CFD Prediction of stability derivatives of a turboprop aircraft using a Cartesian grid based Euler code

G. Waller
Bombardier Aerospace
Downsview, Ontario, M3K 1Y5
email: gwaller@dehavilland.ca

Abstract

Aircraft stability and control derivative estimation has traditionally relied on wind-tunnel testing and data sheets. Computational fluid dynamic methods have now developed to a point where they can represent most of the flow physics over the flight envelope. CFD methods can be used, therefore, to get a better understanding of the aircraft stability and control derivatives earlier in an aircraft design program.

To validate the 3-D Euler code predictions, it was decided to use the wind-tunnel data base for the DASH 8 Series 400 regional turbo-prop aircraft. The low speed wind-tunnel model was tested with powered pro-pellers in both high lift and cruise configuration. Computational results are shown to agree reasonably well with experiment.

1 Introduction

Computational fluid dynamic (CFD) methods have developed to a point where complete aircraft configurations, including powerplants, can be modelled so that predictions of aircraft stability derivatives are possible. At Bombardier Aerospace CFD codes have been used for analysis of particular stability issues arising from wind-tunnel or flight testing but a systematic study of stability derivative prediction over the full incidence, sideslip and power setting range of a typical aircraft certification wind-tunnel program has not been done.

The DASH 8 Series 400 turbo-prop certification programme was chosen as the datum for a systematic study of longitudinal, lateral and directional stability and control derivative prediction because of the comprehensive range of data available from wind-tunnel testing and an aircraft response program validated against flight test data.

The CFD code used was MGAERO[1], a finite-difference Euler code which uses Cartesian grids, developed by IAI and marketed by Analytical Methods Incorporated of Redmond, Washington.

2 Description of wind-tunnel model

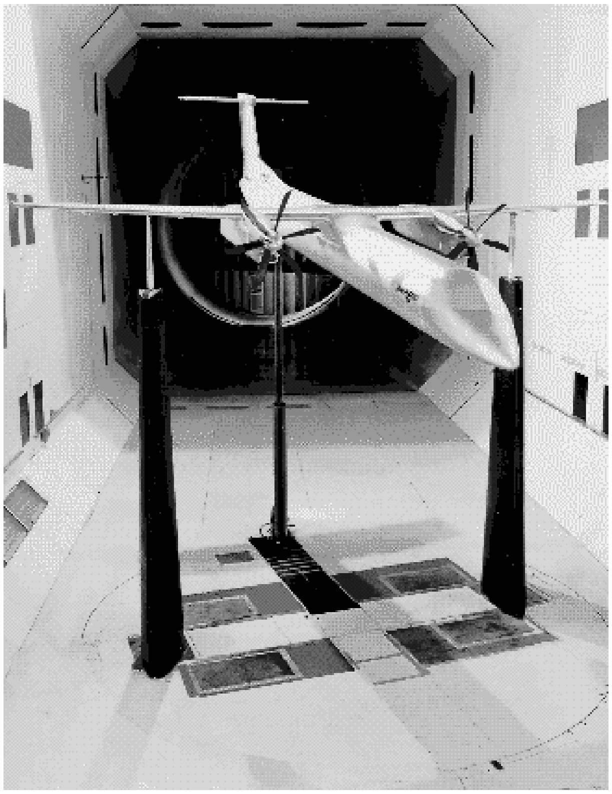

Figure 1 DASH 8 Series 400 Low Speed Wind-Tunnel Model (WTDK-7)

The wind tunnel model used for certification of the de Havilland Dash 8 Series 400 aircraft was a ¼ scale model tested in the IAR 9 meter windtunnel in 1996. The model was fully representative of the production aircraft, including control and high-lift surfaces and powered propulsion as shown in Figure 1.

The model was mounted from two columns in line with the wing quarter MAC, outboard of the nacelles. Angle of attack was controlled by a hydraulic strut which penetrates the rear fuselage just at the start of the fuselage upsweep. Sideslip angle was controlled by the orientation of the turntable on which the model was mounted.

The relationship of the wing, nacelles and T-tail is shown in Figure 2. The unidirectional rotation of the propellers was clockwise, viewed from the rear. The propellers were scale models of the Dowty Type R408H with 6 blades.

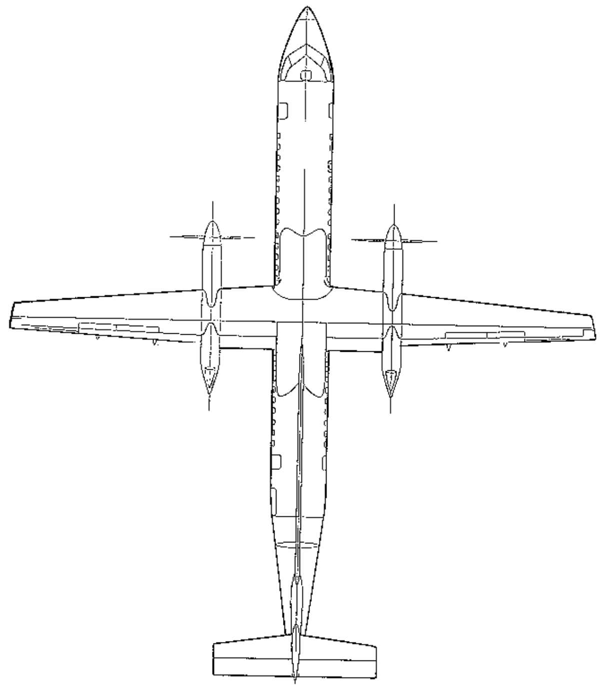

Figure 2 DASH 8 Series 400 Planform

The wind-tunnel model was tested at low-speed, around 100 knots. The results used for this study were limited to an incidence range from –10 degrees to +20 degrees and propeller thrust coefficients for both propellers, based on aircraft wing planform area, from 0.1 to 1.5.

3 MGAERO computational method

The MGAERO Euler code is the standard production program used by the Flight Sciences department at Bombardier Aerospace, Toronto, for aircraft design and analysis. The advantage of MGAERO over Euler codes with body-fitted grids is the ease with which the gridding task is accomplished. This is especially useful when analysing the effects of small geometrical changes, as changes to the grid are minimal. The positions of the fine grid levels used for the WTDK-7 simulation are shown in Figure 3.

The full aircraft is represented in MGAERO i.e. port and starboard sides, as the propeller flow is not symmetrical about the centre-line. The total number of grid nodes was 935000, in 7 multi-grid levels. The total solution time was 4.5 hours on an SGI Origin 200 machine.

A typical solution is shown in Figure 4

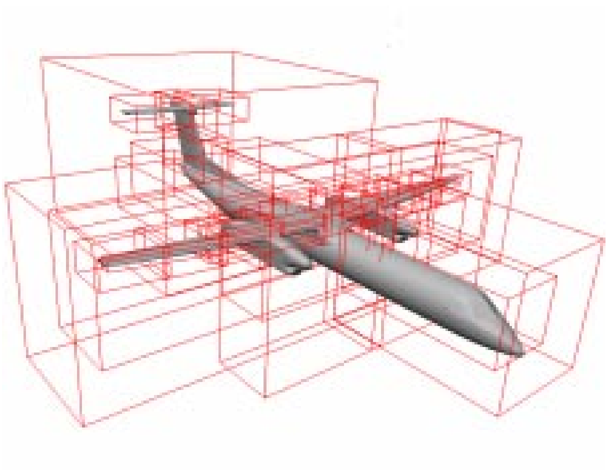

Figure 3 MGAERO Cartesian grids

Figure 4 Surface displacement thickness

The propeller slipstream is represented by an actuator disc model which requires the propeller mass flow, swirl velocity, total pressure, total temperature and Mach number. The propeller flow conditions were obtained by matching Dowty Aerospace propeller strip analysis code results with the specified wind-tunnel propeller model RPM, blade setting and thrust coefficient.

The Reynolds number of the test varied from 1.2 to 2.8 million based on mean aerodynamic chord, so viscous effects are significant. The boundary layer effects in MGAERO are represented by tracing surface streamlines and using the 2-D semi-inverse boundary layer routine of East [2] and Green [3] to calculate the displacement thickness. The boundary layer thickness is then represented in MGAERO by surface transpiration.

The effect of the propeller swirl on the surface streamlines is clearly visible on the wing and fuselage. The colour spectrum shows the displacement thickness

4 Longitudinal static stability results

The initial study was limited to longitudinal characteristics only. The incidence range was from –10 to 20 degrees and thrust coefficients C_T (based on wing reference area) for two engines from 0.1 to 1.5.

Fully converged inviscid solutions are obtained with MGAERO before the viscous coupled iterations are performed, Inviscid/viscous coupling convergence is somewhat compromised when power effects are modelled.Examination of the results showed that the problem was originating on the wing lower surface at high thrust coefficients. The pressure disributions, Figure 5, show a two regions of high positive pressure due to the propeller upwash, one at the leading-edge of the section and the other in the cove.

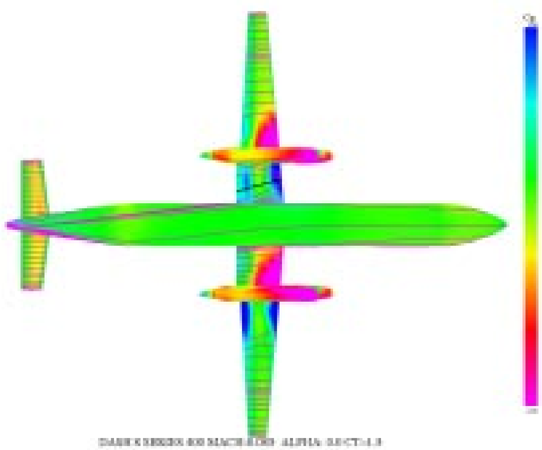

Figure 5 Cp distribution CT:1.5 alpha:0.0 M:0.08 on the under surface

The pressure and shape factor (H) distribution along the streamline on the inboard, starboard wing shown in black, is given in Figure 6

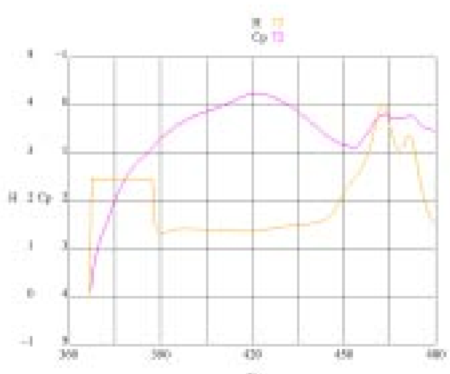

Figure 6 Lower wing pressure(Cp) and shape factor (H) distribution

.The shape factor over 3 indicates flow separation in the cove on the starboard wing. The pressures on the port wing are even higher, so that extensive separations were probably present. The boundary layer routines, however, failed due to the high pressure gradients so MGAERO did not model these separated flow regions properly.

The lift curve predictions are summarised in Figure 7 .

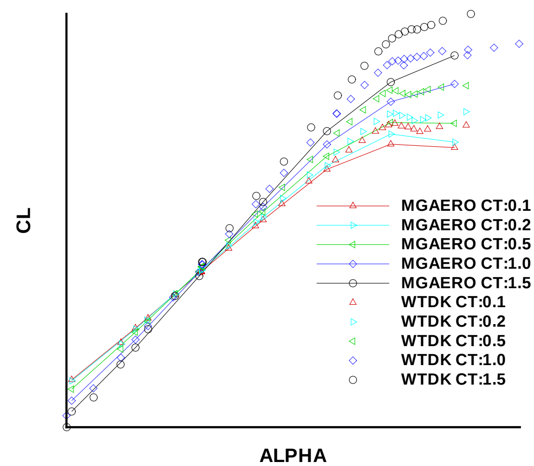

Figure 7 MGAERO lift curve predictions

The MGAERO results at low thrust coefficient match the experimental lifts quite well but show a slightly lower C_{LMAX}. This is probably not a function of the viscous boundary layer corrections, but due to spurious entropy generated by the use of Cartesian grids. Using a finer grid would probably reduce the numerical dissipation and cause C_{LMAX} to increase.

The results at higher thrust settings progressively underpredict lift. The wind-tunnel measured lift coefficient includes the direct thrust terms i.e. the propulsion system was on the live side of the balance and the forces were not corrected from isolated nacelle/propeller tests. The direct thrust term, C_T*SIN(ALPHA), was added to the MGAERO results but the lift from the actual propeller disc was not represented at all in the computational model.

The comparison of the predicted and measured pitching moment coefficients about the wing quarter mean aerodynamic chord (1/4 MAC) is shown in Figure 8.

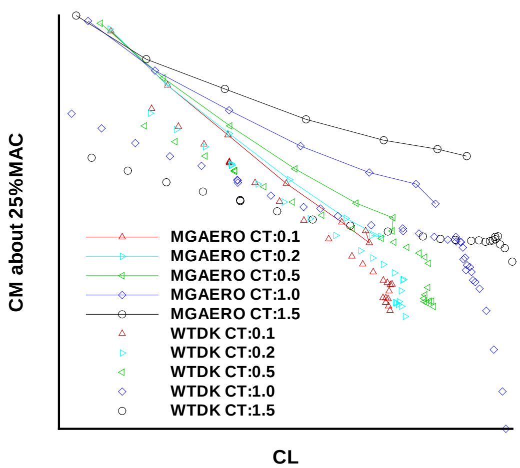

Figure 8 MGAERO pitching moment predictions

The predicted pitching moments include direct thrust effects, but not off-axis forces amd moments from the propeller. The agreement in slope and magnitude of the pitching moments is reasonable at low power settings. As power is increased, however, the MGAERO predictions show significantly more positive, or nose-up, pitching moment compared to experimental results.

The effect of not including the off-axis propeller forces in MGAERO should be to modify the slope of the C_m/C_L curve, making it more stable than the experiment. This is not evident in the plot, the curves are somewhat parallel. The other difference between the experiment and computation is the prediction of separation on the wing lower surface, which is washed by the propeller wake, at high power settings. This might affect the turning of the propeller wake by the wing and hence the downwash at the tail.

The tail downwash was calculated for both the experimental and computational results by plotting the difference between the tail-on and tail-off pitching moments against aircraft incidence. Then, at any particular aircraft incidence, the difference in pitching moment is due to the empennage, so that a plot of tail-alone pitching moment against angle of attack can be used to derive an equivalent angle of attack at the tailplane. The difference between the aircraft incidence and the equivalent tail-alone angle of attack is taken to be the tail downwash.

A comparison of the tail downwash derived from MGAERO and wind-tunnel data is shown in Figure 9

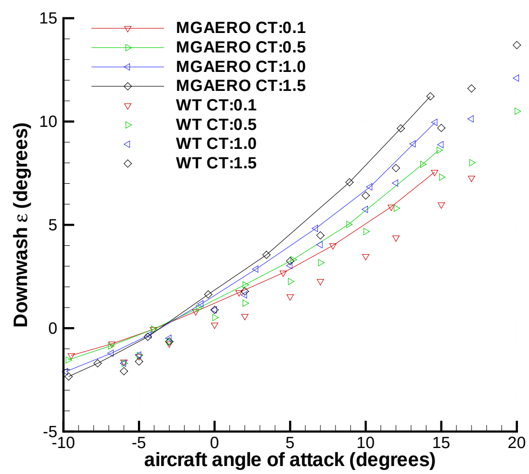

Figure 9 Comparison of estimated downwash at the tail

The downwash comparison shows a surprisingly consistent increase in downwash for the MGAERO predictions, almost independent of power setting, compared to experiment. The agreement between experiment and computation is within 1-2 degrees.

5 Damping derivative predictions

The estimation of dynamic or damping derivatives for use in aircraft dynamic response models to match flight test results is normally done using data sheet methods. A utility was added to MGAERO to estimate quasi-steady dynamic derivatives, so that estimates could be obtained quickly for complex aircraft configurations.

The MGAERO grid/surface intersection boundary conditions specify either zero flow normal to the surface or impose a transpiration velocity derived from the rate of growth of the boundary layer displacement thickness. To represent constant rate manoeuvers, the normal velocity to the surface at each grid intersection point due to the angular rates is imposed as a boundary condition.

To check the MGAERO damping derivative utility a NACA0012, aspect ratio 8 untapered wing was simulated with a non-dimensional roll rate of 0.1 (roll rate * semispan / freestream velocity). The predicted roll damping coefficient is compared with a lifting line estimate at freestream Mach number M= 0.2, 0.6 and 0.78 in Figure 10.

The predictions agree well in terms of trend with lifting line theory but overpredict the numerical values by 15%. This is similar to the results obtained by F. Fortin [4] using an unstructured Euler flow solver (FJ3SOLV).

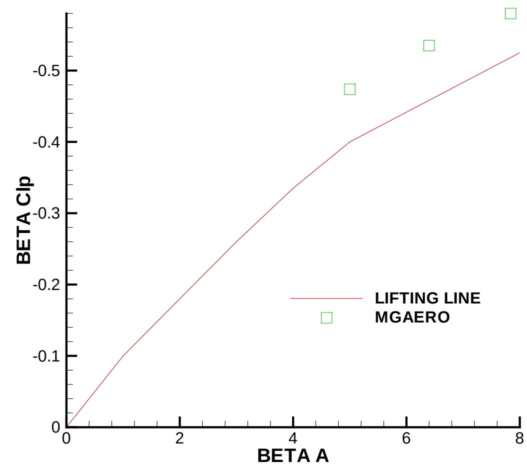

Figure 10 Comparison of roll damping coefficient with lifting line theory

The DASH 8 Series 400 configuration was run at cruise with a roll rate of 20 degrees/second. The predicted roll damping coefficient was C_{lp}= -0.65. The value used to match the flight test data for the lfight dynamics model of the aircraft was C_{ln}= -0.5

Figure 11 DASH 8 400 pressure distribution at 20 deg/sec roll rate M:0.58

6 Conclusions

The Cartesian grid, multigrid Euler code MGAERO was used to predict the longitudinal stability derivatives of the deHavilland DASH 8 Series 400 turboprop aircraft and compare the results with measured wind-tunnel data.

Predictions of lift and pitching moment were found to agree fairly closely with measurement at low power settings. The stall was slightly underpredicted, probably due to using too coarse grids for a complete, non-symmetric aircraft configuration.

At high power settings lift was underpredicted and pitching moment was more nose-up than the wind-tunnel data. Two factors contributed to this; the off-axis forces and moments of the propeller were not represented in the MGAERO model and flow separations on the lower wing surface were not captured by the MGAERO boundary layer model.

The predicted downwash at the tail was consistently overpredicted by MGAERO although the trends and power effects were close to the experimentally derived values.

Roll damping magnitude estimates were higher than those derived from lifting line theory or from matching flight test results. The detailed physical model represented by the MGAERO Euler code, however, suggests that dynamic derivatives should be at least as accurate as those derived from data sheet methods.

Further work involving grid sensitivty, investigation of slipstream effects on the boundary layer and off-axis forces and moments will be pursued.

7 References

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[3] East, L.F., Smith P.D. and Merryman P.J., ”Prediction of the development of separated turbulent boundary layers by the lag-entrainment method”, RAE Technical Report 77046, 1977

[4] Fortin F., “Unsteady Euler techniques for moving body problems: a comparitive study”, *8th CASI Aerodynamics Symposium* pp. 37-46, Toronto, Canada, April 29-May 2, 2001