COMPUTATIONAL INVESTIGATION OF NON-BODY-OF-REVOLUTION HULL FORM MANEUVERING CHARACTERISTICS

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1 INTRODUCTION

In this study, Reynolds Averaged Navier-Stokes (RANS) computations are used to shed insight into maneuvering characteristics for the DTMB Series 66 non-body-of-revolution (Non-BOR) hull forms. Non-BOR hull forms are of interest due to their potential for payload modularity vice traditional body-of-revolution (BOR) hull forms. Maneuvering characteristics of BOR hull forms are well understood from decades of testing, while less traditional Non-BOR hull forms are not nearly as well understood.

Series 66 is a systematic sequence of bodies: Single Tail, Twin Tail, and an equivalent BOR hull forms. Figure 1 shows the complete Series 66 hull form family. Only the BOR, wide-body long Single Tail, and wide-body Twin Tail configurations (marked with arrows in Figure 1) are investigated in this study. Other Series 66 hull forms will be investigated in future studies. The wide-body Single and Twin Tail hull forms share the same bow and midsection, which are essentially stretched in the span-wise direction from the BOR, while only the sterns are different.

Figure 1. Series 66 hull forms with configurations used in this study marked with arrows.

This computational investigation of the Series 66 Non-BOR hull forms is complementary to experimental tests performed by Roddy *et al* (2010) at the Naval Surface

Warfare Center, Carderock Division (NSWCCD). All experimental data presented in this study is from the work of Roddy *et al.*

Initially, global in-plane (vertical and horizontal) forces and moments on the hull forms over various angles of attack are studied. Both bare hull and X-configuration stern appended hull forms are compared to analyze the affect of stern appendages for each of the hull forms. Figure 2 shows larger views of the Single and Twin Tail stern appended hull forms.

Next, steady turn computations are performed for all of the stern appended configurations over varied turning radii. Vertical and horizontal plane steady turn maneuver computations are used to compute rotary derivatives from the resulting force and moment curves.

Finally, information from the in-plane force and moment computations is combined with rotary derivatives to compute indices of stability. Indices of stability in the vertical (G_v) and horizontal (G_h) planes quantify the maneuvering stability of the underwater body. Table 1 shows the relationship between stability indices and maneuvering stability. Typical applications that the Series 66 hull forms would be used for target G_v and G_h values of 0.6 and 0.2, respectively. It is typically desired that the underwater body be slightly more stable in the vertical plane. It is important for an underwater body to not have too high of an index of stability or else the body will not turn and maneuver readily enough. Conversely, it is important for the hull form's index of stability to not be too low, or else the body will have a hard time maintaining a consistent level in turning maneuvers.

Figure 2. Series 66 Single (left) and Twin (right) Tail stern appended hull forms.

G	Degree of Stability
Negative	Unstable
Positive	Stable
0 to 0.2	Marginally Stable (Satisfactory in the Horizontal Plane)
0.5 to 0.7	Stable (Satisfactory in the Vertical Plane)
> 0.8	Highly Stable

Table 1. Index of Stability (G) definitions.

2 NUMERICAL METHODS

NavyFOAM V1.0's single-phase RANS solver is used for this work. NavyFOAM V1.0 (Shan *et al* 2011) was developed from the extended version of OpenFOAM (www.wikki.co.uk), which is extended from the standard release (www.openfoam.com). The solver employs a cell-centered finite-volume method that permits use of arbitrary polyhedral elements including quadrilateral, hexahedral, triangular, tetrahedral, pyramidal, prismatic, and hybrid meshes. The single-phase solver is run in parallel using domain decomposition and message passing.

For incompressible flows the continuity (mass conservation) and momentum equations can be written as Equations 1 and 2, respectively.

$$\frac{\partial U_i}{\partial x_i} = 0 \quad (1)$$

$$\frac{DU_i}{Dt} = -\frac{1}{\rho} \frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left(\nu \frac{\partial U_i}{\partial x_j} - \overline{u_i' u_j'} \right) \quad (2)$$

Where ρ is the density of the fluid, ν is the kinematic viscosity, p is the pressure, U_i is the mean velocity component and u_i' is the fluctuating velocity component. The term $\overline{u_i' u_j'}$ is the Reynolds stress. The Boussinesq approximation is used to relate the Reynolds stress to velocity gradients by Equation 3.

$$\overline{u_i' u_j'} = \nu_t \left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right) - \frac{2}{3} k \delta_{ij} \quad (3)$$

Where k is the turbulent kinetic energy and ν_t is the turbulent viscosity. Closure for the RANS equations is achieved by modeling ν_t using Menter's shear stress transport (SST) turbulence model, which is a two-equation k - ε / k - ω hybrid model (Menter 1994).

3 GRID GENERATION

Due to the necessity for quick turnaround time and relatively complex geometry around the various appendages and stern sections unstructured gridding methods are preferred over structured gridding methods for this study. Multi-element unstructured grids are developed using SolidMesh (Gaither 1997), a suite of tools developed at Mississippi State University. SolidMesh provides tools for geometry preparation and surface grid generation. The volume grid is generated by using an advancing normal methodology for the boundary layer prism elements and an Advancing Front/Local Reconnection technique (Marcum and Gaither 1999) to develop isotropic elements. Using these tools, multi-element unstructured grids can be created around complex geometries, like those presented in this work, significantly faster than traditional structured grids. Typical unstructured grids used in this study contained 5 to 25 million cells. All grids were created with a non-dimensional normal

wall spacing (y^+) of 1. Figure 3 shows typical unstructured surface meshes used for these computations.

Figure 3. Views of the unstructured mesh on the Twin Tail bow and a stream-wise centerline plane (left) and on the stern (right).

4 IN-PLANE FORCES AND MOMENTS

Results from in-plane pitch (vertical) and drift (horizontal) angles are presented for the various hull forms under bare hull and stern appended configurations. Computational results for all hull forms are compared to experimental data up to 20 degrees angle of attack as a means of validation and comparison. However, for maneuvering purposes of this study only the forces and moments from ± 4 degrees are important as stability indices include the slope of force and moment curves over this range. All forces and moments are presented in non-dimensional form according to Equations 4 and 5.

$$F' = \frac{F}{\frac{1}{2} \rho U^2 L^2} \quad (4)$$

$$M' = \frac{M}{\frac{1}{2} \rho U^2 L^3} \quad (5)$$

Where L is the characteristic length of the hull form, F and M are the dimensional forces and moments, and F' and M' are the non-dimensional forces and moments.

Figure 4 shows the Single Tail hull form forces and moments plotted over a range of pitch and drift angles. As an important note, all of the experimental results at large negative drift angles used in this study should be considered unreliable. In the experimental tests two struts were connected to the body, and at negative drift angles the body was turned into the wake of the struts, thus altering experimental results. Nevertheless, Figure 4 shows that for the appropriate conditions computational predictions match experimental measurements very well over a wide range of pitch and drift angles for both bare hull and stern appended hull form configurations.

One interesting note from the pitch angle results is that the Single Tail bare hull and stern appended cases yield similar lifting force and pitching moment results for both computation and experiment. This indicates that the stern appendages add little control in the vertical plane. In the horizontal plane there is a noticeable difference in forces and moments for the bare hull and appended cases. Also, in general the forces and moments in the vertical plane are an order of magnitude larger than in the horizontal plane. This is to be expected, as the body appears as a well-rounded BOR in the

horizontal plane, whereas there is a large flat midsection that is exposed to the flow in the vertical plane.

Figure 4. Single Tail forces and moments for the bare hull (BH) and stern appended (StAp) hull forms.

As previously mentioned for stability index purposes the slope of the force and moment curves around 0 angle of attack is important. Figure 5 shows pitch and drift forces around 0 degrees angle of attack for the Single Tail hull form. At times there is a slight offset in the experimental data as the drift angle force plot shows, where the force and/or moment curve does not cross through 0 exactly at 0 degrees angle of attack. Despite the slight offset in force for the drift angle case the experimental and computational slopes line up very well.

Figure 5. Single Tail forces and moments around 0 degrees angle of attack.

Figure 6 shows the Twin Tail hull form force and moment results. There are no Twin Tail bare hull form experimental drift angle results to compare to, so only computational predictions are presented. As in the Single Tail case the experimental measurements and computational predictions agree very well over a wide range of attack angles. The stern appendages seem to alter the force and moment results slightly more than in the Single Tail case, but again the vertical plane difference is minimal compared to the horizontal plane difference. Again, the forces and moments in the vertical

plane are an order of magnitude larger than in the horizontal plane, because the flat midsection is directly exposed to the incoming flow in the vertical plane.

Figure 6. Twin Tail forces and moments for the bare hull (BH) and stern appended (StAp) hull forms.

Lastly, Figure 7 shows the forces and moments for the equivalent BOR hull form. The plot on the left is presented with the experimental data in original form, and the plot on the right is presented with experimental results shifted by an offset to make forces and moments cross through 0 at 0 degrees angle of attack. The vertical and horizontal plane results are presented in one plot, as the body is symmetric in both planes. The forces and moments of the BOR are of the same order of magnitude as the Single and Twin Tail drift angle results. This makes sense, as the Non-BOR hull forms appear as a BOR in the horizontal plane profile. There is a slight disagreement in computed and experimental results that is exaggerated by the offset, but generally the results and slopes agree well.

Figure 7. Body-of-Revolution forces and moments without (left) and with (right) adjusted experimental data.

5 STEADY TURN RESULTS

Steady turn computations are completed for all of the stern appended hull forms with the intention of computing rotary derivatives that are needed for stability indices. The various hull forms

undergo a steady turn maneuver (similar to a rotating arm tow tank experiment) at various radii. Computations are done for vertical steady maneuvers where the simulated body undergoes a constant pitch, and for horizontal steady maneuvers (the body is rotated 90° from the vertical turn) where simulated body undergoes a constant drift. Equation 6 defines the non-dimensional radii used for this work.

$$r' = \frac{L}{R} \quad (6)$$

Where R is the dimensional radius of the steady turn. Figure 8 shows the computational domain for the Twin Tail hull form at r' of 10. The relative velocity varies with the radius as the contours and vectors show.

Figure 8. Twin Tail hull form $r'=0.1$ steady turn plot with relative velocity contours and velocity vectors on the cut plane.

Figure 9 shows computed rotary forces and moments for various turning radii in the vertical plane for the Single and Twin Tail hull forms. Rotary derivatives that are used to compute stability indices are taken as the slope of rotary curves like those in Figure 9.

Figure 9. Computed rotary vertical force and moment curves for the Single (left) and Twin (right) Tail hull forms.

Figure 10 shows some results from the Twin Tail hull form $r'=0.1$ computations. The port/starboard asymmetry in the flow field is due to the varied angle of attack over the body. The asymmetry is most noticeable in the relative velocity contours in the stern wake.

Figure 10. Twin Tail hull form $r'=0.1$ steady turn contour plot with relative velocity on the cut plane and pressure on the body.

There are no steady turn experimental results to compare with; instead experimental rotary derivatives were computed from planar motion mechanism (PMM) tow tank tests. The experimental PMM tests were performed by dynamically pitching (or drifting) the body as it is pulled down the tow tank. These differences will be discussed in greater detail in the next section.

6 STABILITY INDICES

The stability indices from Table 1 are computed from slopes of the in-plane (pitch and drift) and rotary (vertical and horizontal) curves as discussed in the previous sections. Equations 7 and 8 show the vertical (G_v) and horizontal (G_h) indices.

$$G_v = 1 - \frac{M'_w \cdot Z'_q}{Z'_w \cdot M'_q} \quad (7)$$

$$G_h = 1 - \frac{N'_v \cdot Y'_r}{Y'_v \cdot N'_r} \quad (8)$$

Where Z'_w and M'_w are the slopes of the straight ahead vertical force and moment curves, respectively. Z'_q and M'_q are the slopes of the vertical rotary force and moment curves, respectively. Y'_v and N'_v are the slopes of the straight ahead horizontal force and moment curves, respectively. Y'_r and N'_r are the slopes of the horizontal rotary force and moment curves, respectively.

Computational rotary derivatives were calculated from the steady turn runs above; however, experimental rotary derivatives were determined from dynamic pitch and drift PMM tests in a straight ahead tow tank. Given the scope of this project it was not feasible to perform computational PMM predictions or experimental steady turn runs. Thus, the stability indices for computation and experiment were calculated in different manners. As a result of the different rotary tests, there are fundamental differences in the stability index formulations. The computational formulation contains RANS and steady turn modeling assumptions. While the experimental model contains free surface, strut wake interference, tank blockage, and radii quantification effects. Nevertheless, stability indices for the various bodies are compared between experiment and computation. However, it is unrealistic to

expect the indices to agree completely. Instead if the stability indices that are computed from steady turn and PMM tests show the same overall maneuvering performance characteristics it is considered a successful comparison.

Table 2 shows the experimental and computational stability index comparisons for the various stern appended hull forms. For all cases experiment and computation display the same maneuvering characteristics, but in differing degrees. Both show that the equivalent BOR hull form is stable in the vertical and horizontal planes. More specifically, in the vertical plane both show the BOR to be stable, but slightly shy of the target vertical stability range of $G_v=0.5-0.7$. In the horizontal plane computations show the body to be marginally stable (which is satisfactory), while experiments show the body to be more stable than the horizontal target range of $G_h=0.0-0.2$. Both experiment and computation indicate that additional control surfaces or modifications to existing surfaces need to be added to the body to achieve the acceptable amount of vertical stability.

Both experiment and computation show that the Twin Tail hull form is stable in the vertical plane, but shy of the vertical stability target range similar to the BOR case. It is interesting that experiment and computation show that the Twin Tail hull form is only slightly more stable than the BOR in the vertical plane, despite the large parallel midbody. Experiment and computation also show the Twin Tail hull form to be highly stable (to varying degrees) in the horizontal plane. The Twin Tail hull form is different from the BOR in that a ship designer would need to remove a significant amount of horizontal stability from the body for typical applications. If the hull form were too stable then the body would be difficult to readily turn and maneuver.

Meanwhile, experiment and computations show that the Single Tail hull form is highly stable in the horizontal plane and unstable in the vertical plane. Thus, new control surfaces or modification to existing surfaces would be needed to improve vertical plane stability performance, while reducing the horizontal plane stability.

Between the two Non-BOR hull forms it would appear that the Twin Tail hull would be a better candidate to select for future design based on the greater inherent stability. The Twin Tail hull form's superior stability as compared to the Single Tail hull form is most likely due to the wedge-like section in between the two tails which acts as a vertical stabilizer.

	BOR			Twin Tail			Single Tail	
	Gv	Gh		Gv	Gh		Gv	Gh
CFD	0.21	0.21		0.25	1.59		-0.50	1.35
EXP	0.37	0.37		0.46	3.53		-2.08	2.70

Table 2. Computational (CFD) and experimental (EXP) Stability Indices for the Series 66 hull forms.

7 CONCLUSIONS

In conclusion, a computational investigation on the maneuvering capability for two non-body-of-revolution (Non-BOR) hull forms and an equivalent body-of-revolution (BOR) hull form was completed. This study was complimentary to previous experimental tests done by Roddy *et al* at NSWCCD. Initially, in-plane force and moment predictions over various pitch and drift angles were analyzed. Computational predictions on the Single Tail hull form showed that the stern appendages did not seem to affect control in the vertical plane, but had a significant effect in the horizontal plane.

The stern appendages seem to make a relatively larger difference for the Twin Tail configuration in the vertical plane, and show the same significant effect in the horizontal plane. For both Non-BOR hull forms the forces and moments in the vertical plane are an order of magnitude larger than horizontal forces and moments. This is to be expected as the large flat midsection is exposed to the flow in the vertical plane. Meanwhile, in the horizontal plane the bodies appear more as a faired traditional BOR in profile, thus resulting in lower forces and moments. Equivalent BOR computations confirmed that the forces and moments are of similar magnitude to Non-BOR horizontal plane results.

Next, steady turn computations were completed with the intention of using the results to compute rotary derivatives that are used in stability indices. Experimental results used planar motion mechanism (PMM) tests to determine rotary derivatives. Each method for computing rotary derivatives includes their own uncertainties and modeling errors.

Finally, stability indices were computed for all of the stern appended bodies in the vertical and horizontal planes. Computationally predicted stability indices displayed the same maneuvering characteristics as experimental measurements. The Twin Tail hull form was shown to be stable in both the vertical and horizontal planes. The Single Tail hull form was unstable in the vertical plane and highly stable in the horizontal plane, indicating that additional control surfaces would be necessary to add stability in the vertical plane for typical applications. The wedge-like surface that connects the twin tails proved to add vertical stability that made the Twin Tail hull form stable, while the Single Tail hull form lacked any such surface and suffered a lack of vertical stability. The BOR proved to be marginally stable to stable in both planes. The results of this study show that the Twin Tail hull form would be more suitable from a maneuvering standpoint than the Single Tail hull form in future Non-BOR design studies.

Future work will center around altering the two Non-BOR configurations and analyzing the effect on maneuvering. The length-to-beam ratios of the bodies will be altered, and the resulting vertical and horizontal stability indices will be compared.

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