Effect of Turbulence Modelization in Hull-Rudder Interaction Simulation

DENG G., LEROYER A., GUILMINEAU E., QUEUTEY P., VISONNEAU M., WACKERS J.

METHRIC, LHEEA/UMR 6598 CNRS, Ecole Centrale de Nantes, France.

Email: Ganbo.Deng@ec-nantes.fr

Abstract: This paper is devoted to the assessment of turbulence modelization for hull-rudder simulation. Hull-rudder configuration with different rudder angles is simulated to assess the performance of three different turbulence models by using the measurement data obtained by two different institutions. The Separation Sensitive Corrected explicit algebraic Reynolds stress model (SSC-EARSM) provides the best prediction at high rudder angles when flow is massively separated.

Key words: Hull-rudder interaction, Separated flow, Turbulence model.

1 Introduction

With progresses made both in simulation software and computer hardware in recent years, ship maneuvering simulations with CFD become possible now. One of the most challenging task in such simulation is the physical modelization of the complex flow around the rudder. At high rudder angle, flow separates. It is well known that conventional linear eddy-viscosity type turbulence model fails to predict separated flow with accuracy. The size of separation zone is usually over-predicted, resulting in under-estimation for the lateral force and the yaw moment. Detached eddy simulation and large eddy simulation are believed to be more suitable to simulate separated flow. However, they are too expensive for routine engineering applications. There is a renewed interest in turbulence model development aiming at improving RANSE model performance for more complex situation such as flow with separation. Monté et al. [1] has proposed a new SSC-EARSM model specially designed for improving the prediction of separated flow with RANS simulation. The improvement is achieved by increasing the turbulence production in a specific region of the flow and by increasing the turbulence mixing between the separated shear layer and the freestream with a sensitization to the separation correction term added to the turbulence frequency equation. The present paper aims at validating this newly proposed turbulence model for hull-rudder interaction simulation.

2 Numerical simulation

The selected test case is the well-known KCS container ship. To better assess the performance of turbulence model, we focus only to the hull-rudder configuration without propeller. Experimental data obtained by two different institutions are selected for validating CFD computation. The first one is contacted by NMRI at 1/75.5 model scale [2], while the second one is performed by CSSRC at 1/52.667 model scale[5]. Table 1 summarizes the main characteristics of the ship model for both measurements. They are all conducted at the designed Froude number Fr=0.2 with the designed draft T=0.04694Lpp. The rudder angles range from -25 degree to 25 degree with an interval of 5 degrees in the measurement performed by NMRI. The measurement performed by CSSRC use the same rudder angles with two additional configurations with -30 degree and 30 degree.

Table 1 Characteristic of ship model

	Lpp(m)	U(m/s)	T(m)	Re
CSSRC	4.367	1.318	0.205	5.19e6
NMRI	3.046	1.100	0.143	2.57e6

CFD computation has been performed with our in-house finite volume RANSE solver ISIS-CFD[4], also available in the commercial software Fine-Marine. The unstructured hexahedral mesh generator Hexpress provided in the Fine-Marine package is used for mesh generation. The gap between the mobile part and fix part of the rudder in the original geometry is very small. In order to reduce the computational resources, the rudder gap is enlarged in the present simulation. The rudder geometry is modified such that the surface area of the mobile part remains unchanged. Computation with two different modified rudder geometries with the width of rudder gap about 1/110 C and 1/44 C (C being the chord of the rudder section) shows that the effect of this rudder geometry modification is negligible. In order to avoid modelization uncertainty due to wall function, all computations except one series have been performed using low Reynolds number turbulence model. The number of cells ranges from 10 million to 14 million. Based on our experiences, such grid density is fine enough to ensure that the numerical discretization error is much smaller than the physical modelization error. As in the measurement, trim and sinkage are free in CFD computation. Three representative turbulence models have been selected for the simulation. The first one is the well-known K-ω SST model proposed by Menter. It is a linear eddy-viscosity RANS model widely used for industrial application. The second one is the above mentioned SSC-EARSM model. It is a two-equation non-linear model including quadratic and cubic non-linear terms recently implemented in the ISIS-CFD solver. The last one is also a recently implemented Reynolds stress turbulence model based on the SSG-LRR pressure strain model proposed by Cecora et al. [3].

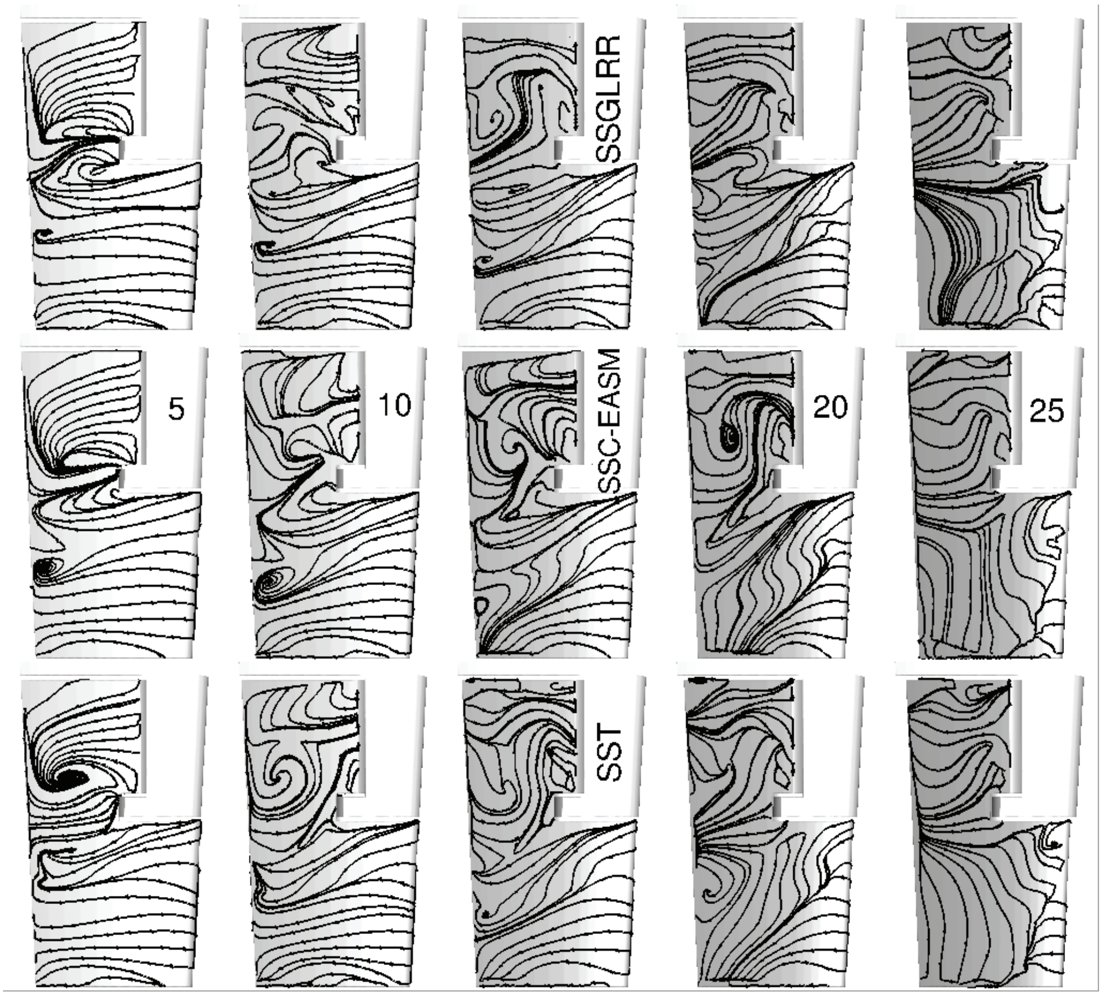

Figure 1 Wall limiting streamlines

Figure 1 show the predicted wall limiting streamlines obtained with different turbulence models for different rudder angles ranging from 5 to 25 degree. The predicted flow around the rudder is quite different from flow around a hydrofoil. Flow around a hydrofoil usually remains attached for small incident angle up to about 15 degree in general. The situation is different for the flow around the rudder. The gap between the fix and the mobile part of the rudder forms a passage between the windward side and the leeward side of the rudder. When rudder deflects, flow is driven from the high pressure windward side to the low pressure leeward side through the gap. It is escaped near the C-shape gap at the leeward side of the rudder, forcing the flow to separate behind this gap even at the lowest rudder angle 5 degree. Flow remains attached in the other parts at this smallest rudder angle. Although it is a pressure induced separation due to the rudder geometry, the effect of turbulence modelization can still be observed on the size of the separation zone. The SST model predicts a larger separation zone, resulting a lower lateral force and yaw moment as shown in figure 2 compared with the two other turbulence models who give similar prediction. At 10-degree rudder angle, flow separates at the trailing edge above the separation region extended from the C-shape gap. The sharp leading edge of the mobile part of the ruder above the C-shape gap forms an obstacle to the flow coming from the upstream fix rudder. A small separation bubble is formed immediately after the sharp leading edge. With the SSG-LRR Reynolds stress model and the SSC-EARSM model, flow quickly reattaches again on the rudder surface except at the upper part of the rudder where flow separation is formed due to a vortex generated in the corner between the rudder and the hull. With the SST model, flow separation in the trailing edge is much more intense. The leading edge separation bubble tends to merge into the trailing edge separation region. At 15-degree angle, flow structure is similar. The trailing edge separation zone is extended upstream, making the reattached flow region shorter, especially for the simulation obtained with the SSG-LRR Reynolds stress model. Unlike the two other models, the SSC-EARSM model is capable to predict a well-established corner vortex between the upper part of the rudder and the hull, resulting a higher lateral force and yaw moment compared even compared with the SSG-LRR model as shown in figure 2. At 20-degree angle, the trailing edge separation zone merges with the leading edge separation bubble. The wall limiting streamlines predicted by the SSG-LRR model is similar to the result obtained by the SST model. Both models provide similar prediction for forces and moments. Corner vortex between the rudder and the hull is still well predicted with the SSC-EARSM model. The size separation bubble is also smaller compared with the results obtained by the two other models. Consequently, the predicted forces and moments are higher. At higher rudder angles (25 and 30-degree), flow separates completely at the upper part of the rudder. Although wall limiting streamlines are similar for all turbulence models, the separation zone observed with a X-Y cutting plane indicates that the SSC-EARSM model predicts a smaller recirculation zone. This is correlated with the higher force and moment prediction given by this model shown in figure 2. The predicted flow structures at the lower part of the rudder are similar for all turbulence models. The separation zone created from the C-shape gap extends downward with increasing rudder angle. Flow is completely separated at the highest 30-degree rudder angle for which highest discrepancies between the CFD prediction and measurement data are observed. Computations using wall function have been performed with the SST model for the CSSRC configuration. Results compared with those obtained with the low Reynolds number version of the same model differ only slightly around 10-degree rudder angle due to the existence of complex flow reattachment phenomena observed after the sharp leading edge at the upper part of the rudder.

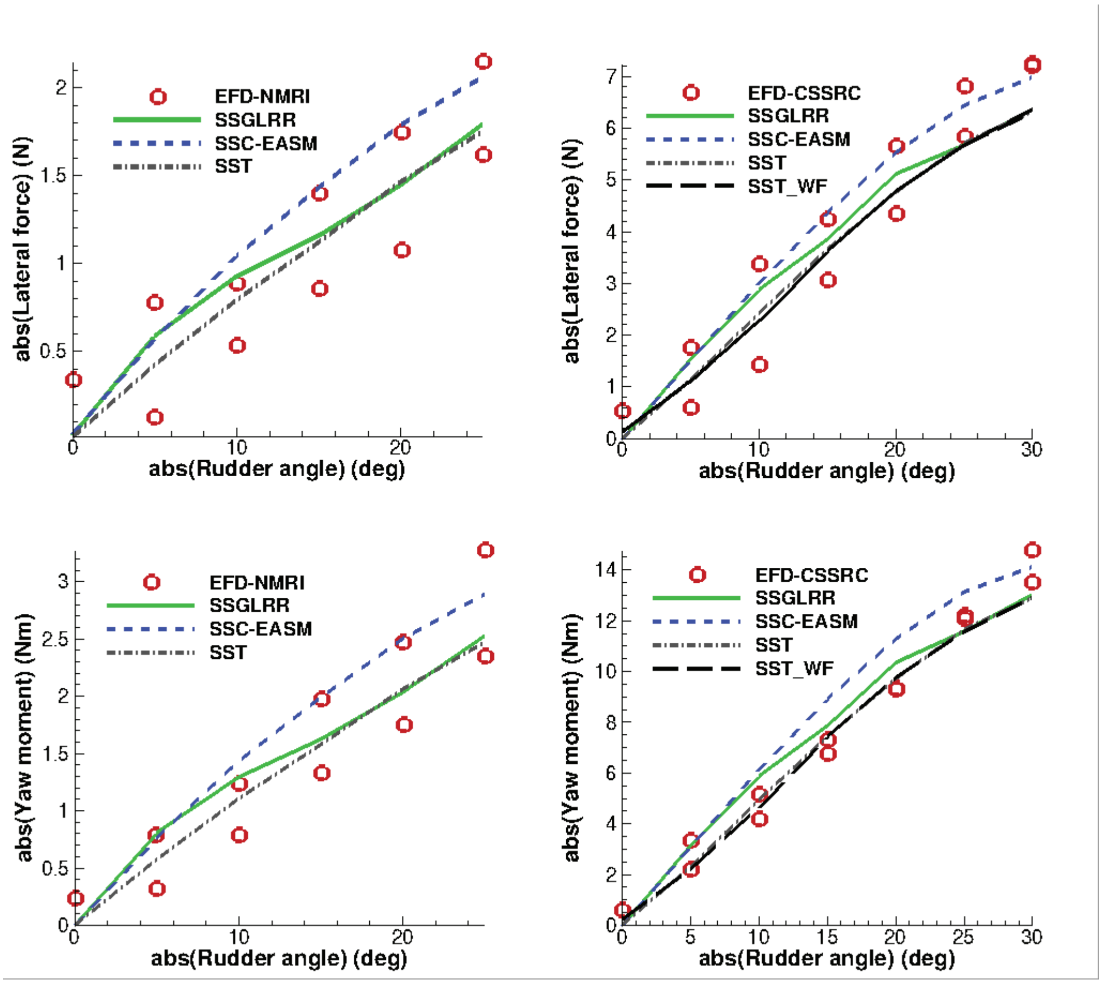

Figure 2 Predicted lateral force and yaw moment

There are some confusion concerning the validation with measurement data. Force and moment results obtained by both institutions are not asymmetric with respected to rudder angle as expected. At zero rudder angle for instant, yaw measurement results are far from zero, especially for the measurement data obtained by NMRI. Instead, CFD prediction using wall function shown in the right side in figure 2 contains both positive and negative rudder angles. Results are perfectly asymmetric as expected. If we consider that the mean measurement value is the expected solution, we can conclude that the SST model provides the best prediction at low rudder angles when geometry imposed separation is dominant. At high rudder angles when flow is completely separated around the rudder, the SSC-EARSM model improves the prediction.

3. Conclusions

Hull-rudder interaction problem has been simulated with three different turbulence models for the same geometry with two different model scales at the same Froude number. The violation of the asymmetric behavior observed in both measurements for forces and moments make the validation task difficult. The newly proposed SSC-EARSM model provides high value for force and moment prediction compared with other two turbulence models and provides better result only at high rudder angle when flow is completely separated around the rudder. As flow separation is mainly due to rudder geometry, wall function approximation has negligible additional modelization error. The performance of Reynolds stress model is similar to a simple linear eddy viscosity model except for the case with small rudder angle.

Acknowledgements

This work was granted access to the HPC resources of CINES/IDRIS under the allocation 2019-A0052A01308. The authors are indebted to Professor ZHAO Qiaosheng for providing information related to the measurements performed in CSSRC.

References

1 Monté S, Temmerman L, Léonard B, Tartinville B, Hirsch C. A novel EARSM model for separated flows. 2016, ETMM11 conference, Palerme.

2 Ueno M, Yoshimura Y, Tsukada Y, Miyazaki H. Circular motion tests and uncertainty analysis for ship maneuverability. J. Mar. Sci. Technol., 2009, 14: 469–483

3 Cecora R D, Eisfeld B, Probst A, Crippa S, Radespiel R. Differential Reynolds stress modelling for aeronautics. 2012. AIAA paper 2012-0465.

4 Queutey P, Visonneau M. An interface capturing method for free-surface hydrodynamic flows. Computers & fluids, 2007, 36(9), 1481-1510.

5 Zhao Q, Wu B, Du M, et al. Research on maneuverable of ship semi-constrained model test. Proceedings of the Academic Conference on Ship Hydrodynamics, 2015.