Three-Dimensional Simulation of Rotor-Stator Cavity Flow

T. J. Craft, S. E. Gant, H. Iacovides and B. E. Launder (School of Mechanical, Aerospace and Civil Engineering, University of Manchester)
E. Serre (MSNM-GP, Université d'Aix-Marseille)

There have been numerous numerical simulations and experimental studies of flow between rotating and stationary discs with a stationary shroud and no through-flow (a "rotor-stator cavity"). The flow has significant industrial applications, such as internal gas-turbine flows and computer hard disks, and the geometry is relatively simple. Most of the numerical simulations to date have treated the flow as axisymmetric. However, recent experimental flow visualization studies have shown that large coherent eddy structures exist within the cavity at certain operating conditions.

Some of these structures have since been simulated, albeit at low Reynolds number, using Direct Numerical Simulation (DNS) by Serre and co-workers at Marseille University [1].

The purpose of the current work is to investigate whether less costly Unsteady Reynolds-Averaged Navier-Stokes (URANS) and Large-Eddy Simulation (LES) models are also able to predict these time-dependent flow features.

Two sets of calculations have been performed using the parallel MPI version of the in-house CFD code, STREAM [2]. The first used a relatively coarse grid (61 x 50 x 38 nodes in the radial x circumferential x axial directions) and an embedded-grid wall-function which solves numerically boundary-layer-type equations [3]. The ratio of the disc-spacing (H) to radius (R) of the flow domain tested was H / R = 0.126 and the Reynolds number, based on the maximum rotor velocity and disc spacing was Re = Ω RH / ν = 112,000. These conditions

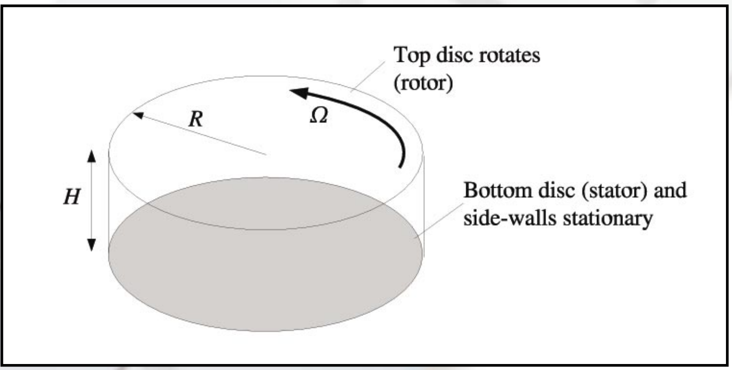

Figure 1: Computational Model

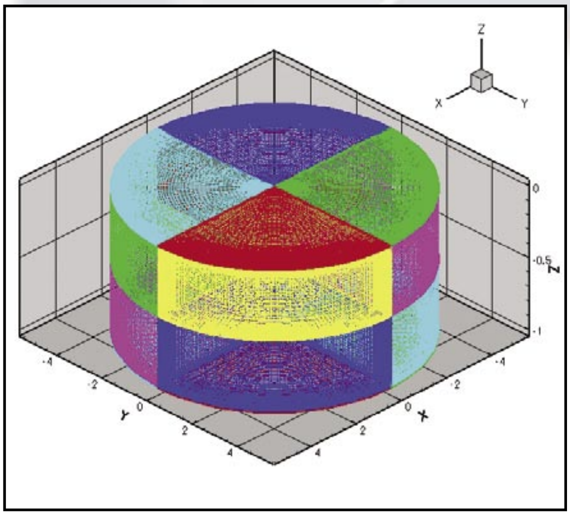

Figure 2: 16 Block Computational Grid
(150 x 100 x 141)

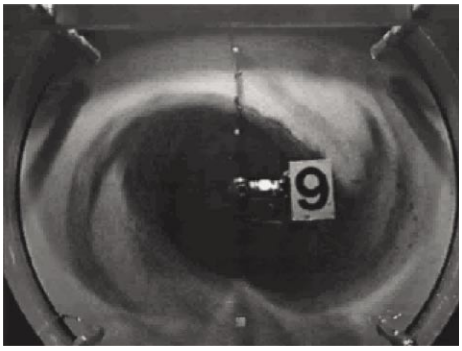

Figure 3: Experimental ink-in-water experiments for H /R = 0.126 case from Czarny et al.

corresponded to a particular experiment undertaken by Czarny et al. [4] in which a distinct two-lobed coherent eddy structure was observed (see photo in Figure 3).

Nine different turbulence models were tested:

- "No-model" approach (i.e. only molecular viscosity, in conjunction with an upwind-biased convection scheme)
- Linear k - ε model of Launder & Sharma
- Linear production model of Guimet & Laurence
- Organised Eddy Simulation (OES) model
- Cubic non-linear k - ε model of Craft et al.
- Speziale, Sarkar & Gatski (SSG) differential stress model
- Two-Component Limit (TCL) differential stress
- Filter-based RANS model of Johansen et al.
- Smagorinsky LES

An ongoing second set of calculations using a finer 2.1 million-node grid (150 x 100 x 141) is resolving the near-wall flow (i.e. not using wall functions). The domain geometry is H / R = 0.195 and Reynolds number, Re = 166,000. Three-lobed structures were observed in the experiments at these operating conditions. Calculations are being performed using 16 processors on "Newton" with a reasonable speed-up of 14.3. At present, results have been obtained using a "no-model" approach and computations using a k - ε model are in progress.

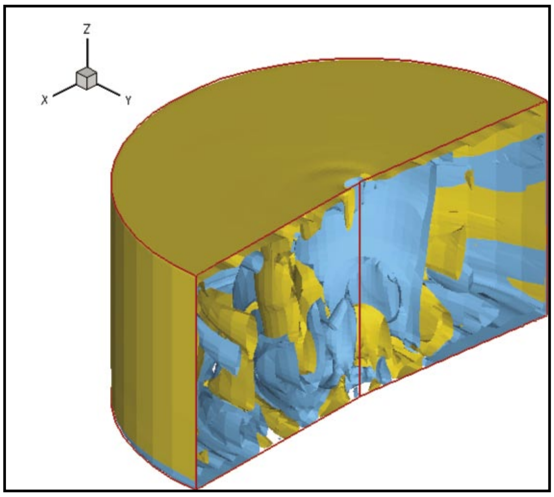

Figure 4: Instantaneous radial velocity isocontours: yellow = positive, blue = negative

In the thinner cavity (H / R = 0.126) the "no-model" approach produced a disturbed, non-axisymmetric, flow field. A plot of the instantaneous radial velocity isocontours (see Figure 4) shows the positive (outward) radial velocity in the Ekman layer near the upper rotor surface and predominantly negative (inward) radial velocity in the layer near the lower stator surface. Within the bulk of the cavity itself there are numerous, disordered regions of positive and negative radial velocity. Spiral structures, which have been observed in DNS results for the annular rotor-stator cavity, cannot easily be discerned.

None of the URANS and LES models tested in this geometry produced coherent flow structures. The calculations were started from the disturbed "no-model" result and over time, the fluctuating velocity field decayed to practically steady, axisymmetric flow.

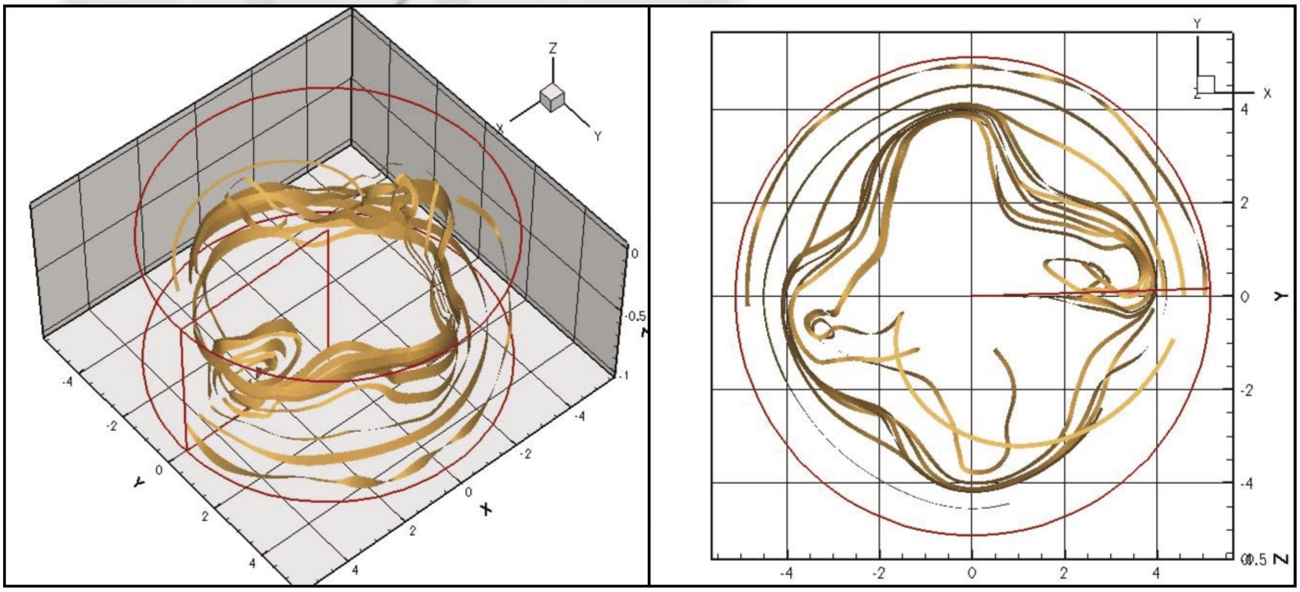

Figure 5: "No-model" 3-D and 2-D steamtraces after 15 revolutions

A very small degree of unsteadiness was observed with those models that gave lower eddy-viscosity (namely the OES and filter-based models).

In the deeper cavity (H / R = 0.195), the "no-model" approach gave an unsteady three-dimensional flow field. After around 15 revolutions of the rotor a distinct four-lobed pattern was observed in the pressure and streamtrace plots (see Figure 5). A further 15 revolutions later, the four-lobed pattern merged into two lobes (see Figure 6). The magnitude of these disturbances were far greater than those which appeared previously in the thinner cavity. Recent results have indicated that as the calculation progresses still further, the two-lobes merge into a single-lobed axisymmetric flow pattern. Preliminary results using a standard low-Reynolds-number k - ε model show spiral structures emerging in the velocity contours near the stator surface, similar to those observed in the DNS rotor-stator simulations.

These preliminary results show that large coherent turbulent structures can be resolved in rotor-stator flows. At present, it is difficult to conclude whether the different results in the shallow and deeper cavities are a consequence of flow in the deeper cavity being naturally more unstable or a result of the numerical methods employed being different (grid resolution, turbulence model and wall treatment). In the experiments, they noted that coherent structures appeared more freely in the deeper cavity.

It is also not yet clear what causes the magnitude of the resolved unsteady motions to diminish in the thicker cavity. The calculation was started from an initially zero flow field with the rotor spinning at full-speed and therefore resembled computationally an impulsively-started rotor-stator flow. Whether the structures are only a transient phenomena linked to the initial conditions or whether they are being damped by some numerical diffusion effects is being investigated.

References

[1] E. Serre, O. Czarny, H. Iacovides, P. Bontoux and B. E. Launder Precessing vortex structures in flow within rotor-stator disc cavities: DNS and visualization studies. In I. P. Castro, P. E. Hancock and T. G. Thomas (editors) Advances in Turbulence IX: Proceedings of the Ninth European Turbulence Conference, Barcelona, 2002

[2] F. S. Lien and M.A. Leschziner. A general non-orthogonal finite-volume algorithm for turbulent flow at all speeds incorporating second-moment turbulent-transport closure. Comp. Meth. Appl. Mech. Eng., 114:123-167, 1994

[3] T. J. Craft, S. E. Gant, H. Iacovides and B. E. Launder. A new wall function strategy for complex turbulent flows. Numerical Heat Transfer, Part B: Fundamentals, 45(4):301-318, 2004

[4] O. Czarny, H. Iacovides and B. E. Launder. Precessing vortex structures in turbulent flow with rotor-stator disc cavities. Flow, Turbulence and Combustion, 69:51-61, 2002.

Contact Details

Simon Gant, School of Mechanical, Aerospace and Civil Engineering, University of Manchester, Manchester M60 1QD simon.gant@umist.ac.uk

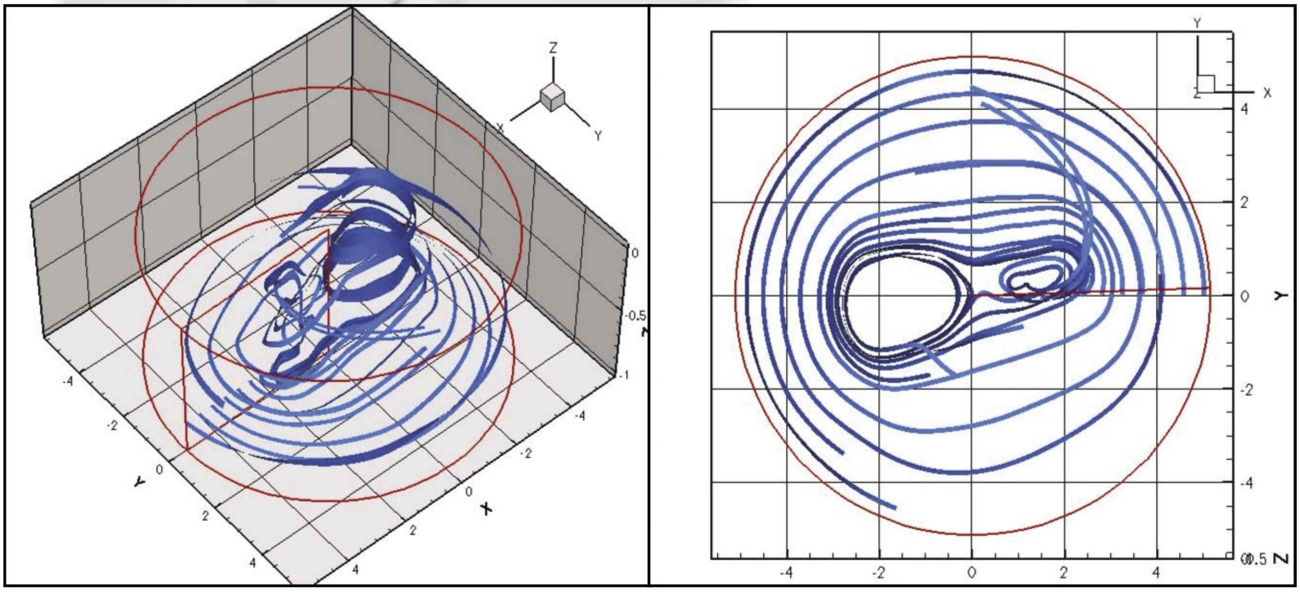

Figure 6: "No-model" 3-D and 2-D streamtraces after 30 revolutions