Numerical Flow Analysis (NFA) Predictions of the Stability of the Joint High Speed Sealift (JHSS) Monohull in Head Seas

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ABSTRACT
The results of a set numerical simulations of the Joint High Speed Sealift (JHSS) monohull in calm water, at steady forward speed, and in head seas are presented and discussed. The majority of the paper is focussed on how steady forward speed and head seas affect the righting arm. The effect of steady forward speed on the righting arm is found to be small (+1.6%) at a 30° heel angle. The results of the head-seas simulations are compared to the results of a Froud-Krylov-type analysis based on the simulated wave field sans body. The Froud-Krylov analysis over-predicts the loss of righting moment between for wave phases 30° and 180° and has a phase-lead for wave phases between 0°-30° and 180°-360°. Visualizations from a four-degrees-of-freedom simulation of the JHSS monohull in an unstable configuration illustrate the capsizing in head seas.

KEYWORDS
Numerical Flow Analysis (NFA); Joint High Speed Sealift (JHSS); Extreme sea-states; Phase-Stability; Capsizing

INTRODUCTION
The design of current and future ships is becoming more complex with the incorporation of advanced hull forms such as the tumblehome bows and trimaran hulls currently employed in the DDG 1000 and Littoral Combat Ship (LCS) designs. In addition, these novel and advanced hull forms are operating in more extreme environments and conditions. The design and analysis process requires extrapolation from current design databases and will increasingly rely on computational tools.

The objective of this paper is to show that the Numerical Flow Analysis (NFA) software is capable of providing design support for assessing the performance of the next generation of naval vessels undergoing extreme loads and motions while operating at high speed. To this end, the results of a systematic study of the static and dynamic roll-stability of the Joint High Speed Sealift (JHSS) monohull in head seas are presented.

The layout of the paper is as follows. The numerical approach section provides details of the hull model, computational domain, and parameters used in the study. The static stability section briefly discusses the hydrostatic stability as a baseline for comparison in following sections. The next two sections discuss the effects of steady forward speed and head seas on the righting arm curves. Specifically, a comparison to hydrostatics
based on a Froude-Krylov analysis for a fixed heel angle of 30° and the change in the righting arm as a function of wave phase (position of crest along hull) are discussed. Last, the capsizing section shows visualizations from a four-degrees-of-freedom (4DOF) simulation to illustrate the capsizing of the JHSS monohull in head seas.

NUMERICAL APPROACH

The NFA computer code is employed in this study. NFA solves the Navier-Stokes equations utilizing a cut-cell, Cartesian-grid formulation with interface-capturing to model the unsteady flow of air and water around moving bodies. The interface-capturing of the free surface uses a second-order accurate, volume-of-fluid technique. The cut-cell method is used to enforce free-slip boundary conditions on the body. A boundary-layer model has been developed (Rottman, et al., 2010), but it is not used in these numerical simulations. NFA uses an implicit Subgrid-scale model that is built into the treatment of the convective terms in the momentum equations (Rottman, et al., 2010). A panellized surface representation of the ship hull (body) is all that is required as input in terms of body geometry. The numerical scheme is implemented on parallel computers using Fortran 90 and Message Passing Interface (MPI). The interested reader is referred to Dommermuth, et al. (2007), O’Shea, et al. (2008), and Brucker, et al. (2010) for a detailed description of the numerical algorithm and of its implementation on distributed memory High Performance Computing (HPC) platforms.
simulations, respectively. In the fine simulation, the grid points are distributed in 128x128x64 blocks over 1024 cores. The grid is stretched with nearly uniform spacing around the ship where the grid spacing is $0.008L^c$, $0.004L^m$, $0.002L^f$. The maximum grid spacing far away from the ship along the Cartesian axes is $[0.028L^c, 0.073L^m, 0.112L^f]$, $[0.014L^c, 0.037L^m, 0.056L^f]$, $[0.006L^c, 0.018L^m, 0.028L^f]$.

All simulations have been run on the Cray® (Cray Inc.) XT4 at the U.S. Army Engineering Research and Development Center (ERDC). The coarse simulations require one wall-clock hour per boat length. The medium simulations require 2.2 hours per boat length. The fine simulations require nine hours per boat length. The forces and moments are output every two iterations for all cases. This data output rate corresponds to a dimensional sampling frequency of 200Hz, 400Hz, and 800Hz for the coarse, medium and fine grids, respectively.

**STATIC STABILITY**

The results of a hydrostatic stability analysis of the JHSS model are presented to provide a baseline to which the stability at forward speed and in waves can be compared. Figure 2 shows the cross-section of the JHSS model at mid-ship, the water static water line (horizontal blue line), and the positions of the center of gravity, $G$, center of buoyancy, $B$, keel depth, $K$, and metacentric height, $M$. drawn to scale. The metacentric height, $M$, is calculated as

$$GM = KB + BM - KG$$

Based on linear theory $BM$ may be estimated as $BM = I_{xx} / V$, where $V$ is the volume of water displaced by the boat and $I_{xx}$ is the moment of inertia of the water plane area. The center of buoyancy, $B$, and the moment of inertia of the water plane, $I_{xx}$, are computed by slicing the panellized geometry into thin strips in $z$ and computing the appropriate contour integrals for the moments of inertia and area. These quantities are computed to check the static righting curve, as the total righting moment about the x-axis and displacement are directly output from NFA.

Hence the righting arm, $GZ$, can be directly calculated as:

$$GZ = \frac{R_M}{\Delta},$$

where, $R_M$ is the total moment about the x-axis.

The hydrostatic righting arm curve in Figure 3 is created by rolling the model in small angular increments and then iteratively sinking and trimming the rotated model until it is in hydrostatic equilibrium. This hydrostatically balanced, rotated, sunk and trimmed model is used as the input for the steady forward speed and head seas studies. Figure 3 shows the hydrostatic stability curves and the approximations $GM\phi$ and $GM\sin(\phi)$. The results are shown for various vertical centers of gravity (VCG), as the 4DOF simulation uses a more unstable VCG position. All other simulations use VCG=0, i.e., at the static water line.

**EFFECT OF STEADY FORWARD SPEED**

The effect of steady forward speed on the righting arm is considered for a heel angle of $30^\circ$. Figure 4 serves a dual purpose; the first is to illustrate that the solution converges as the grid is refined, and the second is to show the correction to the righting moment that occurs when the unsteady two-phase flow around the hull is included. The coarse (black), medium (red), and fine (blue) results are shown in addition to the hydrostatic righting arm (dashed black line). Between $T=0$ and $T=2$, the
flow is accelerated from rest to the free-stream value. After the initial transient, the righting arm increases to 0.01266L a 1.6% gain over the hydrostatic value.

The results of an NFA simulation of the JHSS monohull at a fixed heel angle of 30° in waves with \( \lambda=L \) and \( a=0.015L \) at the medium grid resolution are discussed in figures 5-7. Figure 5 compares the hydrostatic righting arm calculated based on the Froude-Krylov force to the righting arm from NFA. In the subsequent discussion, the wave phase, \( \theta \), is as follows: zero phase is defined as the phase when the crest of the wave is at the bow. Comparing the positive and negative changes to the righting arm in figure 5, the Froud-Krylov prediction is in better agreement for gains to the righting arm (\( \theta =0°-30°,180°-360° \)), albeit with a phase-lead. The prediction for losses to the righting arm are over-predicted. The maximum over prediction is 7% and occurs at \( \theta =130° \).

Figure 6 shows the waves when (a) the maximum loss in righting arm occurs, (b) the righting arm is equal to the hydrostatic righting arm, and (c) the maximum gain in righting arm.

Figure 7 shows the stacked data from six full wave periods (open circles) plotted along with the average over all six wave periods (solid black line). The six wave periods were all after \( T=2 \) when fully developed waves were along the entire length of the boat. The phase average is in good agreement with the instantaneous values.
The results of NFA simulations at heel angles of 10°, 20°, 30°, 40°, 50°, and 60° with the same waves and at the medium grid resolution are used to construct figures similar to figure 7. These plots are used to construct figure 8. Figure 8 shows the change in righting arm as a function of heel angle, for lines of constant wave phase. The maximum righting arm lost, -10%, occurs at a heel angle of 60° and phase angle of 120°. The maximum righting arm gained, +10%, occurs at a heel angle of 60° and phase angle of 300°.

CAPSIZING

Attention is now focussed on the results of a 4DOF simulation. The JHSS monohull model at 0° initial heel is put in waves and free to sway, heave, roll, and pitch. Without propulsion and rudders, surge and yaw would allow the model to be pushed parallel to the waves and exit out of the domain, and hence both are fixed at zero for the simulations.

Based on the hydrostatic stability plot, the vertical position of the center of gravity (VCG=0.025L above the mean water line) was chosen so that roll of more than ~30° should allow for capsizing only when additional losses to the righting arm due to wave interactions occur. Figure 9 shows a time series of renderings from the 4DOF simulation illustrating the capsizing in head seas.

CONCLUSIONS

The results of a set of NFA simulations of the JHSS monohull in calm water at steady forward speed and in head seas are presented and discussed. The change in righting arm due to steady forward speed at a fixed heel angle of 30°
was found to be 1.6%. Differences between the hydrostatic righting arm based on the Froude-Krylov predictions and the numerical simulations are observed. The hydrostatic Froude-Krylov predictions for gained righting arm are in agreement with respect to amplitude but show a phase lead when compared to the numerical simulations. For a heel angle of 30° the Froude-Krylov force predictions for lost righting arm are over-predicted. The maximum over-prediction is 7% and occurs at a wave phase of 130°. For a 60° heel angle, the over prediction is 10% and occurs at a wave phase of 120°.

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REFERENCES


Fig. 9: Instantaneous visualizations of a 4DOF simulation of the JHSS monohull in head-seas with $a=0.015L$ and $\lambda=L$, where $L$ is the ship length, $\lambda$ is the wave length, and $a$ is the wave amplitude.