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Technical Notes

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Capturing Effects of Rotation in Sudden Expansion Channels Using Detached Eddy Simulation

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I. Introduction

THE effects of system rotation are of interest in flows in hydro/turbo machinery especially in the design of centrifugal compressor impellers and runner blades. When the direction of rotation is in tandem with the fluid rotation vector, that is, the vorticity, the flow is stabilized, whereas the flow is destabilized if the directions are opposing. As with boundary layers, shear layers are also stabilized or destabilized by rotation. Rotation (or streamline curvature) generates extra strain rates that significantly affect turbulent stress production. Bradshaw [1] formulated an analogy between meteorological parameters and parameters describing rotation about the axis normal to the plane of rotation. He defined an effective Richardson number (Ri) for flows undergoing rotation that is used to define a modified mixing length [$l = l_0(1 - \beta \mathrm{Ri})$]. Most of the later studies also propose a similar definition, where the effects of rotation are modeled by formulating corrections using a rotation Richardson number.

Nilsen and Andersson [2] used an algebraic second moment closure model to predict the rotational effects on backward facing step flows. It was observed that rotation induced variation in the mean flow pattern was a result of significant changes in turbulent fluctuations in the free shear layer. However quantitative predictions of the reattachment length showed only partial agreement with the experimental data (Rothe and Johnston [3]). A similar study was carried out on rotating flows using a v^2–f model by Iaccarino et al. [4]. Both the original and a modified version of the model were used to predict the reattachment length downstream of a backward facing step. The modified model predicted the reattachment length better than the original model. However it was observed that the predictions of the modified model, like the algebraic second moment (ASM) model of Nilsen and Andersson [2] showed only partial agreement with the experiments. Therefore in spite of the continual development of Reynolds-averaged Navier–Stokes (RANS) models, predicting the effects of rotation in turbulent flows is a major challenge.

The eddies formed in the massively separated regions downstream of the step are geometry specific. The "detached" eddies are not as universal as the eddies in typical thin shear layers where RANS models are calibrated. This is the reason why RANS models are often observed to fail in flows undergoing massive separation. Large eddy simulation (LES) resolves the large energy carrying eddies while modeling the smaller isotropic eddies using a subgrid scale stress model. LES is a viable and a reliable method for simulating flows undergoing massive separation. However the near-wall resolution necessary for LES makes it prohibitively expensive at high Reynolds numbers.

A solution to the computational challenges associated with the reliable prediction of massively separated turbulent flows is detached eddy simulations (DES). DES sensitizes a RANS model to grid length scales, thereby allowing it to function as a subgrid scale model in critical regions of interest. This allows the natural instabilities of the flow in this region to develop, the energy cascade to grow, and improves the quality of the solution in this region. Though DES was initially proposed for the Spalart–Allmaras model, it can be easily extended to other models (Strelets [5]), by appropriately defining a turbulent length scale. The credibility of the approach has been validated by numerous applications in the literature for external and internal flows.

The objective of the current study is to investigate the capabilities of DES in capturing the effects of rotation induced Coriolis forces on turbulent separation and reattachment in a backward facing step geometry. To evaluate the accuracy of the scheme in predicting the effects, the reattachment lengths predicted by DES are compared with experimental measurements by Rothe and Johnston [1] and also compared with other RANS models from the literature.

II. Computational Details

The turbulent flow over a backward step of expansion ratio 2 is studied with the step height H equal to the height of the channel h, upstream of the backward facing step. A uniform inlet velocity of $U_0(=1)$, is prescribed at the inlet of the channel. The inlet is placed $20H$ upstream of the step so as to allow the flow to be fully developed before it enters the sudden expansion region. The expanded portion of the duct extends up to $30H$ downstream of the step to eliminate any disturbances from the prescribed exit conditions. The global Reynolds number ($Re = U_0 H/\nu$) based on the inlet velocity and the step height is 10,000 and the global rotation number ($Ro = \Omega H/U_0$) is varied from −0.08 (clockwise rotation) to +0.08 (anticlockwise rotation). The width W of the duct upstream of the step is $2H$.

The governing flow and energy equations are solved in their nondimensional form. In addition, the equations for the DES form of the two equation k–ω model are solved to incorporate the effects of turbulence. Based on modifications of the RANS equations to derive the DES turbulence equations (Strelets [5]) the k-transport equation for DES is

$$\frac{\partial k}{\partial t} + \frac{\partial (u_j k)}{\partial x_j} = \tau_{ij}\frac{\partial u_i}{\partial x_j} - \frac{k^{3/2}}{\delta} + \frac{\partial}{\partial x_j}\left[\left(\frac{1}{\mathrm{Re}} + \frac{\sigma^*}{\mathrm{Re}_t}\right)\frac{\partial k}{\partial x_j}\right]$$

By this modification, DES is used as a general purpose RANS–LES model that adjusts to local flow conditions via turbulent length scale and grid specification. When the grid is finer than the local instantaneous turbulent length scale, the model behaves as a subgrid model and eddies are directly resolved on the grid. This allows the energy cascade to extend to length scales close to the grid spacing. In

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contrast, if the local instantaneous length scale is larger, the RANS turbulence model gains full control of the solution (even in regions away from the wall). This DES formulation of the k–ω equations is analogous to the formulation proposed for Menter's shear stress transport (SST) models (Strelets [5]).

III. Results

A. Numerical Method

DES, like LES, is sensitive to the grid resolution. Refining the grid in the regions of interest allows the model to resolve more turbulence. Three grids, $50 \times 24 \times 32$ (coarse grid), $72 \times 24 \times 32$ (baseline grid), and $100 \times 24 \times 32$ (dense grid), are used to discretize the computational domain downstream of the step. A comparison of the reattachment lengths predicted downstream of the step shows that the baseline and fine grid predict reattachment at a distance of $7.2H$ downstream of the step. On the other hand the coarse grid predicts a value close to $5.5H$. Rothe and Johnston [1] experimentally showed the reattachment point for this case to lie at a distance of $6.5H$. The baseline and fine grid predict reattachment lengths that are within 10% of the experimental measurements. A comparison of the streamwise velocity at two stations downstream of the backward facing step is shown in Fig. 1. The comparison shows that although at the first station all the three grids show profiles in close agreement, the velocities predicted at the second station show better concurrence between the baseline and the fine grids especially in the separated region. Similar plots of the turbulent kinetic energy (TKE) at these locations were also studied. [The sum of the TKE resolved by the grid and the TKE modeled by the unsteady RANS (URANS) model is reported for all the DES and URANS computations.] It is observed from the values of TKE in the shear layer and the separated region that the coarse grid overpredicts the TKE as compared with the dense and the baseline grids. Because the baseline and the fine grid give similar results, the baseline grid was used for further computations keeping in mind the lower computational cost afforded by its use.

The a posteriori evaluation of the wall normal grid spacing for the baseline grid shows that the $\Delta^+ < 1$ in the region downstream of the backward facing step. The streamwise grid distribution gives $\Delta^+ \sim 1$ near the backward facing step wall, which gradually increases to a value of $\Delta^+_{\max} \sim 1000$ near the outlet. The spanwise distribution yields $\Delta^+ \sim 1$ near the side walls and $\Delta^+_{\max} \sim 75$–80 toward the center of the duct. In contrast, LES computations by Ghosal et al. [6], in expansion channels used a $\Delta x^+_{\max} = 273$ and a uniform $\Delta z^+ = 36$, which is much finer than the grid resolution used for the current computation

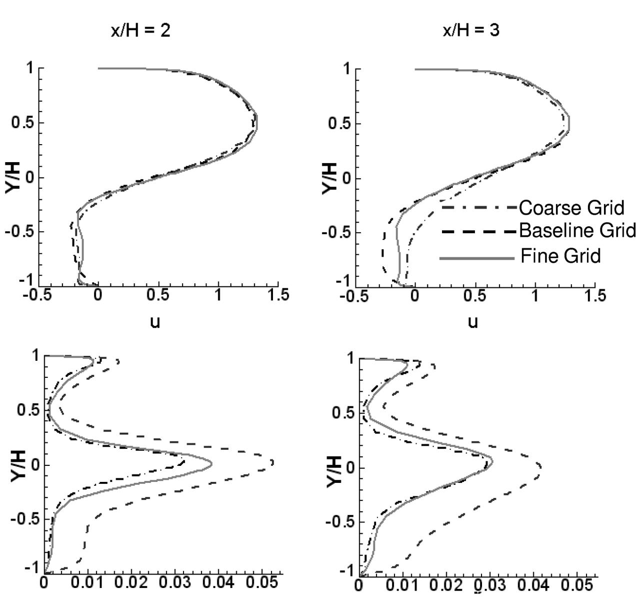

Fig. 1 Comparison of the reattachment lengths for the three grids used for DES computation.

B. Comparison of Turbulence Modeling Strategies

Rotation introduces Coriolis forces that stabilize or destabilize the flow downstream of the backward facing step. In spite of the Coriolis forces being included in the main momentum equations, the attenuation/augmentation of turbulence has to be computed accurately for predicting the correct reattachment length. A plot of the total TKE (Fig. 2) in the region downstream of the step for $\mathrm{Ro} = 0.00$ (stationary case) shows that DES predicts TKE values of up to 3.6% in the separated shear layer. An earlier study of the turbulent flow in a backward facing step by Avancha and Pletcher [7] shows a very similar distribution of TKE in the region downstream of the step. URANS on the other hand predicts TKE values as low as 1.0% in the separated shear region.

To establish the superiority of the DES results in comparison to RANS, computations were carried out on the same grid for all the rotation cases and compared with experimental measurements by Rothe and Johnston [1]. Figure 3 shows the comparison of the reattachment lengths predicted by k–ω URANS and DES as compared with the experiments. Results from earlier numerical studies using the ASM RANS model (Nilsen and Andersson [2]) for the duct of aspect ratio 2 and RANS second moment closure (SMC) and v^2–f RANS models (Iaccarino et al. [3]) are also presented along with the current results. The ASM RANS computation was carried out by assuming a uniform velocity at the inlet which was placed at a distance of $10H$ upstream of the backward facing step, whereas the other cases were carried out by imposing a fully developed turbulent velocity profile $4H$ upstream of the step. As mentioned earlier in Sec. II, the current study imposes a uniform velocity at the inlet placed at a distance of $20H$ upstream of the step, which allows the flow to be fully developed as it reaches the step. Thereby it is ensured that the effects of the flow conditions upstream of the step are similar in all the cases compared. It is observed that the ASM RANS model overpredicts the reattachment lengths for destabilizing rotation and underpredicts the length for stabilizing rotation. Although the v^2–f RANS model overpredicts the reattachment lengths for all the rotation cases considered, the SMC RANS model shows mixed trends like the ASM RANS model. A comparison of the k–ω URANS studied in this computation shows that its use underpredicts the reattachment length for almost all the rotation cases studied, while overpredicting the reattachment length for the stationary flow.

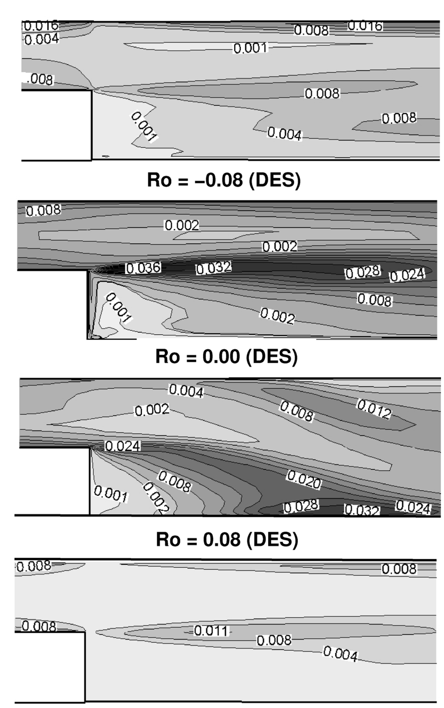

Fig. 2 Comparison of the total TKE downstream of the backward facing step.

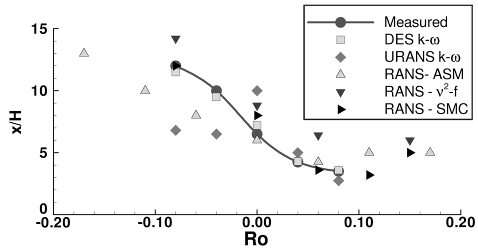

Fig. 3 Comparison of the reattachment lengths as predicted by DES k–ω (duct AR = 2), URANS k–ω (AR = 2), and earlier studies by Nilsen and Andersson [2] (Re = 5500, AR = 2) and Iaccarino et al. [3], with experimental measurements by Rothe and Johnston [1].

The overprediction of the reattachment length by the URANS model is attributed to the underprediction of the TKE values in the separated region downstream of the step. It is observed that DES overcomes the shortcomings of all the RANS models, predicting reattachment lengths within 13% of the experimental measurements.

It is observed that for the stationary case, the flow separates and reattaches at around 7.20 times the step height. This value predicted by DES compares well with the experimental value of 6.50. As the duct is rotated in the clockwise direction (negative rotation) the Coriolis forces acting on the flow force the flow to stay separated longer than in the stationary case. The turbulence in the separated zones is attenuated as rotation increases, which further delays the reattachment. It is observed that the reattachment length increases to a value of around 9.50 for Ro = −0.04 and further to 11.50 for Ro = −0.08.

On the other hand, the reattachment length for anticlockwise (positive) rotation decreases as the Coriolis forces act to force earlier reattachment. The turbulence in the separated region is augmented, thereby aiding reattachment. It is observed that the reattachment length decreases to a value of 4.30 for Ro = 0.04 and further to 3.60 for Ro = 0.08. As the system is rotated in the anticlockwise direction, flow separates at the top wall (around 2.0 step heights) downstream of the step and reattaches around 14.0 step heights downstream. The values predicted by DES lie within 13% of the measured values.

The augmentation and attenuation of turbulent energy is reiterated by comparing the TKE contours downstream of the backward facing step for the stationary case, a clockwise (Ro = −0.08) and a counterclockwise (Ro = 0.08) rotation rate in Fig. 2. Contour plots at the center plane of the duct show that although the peak TKE value in the separated shear layer for Ro = −0.08 is about 0.8%, the values increase by almost a factor of 4 when rotated at a rate of Ro = 0.08.

IV. Conclusions

DES computations were carried out for 5 different rotation rates ranging from Ro = −0.08 to Ro = 0.08, replicating the experiments of Rothe and Johnston [1]. The reattachment length predicted by DES showed consistent agreement with the experimental observations for all the cases studied, predicting the reattachment lengths with an accuracy of 13%.

The prediction of the rotation dominated separated flow downstream of the backward facing step undergoing rotation is observed to be superior to what can be achieved using RANS and URANS modeling. It is also concluded that using eddy-viscosity models in the DES mode overcomes some of the inherent shortcomings of the base RANS model. The effect of rotation on the reattachment length is captured accurately by DES without the need for defining additional production terms for rotation in the turbulence equations.

Based on the encouraging results obtained from these calculations, DES was extended to more complex cases. Studies on the effects of rotation in ribbed ducts were carried out by Viswanathan and Tafti [8]. The mean and turbulent flow and heat transfer predicted by DES in these studies for the various rotation cases showed good agreement with LES and experiments.

Acknowledgment

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