A Perspective on the Role of RANS Codes for Predicting Large Amplitude Ship Motions

Joseph Gorski, Naval Surface Warfare Center, Carderock Division,
West Bethesda, Maryland (gorskijj@nswccd.navy.mil)

SUMMARY

This paper discusses progress that has been made in using the Reynolds Averaged Navier-Stokes (RANS) equations for solving problems related to maneuvering and seakeeping of surface ships. Although RANS codes cannot yet be used effectively for capsize or large amplitude ship motions they can contribute by proving information on roll damping, maneuvering, propeller, and appendage forces as well as their interactions. Additionally, because of the significant increases in computer power, RANS codes are starting to be used to simulate actual maneuvers, which may provide a wealth of information in the future.

1. INTRODUCTION

A paper on using the Reynolds Averaged Navier-Stokes (RANS) equations for predicting large amplitude ship motions and capsize seems somewhat premature. The majority of surface ship RANS efforts have focused on straight ahead flow related to resistance and powering. There have been numerous demonstrations that RANS codes can predict propulsor inflow and wave heights for a number of bare hull forms under straight ahead calm water conditions (Gorski, 2002). Maneuvering and seakeeping is a relatively new area for RANS calculations, but they are being applied to problems such as roll, straight ahead flow with small waves and horizontal plane motions without waves. Inviscid based computational methods, involving both seakeeping and maneuvering effects, have progressed to the point where they can be used with some degree of confidence up to the point of deck immersion (Grochowalski et al., 1998) and even for capsize risk analysis (McTaggart and de Kat, 2000) for particular hull forms. With such success one might ask why bother with RANS calculations at all, but there are limitations to these inviscid based prediction capabilities, which are heavily dependent on experimental data. RANS codes offer the possibility of computing more of the physics directly and are being pursued for submarine (Taylor et al., 1998), aircraft (Schütte et al., 2002) and surface ship (Kim, 2001) maneuvering simulations. Thus, it is worthwhile to evaluate where RANS calculations can contribute to the prediction and understanding of large amplitude ship motions.

Current large amplitude ship motion prediction programs have matured to the point where they are routinely used for predicting ship motions in severe seas. Such codes are quite sophisticated and include a variety of individual forces including: Froude-Krylov, radiation, diffraction, rudder and appendages, propeller, maneuvering and viscous. Some of these forces are difficult to predict computationally, as discussed by Beck and Reed (2000), even for the limited case of forward speed in waves. Consequently, a hierarchy of models, which has evolved for the prediction of the individual forces, have been used with varying degrees of success. Despite the limitations of predictive techniques there has been significant success in predicting the large amplitude motions of particular hull forms. Part of the reason for this is that the buoyancy and Froude-Krylov forces, which are relatively straightforward to predict, dominate in large amplitude motions. Another reason such codes can be used with confidence for certain hull forms is their reliance on experimental data for many of the individual force components. This is fine when computing flows for hull forms where the needed experimental data are available. They can also work well for new hull forms where the Froude-Krylov forces dominate and the empirically based approximations are reasonable. However, when applied to a new hull form, or in situations where Froude-Krylov forces may not dominate, one cannot be sure how such methods will perform until they are compared with experimental data. This limits to what extent the codes can be trusted or used in design cycles, as the various forces are included through linear superposition and cannot account for highly complicated flow physics where higher order effects and interactions among the various force contributors becomes significant. Getting such details can be very difficult, time consuming and expensive. Trade-offs must be made between an engineering useful solution and a highly accurate solution, which may or may not be attainable. This is not a criticism of the current large amplitude prediction codes. They are very necessary as there is no acceptable alternative at the present time. However, because capsize is such a catastrophic event any potential improvement in predictive capability that can be achieved should be evaluated.

Because of the move to integrated designs, ship stability and control will probably be evaluated much earlier in a design cycle when it is generally most cost effective to change a design. At the early design phase computations are very attractive and an era is evolving a large number of computational studies fare performed for new hull forms, in some sense replacing the series tests of old, and model testing is done for the final geometry. For radical new hull forms there will be limited confidence in largely empirical based methods and more exact computational methods are desired. This will involve a hierarchy of methods from simple analysis to highly complex RANS calculations and perhaps even more sophisticated simulations such as Direct Numerical Simulations in the future. Rood (2000) discusses how RANS codes are starting to revolutionise ship hydrodynamics design and evaluation procedures from traditional towing tank methods to computational based methods. Examples of how RANS calculations have been used to influence submarine (Gorski and Coleman, 2002) and surface ship (Gorski et al., 2002) designs already exist in the literature.

In many ways RANS codes are not as attractive as the current motion predictions codes and may never replace them due to the much larger computer requirements. However, it is not unreasonable to expect computer power increases to continue to follow Moore's law, where computer power doubles every 18 months, for approximately the next 30 years. This is when it is expected computer hardware will reach the limits at the atomic scale, but will provide computer processing speeds on the order of a million times greater than today (Frank, 2002). This is a phenomenal increase in power that should be available to many of today's young engineers. One can also argue that RANS predictions, which are often considered a brute force approach to a problem, lack the elegance of current motions prediction programs which involve a high degree of knowledge concerning individual forces experienced by a ship and how to model them. However, RANS codes have their own elegance in the development of efficient algorithms, turbulence models, and grids for obtaining good solutions. RANS calculations are also synonymous with viscous effects and it is certainly a reason to use them. Perhaps even more importantly RANS solutions provide the entire flow field, which can be studied and evaluated to extract flow physics and gain new insights into effects for a multitude of geometries. Surface ships in particular are rich in vortical flows (Gorski, 2001) due to bow domes, appendages, and the hull shapes in general leading to complicated flow physics and component interactions. Another attractive feature of RANS codes is the detail they can provide as they progress steadily to more and more detailed representation of real hull forms, at real ship scales, with a minimum of assumptions. Calculations can already include all appendages, shafts, struts and rotating propellers. Much of this detail can also be included with an Euler calculation, but the loss of viscous effects is probably not worth the savings in computer time, which is becoming less significant with increasing computer power.

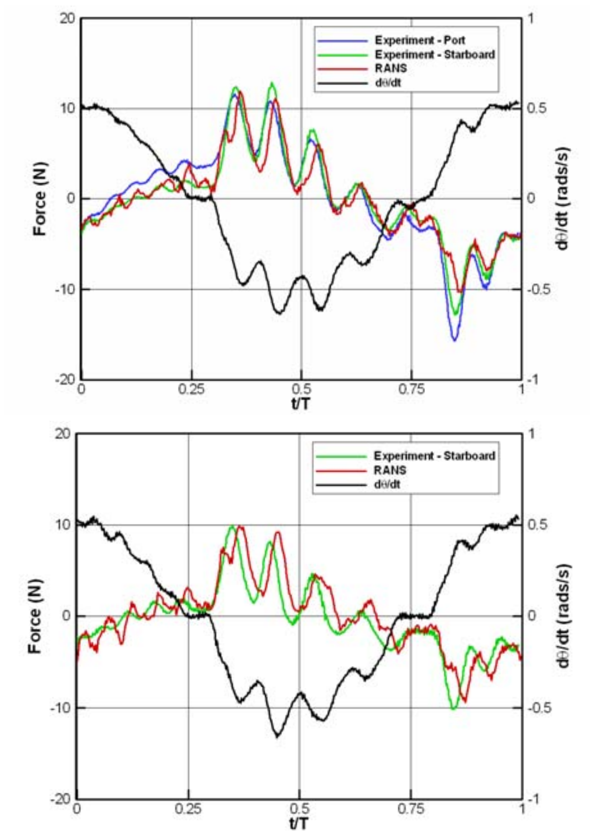
It is already apparent that RANS codes will be pursued in a variety of ways to address large amplitude ship motions and eventually capsize. An obvious way is to use RANS codes to supplement captive model tests. Additionally, time dependent simulations are receiving the attention of the RANS community. This paper will review some of the efforts applying RANS codes to seakeeping and maneuvering simulations. Specifically, efforts related to roll motions, maneuvering forces and horizontal plane maneuvers will be addressed. Also, areas that are posing problems for RANS in predicting large amplitude motions will be discussed

2. ROLL MOTIONS

Ship roll motion is an area where it is expected RANS codes can contribute. Roll motion limits ship operability, affects crew performance and ship habitability, and affects dynamic stability and ship capsize. Consequently, roll damping prediction is one of the critical but difficult parts of the motion prediction process. The roll motion of a ship is significantly influenced by viscous effects. Although the frictional roll damping on a hull form may not be significant, particularly at forward speeds, viscous related phenomena such as flow separation from the bilge and keels with the subsequent vortex formation account for a large amount of the roll damping. Bilge keels will significantly increase the damping of roll motions as well as generate a lift force if any forward motion of the ship is present. Models for roll damping often include components related to frictional forces on the hull, lift forces generated on the hull and bilge keels and appendages as well as damping due to eddy generation of the hull and bilge keels (e.g. Himeno, 1981). Predicting roll effects analytically has been problematic because of the significant viscous effects. Even predicting the damping due to bilge keels is difficult, as demonstrated by Sarpkaya and O'Keefe (1996), since the damping is a result of the vortices shedding from the edge of the keel and the use of damping coefficients from flat plate tests in a free stream is not necessarily accurate for wall bounded bilge keels. Current ship motion prediction methods account for the roll effects based on empirical databases obtained from model-scale tests, which typically involve forced roll or roll decay tests with various forward speeds in calm water. Particular hull details can be important, as demonstrated by Blok and Aalbers (1991) for a high speed displacement hull form and Liut, et al. (2001) for a CG-47.

Past RANS computations of roll motions have largely been two-dimensional and may be of limited value for a ship roll motion model due to the strong dependence on forward speed. A recent effort by Miller et al. (2002) demonstrates RANS simulations of roll motion for a 3-D cylinder, including bilge keels, with and without forward speeds. The calculations correspond to a 35.3-inch

(0.897m) diameter cylinder with 2-inch (0.051m) wide bilge keels as tested in the Circulating Water Channel at the Naval Surface Warfare Center, Carderock Division. Measurements were made with the model fully and partially submerged. Forces were obtained over a 2-foot (0.61m) section of the keels as roll motions were imposed at different frequencies and amplitudes. The vortices shedding from the bilge keels were measured using a Particle Image Velocimetry (PIV) system attached to the rolling cylinder. Time dependent RANS calculations were performed using about 3 million grid points on an IBM-SP3 using 84 processors. The solution for 10 cycles of roll motion took approximately 24 hours. Figure 1 shows representative comparisons of the calculated and measured force on the bilge keel for one period of roll motion. This is for a 15 degree amplitude roll with and without forward speed. The angular roll velocity at which the model is forced to roll is also shown in the figure. The figure shows that the RANS calculations accurately predict both the magnitude and phase of the measured data as well as the highly oscillating variations in the force data. The rapid acceleration and deceleration of the actual roll motion causes the sharp peaks in the force data. More comparisons with data and details of the calculations can be found in Miller et al. (2002).



a)

b)

Figure 1: Forces for cylinder roll from Miller et al. (2002); a) zero forward speed, b) forward speed = 1.0 m/s (2kts)

Recently there have been other three-dimensional RANS calculations of ship roll motions of various types with forward speeds. They include a sailing yacht (Azcueta, 2002) and a naval combatant (Wilson and Stern, 2002), but the results are not compared with experimental data. From these calculations RANS shows promise for predicting roll motions, but more evaluation needs to be done particularly for roll decay. With such RANS calculations it should be possible to also evaluate scale effects between model and full scale.

3. MANEUVERING FORCES

Another area where RANS capability can contribute is in the prediction of maneuvering forces. In fact, the ITTC (1999) noted the considerable progress that has been made with RANS solvers and recommended that CFD approaches be pursued to reduce the number of experiments needed. Maneuvering predictions for surface ships typically refer to the horizontal plane forces. At any yaw angle vortices are shed from the underside of a ship much like tip vortices from a wing. To obtain the lateral forces the hull can be treated as a low aspect ratio lifting surface and estimated using slender body theory (Kaplan et al., 2000). However, the geometry of a surface ship is much more complicated than a wing and these methods must be supplemented with experimental data to properly model the forces generated by particular hull forms. Three-dimensional panel methods can be used to introduce much of the complexity of the hull, but they cannot provide the effect of the generated vortices. Because the forces generated by a ship hull are so dependent on the strength and position of these hull generated vortices, these methods must be supplemented with experimental data or a priori knowledge of the vortex field. RANS computations can provide these forces and flow information. A variety of efforts to demonstrate this for ships at angles of yaw have been performed including: Series 60 (Tahara et al., 1998; Cura Hochbaum, 1998), a Mariner class ship (Cura Hochbaum, 1998), a tanker (El Moctar, 2002), and VLCC hull forms (Sato et al., 1998). Besides providing the mean flow field and total forces, Sato et al. (1998) and Ohmori (1998) show good comparisons of the longitudinal distribution of the lateral force along the length of a hull and thus demonstrate another type of information RANS can provide.

As mentioned these flow fields can be very complicated due to the vortical flow structure created. To demonstrate this flow complexity, shown in Figure 2 is the computed axial velocity contours for a destroyer hull form at a 20 degree yaw angle computed at model scale. The dominant feature is the vortical flow generated from the keel line just behind the bow dome, which has many similarities to a tip vortex shed from an appendage. Complicating the flow field is the bow dome creating its own wake structure and a second vortex is formed near the stern from the skeg. Additionally, just downstream of the formation of the primary vortex there are interactions of the flow near the keel line as well as the vortex "pulling" boundary layer flow off of the hull. At different angles of attack these interactions change, but RANS calculations should be able to predict them. At very high angles of attack the flow gets more complicated with large separated regions. These large angles of attack should be of interest for estimating cross flow drag. For the beam case, Figure 3, the flow is highly complex with distinct differences between the bow, stern and midship regions. The flow near midships appears to be two-dimensional and similar to the flow passing over a blunt body with separation behind it. At the bow and stern the flow separates from the keel line and there are more three-dimensional effects, probably due to the flow coming around from the sides. For a bare hull such as this, a variety of yaw angles can be computed quite readily with a double body approximation providing force and moment data. The predicted axial and lateral forces versus yaw angle for this hull form are shown in Figures 4 and 5. Figure 5 contains both the total side force and that component of the lateral force due to shear stresses at model scale. The viscous shear stress force on the hull is small, compared to the total force, so the dominant component is from the pressure differences on the hull.

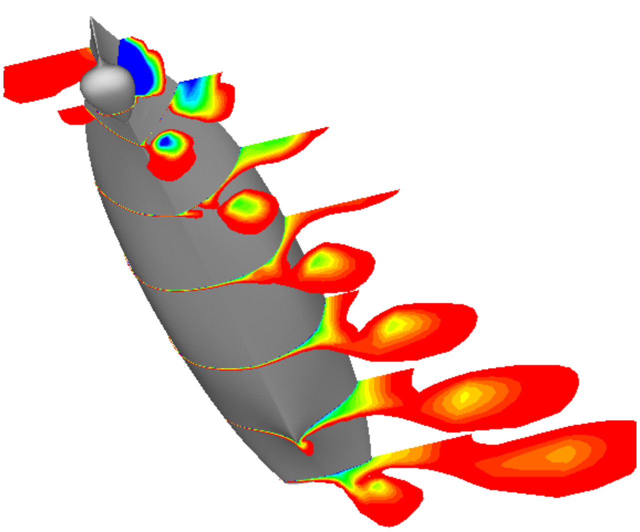


Figure 2: Axial velocity contours for 20 degree yaw case

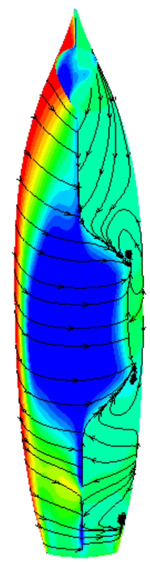


Figure 3: Surface pressures and streamlines for beam flow

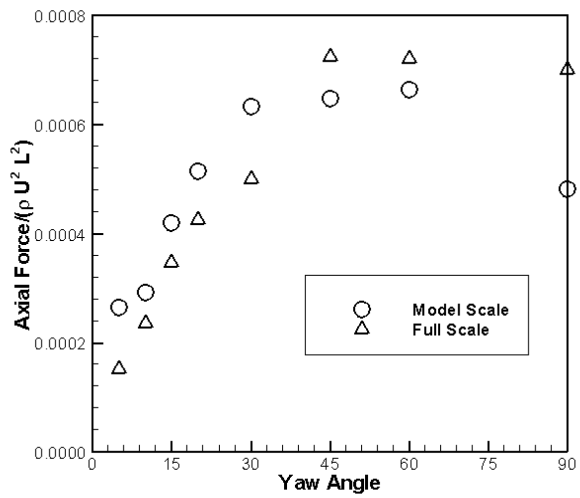


Figure 4: Computed axial forces

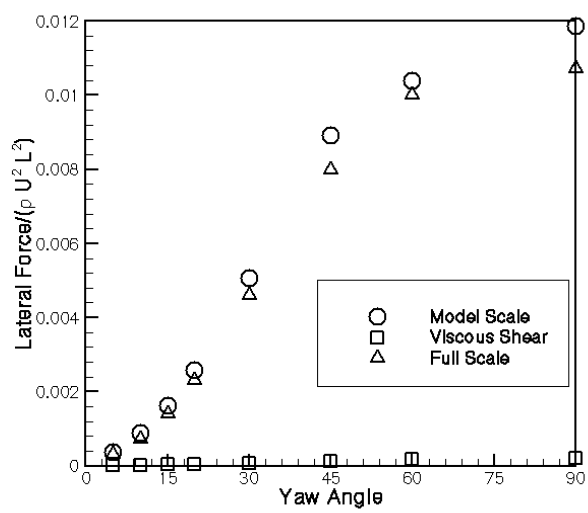
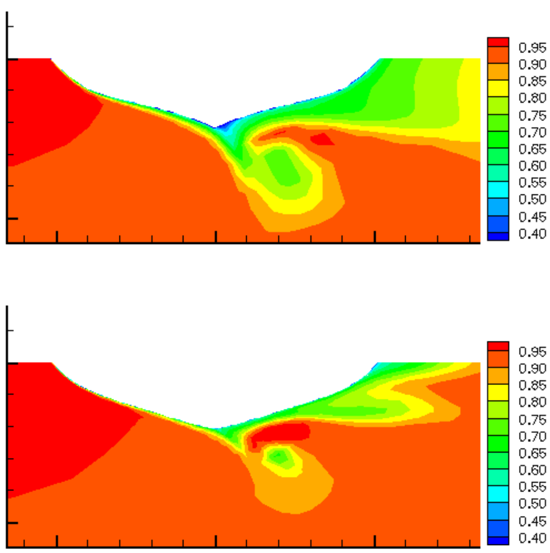


Figure 5: Computed lateral forces

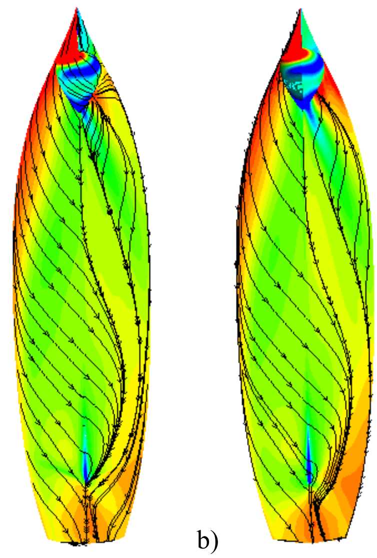
The above discussion does not mean that viscous effects are unimportant. The vortical structure generated from the hull has a large effect on the surface pressures. One of the great potentials for RANS is to evaluate scale effects. This same hull can be computed at full scale as well as model scale. Because of the larger Reynolds number at full scale a finer grid is needed, but large computers can handle the required grids and full scale calculations are becoming more routine. At full scale the boundary layers are relatively thinner, compared to ship length, and the resulting vortical flow structure will be affected. A comparison of the computed axial velocity at X/L = 0.895 at both model and full scale, Reynolds numbers of 12 and 900 million based on body length, for this destroyer are shown in Figure 6 for the 20 degree yaw angle. Although the flow is similar, the different hull wakes and vortex strengths lead to differing flow fields on the hull. This can be seen in Figure 7, which has surface streamlines and pressures for these two calculations. The limiting streamlines created by the hull generated vortex as well as the surface pressure has changed near the stern. These changes provide the force differences demonstrated in Figures 4 and 5 between model and full scale. The differences seen for the lateral force are larger than the viscous shear force at model scale indicating the change of the overall flow field and its resulting impact on the pressure field is probably a larger driver in scale effects than the viscous shear alone.



a)

b)

Figure 6: Computed axial velocity contours at X/L = 0.895: a) model scale, b) full scale



a) b)

Figure 7: Surface pressure and streamlines for 20 degree yaw case; a) model scale, b) full scale

The above computations demonstrate the flow fields for various yaw angles. It is also straightforward to obtain similar information for a turning boat and results have been demonstrated for a variety of turning hull forms (e.g. Cura Hochbaum, (1998), El Moctar (2001) and Ohmori (1998)). Unlike a constant yaw angle, where the entire boat experiences the same angle of attack, a boat undergoing a turning maneuver will experience different angles of attack along the length of the hull. This is demonstrated in Figure 8 for the destroyer hull form used previously. For this boat orientation, and turning diameter of six boat lengths, the flow over the bow is from port to starboard and creates a wake on the starboard side near the bow. Again a vortex is formed from the keel similar to what was shown previously. The hull rotates about its midships section so the port to starboard flow is a maximum at the bow, decreases to zero at midships, and becomes a starboard to port flow at the stern. Consequently, past midships the starboard to port flow starts to dominate and the keel vortex that formed is pushed from the starboard to the port side and a new vortex starts to form along the keel at the stern. These calculations can be run as steady predictions and obtained almost as easily as the yaw cases already shown to obtain force information for various hulls. RANS calculations provide the entire flow field, make it possible to visualise what is occurring physically, and may help researchers understand the flow. This could also lead to better modelling of particular aspects of the flow field.

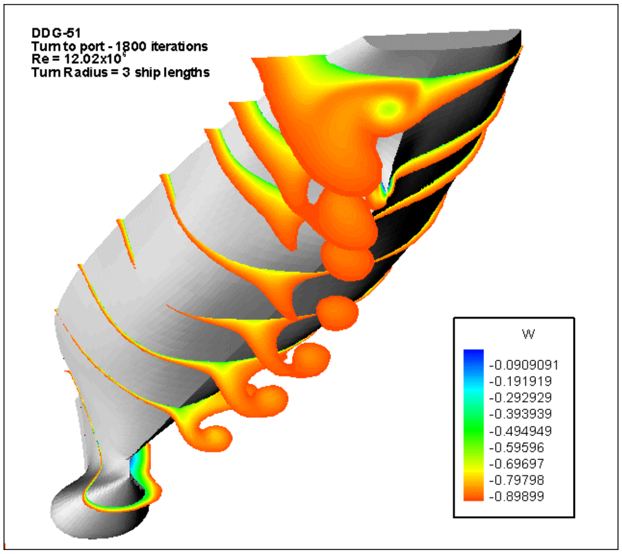


Figure 8: Flow field for steady turning case

4. RUDDER AND PROPELLER FORCES

Rudder and propeller forces can be obtained from inviscid methods with sufficient accuracy for many practical purposes. However, as higher fidelity is required in ship maneuvering and seakeeping predictions, such methods do not provide all of the physics needed for accurate representation of their respective forces. Particular effects that are often not included in simple analysis include (Kaplan et al, 2002) flow straightening effect of the hull, propeller wake fraction and thrust deduction, propeller slip stream effect on the rudder, and the interaction of the hull, propeller, and rudder forces. These additional effects often need to be included based on experimental data. RANS codes can provide some if not all of this information. As already shown in the previous section RANS codes can be used to predict the flow at the propeller plane as well as the flow field the rudder experiences for a particular hull orientation. Such calculations may already be adequate for many ships with a single screw propeller, although care must be used when strong vortices are involved to ensure the turbulence modelling is adequate (Gorski, 2002). Additionally, the progress made in gridding and computer power is making it progressively easier to do complicated hull/appendage calculations. An example of this is the fully appended Model 5415 hull form shown in Figure 9. This consists of the bare hull shown previously as well as shafts and struts for the propeller and the rudder. The figure shows the computed surface pressure and streamlines without a propeller model. The hull flow field and wakes created by the shaft and struts is shown in Figure 10. A very good prediction of the flow field is obtained as compared with the experimental data of Chesnakas, Figure 11. For this calculation the computed flow field may be more accurate than the measured as it more clearly captures the strut wakes, than does the experiment. This is because the experimental data were obtained with LDV measurements, at locations too sparse to provide adequate resolution of the strut wakes. In any case the shaft wake provides the dominant perturbation to the mean flow and the RANS prediction provides a good estimate of the wake entering the propeller.

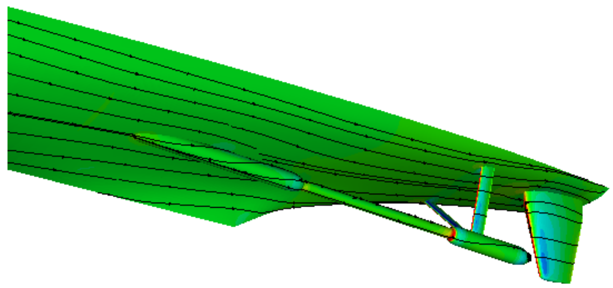


Figure 9: Computed surface pressure and streamlines for Model 5415

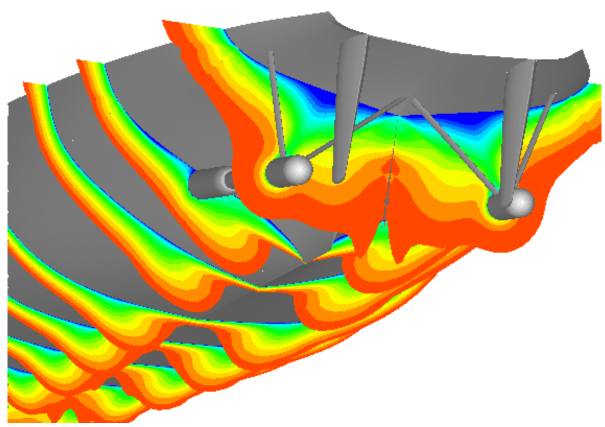


Figure 10: Computed axial velocity for Model 5415

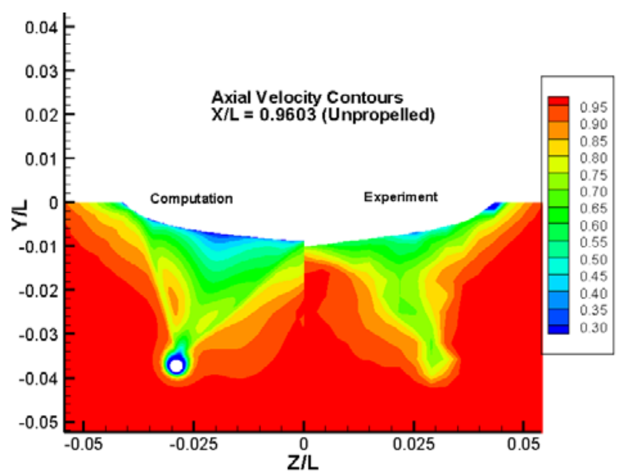


Figure 11: Comparison of computed and measured axial velocity

Propulsor effects can also be included in RANS calculations. This can be done with a simple actuator disk model with a prescribed thrust and torque. With the actuator disk model, the effect of the propulsor on the hull and the propeller slipstream on the downstream rudders, is obtained in the calculation. The change in thrust or torque due to various angles of attack is often ignored or it can be input from available open water data. Another option is to couple the RANS code with an inviscid propeller performance program and iterate between the two codes to provide the propelled effect in the RANS code. This technique was first proposed by Stern et al. (1988) and a number of researchers have used it or variations of the method since then. These methods can be used with propeller codes which provide a tangentially and radially varying force distribution based on the three-dimensional inflow to the propeller (Zawadzki et al., 1997). This level of sophistication is required to properly account for the angle of attack and hull wake into the propeller as well as the influence of the propeller on the hull. The advantage of the above methods is that they can often be used with a grid generated for a hull with a minimum of extra effort spent gridding specifically for the propeller. This could still include all stern appendages and shafts. A disadvantage is that the inviscid propeller modeling may start to break down at high angles of attack on the propeller. As computers get faster it becomes increasingly possible to do RANS calculations about an entire ship hull and propeller. Such calculations have already been demonstrated by Hyams et al (2000) and Burg et al (2002) for a naval combatant and Abdel-Maksoud et al (2000) for a container ship. Such calculations require good grids not only around the hull, but also around the propeller. In addition, the RANS codes must account for non-rotating grids around most of the hull interacting with rotating grids around the propeller.

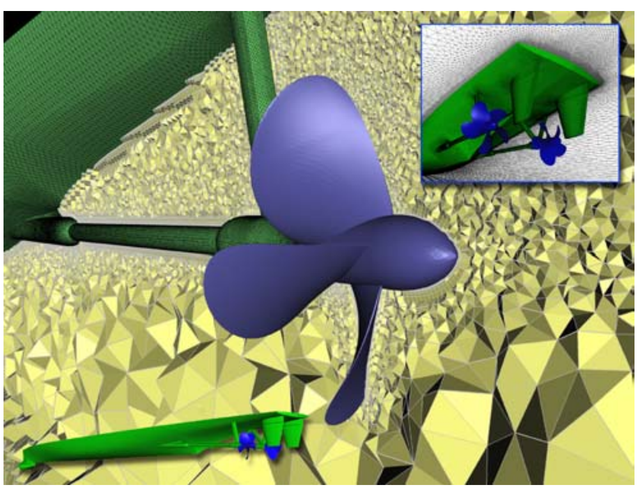


Figure 12: Unstructured grid for fully appended Model 5415, from Kim (2001)

Consequently, conventional structured grids are not typically used or recommended for such calculations and the thrust has been on using unstructured or Chimera grids for such approaches. An example of an unstructured grid for this geometry is shown in Figure 12 as given by Kim (2001).

5. FULL MANEUVERING SIMULATIONS

As discussed by Kim (2001) full simulations have been done for a conventional combatant, the fully-appended Model 5415 with propeller shafts, support struts, rudders and propellers for straight ahead and a restricted maneuver in the horizontal plane. Here a 6-DOF prediction capability is coupled with the RANS code and the motion of the ship predicted due to the rotating propeller and turning rudders. A startup solution is obtained with straight-line motion at constant velocity, which is steady except for the periodic unsteadiness induced by the rotating propellers. Using this solution as an initial condition, a maneuver was initiated by rotating the rudders, leading edge to port, at a rate of approximately eleven degrees per second. The surface pressure distribution and cutting planes of axial velocity are shown in Figure 13 for the initial stages of this maneuver. The rudders have deflected approximately six degrees at this point and the asymmetry in the pressure distribution on the port and starboard rudders is evident. Axial velocity is displayed on a vertical cutting plane through the center of the propeller shaft in the upper left-hand corner of this figure. Axial velocity is also shown on a horizontal cutting plane through the propellers and rudders in the lower right-hand corner of this figure.

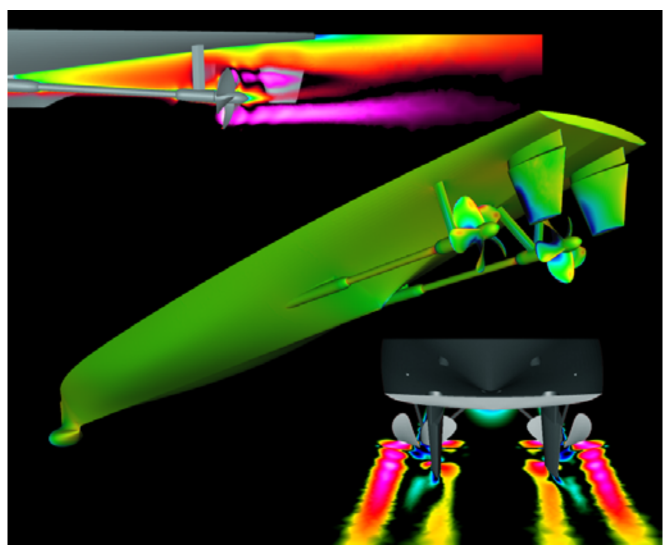


Figure 13: Computation of Model 5415 at 6 degrees of rudder deflection with deflection rate of 11 deg./sec, from Kim (2001)

These computations are extremely computer intensive. Each propeller revolution required 48 hours on 75 IBM-SP3/512Mb processors (3600 processor hours). Consequently, they will not replace simpler theories for quickly assessing maneuvering and seakeeping performance of a particular ship in the foreseeable future. However, these types of calculations provide much of the detail of a fully operating ship. Such computations can eventually be used for simulating particular maneuvers of interest to better understand the forces generated on the hull and associated flow field and their interaction, all of which is available from a RANS calculation. In this way RANS codes can be used to aid in the study of ship capsize problems even with their extensive computational requirements.

6. ISSUES

Perhaps the biggest difficulty RANS predictions have to overcome is the level of confidence one has in them. RANS calculations are often not trusted unless they are compared with experimental data. However, one of the main reasons to do a RANS calculation is to reduce the amount of experimental testing needed. Grid dependence and turbulence modelling deficiencies are often mentioned as the main reasons a RANS calculation cannot be trusted. Simplifying assumptions must be made to model turbulence. The large number of good RANS predictions that have been made for some very complex flows seems to indicate that basically the models are doing a decent job of representing the physics of interest. There are indications more complete turbulence models, such as full Reynolds Stress models or detached eddy simulation (DES), may be needed for some very complicated and highly separated flows depending on the level of accuracy needed in a solution. However, the community can probably get much of the accuracy it needs for ship motions with current turbulence models. In any case, as the more sophisticated models continue to mature the accuracy of predictions should increase.

Grids may play a more important role in the quality of a solution than the turbulence model and many deficient results that are blamed on poor turbulence modelling may be due to poor grids. It is not necessarily clear or obvious what is a good grid for a particular flow field prediction and results are often experience driven for complicated predictions. To better estimate the quality of a solution there have been efforts to develop uncertainty estimates and validation procedures for computations (e.g. AIAA, 1998; Roache, 1998). This is an area of significant importance as the computational community tries to provide metrics for how good a computation is and more work needs to be done in this area. Stern et al. (1999) established a formal procedure for estimating the uncertainty of RANS solutions from predictions on different grids. However, as demonstrated by Eca and Hoekstra (2002) using similar techniques widely varying uncertainty estimates for RANS calculations can be obtained with different sets of grids for a particular problem. Determining uncertainty estimates for time dependent flows will be even more problematic. This does not mean good RANS solutions cannot be obtained for them, but it does indicate getting good RANS predictions will continue to be experience driven. Uncertainty estimates of predictions will continue to evolve and as computer power increases it will become more possible to do automatic grid adaptation as part of a solution, and some of these grid issues will hopefully lessen.

The biggest problem currently preventing the RANS prediction of large amplitude ship motions and capsize is probably the free surface prediction. RANS codes can handle large amplitude motions of a geometry in a single-phase flow. However, accurately accounting for the interaction of the free surface with a hull and its appendages, while undergoing large motions may be beyond current capability for. The dominant method of predicting the free surface has been to use tracking methods where the water surface is treated like a material boundary. This bounds the domain and the flow field is solved for the water portion of the problem. Because the water surface is now a boundary to the domain a grid must be generated in the domain using the hull and water surface as its boundaries. This technique has worked very well for a variety of hull forms, but can be problematic. Once the free surface starts changing the grid must adjust, usually along existing grid lines, to accommodate the new free surface height. Here good grid quality is easily lost and if changes become too large the grids often become too highly skewed for stable running of the RANS code. Considering how difficult it can be to generate a good grid with predefined surfaces one can easily see that it will be difficult to automatically adjust a structured grid to any new water surface for a complicated geometry. Unstructured grids have the potential to overcome some of these inherent limitations (e.g. Lohner et al, 1998; Burg et al, 2002), but such complexities as wave breaking probably cannot be handled by such methods without ad hoc corrections. Capturing methods are receiving increased attention in ship hydrodynamics. These include level set approaches (Bet et al, 1998; Chun et al, 2000; Cura Hochbaum and Vogt, 2000), marker-density-function methods (Sato et al, 1999), and VOF type approaches (Azcueta, 2002). With these approaches both the air and water are often computed with a discontinuous jump in density and viscosity allowed across the interface between them. The interface evolves as part of the solution. There is a thickness associated with the interface, but this can be controlled by the local grid size. Results are promising for motion prediction without the difficulties associated with grids evolving to conform to the free surface. The above methods can handle ambient wave fields (e.g. Cura Hochbaum and Vogt, 2002) and very complex interfaces, including wave breaking, and may allow RANS codes to be used more for maneuvering and seakeeping calculations in the future.

7. CONCLUSIONS

RANS codes may not currently be contributing significantly to the study of surface ship seakeeping and maneuvering, due to their relative immaturity and large computational requirements. However, as the application of RANS codes to these problems matures and computer power increases it seems inevitable that they will play a larger role in the future. RANS predictions can be a time and cost effective way to improve prediction capability for new designs where experimental data bases do not exist. However, it will take some effort to have the confidence in the RANS codes that currently exists from the model tests or current motion prediction programs. To expect to be able to simply replace such techniques with RANS simulations is unrealistic. It has taken considerable time, effort, and resources for model tests and current motions prediction programs to evolve to their current state of usefulness. To reach this level has not only involved improvements to the basic methods, but determination to use these techniques despite their limitations. Similar efforts will be needed with RANS. One way to achieve this confidence may be to do side by side experiments and computations such as being pursued in the submarine maneuvering area by Bellevre, et al. (2000) who are replacing captive model coefficients with those obtained from RANS calculations with some success. In the end the question is not can RANS be used for large amplitude ship motions and capsize predictions, but how to use RANS intelligently for their prediction.

ACKNOWLEDGEMENT

The calculations performed here were supported by ONR under the direction of Dr. L. Patrick Purtell. The author would also like to thank Roderick Coleman, Meridith Fry, Minyee Jiang, Ronald Miller and John Telste for their help with the paper. The computations were performed using facilities at Maui and ARSC under DOD HPCMO.

REFERENCES

Abdel-Maksoud, M., Rieck, K., and Menter, F. R., "Unsteady Numerical Investigation of the Turbulent Flow Around the Container Ship Model (KCS) With and Without Propeller,'' *Proc. Gothenburg 2000 A Workshop on Num. Ship Hydro.,* Goteborg, Sweden, 2000.

AIAA, Guide for the Verification and Validation of Computational Fluid Dynamics Simulations, G-077-1998, 1998.

Azcueta, R., "Computations of Turbulent Free-Surface Flows around Ships and Floating Bodies," *Ship Technology Research*, Vol. 49, pp. 46-69, April 2002.

Beck, R. F. and Reed, A. M., "Modern Seakeeping Computations for Ships," *Proc. 23rd Symp. Naval Hydro*., Val de Reuil, France, 2000.

Bellevre, D., Diaz de Tuesta, A., Perdon, P., "Submarine Maneuverability Assessment Using Computational Fluid Dynamic Tools," *Proc. 23rd Symp. Naval Hydro*., Val de Reuil, France, 2000.

Bet, F., Hanel, D. and Sharma, S., "Numerical Simulation of Ship Flow by a Method of Artificial Compressibility,'' *Proc. 22nd Symp. Naval Hydro*., Washington D. C., pp. 173 – 182, 1998.

Blok, J. J. and Aalbers, A. B., "Roll Damping Due to Lift Effects on High Speed Monohulls," FAST'91, 1991.

Burg, C. O. E., Sreenivas, K., Hyams, D. G., and Mitchell, B., "Unstructured Nonlinear Free Surface Simulations for the Fully-Appended DTMB Model 5415 Series Hull Including Rotating Propulsors," *Proc. 24th Symp. Naval Hydro*., Fukuoka, Japan, July 2002.

Chesnakas, C. J., Experimental data provided courtesy of Code 5400, Naval Surface Warfare Center, Carderock Division, West Bethesda, MD.

Chun, H. H., Park, I. R., and Lee, S. K., "Analysis of Turbulence Free-Surface Flow around Hulls in Shallow Water Channel by a Level-set Method,'' *Proc. 23rd Symp. Naval Hydro*., Val de Reuil, France. 2000.

Cura Hochbaum, A., "Computation of the Turbulent Flow Around a Ship Model in Steady Turn and in Steady Oblique Motion," *Proc. 22nd Symp. Naval Hydro.*, Washington D. C., 1998.

Cura Hochbaum, A. and Vogt, M., "Flow and Resistance Prediction for a Container Ship,'' *Proc. Gothenburg 2000 A Workshop on Num. Ship Hydro.,* Goteborg, Sweden, 2000.

Cura Hochbaum, A. and Vogt, M., "Towards the Simulation of Seakeeping and Manoeuvering Based on the Computation of the Free Surface Viscous Ship Flow," *Proc. 24th Symp. Naval Hydro*., Fukuoka, Japan, July 2002.

Eca, L. and Hoekstra, M., "An Evaluation of Verification Procedures for CFD Applications," *Proc. 24th Symp. Naval Hydro*., Fukuoka, Japan, July 2002.

El Moctar, O. M., "Numerical Computations of Flow Forces in Ship Manoeuvering," *Ship Technology Research*, Vol. 48, No. 3, Sept. 2001.

Frank, M. P., "The Physical Limits of Computation," *Computing in Science and Engineering,* pp. 16 – 26, May/June 2002.

Gorski, J. J., "Marine Vortices and Their Computation," *Proc. NATO AVT Symposium on Advanced Flow Management*, Loen, Norway, May 2001.

Gorski, J. J., "Present State of Numerical Ship Hydrodynamics and Validation Experiments," *J. Offshore Mechanics and Arctic Eng.* pp. 74 – 80, May 2002.

Gorski, J. J. and Coleman, R. M., "Use of a RANS Calculations in the Design of a Submarine Sail", *Proc., NATO RTO AVT Symp.*, Paris, France, April 2002.

Gorski, J. J., Haussling, H. J., Percival, A. S., Shaughnessy, J. J., and Buley, G. M., "The Use of a RANS code in the Design and Analysis of a Naval Combatant," *Proc. ONR 24th Symp. Naval Hydro*., Fukuoka, Japan, July 2002.

Grochowalski, S., Hsiung, C. C., Huang, Z. J., and Cong, L. Z., "Theoretical Modeling of Ship Motions and Capsizing in Large and Steep Waves," *SNAME Trans*., Vol. 106, pp. 241 – 267, 1998.

Himeno, Y., "Prediction of Ship Roll Damping – State of the Art," Report 239, Dept. of Naval Arch. and Marine Eng., Univ. of Michigan, 1981.

Hyams, D. G., Sreenivas, K., Sheng, K., Nichols, S., Taylor, L., Briley, W. R., Marcum, D. L., and Whitfield, D. L., "An Unstructured Multielement Solution Algorithm for Complex Geometry Hydrodynamic Simulations," *Proc. 23rd Symp. Naval Hydro*, Val de Reuil, France, 2000.

ITTC, "The Manoeuvering Committee Final Report and Recommendations to the 22nd ITTC," *Proc. 22nd ITTC*, Seoul Korea & Shanghai China, Sept. 1999.

Kaplan, P., Ankudinov, V., and Jakobsen, B. K., "Modular Mathematical Models for Ship Maneuvering," SNAME Tech. & Research Report NO. 56, 2002.

Kim, K-H., "Unsteady RANS Simulation for Surface Ship Dynamics," *DoD HPCMP Users Group Conf.*, Biloxi, MS, June 2001.

Liut, D., Mook, D., Weems, K., and Nayfeh, A., "A Numerical Model of the Flow Around Shipmounted Fin Stabilizers," *Int. Shipbuilding Progr.*, Vol. 48, No. 1, pp. 19 – 50, 2001.

Lohner, R., Yang, C., and Onate, E., "Viscous Free Surface Hydrodynamics Using Unstructured Grids,'' *Proc. 22nd Symp. Naval Hydro*., Wash. D. C., pp. 476 – 490, 1998.

McTaggart, K. and de Kat, J. O., "Capsize Risk of Intact Frigates in Irregular Seas," *SNAME Trans.*, Vol. 108, pp. 147 – 177, 2000.

Miller, R. W., Gorski, J. J. and Fry, D., "Viscous Roll Predictions of a Circular Cylinder with Bilge Keels," *Proc. ONR 24th Symp. Naval Hydro*., Fukuoka, Japan, 2002.

Ohmori, T., "Finite-Volume Simulation of Flows About a Ship in Maneuvering Motion," *J. Mar Science Tech*., Vol 3, pp. 82 – 93, 1998.

Roache, P. J., *Verification and Validation in Computational Science and Engineering*, Hermosa Publishers, Albuquerque, New Mexico, 1998.

Rood, E. P., "Computational Ship Hydrodynamics for Revolutionary Naval Combatants,'' *DoD HPC User's Group Conf*., Albuquerque, NM, 2000.

Sarpkaya, T. and O'Keefe, J. L., "Oscillating Flow about Two and Three-Dimensional Bilge Keels," *J. Offshore Mech. Arctic Eng*., Vol. 118, pp. 1 – 6, 1996.

Sato, T., Izumi, K., and Miyata, H., "Numerical Simulation of Maneuvering Motion," *Proc. 22nd Symp. Naval Hydro.*, Washington D. C., 1998.

Sato, Y., Miyata, H. and Sato, T., "CFD Simulation of 3-Dimensional Motion of a Ship in Waves: Application to an Advancing Ship in Regular Head Waves,'' *J. Mar. Science and Tech*., Vol. 4, pp. 108-116, 1999.

Schütte, A., Einarsson, G., Madrane, A., Schöning, B., Mönnich, W., and Krüger, W.-R., "Numerical Simulation of Maneuvering Aircraft by Aerodynamic and Flight-Mechanic Coupling," *Proc., NATO RTO AVT Symp.*, Paris, France, 2002.

Stern, F., Kim, H. T., Patel, V. C., and Chen, H. C., "A Viscous Flow Approach to the Computation of Propeller-Hull Interaction,'' *J. Ship Research*, Vol. 32, pp. 246 – 262, 1988.

Stern, F., Wilson, R., Coleman, H., and Paterson, E., "Verification and Validation,'' IIHR Report No. 407, The Univ. of Iowa, Iowa City, 1999.

Tahara, Y., Longo, J., Stern, F., and Himeno, Y., "Comparison of CFD and EFD for the Series 60 C_B = 0.6 in Steady Yaw Motion," *Proc. 22nd Symp. Naval Hydro.*, Washington D. C., 1998.

Taylor, L. K., Pankajakshan, M., Jiang, M., Sheng, C., Briley, W. R., Whitfield, D. L., Davoudzadeh, F., Boger, D. A., Gibeling, H. J., Gorski, J. J., Haussling, H., Coleman, R., and Buley, G., "Large-Scale Simulations for Maneuvering Submarines and Propulsors," AIAA Paper No. 98-2930, 1998.

Wilson, R. and Stern, F., "Unsteady RANS Simulation of a Surface Combatant with Roll Motion," *Proc. 24th Symp. Naval Hydro*., Fukuoka, Japan, 2002.

Zawadzki, I., Fuhs, D., and Gorski, J., "Integration of a Viscous Flow RANS Solver with an Unsteady Propulsor Force Code," CRDKNSWC/HD-0011-26, Dec. 1997.