constant plane separating adjacent sections and the pressure over the free surface above the section will be zero, the RHS of (7) complete encompasses the submerged portion of the section. Gauss's theorem can then be applied in order to define the sectional force in terms of the integral of the gradient of the approximated pressure field over the incremental volume:

$$\delta\mathbf{F}(t)=\iint_{\delta S_B(t)}P\hat{\mathbf{n}}\,ds=-\iiint_{\delta V(t)}\nabla P dv \tag{8}$$

This results in a volume-based formula for the sectional incident wave and restoring force:

$$\begin{aligned}\delta\mathbf{F}_{FK+HS}(x_,t) &\cong \rho g\delta V(x_i,t)\hat{\mathbf{k}}\\ &-\rho g\delta V(x_i,t)\overline{\frac{\partial\eta}{\partial x}}\hat{\mathbf{i}}\\ &-\rho g\delta V(x_i,t)\overline{\frac{\partial\eta}{\partial y}}\hat{\mathbf{j}}\\ &+\rho g\delta V(x_i,t)\overline{\frac{\partial^2\phi_0}{\partial z\partial t}}\hat{\mathbf{k}}\end{aligned} \tag{9}$$

$\delta V(x_i,t)$ is the instantaneous volume of the submerged portion of the i^{th} section up to the incident wave surface. The first term in Equation (9) is the familiar buoyancy term, but with the volume integrated up to the incident wave surface. The second and third terms are longitudinal and side forces from the gradient of the incident wave pressure field, evaluated in terms of the incident wave slope. The final term can be considered to be a "correction" to the vertical incident wave force, using a linear approximation of the exponential decay of the incident wave pressure field with depth.

Similarly, expressions for the moments can be derived by applying the relation:

$$-\iint_S(\hat{\mathbf{n}}\times P\mathbf{r})\,ds=\iiint_V\nabla\times P\mathbf{r}dv \tag{10}$$

This gives the following formula for the roll and pitch moments:

$$\begin{aligned}\delta Mx_{FK+HS}(x_i,t) &\cong \rho g\delta V(x_i,t)y_{CV}(x_i,t)\\ &-\rho g\delta V(x_i,t)\overline{\frac{\partial\eta}{\partial y}}z_{CV}(x_i,t)\\ &+\rho g\delta V(x_i,t)\overline{\frac{\partial^2\phi_0}{\partial z\partial t}}y_{CV}(x_i,t)\end{aligned} \tag{11}$$

$$\begin{aligned}\delta My_{FK+HS}(x_i,t) &\cong -\rho g\delta V(x_i,t)x_{CV}(x_i,t)\\ &+\rho g\delta V(x_i,t)\overline{\frac{\partial\eta}{\partial x}}z_{CV}(x_i,t)\\ &-\rho g\delta V(x_i,t)\overline{\frac{\partial^2\phi_0}{\partial z\partial t}}x_{CV}(x_i,t)\end{aligned} \tag{12}$$

$x_{cv}(x_i,t)$, $y_{cv}(x_i,t)$ and $z_{cv}(x_i,t)$ are coordinates for the center of the instantaneous submerged volume for the i^{th} section up to the incident wave waterline. The sectional roll and pitch moments can be summed to get the total moments on the ship:

$$Mx_{FK+HS}(t)=\sum\delta Mx_{FK+HS}(x_i,t) \tag{13}$$

$$My_{FK+HS}(t)=\sum\delta My_{FK+HS}(x_i,t) \tag{14}$$

The yaw moment can be computed from the sectional lateral forces as:

$$Mz_{FK+HS}(t) = \sum -\rho g \delta V(x_i,t)\overline{\frac{\partial \eta}{\partial y}}(x_i - x_{cg}) \quad (15)$$

With these formulae, the body-nonlinear Froude-Krylov and hydrostatic restoring forces can be computed with a single evaluation of the incident wave per section. The only major assumption in the derivation of these formulae is the Taylor series expansion of the incident wave pressure in Equation (4). This expansion assumes that the wave slope is constant over the beam and the incremental length of each section Δx, and can be considered a long-wavelength assumption in which the wave length is assumed to be long with respect to the beam and increment section length. This assumption should be quite reasonable for waves, or wave components in an irregular sea model, that are longer than two or three times the beam, but the linear approximation of the sinusoidal wave profile will become inaccurate for shorter waves. However, the section-based derivation retains the variation of elevation and slopes from section to section, so the waves are not assumed to be long relative to the ship length and the variation of relative motion along the ship's length, which the primary driver of the change of stability in waves, is considered.

The expansion considers the vertical pressure gradient to be, at most, linear with depth, so the wave is also assumed to be long compared to the draft of the ship. The linear approximation of the exponential pressure decay will become quite inaccurate for shorter waves, so any implementation of the $\partial^2\phi_0/\partial z\partial t$ term will need to treat of short waves or wave components carefully.

3. IMPLEMENTATION OF VOLUME-BASED CALCULATIONS

The implementation of these volume-based formulae in a time-domain numerical code requires the calculation of the submerged volume, up to the incident wave, and volume center for a set of ship hull sections at each time step. In order to accommodate extreme motion problems, these sectional volume calculations should accommodate large amplitude heave and pitch including fully submerged and emerged sections, and large amplitude roll motions including a fully inverted ship.

In the initial implementation, the sectional volume calculations were implemented using an approach similar to the Bonjean curves used for classic stability analysis. Prior to starting the simulation, a set of x=constant stations are cut through the hull and the volume and volume moments for the y>0 half of the hull section are pre-computed for 0 heel up to each station offset point.

At each time of a simulation (or heel angle of a restoring curve calculation), the Froude-Krylov and hydrostatic restoring force for each section is computed as follows:

1. Evaluate the incident wave elevation and slope at the centerline of each station
2. Find the intersection of the incident wave surface and the section centerline considering the wave elevation and vertical motion of the station due to the ship's heave and pitch
3. Find the port and starboard waterline points from the incident wave/center intersection and an effective heel angle, which is the sum of the ship's roll angle and the lateral wave slope at the centerline
4. Interpolate the volume and volume moments up to the waterline point for each side of the hull (dark blue in Figure 1)
5. Correct the volume and volume moments for the effective heel angle by adding or subtracting the contribution of the light blue triangular regions in Figure 1
6. Combine the volume and volume moments for the two sides to determine the volume and volume center for the section

7. Compute sectional forces and moments via Equations (9), (11), and (12).

The sectional forces and moments are then integrated along the length of the ship to get the total forces and moments.

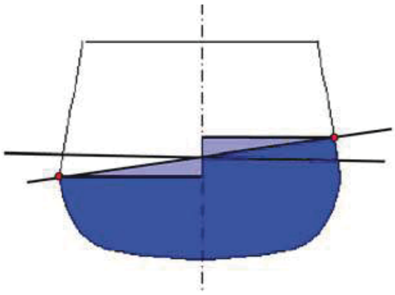

Figure 1: Sample sectional volume calculation for a midships section of the ONR Topsides Series Tumblehome hull

Figure 2 shows the station offsets and the waterline intersection points of each station for a time instant from a simulation in stern oblique irregular waves.

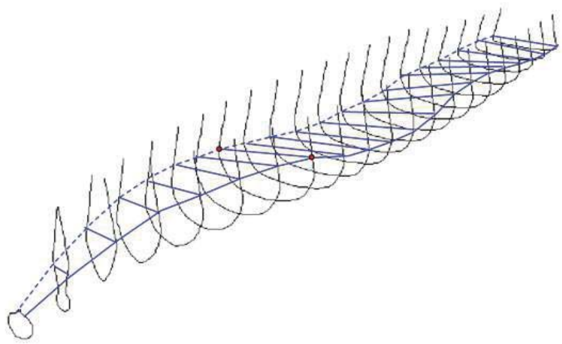

Figure 2: Station/incident wave intersection points for the ONR Tumblehome hull in stern oblique seas

In the initial implementation of the volume-based calculation, the $\partial^2\phi_0/\partial z\partial t$ term has *not* been included. Further work may be required to explore the $\partial^2\phi_0/\partial z\partial t$ term and to develop a robust and accurate handling for shorter waves and irregular wave representation, including short wave components.

The procedure is very fast, since it requires only a single evaluation of the incident wave elevation and its derivatives for each station at each time step. Even this effort can be mitigated by interpolating the wave in space and/or time. For a 3-DOF (heave, roll, pitch) simulation in which surge, sway, and yaw are prescribed based on constant forward speed, the global position of the sections is known *a priori*, so the incident wave values can be pre-computed at a larger time increment and interpolated to the simulation time step.

4. RESTORING CURVE CHECK

In order to verify the formulation and implementation of the sectional volume-based calculation, the roll restoring arm (GZ) curve was computed in both calm water and for the quasi-static wave-pass problem, and the results were compared to results from 3-D surface pressure integration in the Large Amplitude Motions Program (LAMP) and to results from a standard statics code. Figure 3 compares the calm water restoring arm of the different calculations for a 100m x 20m x 6m rectangular barge, while Figure 4 presents a similar comparison for the ONR Topsides Series Tumblehome hull.

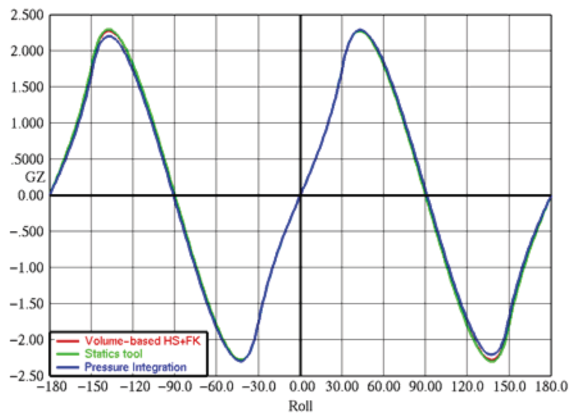

Figure 3: Calm water restoring curve for rectangular barge

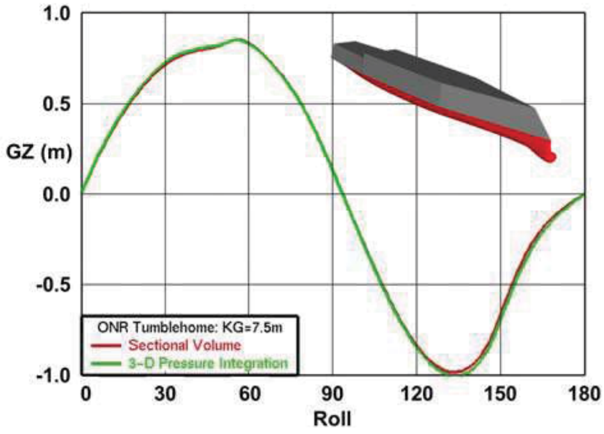

Figure 4: Calm water roll restoring arm (GZ) curve for ONR Tumblehome hull

As expected, the curves are nearly identical. As the calculation of the restoring moment is based on a volume calculation that is nearly exact, the incremental restoring moment about its static or instantaneous dynamic position, which is to say its restoring curve in calm water or in waves, will be nearly exact as well.

5. MOTIONS IN REGULAR WAVES

The volume-based Froude-Krylov and hydrostatic force calculation has been implemented in a 3-DOF (heave, pitch, roll) hybrid numerical simulation tool that incorporates ODE-like models for wave-body perturbation forces and viscous roll damping. In order to test the tool, the predicted response in regular waves was compared to LAMP simulations. LAMP is a general hybrid time-domain ship motions prediction tool that incorporates a conventional surface pressure integration of the hydrostatic and Froude-Krylov pressures with several different options for the wave-body hydrodynamic force (Shin *et al.*, 2003). Most LAMP simulations use its 3-D potential flow solution of the wave-body hydrodynamics, but LAMP also has the option, sometimes referred to as LAMP-0, of substituting coefficient-based added mass and damping terms for the potential flow solution. LAMP's Froude-Krylov pressure terms can also be evaluated without the pressure decay term (e^{kz}).

Figures 5 and 6 show the roll and heave response for a 3-DOF (heave, roll, pitch) simulation of a 100m x 20m x 6m rectangular barge in regular quartering waves with wave length equal to ship length and wave height equal to 1/3rd of the draft. The roll and pitch responses are nearly identical, as was heave (not plotted).

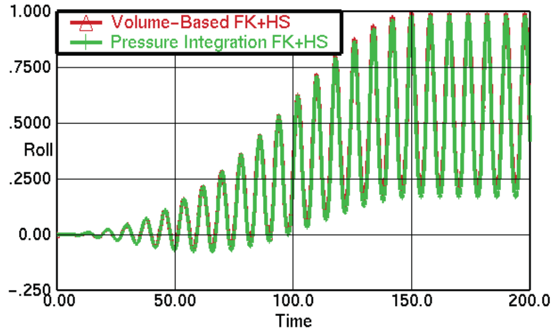

Figure 5: Roll motion for rectangular barge in quartering regular waves, λ=L h=d/3

The "Pressure Integration" results in Figures 5 and 6 are LAMP-0 results in which the incident wave decay (e^{kz}) has been turned off. As such, the incident wave and hydrostatic forces will differ only by the calculation method: volume vs. pressure integration. The viscous damping models and implementation of the hydrodynamic coefficient are similar but not identical. The results indicate that for a wave that is equal to the ship length and long relative to the beam, the magnitude and phase of the wave forcing and restoring, including the coupling that results in the asymmetric roll response, is well represented in the volume-based calculation.

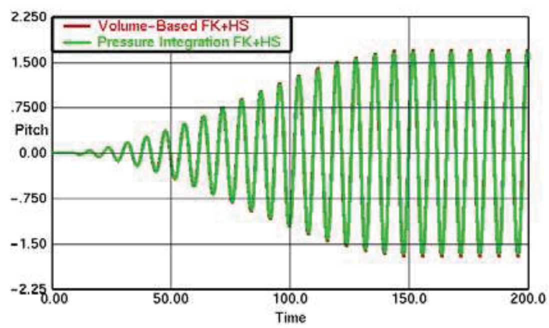

Figure 6: Pitch motion for rectangular barge in quartering regular waves, λ=L h=d/3

In order to evaluate the effects of wave length and calculation options, a series of regular wave response calculations were made for the ONR Topsides Series Tumblehome hull in regular, quartering seas at zero speed. Figures 7 through 9 plot the normalized response amplitude vs. the ratio of ship length to wave length for a wave slope of H/λ=50. The heave response is normalized by wave amplitude while the roll and pitch response are normalized by wave slope (ka).

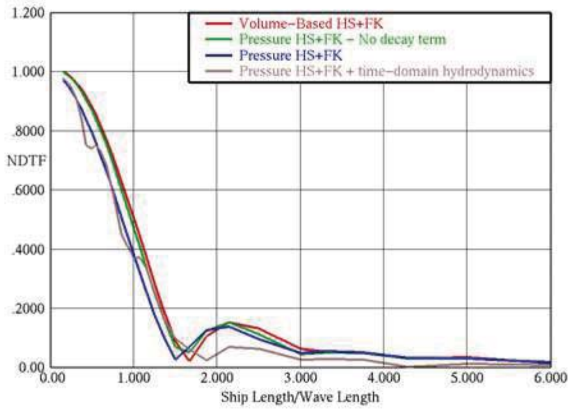

Figure 7: Heave response of ONR Tumblehome in regular, stern quartering waves, 0 knots

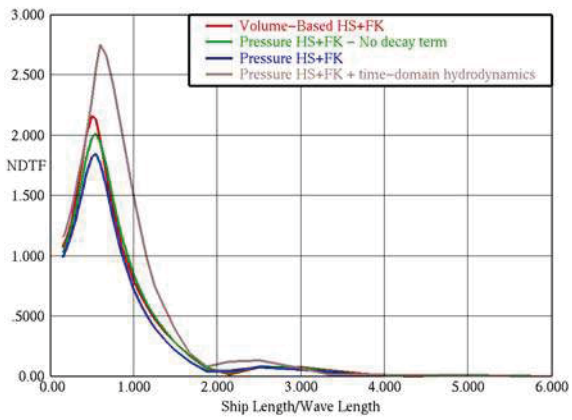

Figure 8: Roll response of ONR Tumblehome in regular, stern quartering waves, 0 knots

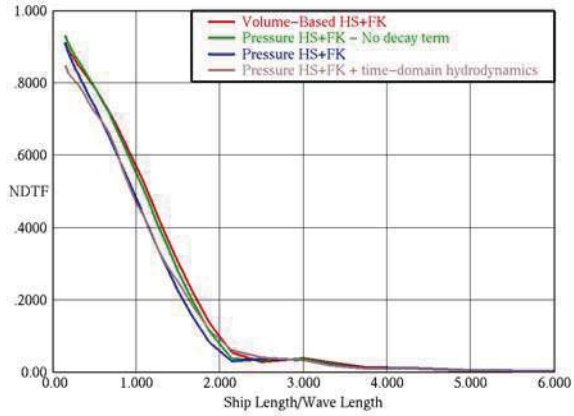

Figure 9: Pitch response of ONR Tumblehome in regular, stern quartering waves, 0 knots

These calculations were made with four different methods, labeled as:

- Volume-Based HS+FK is the simulation tool incorporating the new, volume-based calculation (red line)
- Pressure HS+FK – No decay term is a LAMP-0 simulation with surface pressure integration of HS+FK pressure neglecting the decay (e^{kz}) term (green line)
- Pressure HS+FK is a LAMP-0 simulation with surface pressure integration of HS+FK pressure including the decay (e^{kz}) term (blue line)
- Pressure HS+FK + time-domain hydrodynamics is a regular LAMP simulation with 3-D potential flow solution of the wave-body interaction. (brown line)

The difference between the red and green curves is primarily the difference between the new, volume-based calculation of the HS+FK forces vs. the traditional, pressure integration calculation, but with the effect of the pressure decay removed. There is also some difference in the coefficient-based hydrodynamics and damping models, which is most likely responsible for the difference in the roll response peak. The largest difference between the two calculations is expected to be for the shorter waves, but the response there is equally small for both.

The difference between the green and blue curves is entirely the effect of the decay (e^{kz}) term in the Froude-Krylov pressure integration. The effect is evident, especially in heave and pitch, but does not dominant the results. It is probably worth investigating the $\partial^2\phi_0/\partial z\partial t$ term in Equations (9), (11), and (12), which has been neglected in the initial implementation over the method, to correct for this difference.

The difference between blue and the brown curves is the effect of the more accurate hydrodynamics in the regular LAMP calculation. The effect is large enough that volume-based method must be coupled with a more complete model of hydrodynamics in order to create a quantitative tool for ship motions.

6. MOTIONS IN IRREGULAR SEAS

As described above, the primary purpose for developing the volume-based calculation of the hydrostatic restoring and incident wave forcing was to produce a tool capable of creating very large data sets of ship motions in severe, irregular seas that are at least qualitatively representative of actual, nonlinear data. These data would be used in developing and testing of extrapolation methods for severe roll motion including capsizing.

Figure 10 shows 20 records of the roll response for the ONR Tumblehome ship at a low GM condition (GM=1.5m) in large (Sea State 8) steep stern quartering waves. The seaway is modeled by 220 wave components to provide a statistically independent wave representation over each 30-minute realization. The total calculation time for these 20 realizations was about 7 seconds on a single processor laptop computer. 2,000,000 realizations comprising 1,000,000 hours of data can be generated in a day or so on a modest sized cluster.

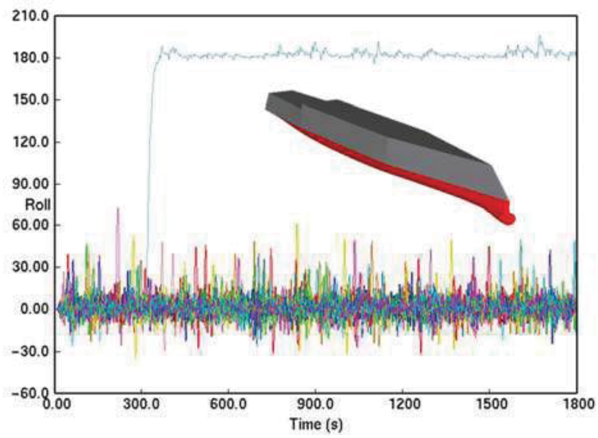

Figure 10: Roll motion for 20 realizations of ONR Tumblehome hull in steep Sea State 8

This example shows that the code is fast enough, but does it reproduce the significant nonlinearities of realistic severe ship motion, especially roll? Since the method captures the key features of the change of stability in waves, it should, at least to some extent. But how does one demonstrate, let alone prove, that it does?

For the present, we look at the distribution of predicted roll motion for the ONR Tumblehome hull at 6 knots in long-crested quartering seas with a significant wave height ($H^{1/3}$) of 9.5m, which is one of the cases used to test the extrapolation methods described in Belenky *et al.* (2015). Figures 11 through 13 compare a histogram of the roll angle from 15 hours of regular (with potential flow hydrodynamics) LAMP simulations (30 30-minute realizations) to a curve derived from 500 hours of simulations using the volume-based HS+FK calculation with simplified hydrodynamics. The horizontal axis is the roll angle divided by its standard deviation (σ). A normal distribution is overlaid for reference.

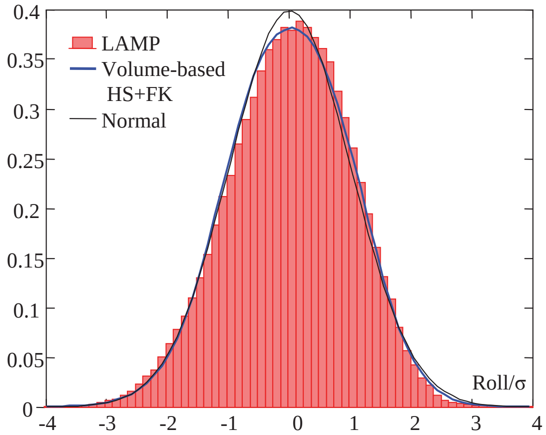

Figure 11: Distribution of Roll Angle for ONR Tumblehome at 6 knots in quartering seas, $H^{1/3}$=9.5m

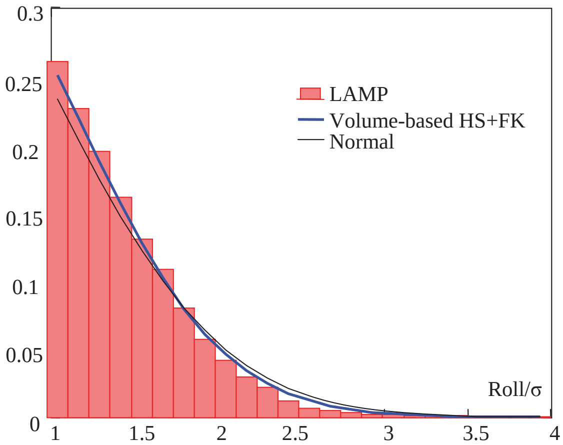

Figure 12: Distribution of Roll Angle – positive tail

The difference between the normal distribution and the LAMP results is not huge, but it has been shown that this difference is important, especially at the tail. Most important is the relative thinness of the positive tail (Figure 12) thickness of the negative tail (Figure 13). The trending of the volume-based result follows the LAMP results rather well. This result is not conclusive by any means, but it is encouraging and provides justification for using the results of the volume-based simulations for the testing of the extrapolation techniques.

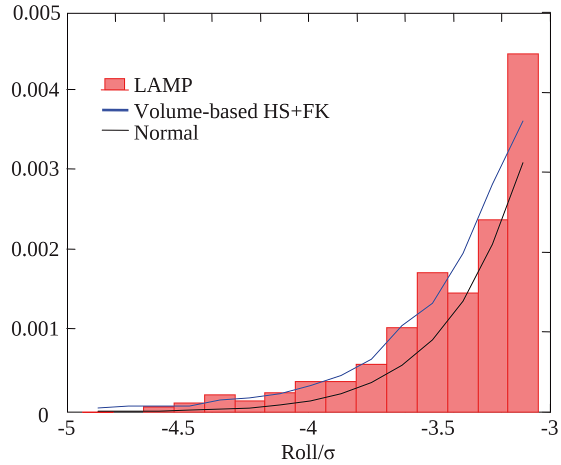

Figure 13: Distribution of Roll Angle – negative tail

7. CONCLUSIONS AND FUTURE WORK

The analysis of rare dynamic stability failures, including extreme roll events and capsizing, can gain considerable benefit from very rapid numerical simulations in irregular waves, as long as the simulations capture the principal physical phenomenon of the events. The very large data sets of irregular sea ship motion generated by such methods would allow the direct observation of rare events or near events and provide a basis for building and testing probabilistic models. Simulations that are even qualitatively correct have potential application for testing such models, especially those which are based on the extrapolation of smaller data sets.

In order to enable the development of such a numerical simulation tool, a very fast calculation method has been developed for the body-nonlinear hydrostatic restoring and incident wave (Froude-Krylov) forcing, which has been identified as a principal contributor to parametric roll and pure-loss-of-stability events. The calculation method uses volume-based formulae for the forces and moments on a series of hull stations as a function of the local relative motion and effective heel angle. The method is very accurate in the assessment of roll restoring and its changes due to relative motions in waves, but is approximate in the evaluation of the incident wave forcing. By requiring only one evaluation of the incident wave per section, it is far faster than traditional methods based on the integration of pressure over the hull surface.

The method has been implemented in a 3-DOF (heave, roll, pitch) hybrid simulation tool which incorporates simple, coefficient-based models for wave-body hydrodynamics and viscous damping. The tool is capable of practically generating very large data sets, *e.g.* millions of hours, but can be considered only qualitatively accurate with its simplified hydrodynamic model. Future work will include an investigation of the vertical derivative term in the formulae, a more complete verification that the method provides a qualitatively accurate representation of ship motion in large waves and the integration of the volume-based calculation with more complete models for the wave-body hydrodynamics, maneuvering forces such as propulsion and hull lift, and other effects.

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