Conclusions and recommendations
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Chapter 24 – CONCLUSIONS AND RECOMMENDATIONS

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Extensive results and findings of the NATO Research and Technology Organization (RTO) Applied Vehicle Technology Panel (AVT) Task Group – 080 "Vortex Breakdown over Slander Wings" have been presented in three major categories.

The Experimental Sub-Group has compiled an extended experimental database consisting of eight test cases generated at various research institutes. Most experimental data has been obtained on models with leading-edge sweeps ranging from 55° to 80°. Most models have sharp leading edges, whereas some models were provided with elliptical or round leading edges. Static and/or dynamic data were generated in water and wind tunnels at Reynolds numbers up to 120 x 10^6 and Mach number up to 0.9. The dynamic data were obtained from tests performed on models undergoing pitch and/or roll oscillations and coning motions.

The test cases were subdivided into three categories; time-average results at static model conditions, ensemble-average results at dynamic model conditions and unsteady results at static/dynamic model conditions.

The static data provided the time-averaged model surface skin-friction-line pattern and conjectured surface flow topology, the surface pressure distribution as measured by pressure taps or Pressure Sensitive Paint (PSP), the time-averaged vortex breakdown location, three-dimensional velocity vector field measured by Laser Doppler Velocimetry (LDV) or Particle Image Velocimetry (PIV), and the forces and moments. At dynamic model conditions results are given of smoke/laser-light-sheet flow visualization, ensemble-average balance data, surface-pressure distributions (measured with unsteady pressure transducers), as well as the free and forced motion history. Unsteady results at static/dynamic model conditions include recordings of the instantaneous azimuthal vorticity, RMS swirl velocity, spectra and fluctuation of breakdown locations, pressure fluctuations on wing and tail fin, etc.

Considering the limited time, manpower and CFD capability available, it has been decided to limit the benchmark for the CFD exercise to a first category test case; a study of the time-averaged vortex behaviour at static model conditions on an ONERA 70° swept delta wing has been taken as the benchmark for the validation and verification of the CFD solutions. Although this and the other compiled test cases provide very valuable data, there still exists an imminent demand for a comprehensive experimental data set containing measurements of both the flow on and off the model surface as well as balance measurements. As vorticity flux and its unsteady behaviour in the boundary layer before its separation have a remarkable impact on the vortex and vortex breakdown, more detailed information is needed on the location of the laminar-to-turbulent transition line and – in the case of a rounded leading edge - the location of the primary separation line and separation on-set. Along with steady data, detailed unsteady surface and flowfield data also needs to be generated in order to complete the dataset on the free shear layer and vortex breakdown flow phenomenon. Moreover, as the vortex, especially its breakdown, has nonlinear response to the model motion, the spectral information, in frequency domain, and time delay or the response function, in time domain, are even challenges both in academic and real application

The CFD-subgroup has generated nine state-of-the-art solutions for the flow over the ONERA 70° swept delta wing and for some other delta wing planforms. The choice of governing equations included Euler, Reynolds-Averaged-Navier-Stokes (RANS) with and without rotation corrections, Detached Eddy Simulations (DES) and Large Eddy Simulations (LES). Both steady and unsteady solutions were computed and structured and unstructured grid solvers were used.

Euler calculations gave a relatively accurate prediction of the vortex breakdown locations, but did not capture the details of the physics of the leading-edge vortices.

Both structured and unstructured solvers demonstrate the ability to capture vortex breakdown as long as there is enough grid resolution in the vortex core and the model has sharp leading-edge. Grid-refinement studies show that a finer grid increases the core properties and turbulence levels within the vortex, whereas vortex breakdown is delayed. It is further demonstrated that adapted-grid solutions are superior in capturing the vortex flow structure over the conventional unadapted-grid solutions. High-order spatial discretization is capable of capturing finer scales of the flow field on a given mesh resolution and of resolving the origin of the so-called unsteady and stationary substructures observed in the vortex flow experiments. Time accuracy is another important parameter when computing unsteady flow phenomenon such as vortex breakdown.

Computational results demonstrate the importance of including both the sting and wind tunnel walls for validation of CFD results with the experimental data at all angles of attack. The solutions show that the local effective incidence along the leading edge increases when the sidewall moves closer to the wing. This increases the vortex helix angle and tends to promote vortex breakdown. The influence of the sidewalls on the secondary vortices was also assessed; the secondary separation line moves towards the leading edge and it's helix angle increases with decreasing tunnel width.

Downstream support structures with a large frontal area were found to have no effect on the flow prior to vortex breakdown. The blockage of the support caused a significant acceleration of the flow, which had the effect of delaying vortex breakdown. The effect of the downstream support is heavily dependent on whether or not the core flow impinges on the structure. The effects are likely to be Reynolds number dependent.

The computational results show the importance of modelling a full-span delta wing in order to accurately capture the oscillations of the vortex breakdown locations and the asymmetry in the breakdown location on the port and starboard halves of the delta wing. The interactions between the leading-edge vortices are lost when semi-span grids are used, especially, at higher angles of attack.

Calculations were performed for the case of a semi-span wing with a symmetry condition in the center section of the wing and for the case of a full wing without such a symmetry condition. Without a symmetry condition, even for symmetrical free stream conditions the flow field turned out to be unsymmetrical: different vortex breakdown positions, frequencies and phase differences in the rotation of the spiral vortex axes and modifications of the vortex axes were found for both sides of the wing.

The calculations were performed using a wide variety of turbulence models. The type of turbulence model applied has a significant effect on both the characteristics of the vortical flow field and the vortex breakdown location. Dissipation of turbulent kinetic energy and vorticity drastically alter the flow field characteristics. Rotational corrections have a significant impact on the computational solutions. DES is capable of predicating the fluctuating vortex breakdown location quite accurately

Transition from laminar to turbulent flow is a key aspect in defining the characteristics of the vortical flow field. Transition occurs over the surface of the delta wing, but also within the vortex core. At this time, there is no reliable method of computationally identifying transition. It can be artificially forced within the computations in order to more closely match the

The Analytical-subgroup has examined three analytical methods.

An engineering method predicts the structure and behavior of the vortex in its broken down state. The dynamics of the inner and outer core regions are treated separately. The breakdown process was modelled as a symmetry-breaking sub critical bifurcation from an axisymmetrical unburst vortex to a helically symmetric translating spiral burst form. Predictions agreed reasonable well with measured helix pitch, inclination, radius, induced and convection velocity, and frequency content. To predict the impact of vortex breakdown on the delta wing characteristics, a simple lift-loss model was developed. Predictions for the magnitude and the rate of onset of breakdown-induced lift loss agree with experimental data.

A modified Non-linear Indicial Response Functional model in conjunction with Internal State-Space representation method (NIRISS) uses the time-averaged vortex breakdown location as an internal variable to approximately describe the state of separated and vortex flow over the delta wing. The mathematical model was applied to estimate time-averaged vortex breakdown locations, normal force over delta wings with different sweep back angles, surface pressures and free-to-roll motion histories on a 65° delta wing. The comparisons between measured and estimated data showed that within the framework of the proposed mathematical model, it is possible to apply this method to predict quantities in the nonlinear flight regime.

An empirical method predicts the forces and moments on delta-wing/body (and other) configurations in symmetric and asymmetric flights, including Mach and Reynolds number effects. The method is based on subsonic lifting surface theory, semi-empirical “attained” thrust and vortex effects and coupled with a model to predict vortex breakdown. Predictions for the forces and moments of 53^o and 58^o swept trapezium wings, with and without sideslip, for various Mach and Reynolds numbers showed a promising correlation with available experimental data.