RANS Modelling of Some Strongly Swirling Aerospace Flows

T. J. Craft, H. Iacovides and B. E. Launder

School of MACE, University of Manchester, PO Box 88, Manchester M60 1QD, UK

Abstract:
Progress is reported on the modelling, via RANS closures, of two swirling turbulent flows important in aeronautics: the trailing wing-tip vortex and the flow in rotor-stator cavities. For the former the decay of the vortex is only well captured at second-moment level while, for the latter, an unsteady flow computation brings out large-scale organized structures, with the number of structures varying with cavity aspect ratio and Reynolds number, a result qualitatively in accord with experiment.

Mots clefs: Modelling, RANS, Fluids dynamics unsteady flows, Large-scale organized structures.

1 Introduction
The paper summarizes progress in the numerical computation of two important classes of turbulent, swirling aerospace flows that have been the focus of steady or unsteady RANS studies in Manchester over the past five years: the wingtip vortex and the flows within rotating disc cavities. In our computations, as in the experiments with which they are compared, the flow is incompressible.

2 The wing vortex study
The initial stage of the wing-vortex study concerned the initiation and very early development of the vortex shed from a NACA 0012 wing with rounded tip at a 10° angle of attack. Computations were made with the STREAM 3D elliptic solver (Lien & Leschziner, 1994) extending from 1.74 chord lengths upstream of the wing and continuing to 0.68 chords downstream. Half-a-dozen turbulence models were tested by Craft et al. (2006) ranging from the standard k-ε linear EVM to second-moment closure. Downstream from the airfoil, in the tip-vortex wake, greatly different behaviour was recorded by the different models, Fig 1, with the best agreement with the experiments of Chow et al. (1997) being achieved by the TCL second-moment closure (designed so that each modelled term complies with the Two-Component Limit with which turbulence must comply at a wall, Craft et al., 1996).

Thereafter, attention was shifted to the EU C-Wake Project which provides data from a NACA 4412 main profile with a NACA 0012 flap at 20° taken up to 10 wingspans downstream (i.e. 100 times as far downstream, in dimensionless terms, as that of Fig 1). In this case the TCL model again led to very satisfactory agreement with experiment, Fig 2 (Craft et al., 2008).
Fig 1: (a) Flow configuration (b) Comparison of swirl velocity contours 0.678 chord-lengths downstream of airfoil. From top left in cyclic order: Experiments, Chow et al (1997); Linear $k$-$\varepsilon$ EVM; TCL 2nd Moment Closure; Non-linear $k$-$\varepsilon$ EVM. From Craft et al. (2006)

Figure 2: C-Wake Swirl Velocity at Initial, Intermediate and Downstream Planes (a) $x/b = 1.25$; (b) $x/b = 5.0$; (c) $x/b = 10.0$. From Craft et al. (2008)
3 Rotating flow in gas-turbine cavities

The second class of problems is related to flow in the cavities found in gas-turbines between adjacent turbine discs which may be rotating or stationary (carrying the blades and guide vanes). While turbulent flows in such cavities had until recently been regarded as axisymmetric and steady, there is evidence (Czarny et al., 2002) that large-scale organized structures are present that may significantly alter the local Nusselt number. Work was thus initiated to try and mimic these structures which rotated at about half the speed of the rotating disc. Again the STREAM code, now in unsteady mode, was employed but using the simpler k-ε EVM since, if large-scale structures were predicted, these would (it was supposed) mainly be responsible for the transport of momentum in the flow. The initial computations employed a ‘low-Reynolds-number’ form which extended all the way to the wall. These captured the near-wall structure with Ekman and Bödewadt spirals but no large-scale vortices appeared in the core. The numerical solution was then modified by using a newly developed form of analytical wall function (Zacharos, 2009; Craft et al., 2008). This relatively rudimentary near-wall treatment nevertheless allowed skewing of the velocity vector across the sublayers of the discs, an essential feature to capture. This economical treatment of the sublayers enabled a much finer, more uniform mesh to be employed over the remainder of the flow. Although the detailed flow in the viscous layers was not resolved, this approach achieved a sufficiently accurate resolution of the near-wall region for the Bödewadt spirals to be captured, Fig 3.

Figure 3: Predicted structures close to the stationary wall. From Craft et al. (2008)

Moreover, large-scale vortices were generated in the nearly homogeneous central core outside of the near-disc shear layers, Fig 4. This success was not complete, however, for the multi-cell structures, which formed in the first few revolutions after starting the computations, gradually decayed: the three-vortex structure first collapsed to two and then one of those eddies weakened suggesting that eventually the computed flow would revert to axisymmetric form (the present study has only tracked the flow development for 70 revolutions). In the earlier experiments that stimulated this study, Czarny et al. (2002), both the three- and the two-vortex structures were a permanent feature of the flow. Further explorations are thus evidently needed to identify and remedy this disagreement.

Figure 4: Evolution of flow structures near the stationary disc for s/R=0.195, Re = 0.9 x 10^6. Contours axial velocity after (a) 20 revolutions; (b) 40 revolutions; (c) 70 revolutions. From Craft et al. (2008)
Computations have also been made for co- and counter-rotating disc cavities, Iacovides et al. (2009). In the case of two discs co-rotating at the same rate but with a stationary shroud, the large-scale vortices arise only over the outer quarter of the disc radius with the flow within the inner core being nearly axisymmetric, Fig 5. This may be expected since it is in the vicinity of the outer shroud that the flow’s angular momentum decreases with radius, a trigger of flow instability. Note, however that the axes of the vortices are in this case transverse to the flow whereas, for the Taylor-Görtler vortices formed in a boundary layer developing on a concave surface, their axes are directed in the primary flow direction around the curved surface. Finally, Fig 6 examines the case of counter-rotating flow with one disc rotating at only half the speed of the faster disc. This test-case has proved troublesome for RANS prediction codes (e.g. Kilic, 1996; Iacovides et al. 1996) at least partly because the Ekman flow is much stronger on the faster disc and a stagnation point (arising from the collision of the two Ekman layers) occurs at about 0.85 of the disc radius on the slower disc. The circumferentially and temporally averaged radial and tangential velocity profiles from the URANS computations shown in Fig 6a display very satisfactory accord with the experiments of Kilic et al (1996) in contrast with the axisymmetric RANS calculations by Iacovides et al. (1996) with a very similar turbulence model shown in Fig 6b.

![Figure 5. Contours of instantaneous, circumferential vorticity at the mid-plane (x/s=0.5) of the co-rotating cavity. From Iacovides et al. (2009)](image)

![Figure 6. Computed radial velocity in contra-rotating discs at r/R=0.85; disc-rotation ratio - 0.5. (a) 3D circumferentially averaged URANS; (b) 2D RANS with very similar turbulence model, Iacovides et al. (1996). From Iacovides et al. (2009)](image)

4 Conclusion

Swirling turbulent flows commonly give rise to severe problems for accurate prediction with RANS treatments. The paper has summarised progress by the CFD group at the University of Manchester of two such classes of flow. The two-component limit (TCL) second-moment closure has been found to be particularly effective in predicting the trailing swirling wake created behind the tips of wings. For the flow within rotor-stator or rotor-rotor disc cavities an unsteady RANS approach used in conjunction with a new
analytical wall-function scheme has enabled the organized vortex structures found in experiments and in DNS studies of these types of flows to be captured even though some questions remain to be resolved.

5 Acknowledgements

It is a pleasure to acknowledge the contributions of former PhD students in the group to the computations summarized above: S.E. Gant, A.V. Gerasimov, C.J. Robinson and A. Zacharos. The research has been supported the UK Engineering & Physical Sciences Research Council and by the European Union under grant MDAW-UMI-N007. Authors’ names are listed alphabetically.

References

Zacharos, A., 2009, PhD Thesis, School of Mechanical, Aerospace & Civil Eng’g, University of Manchester.