Including Diffraction and Radiation into Probabilistic Description of Capsizing

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ABSTRACT

The paper reviews recent development on the assessment of the probability of capsizing in irregular waves using the split-time method with advanced numerical simulation codes. Particular attention is focused on including diffraction and radiation forces in motion perturbation simulations as well as generalizing the calculation scheme for 6 degrees of freedom. The implementation is based on the Large Amplitude Motion Program (LAMP), which is a hybrid code combining body-nonlinear formulation for hydrostatic and Froude-Krylov forces, a potential flow solution for diffraction and radiation and external coefficient-based models for viscous and vortical forces.

Keywords: *Probability of capsizing, numerical simulations, split-time method, motion perturbation.*

1. INTRODUCTION

This paper describes the implementation of the split-time method for the probabilistic assessment of capsizing in irregular waves using advanced numerical codes. It is a direct continuation of the paper presented at the previous workshop (Weems and Belenky, 2016). The motivation and general framework of this development was included in the cited paper and is not repeated in detail here. However, it should be noted that a key element of the split-time method is the use of motion perturbation simulations to compute a metric of the likelihood of capsizing when a particular event occurs in the course of normal random-wave time-domain simulations. In the present work, the event is the upcrossing of an intermediate threshold roll angle and the metric is based on the difference between the ship's roll rate at the upcrossing and a "critical" roll rate which would lead to capsizing. This critical roll rate is computed by performing a series of perturbed motion simulations starting at the upcrossing point with different roll rates. It is the implementation of these perturbed motion simulations which is the focus of the present paper.

2. LAMP

LAMP development began in the early 1990s in order to provide a nonlinear, time-domain prediction of ship motions and loads in waves (Lin and Yue 1990) that would complement linear frequency domain analysis. The submerged portion of the body is represented with a general 3-D panel model, so there are very little limitations in terms of what kind of ship geometry can be handled by LAMP, see Figure 1.

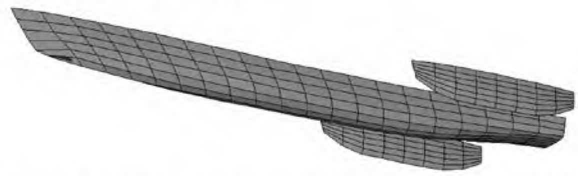

Figure 1: Example of trimaran geometry (Shin, et al 2003)

Hydrostatic and Froude-Krylov forces are generally computed by the integration of pressures over the instantaneous wetted portion of the panel model up to the incident waterline. There is an option to compute Froude-Krylov forces up to the mean waterline and hydrostatic restoring forces from waterplane quantities, but this option is used mostly only for comparison with linear frequency domain codes and the quantification of nonlinear effects (Smith and Silva, 2017).

Forces related to the disturbance of the wave surface by the ship, which includes radiation, diffraction and forward speed effects, are computed by distributing Rankine singularities over the body and free surface panels. The far-field influence is modeled with the damping beach or a set of transient Greens functions distributed over a matching surface. Figure 2 shows an example of LAMP computational domain for a naval combatant.

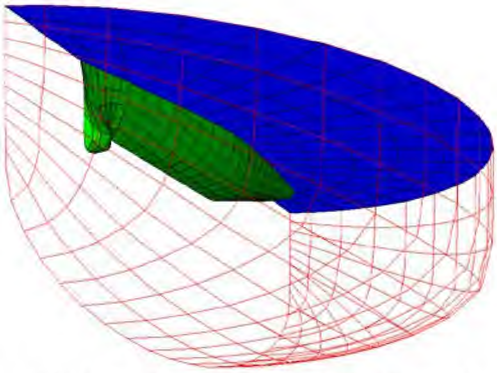

Figure 2: Example of LAMP computational domain

In the general case, the velocity potential of the wave-body disturbance is computed by applying combined body and linearized free surface boundary conditions, advancing the free surface in time, solving for the disturbance potential and computing the surface pressure distribution using Bernoulli's equation. This is known as the "direct" solution. The solution has been implemented in two coordinate systems. The basic solution is solved in a sliding system which moves with the constant forward speed, which provides robustness but cannot be used for cases with large lateral motion (large sway or yaw or significant change in speed). The extended solution allows large lateral motion but may require a smaller time step for stability.

An alternative is the Impulse Response Function (IRF) based solution, in which the perturbation velocity potential on each body panel is decomposed as:

$$\Phi_k(\vec{x},t) = \sum_{k=1}^{6} \Phi_k(\vec{x},t) + \Phi_7(\vec{x},t) + \Phi_8(\vec{x},t) \quad (1)$$

where the Φ_k, $k=1..6$ are the radiation potentials for the six rigid-body motions, Φ_7 is the diffraction potential related to the incident wave potential Φ_0, and Φ_8 is the steady state potential related to the constant forward speed U. To solve for the six radiation potentials Φ_k, six corresponding impulse response functions φ_k are introduced via the convolution integral:

$$\Phi_k(\vec{x},t) = \int_0^t \varphi_k(\vec{x},t-\tau)\dot{X}(\tau)d\tau \quad (2)$$

where X_k is the ship motion in mode k and the dot signifies the derivative with respect to time. The diffraction potential Φ_7, the diffraction IRF φ_7 is introduced via the convolution integral

$$\Phi_7(\vec{x},t) = \int_{-\infty}^{\infty} \varphi_7(\vec{x},t-\tau)\zeta_0(\tau)d\tau \quad (3)$$

where ζ_0 is the incident wave elevation at the origin of the ship-fixed frame. In its present implementation, the IRF formulation is solved in the sliding system and cannot be used for cases with large lateral motion (large sway or yaw or significant change in speed). Further details on IRF formulation can be found in Weems, et al. (2000), while a summary description is available in Shin, et al. (2003).

There are two options for the principle frame of reference of the dynamic solver: ship-fixed and global. In either frame of reference, individual modes can be free, constrained or prescribed.

Different combinations of these options provide different "levels":

LAMP-1 Body-linear solution is used for both Froude-Krylov/hydrostatic and diffraction/radiation forces; limited to small lateral motions; IRF option is available. Not suitable for capsizing simulation due to linear restoring.

LAMP-2 Body-nonlinear solution for Froude-Krylov/hydrostatic forces and body-linear solution for diffraction and radiation; limited to small lateral motions; IRF option is available. Suitable for 3-DOF capsizing simulations where surge, sway and yaw are constrained to constant forward speed.

LAMP-3 Body-nonlinear solution for Froude-Krylov/hydrostatic forces and body-linear solution for diffraction and radiation; allows large lateral motion but is limited to ship-based motion constraints. Suitable for 6-DOF capsizing simulations.

LAMP-4 Body-nonlinear solution for both Froude-Krylov/hydrostatic forces, diffraction and radiation; allows large lateral motion. LAMP-4 is too slow to be practically used in perturbation simulations for all but exploratory studies and has not been fully integrated into the present rare problem solver. However, a set of exploratory studies for critical roll rate in calm water suggested that the body-nonlinear disturbance potential had little effect on the critical roll rate.

In addition to these levels, there is an option to suspend the potential flow solution of the wave-body disturbance and substitute user-defined coefficients for diffraction and radiation forces. This option is referred to as LAMP-0 and can be used with global or ship-based constraints.

3. LAMP_LITER

LAMP_Liter is a specialized implementation of the LAMP solver that performs motion perturbation simulation from the instants of upcrossing of the intermediate level by the roll motion, iterating to find the critical roll rate leading to capsizing. The general structure of the program is described in Weems and Belenky (2016), presented at the previous workshop; the present focus is on computational / modeling aspects of the problem.

LAMP_Liter can be configured with any of LAMP's hydrodynamic and dynamic options other than LAMP-4. The configuration and options of the perturbation simulation, which is part of the "rare" problem, does not need to exactly match the configuration for the original random wave simulation, which is the non-rare problem. As a result, it is possible to run the non-rare problem with LAMP-2 and then opt for LAMP-0 for the rare problem. Justification of these and other modeling choices must come from the context of the problem.

The ability to prescribe individual modes of motion has been used to allow a "mix-and-match" of degrees of freedom in the perturbation simulations. It is possible to simulate the perturbed motion in some mode(s) while using unperturbed solution for the rest. For example, 1-DOF roll only simulations can be performed for 3-DOF or 6-DOF non-rare data by allowing roll to be a free mode of motion while all other modes are prescribed using the results of the original non-rare simulation. Similarly, a 3-DOF (heave, roll, pitch) perturbation simulation could be used with a 6-DOF non-rare solution by prescribing surge, sway and yaw to match the unperturbed solution. This latter option preserves the ship's position in the wave from the original simulation.

Some care must be taken in selecting the dynamic system and motion constraints. For example, if a 3-DOF (heave, roll, pitch) set of constraints are applied in the ship-fixed system, the yaw constraint becomes un-physical as the roll angle nears 90 degrees. This is generally not a problem when roll motions are moderate but can become so for perturbation simulations searching for very large roll motions or the transition to capsizing.

The biggest challenge with LAMP-based perturbation simulations is the potential flow based hydrodynamic disturbance inducing radiation and diffraction.

LAMP-0 3DOF

The most basic LAMP-based capsizing analysis is a 3-DOF (heave-pitch-roll) motion using the LAMP-0 model. It provides a verification of the implementation of the motion perturbation method in LAMP and can be directly compared to simpler models such as the SimpleCode that was used for statistical validation of the split-time method (Weems *et al.* 2016). Since the LAMP-0 model does not include the potential flow hydrodynamic disturbance model, it can provide directly continuous perturbation simulation from the crossing point (Weems and Belenky 2016).

LAMP-2 Direct Calculations

The first significant challenge introducing LAMP-2 hydrodynamics into the perturbation simulations is the transition of the hydrodynamic disturbance model. The most straight-forward approach is the "dead start" concept. In this approach, the hydrodynamic solution is being re-initialized at the start of each perturbation simulation, with the disturbance potential and elevations set to zero. The radiation and diffraction forces at the start will also be zero at the start of the perturbation, but are calculated as the simulation proceeds. Initial calculations in low to moderate speed (up to 15 knots) have shown this approach to be very effective, with only minor difference in motion for an "unperturbed" simulation, starting at the upcrossing point with the observed upcrossing rate as compared to the original non-rare simulation. While this may become more of an issue for higher speeds, the effects of inertia and restoring are still likely to dominate at larger initial roll rates.

A second potential issue with LAMP-2 hydrodynamics is the body-linear formulation of the potential flow problem, which is solved over the mean wetted surface. As the roll angle gets very large, this solution loses accuracy and may become numerically unstable. However, this instability has only been observed when the roll angle exceeds 100~120 degrees, at which point the capsizing event already became a certainty and the critical roll rate evaluated. In order to enable simulation beyond those values, the calculations switch to the coefficient-based hydrodynamic forces model once the roll angle exceeds the prescribed value.

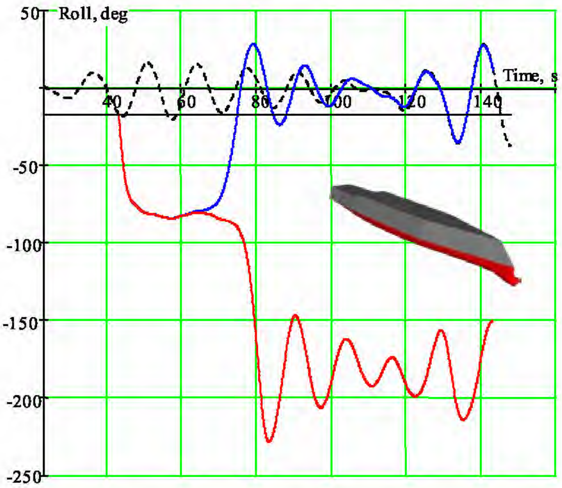

Figure 3: Perturbed and unperturbed roll motions calculated with LAMP-2

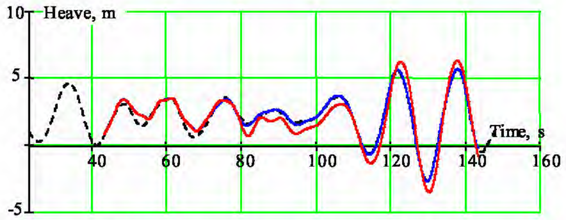

Figure 4: Perturbed and unperturbed heave motions calculated with LAMP-2.

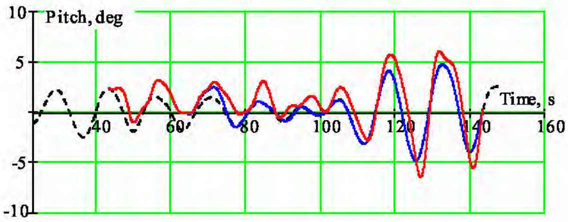

Figure 5: Perturbed and unperturbed pitch motions calculated with LAMP-2.

Figure 3 through 5 shows the results of a set of perturbation calculations using the direct LAMP-2 hydrodynamic calculations. The ship is the tumblehome variant of the ONR Topsides Series. The seaway is long-crested and is modeled by a Bretschneider spectrum with a significant wave height of 9.0m and modal period of 14.0 seconds. The ship speed is 10 knots and the heading is 45° (stern quartering waves). The dashed line indicates the original "non-rare" simulation. Two perturbed solutions from the iteration for the critical roll rate are plotted. The first (blue) is just short of capsizing while the second (Red) is the smallest roll rate perturbation leading to capsizing. As expected, roll time history exhibits "hanging" around simultaneous position of unstable equilibrium before "deciding to capsize or not." The duration of this hesitation depends on the tolerance required from the iterative process.

A second approach that has been explored for LAMP-2 motion perturbation simulations is the "re-start" concept. In this approach, the numerical solution– distrubance potential, free surface elevations, etc. – of the non-rare solution is stored at the moment of upcrossing and then used to initialize each perturbation calculation. This provides a full hydrodynamic solution from the start and a completely smooth transition when the perturbations are small, but the jump in velocity for larger perturbations can cause a larger problem than the dead start case. The complexity of identifying upcrossings and saving restarts during the non-rare run is a disadvantage to this approach.

Some of the disadvantages of both the deadstart and restart approaches could be mitigated by starting the perturbation simulatior a short time before the upcrossing and prescribing all modes of motion up to the upcrossing point. This would mitigate the impulsive start of the deadstart approach and allow restart sets to simply be periodically saved without having to identify upcrossings in the non-rare problem. The perturbation could be feathered into the prescribed motion period. This approach has not been fully implemented but is being condidered for future work.

LAMP-2 IRF Calculations

The IRF formulation was originally implemented to speed up simulations, as the cost of the convolutions with pre-computed IRF potentials is a fraction of the direct method, and a set of IRF potentials is dependent only on speed and heading and can be re-used for many wave conditions.

The same is true for the perturbation calculations, however there are additional benefits. The diffraction potential (3) does not include motions, only incident wave elevations. As the wave elevations are known exactly, the complete diffraction potential can be used from the start of the perturbation. The steady forward speed potential, Φ_8 in (1), can also be used from the start. Only the radiation potential (2) needs to be re-started, and that could be mitigated by initializing the motion history with non-rare data, though this has not been done in the present simulations.

Figures 6 through 8 shows the original solution (dashed line) and two perturbations (solid lines: red – leading to capsizing and blue – short of capsizing). It is noticeable that the difference between the direct and IRF calculation is not that large actually. However, it is still too early to make any conclusions about the effect of diffraction and radiation forces on capsizing in the perturbation simulations.

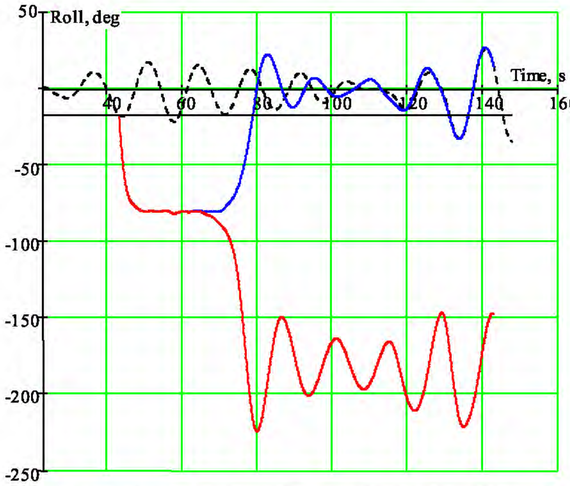

Figure 6: Perturbed and unperturbed roll motions calculated with LAMP-2 / IRF option.

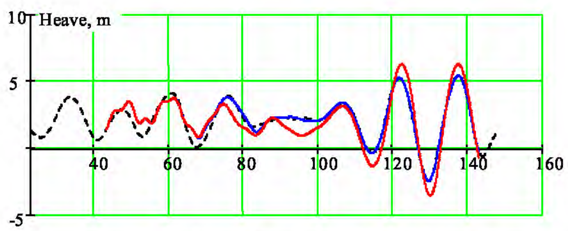

Figure 7: Perturbed and unperturbed heave motions calculated with LAMP-2 / IRF option.

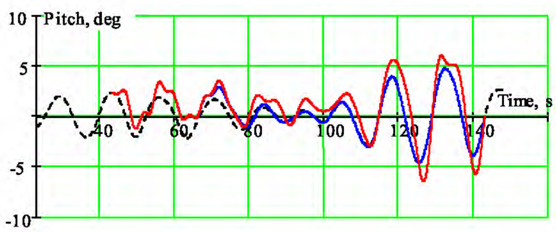

Figure 8: Perturbed and unperturbed pitch motions calculated with LAMP-2 / IRF option.

LAMP-0 6-DOF

The next complication in perturbation simulations is to include all 6 degrees of freedom. Including horizontal motion into a potential flow code is not trivial as the flow model does not implicitly capture maneuvering forces of a viscous or vortical nature. Modeling maneuvering forces with coefficients from a model test or CFD calculation is also not trivial as both experimental and CFD data do include wave forces that are also internally calculated within a potential flow code. To avoid potential double counting for wave forces, they have to be "subtracted" from the empirical coefficients, see Lin, *et al* 2006 for details.

A set of 6-DOF perturbation simulations are presented in Figure 9 through 14.

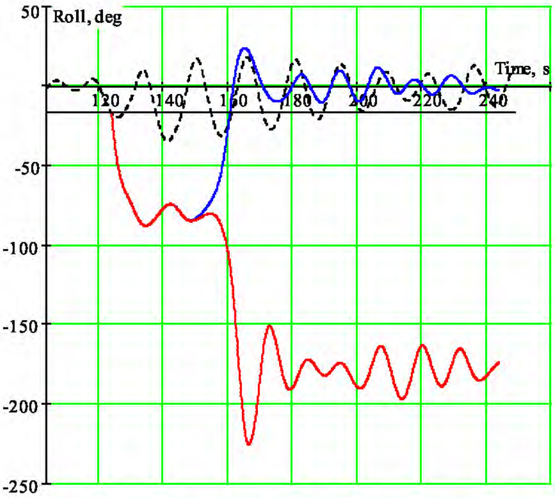

Figure 9: Perturbed and unperturbed roll motions calculated with LAMP-0 / 6-DOF

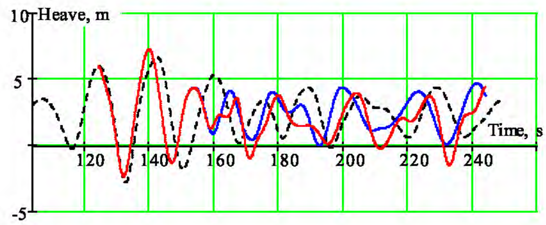

Figure 10: Perturbed and unperturbed heave motions calculated with LAMP-0 / 6-DOF.

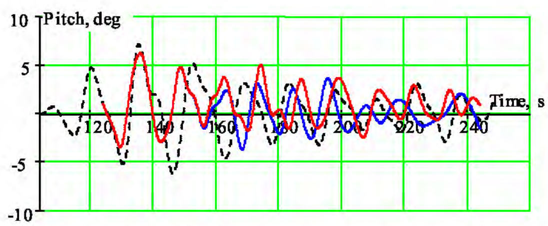

Figure 11: Perturbed and unperturbed pitch motions calculated with LAMP-0 / 6-DOF.

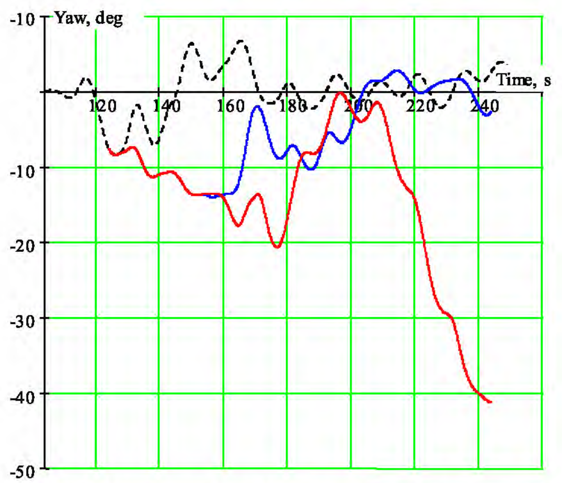

Figure 12: Perturbed and unperturbed yaw motions calculated with LAMP-0 / 6-DOF.

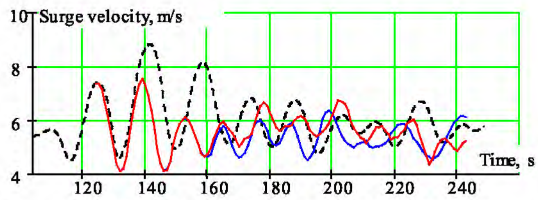

Figure 13: Perturbed and unperturbed surge velocity calculated with LAMP-0 / 6-DOF.

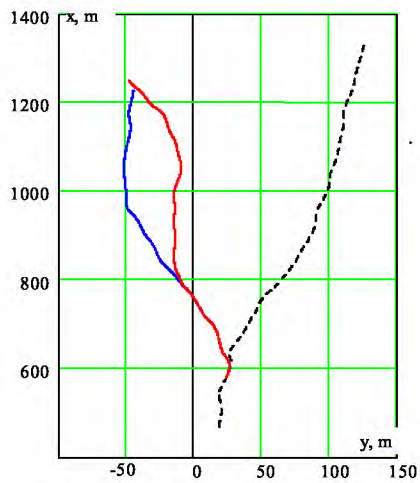

Figure 14: Perturbed and unperturbed trajectories calculated with LAMP-0 / 6-DOF

The results presented in Figure 9 through 14 are computed with LAMP-0, which is a natural starting point. While, in principle, the problem of double counting in the inclusion of horizontal motions has been solved, the full implementation of direct LAMP-3 hydrodynamic calculations for perturbations had not been completed at the time of writing this paper.

As expected in Weems and Belenky (2016), the 6-DOF perturbed solutions do not necessarily converge to the unperturbed time history as in the 3-DOF. The development of significant unsteady surge, sway motion and yaw angle (Figure 12) means that the ship in the perturbation simulations may encounter different waves in different places as it can be seen from trajectories in Figure 14. As a result, the convergence of the motion history can no longer be used as a criteria for truncating perturbation simulations. Aside from this, the 6-DOF rare problem is fundamentally identical to the 3-DOF problem.

As described above, the perturbation simulations for 6-DOF non-rare motions can alternatively be performed with 3-DOF (heave, roll pitch) or even 1-DOF (roll) free motions. The appropriateness of different DOFs, and of modeling options in general, will depend on the requirements of the perturbation-based analysis. For the present application of the split-time method to pure-loss-of-stability events, reduced DOF solutions appear to be adequate, but the full effects of DOF have yet to be evaluated.

4. SUMMARY AND CONCLUSIONS

The paper continues the discussion from the previous workshop regarding the implementation of motion perturbation analysis in a numerical seakeeping code. The focus is on the LAMP-based solution of the rare problem for critical roll rate in the split-time method for estimating a probability of capsizing in irregular waves.

Those motion perturbations are handled by a special implementation of the LAMP solver called LAMP_LITER. LAMP_LITER can be configured to use a number of computational models and up to 6-DOF, using direct calculations of diffraction and radiation, while an option to use pre-computed IRFs is available for select models.

The principal conclusion is that it is possible to implement motion perturbation simulations within the framework of potential flow hybrid codes originally intended for large amplitude motions and loads. However, the implementation is non-trivial and some effort is required in order to ensure that the code and selected options are appropriate to and consistent with the analysis being undertaken. In particular, it does appear that such codes can be incorporated within the split-time method for evaluating extreme events.

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REFERENCES

Lin, W.M., and Yue, D.K.P., 1990 "Numerical Solutions for Large Amplitude Ship Motions in the Time-Domain," *Proc. 18th Symp. on Naval Hydrodynamics*, Ann Arbor, Michigan, USA, pp. 41–66

Lin, W. M., Zhang, S., Weems, K. and D. Luit, 2006 "Numerical Simulations of Ship Maneuvering in Waves", Proc. of 26th *Symp. on Naval Hydrodynamics,* Rome, Italy.

Shin, Y.S, Belenky, V.L., Lin, W.M., Weems, K.M. and A. H. Engle 2003 "Nonlinear time domain simulation technology for seakeeping and wave-load analysis for modern ship design" *SNAME Trans*. Vol. 111, pp. 557-578.

Smith, T. and K. Silva, 2017 "Linear Seakeeping High Sea State Applicability," *Proc. 16th Intl. Ship Stability Workshop*, Belgrade, Serbia.

Weems, K., Lin, W.M., Zhang, S, Treakle, T., 2000. "Time Domain Prediction for Motions and Loads of Ships and Marine Structures in Large Seas Using a Mixed-Singularity Formulation", Proc. OC2000, Osaka, Japan.

Weems, K., and V. Belenky, 2016 "Split-time Algorithm Implementation in Advanced Hydrodynamic Codes" *Proc. 15th Intl. Ship Stability Workshop*, Stockholm, Sweden, pp. 83-88.

Weems, K., Belenky, V., Campbell, B. 2016 "Validation of Split-time Method with Volume-Based Numerical Simulation", *Proc. 15th Intl Ship Stability Workshop*, Stockholm, Sweden. pp. 103-108.