COMPARISON OF EXPLICIT ALGEBRAIC STRESS MODELS AND SECOND-ORDER TURBULENCE CLOSURES FOR STEADY FLOWS AROUND SHIPS

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ABSTRACT

The flow around the HSVA tanker is computed with an explicit algebraic stress model (EASM) and a Reynolds stress model. Near-wall models based on a transport equation for the turbulent frequency are proposed for both closures such that the same pressure-strain model can be employed. The EASM model improves the prediction in all aspects compared with simple linear eddy-viscosity model. Further improvements on the prediction of the longitudinal vortex are obtained with the Reynolds stress model. The analysis of the computational results reveals the limitation of the linear eddy-viscosity model as well as the existence of flow regions where the local equilibrium assumption, on which the algebraic stress model is based, is no longer valid.

INTRODUCTION

This paper is devoted to the assessment of the most recent turbulence models for steady flows around ships. The flow around the HSVA tanker (Wieghardt and Kux, 1980) [1] is still chosen as reference databasis. It is characterized by a strong thickening of the boundary layer, the generation of an intense longitudinal vortex motion creating complex "hook-shaped" velocity contours in the central part of the wake near the location of propeller and many other characteristics which are not recalled here for the sake of brevity (see Figs. 1 and 2).

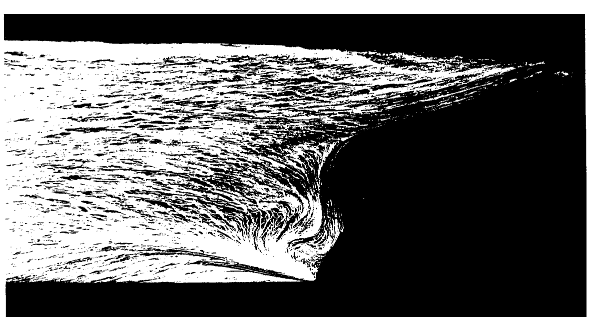

Figure 1: HSVA Tanker – Re = $5.0\,10^6$ Experimentally observed wall flow.

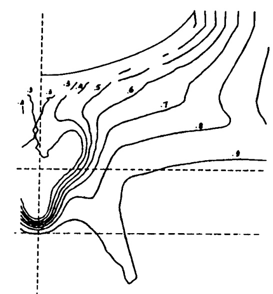

Figure 2: HSVA Tanker – Re = $5.0\,10^6$ Experimental isowake contours at x/L=0.978

Although the $k-\omega$ model developed by Wilcox (1993) [2] and its variants due to Menter (1993) [3] bring noteworthy improvements in the simulation of the near-wake flow, as indicated by Deng & Visonneau (1996) [4] and confirmed recently by [5], they cannot be considered as a fully satisfactory answer. Not only unable to simulate turbulence anisotropy, the limitations of eddy-viscosity models for modeling complex flows are related to models' inability to account for the selective amplification or attenuation of Reynolds stresses by curvature-related strain components, which explains their bad performances on flows characterized by intense longitudinal vortices.

Whereas second-order closures (RST models) are based on the solution of a modeled form of the full Reynolds stress transport (RST) equations, the explicit algebraic stress models (EASM) are derived from equilibrium hypotheses imposed on the convective and diffusive terms in the RST equations. Both models are able to provide an anisotropic description of the turbulence but the RST closures include additional physical terms such as the convection and the turbulent diffusion of the Reynolds stresses which makes possible a more accurate description of turbulent complex flows.

Therefore, the main goal of this paper will be to evaluate the relative importance of transport and diffusion mechanisms of the Reynolds stresses for the steady flows around ships. The EASM model proposed by Gatski & Speziale [6] will be used in conjunction with a turbulent frequency ω equation proposed by the authors which allows direct integration of the EASM model up to the wall. In order to facilitate the evaluation of the role played by these additional physical terms, the same models for the pressure-strain and turbulent dissipation terms will be implemented in both EASM and RST closures.

NUMERICAL METHOD

The simulation has been performed with the HORUS code developed in our CFD group. The solution of the Reynolds Averaged Navier-Stokes Equations is obtained by using finite difference method with a body-fitted structured grid. A cell-centered layout is employed in which the pressure, turbulence and velocity unknowns share the same location. The momentum and continuity equations are coupled through the PISO procedure and several implicit first and second order accurate schemes are implemented for the space and time discretizations. In the present computation, convection terms written in convective form are discretized with a third order upwind-biased scheme which is similar to the well known Quick scheme for the conservative formulation. Finally, preconditioned conjugate gradient solvers (CGS, CGSTAB) are used to solve the linear systems.

Implementation of a Reynolds stress transport model in a non-staggered layout is not straightforward. Because of the absence of numerically stabilizing eddy viscosity and the predominant influence in the momentum transport equations of the equilibrium between several strong and opposite source terms, namely the pressure and Reynolds stress gradients, a special numerical stabilizing technique has been devised in Deng & Visonneau (1996) [4]. In addition to the above mentioned technique, a defect correction approach described in [7], is used to take into account the contribution of the Reynolds stress in the momentum transport equation.

TURBULENCE MODEL

Three different turbulence closures are evaluated in this paper. The first one which will be used as a reference of the current industrial state of the art, is the isotropic eddy-viscosity based $k-\omega$ model ([2]) with the SST variant due to [3]. The second closure is based on a local equilibrium hypothesis which makes possible the building of an algebraic stress model which can be considered as a very simplified form of the Reynolds Stress transport equations. Explicit algebraic stress models (EASM) have been first proposed by Pope [8] for two-dimensional flows. EASM models for 3D flow have been developed by Gatski & Speziale [6] and widely used. In this study, we use the EASM model proposed by Gatski & Speziale [6] with an original near-wall formulation described in [7]. After the EASM model which is of intermediate complexity, the third closure relies on the full Reynolds Stress transport equations. Details of the original closures developped by the authors to address this complex flow, may be found in [7] and are not recalled for the sake of brevity.

NUMERICAL RESULTS

Computations have been performed on a domain covering the whole ship with $120 \times 81 \times 34$ nodes in the streamwise, radial and girthwise directions respectively. A third order upwind-biased scheme is used to discretize the convection term. The convergence is ensured by checking the evolution of the wall friction velocity. Several thousand iterations are necessary to achieve convergence. Computational time with the Reynolds stress model is about twice more important than with the EASM or two-equation models.

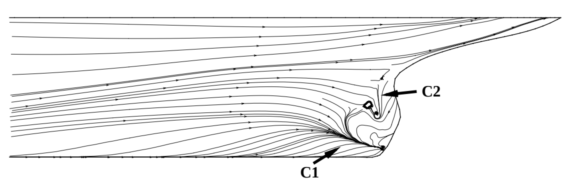

Figure 3: Wall limiting streamlines predicted with the Menter's SST model

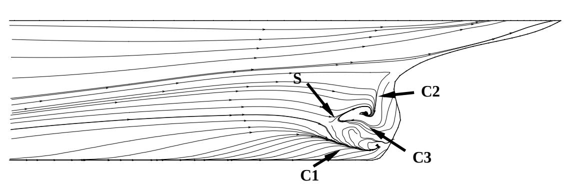

Figure 4: Wall limiting streamlines predicted with the EASM model using the SSG pressure-strain model

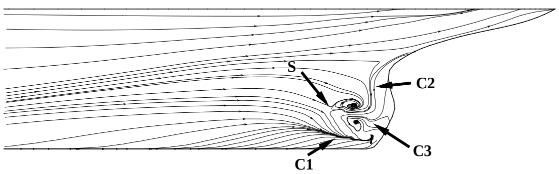

Figure 5: Wall limiting streamlines predicted with the Reynolds stress model.

The wall limiting streamlines are found to be very sensitive to turbulence models. The limiting streamlines predicted with the SST model, the EASM-SSG model, and the Reynolds stress model are shown in figures 3 to 5 respectively. All turbulence models predict the main features of the wall limiting streamlines observed in the experiments: an horizontal line of convergence C1, a vertical line of convergence C2, and a reversed flow region. Among the computational results, two different patterns can be distinguished. With the EASM-SSG model and the Reynolds stress model, a line of convergence C3 can be observed in the reverse flow region. Above this line, a spiraling flow can also be identified. A saddle point S associated with the line of convergence C3 can be also identified in front of the reversed flow region. Although experimentally visualized limiting streamlines seem to be in better agreement with the computed limiting streamlines obtained with the SST model for which the above mentioned features are not observed, flows with the former limiting streamlines pattern give better agreements concerning prediction of the mean velocity field. The existence of the spiraling flow above the C3 line is associated with a strong longitudinal vortex. The EASM-SSG model predicts similar results (figure 4) as the Reynolds stress model (figure 5).

The predicted mean streamwise and vertical velocity components will be compared with the experimental data at several horizontal sections. Comparisons are now carried out between the SST model, the EASM-SSG model and the Reynolds stress model.

At section x/L=0.941, the Reynolds stress model gives a better prediction of the streamwise velocity component near the keel where the curvature (profiles in the lower part of the figure 6). Improvement is also observed in the region with the EASM-SSG model compared with the SST model. Near the water surface however, the Reynolds stress model fails to capture correctly the growth of the turbulent boundary layer, while both the EASM model and the SST model provide a good prediction. The imperfections of the Reynolds stress model are also observed in the free stream region where a low momentum domain exists because of the convection of lower momentum from the upwind station. Comparison of the vertical velocity component (figure 7) also indicates that the most satisfactory result is obtained with the EASM-SSG model, while the Reynolds stress model underestimates the vertical velocity component near the wall.

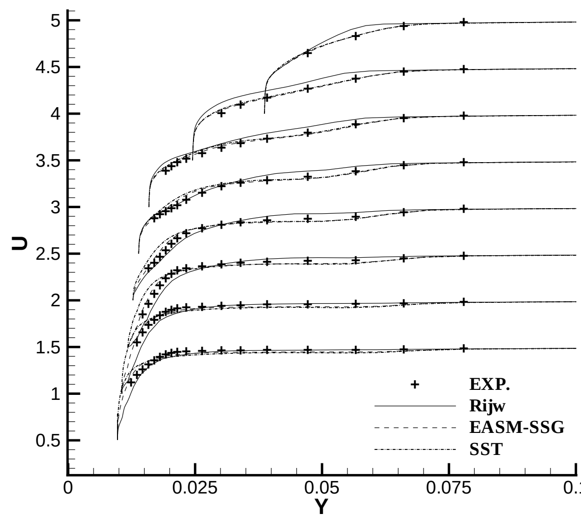

Figure 6: Streamwise velocity profiles at x/L=0.941 as function of y for several depths

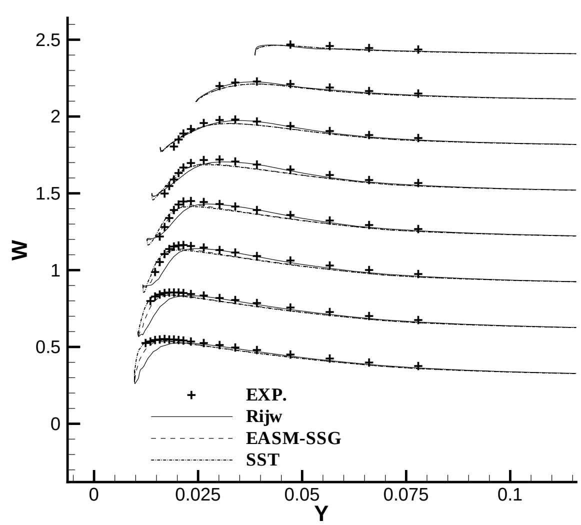

Figure 7: Vertical velocity profiles at x/L=0.941 as function of y for several depths

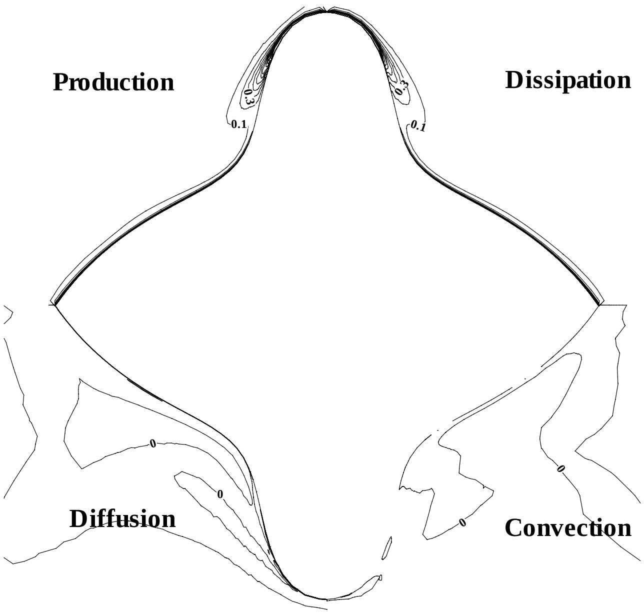

Figure 8: Budget of the kinetic energy equation predicted by the SST model at the section x/L=0.941

The EASM model is deduced from the Reynolds stress model under a local equilibrium assumption. Thus, the domain of validity of the Reynolds stress model is expected to be larger than that of the EASM model. However, the opposite conclusion must be drawn from the present computation. Since the same pressure-strain model is used in both models, the only differences between the Reynolds stress model and the EASM model concern the local equilibrium assumption, the approximations employed to obtain the explicit solution of the algebraic stress model, and the wall reflection terms used only in the Reynolds stress model. The local equilibrium assumption can be easily checked with the budget of the kinetic energy transport equation. From the budget predicted with the SST model shown in figure 8, it can be observed that, at this station, both convection and turbulent diffusion terms are small, compared with the production and turbulent dissipation terms. Therefore, the flow can be considered in local equilibrium. It is unlikely that the approximations employed to obtain the explicit solution of the algebraic Reynolds stress model significantly improve the deficiencies presented in the original model. This is the reason why the authors believe that the deficiencies of the Reynolds stress model at this station are mainly due to the modelization of the wall reflection term.

X/L=0.978 is the station where the propeller should be present. The successful prediction of the hook-shaped mean streamwise velocity contours observed in the measurements has always been considered as a key criterion for assessing the performance of a turbulence model designed for ship flows. The width of the longitudinal vortex is however better captured with the EASM-SSG model, compared with the classical isotropic SST closure. Compared with its simulations at the previous stations, the Reynolds stress model provides here a dramatically improved answer.

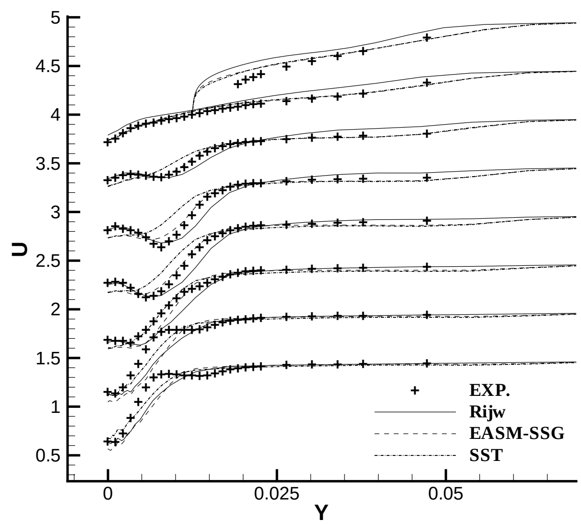

Figure 9: Streamwise velocity profiles at x/L=0.978 as function of y for several depths

By comparing the predicted mean streamwise velocity contours with the experimental measurements at this station (figures 11 to 13), it can be observed that the hook-shaped velocity contours are remarkably well captured with this new Reynolds stress model (figure 13). With the EASM model and the SST model, the streamwise velocity at the center of the longitudinal vortex is clearly under-predicted.

Finally, the turbulent kinetic energy budget at the station x/L=0.978 shown in figure 14 reveals that the sum of the convection and the turbulent diffusion terms is almost as important as the turbulent dissipation term. Consequently, the convection and the turbulent diffusion terms, intrinsically present in the Reynolds stress transport equations, can not be neglected. A full Reynolds stress transport model is the only alternative.

CONCLUDING REMARKS

The flow around the HSVA tanker has been calculated by using different turbulent models ranging from linear eddy-viscosity model, the explicit algebraic stress model, to full Reynolds stress transport model. A

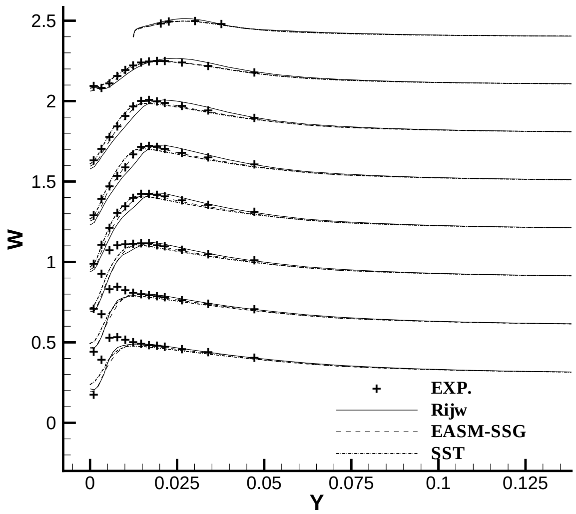

Figure 10: Vertical velocity profiles at x/L=0.978 as function of y for several depths

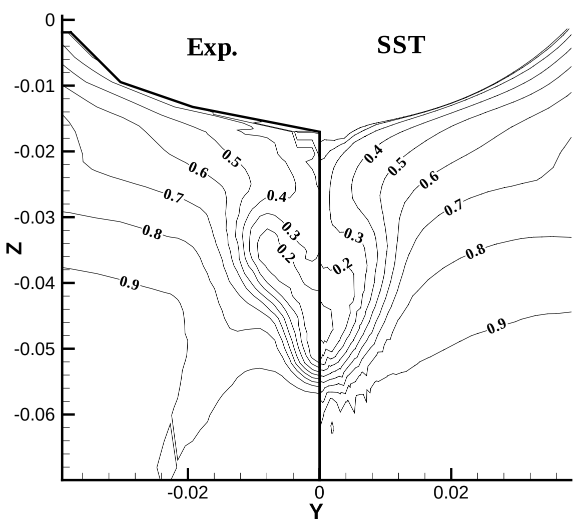

Figure 11: SST model - Comparison between experimental and computed isowakes at x/L=0.978

stable solution of the Reynolds stress transport equations has been obtained by implementing a new near-wall model and a defect correction approach. On one hand, non-linear models obtained from an approximate explicit solution of the algebraic stress models improve the prediction in all aspects compared with simple linear eddy-viscosity models. On the other

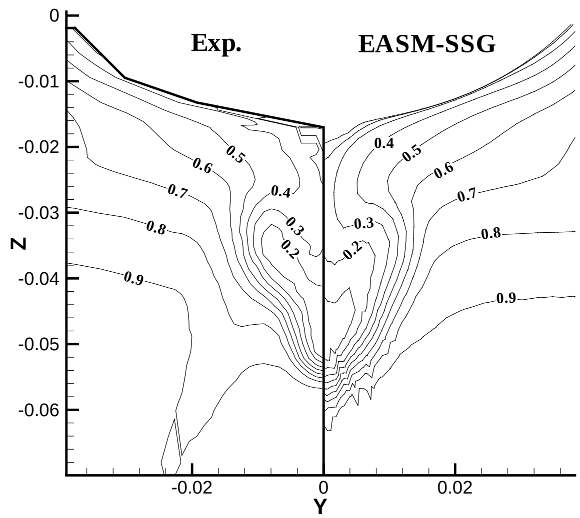

Figure 12: EASM-SSG model - Comparison between experimental and computed isowakes at x/L=0.978

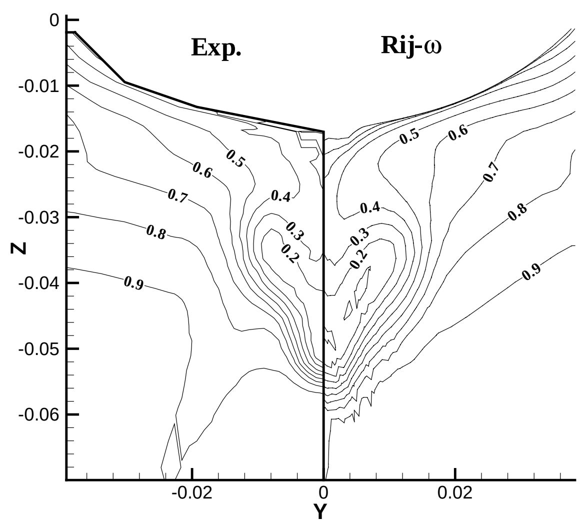

Figure 13: Reynolds stress model - Comparison between experimental and computed isowakes at x/L=0.978

hand, the solution of the Reynolds stress transport equations shows that the local equilibrium assumption on which the algebraic stress model is based is not valid in the region where the longitudinal vortex is intense. Physically accurate computations of this flow can only be obtained by solving the Reynolds stress transport equations. However, although a dramati-

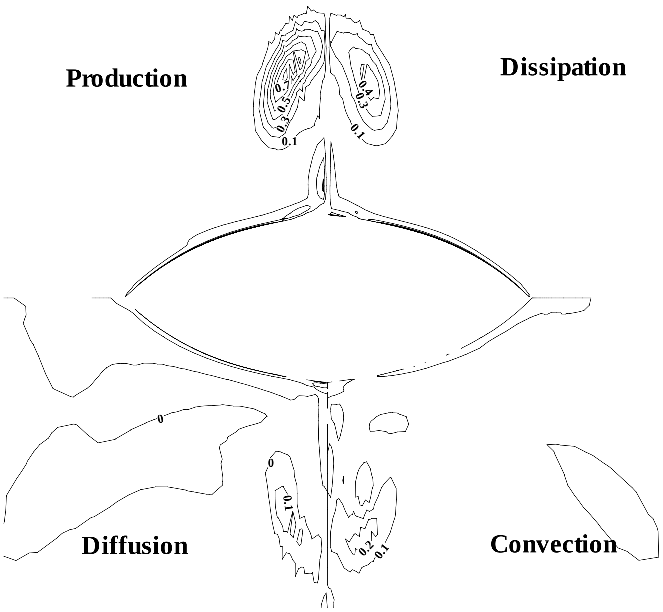

Figure 14: Budget of the kinetic energy equation predicted by the SST model at the station x/L=0.978

cally improved prediction has been obtained in the region where the convection of the Reynolds stress is important, the present Reynolds stress model provides a relatively less satisfactory prediction elsewhere compared with less sophisticated turbulence models. The weaknesses of the proposed Reynolds stress model are likely due to the modelization of the wall reflection and the turbulent diffusion terms. Finally, the computational results suggest that the exact representation of the convection and production terms is mandatory but not sufficient to improve the prediction in the whole fluid domain. It is necessary to improve simultaneously the modelization of the pressure-strain, turbulent diffusion and turbulent dissipation terms, otherwise the solution may be globally less accurate than the one provided by cruder turbulence closures.

ACKNOWLEDGMENTS

Thanks are due to the Scientific Committee of IDRIS and the DS/SPI for attributions of CPU on the Cray C98, the Cray T3E and the VPP machines.

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