Revised Reynolds-Stress and Triple Product Models

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Accurate computational flowfield predictions are essential for both design and operation of aerospace vehicles. As computer speeds and memory size continue to increase, Computational Fluid Dynamics (CFD) can be used to predict the flowfield around not only simple configurations, but also complete vehicle configurations. The advances in computer clock speed and memory capacity have allowed the modeling of turbulent flow, at least at lower Reynolds number, using Direct Numerical Simulations (DNS). Large Eddy Simulations (LES) continues to be developed for application to higher Reynolds numbers, but for complex configurations, DNS or even LES are still impractical because the grid required (in both time and space) is well beyond current computational capabilities.

Reynolds-stress turbulence models were envisioned to overcome a number of shortcomings evident in simple Boussinesq eddy-viscosity models. Although Reynolds-stress models have had a long history of development,[1,2] they have had, until recently, limited success in actually overcoming these shortcomings in practice. Reynolds-stress models have enjoyed a resurgence in the past few years,[2–4] with one new methodology incorporating the desired flow history effects on the Reynolds-stress tensor in a formulation that is numerically robust.[5,6] This Lag methodology allowed a further expansion of the flow history to include triple velocity products in a bid to obtain more accurate and complete turbulent transport predictions. This new model,[7] denoted "TTR" for Turbulent TRansport, augments the second-moment predictions of the Lag Reynolds-stress models by adding field equations for the third-order-moments. These are an attempt to fulfill the need for turbulent transport predictions in regions of separation, where their relative importance is larger than it is for attached flows.

The TTR model was modified slightly when it was applied to a rotating pipe flow.[8] The modifications that improved separated flow prediction on the Bachalo-Johnson bump also improved predictions in the similar region of the pipe axis, where turbulent production vanishes and turbulent transport is balanced by convection and dissipation. This gives evidence that the separation prediction improvements were the result of improved physical modelling and not simply the addition of an additional model degree of freedom.

One of the remaining issues with the higher order Lag models is that they are tuned to a outdated model of the flat plate Reynolds-stress distribution. In the four decades since the publication of Townsend's "The Structure of Turbulent Shear Flow",[9] our knowledge of the subject has advanced. It has been acknowledged that the equilibrium stress relationship was based on the relatively complete, but inaccurate, picture of turbulent shear structure.

At this point in the development of the Lag methodology, some of the known deficiencies in the underlying stress-strain relations are now being addressed. The normal stress predictions are being brought more in line with the more recent data available. For example, there is not a clear consensus on what the actual R^+_{11} values in the log layer should be at high Reynolds number,[10–14] but the value predicted in the earlier Lag models is below what is consistent with current data.

Utilizing equilibrium stress-strain relationships that are more consistent with the new knowledge base, but retaining the flat plate skin friction prediction and log-law predictions as model constraints, seems to yield improved predictions for separated flows such as the Bachalo-Johnson bump.[15] Improvements in reattachment location prediction are one result. In addition, prediction of the Reynolds-stress state (Figs. 1,2,3) in the separated zone is significantly improved. The model denoted "New" in these figures is not the

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final model, but rather one of the current candidates, tuned to improve the $R_{11}+$ predictions on the flat plate.

The wall normal Reynolds-stress is not well predicted by this model. Tuning of the wall normal Reynolds-stress prediction, consistent with the constraints imposed by the flat plate and other canonical flowfields, will be pursued. In this modelling system, improving the fidelity of the normal stress predictions should improve the turbulent transport (T_{ijk}) predictions, and these should all directly improve the reattachment predictions which are intimately linked with the separated zone flowfield predictions.

The final paper will have comparisons for the improved Lag-R_{ij} and Lag-T_{ijk} models with the previous versions, as well as Spalart/QCR and SST models. Flat plate and rotating pipe results will highlight the attached flow behavior of the models, and the Bachalo-Johnson bump flow will feature prominently as one of the separated flowfields studied. The transonic MPCV/Orion capsule flowfield will also be included, as an example of a massively separated flowfield. Additional separated flowfields are planned for analysis, to demonstrate the performance of the models on a wide selection of such flowfields.

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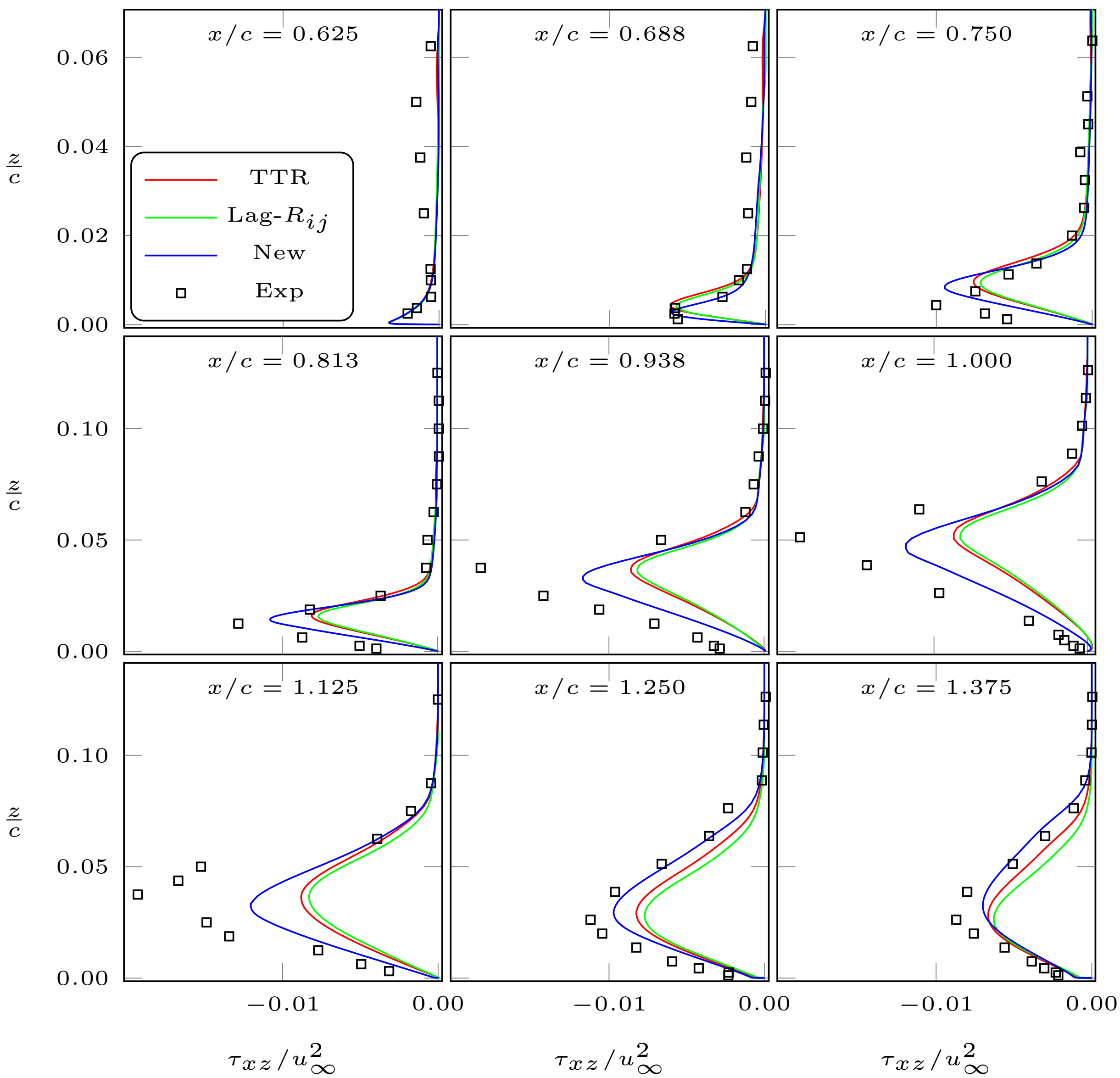

Figure 1: Reynolds Shear-Stress Progression, Bachalo-Johnson Bump Flow, $M_\infty = 0.875$

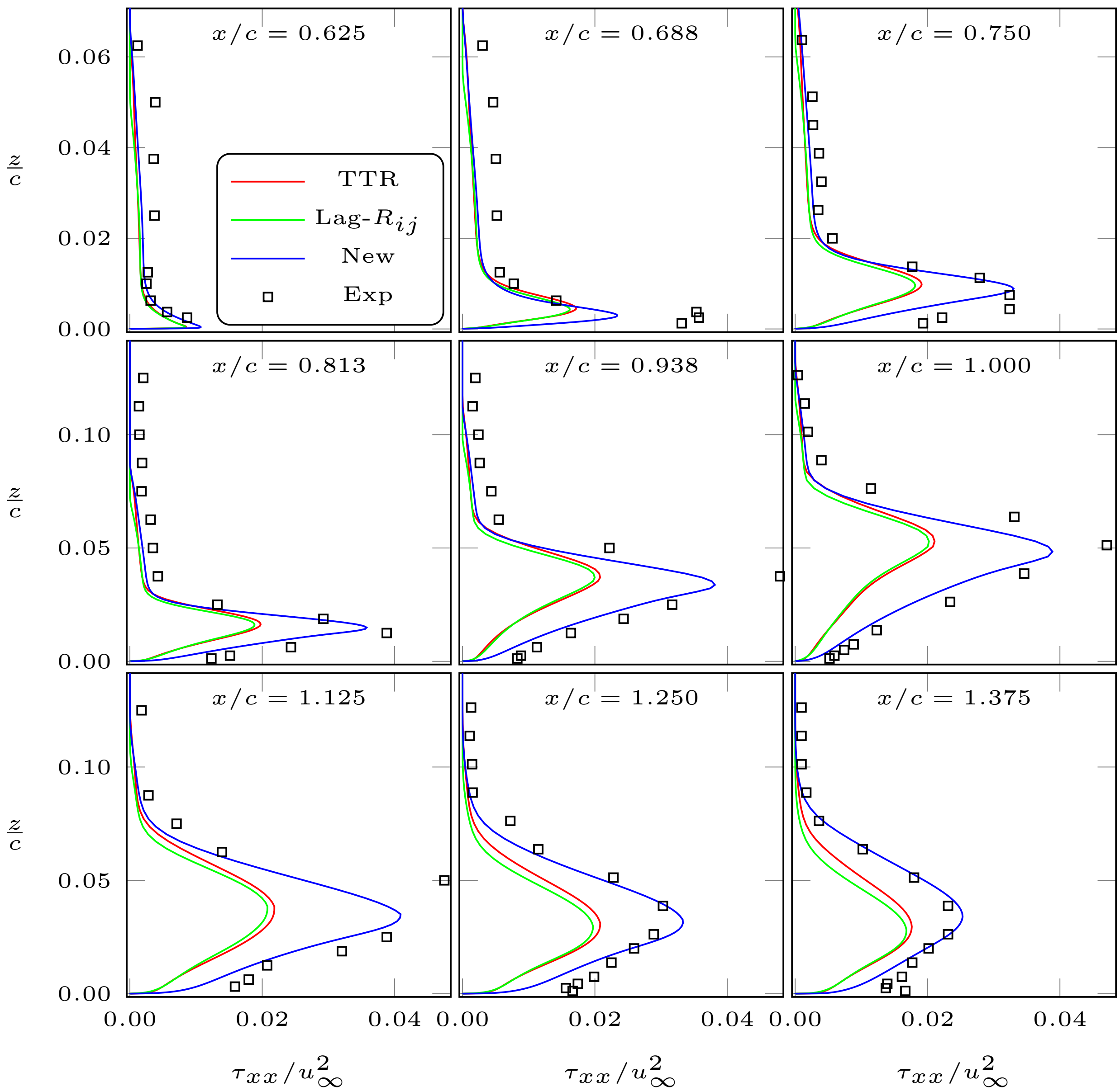

Figure 2: Reynolds Axial Normal-Stress Progression, Johnson-Bachalo Bump Flow, $M_\infty = 0.875$

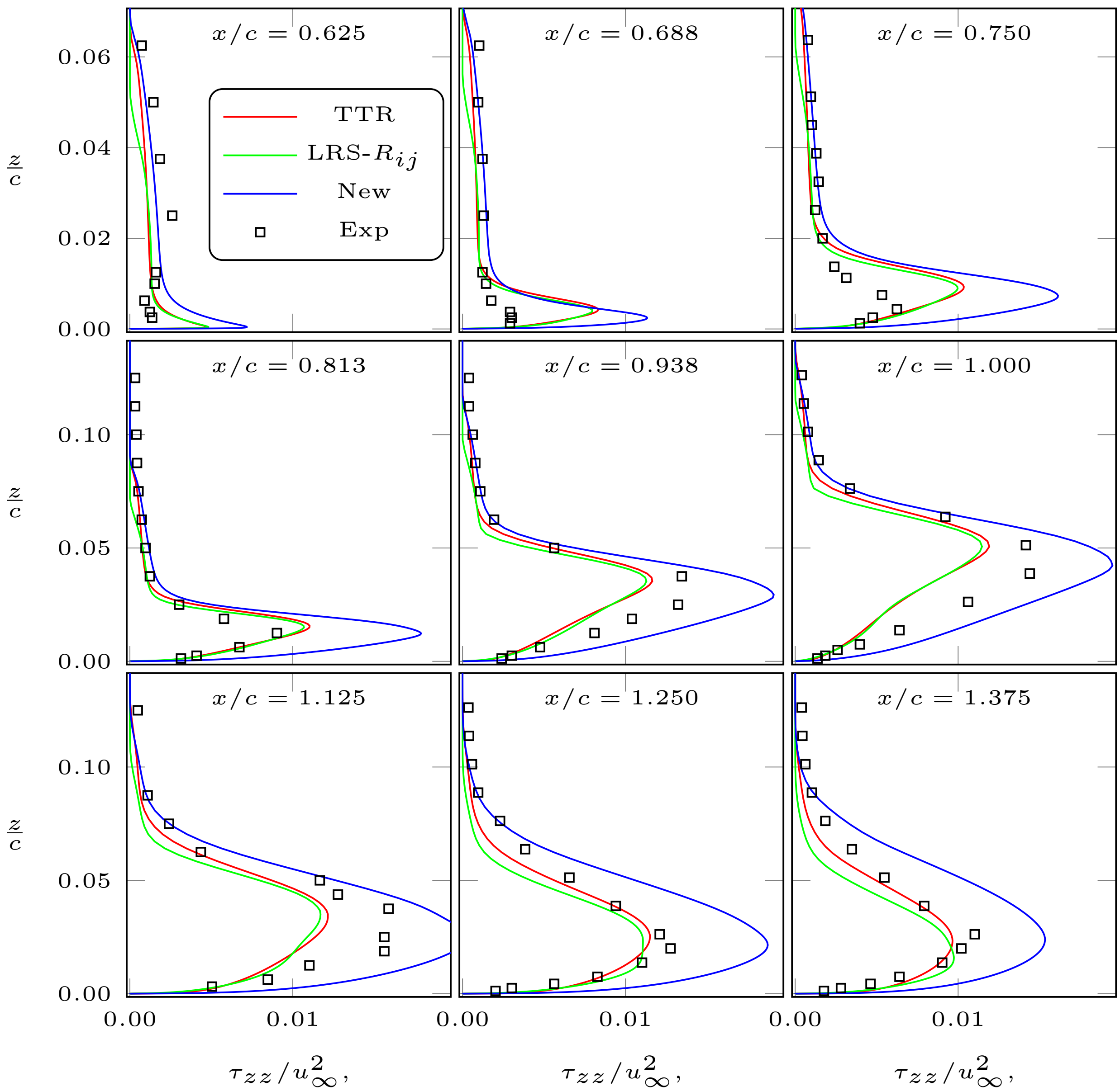

Figure 3: Reynolds Wall-Normal Normal-Stress Progression, Johnson-Bachalo Bump Flow, $M_\infty = 0.875$