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Implementing and testing a natural transition model in a multi-block finite-volume time-resolved RANS scheme

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ABSTRACT

Transition is inherently a stochastic process that occurs where a flow is observed to change from laminar to turbulent, as often happens, for example, on aircraft wings or past turbine blades. This project aims to combine an in-house laminar flow solver and a RANS $k-\omega$ [4] solver through incorporating an intermittency transport model into the computation, thus creating a transitional flow solver. The intermittency transport model uses empirical correlations that have shown some success in predicting transitional flows past conventional geometries.

A two-equation turbulence model was modified to include the effect of transition in CFD predictions. The in-house multi-block finite volume time-resolved RANS scheme Cosmic is used to compute the seven conservative variables that define the flow state in the discretized Navier-Stokes equations. The code uses a 2D finite-volume four-point stencil approximate Riemann solver with a Monotone Upstream-centred Scheme for Conservation Laws (MUSCL) interpolation by Van Leer et al. to compute the convective fluxes. This gives up to a third order accurate reconstruction of the spatial gradients in regions of smooth flow. The scheme is explicit and a standard multi-stage second-order Runge-Kutta (RK) integration is used to time-march the flow. The turbulent flux vector is estimated using a second order accurate gradient reconstruction method, based on the Gauss divergence theorem.

This paper presents the implementation of the transition model of Suzen & Huang [1]. Suzen & Huang developed an intermittency transport model which can produce both the experimentally observed streamwise variation of intermittency and a realistic profile in the cross-stream direction. The model combines the transport equation models of Steelant & Dick [2] and Cho & Chung [3]. Specifically, the transport of intermittency, γ, is given by:

$$\frac{\partial \rho\gamma}{\partial t} + \frac{\partial \rho u_j \gamma}{\partial x_j} = (1-\gamma)[(1-F)C_o\rho\sqrt{u_k u_k}\beta(s) + F(\frac{C_1\gamma}{\kappa}\tau_{ij}\frac{\partial u_i}{\partial x_j} - C_2\gamma\,\varrho\frac{\kappa^{\frac{3}{2}}}{\varepsilon}\frac{u_i}{(u_\kappa u_\kappa)^{\frac{1}{2}}}\frac{\partial u_i}{\partial x_j}\frac{\partial \gamma}{\partial x_j})]$$
$$+ C_3\rho\frac{\kappa^2}{\varepsilon}\frac{\partial \gamma}{\partial x_j}\frac{\partial \gamma}{\partial x_j} + \frac{\partial}{\partial x_j}(((1-\gamma)\gamma\sigma_{\gamma t}\mu + (1-\gamma)\sigma_{\gamma t}\mu_t)\frac{\partial \gamma}{\partial x_j}) \quad (1)$$

Further details of the transport model algorithm are given in Suzen & Huang [1]. Equation 1 has been implemented explicitly in the scheme. Specifically, the upwind Riemann solver of Roe convects γ

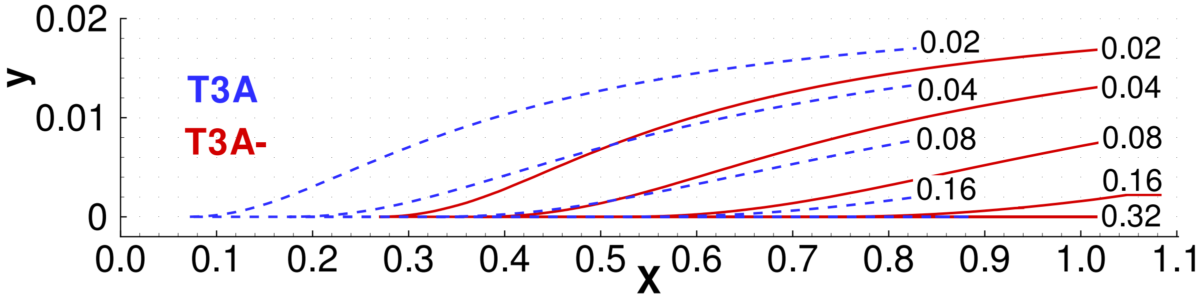

Figure 1: γ contours, $(--)$ T3A, $(-)$ T3A-. Proportional contour spacing from $\Delta\gamma = 0.02$.

around the flow field. The γ-diffusion term has been implemented using the Gauss divergence theorem around cell interfaces. All derivatives in the source terms are discretized by central differencing. The intermittent behaviour of transitional flows is modelled by modifying the eddy viscosity μ_t by the intermittency factor γ. While the intermittency transport equation defines the intermittency distribution for transitional flows in the simulation, the onset of transition is defined by correlations. The onset of attached flow transition is determined as a function of the turbulence intensity, Tu, and the acceleration parameter, Kt. Specifically, for by-pass transition, the Abu-Ghannam & Shaw correlation is used, and for natural transition an instability approach is followed based on the Orr-Sommerfield equations. The length of the transition region is obtained from the Solomon, Walker and Gostelow correlation. The predicting capabilities of this model have been validated against the ERCOFTAC T3A- and T3A experiments of Roach & Brierley [5]. Cases T3A- and T3A include both laminar and transitional boundary layers over a 2.0 m long flat plate. These cases have zero pressure gradient. The inflow turbulence intensity is 0.9% and 3.0% and the freestream velocity is 19.8m/s and 5.4m/s for T3A- and T3A respectively. At the streamwise distance of x=495mm and x=295mm, respectively, from the leading edge, a laminar profile (γ=0) is imposed as the inflow of the computational domain. Figure 1 shows the predicted intermittency countours for both test cases. The models predicted an intermittency distribution that is similar to that in the experiment [5]. With a higher free-stream turbulence intensity, the intermittency raises quicker along the flat plate, as in the experiment [5]. In conclusion, a numerical model has been developed of the transitional flow over a flat plate, using the intermittency transport equation. This test validated the implementation of an intermittency transport model on a structured compressible finite-volume CFD scheme. The model captured the earlier transition that occurs in a zero pressure gradient boundary layer with a higher turbulence level inflow. The $k-\omega-\gamma$ numerical method is now able to tackle flow regimes of interest to the turbomachinery community.

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