Effect of Asymmetric Propeller Thrust on Aircraft with Rudder Deflection: A CFD Perspective

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Abstract

Aerodynamic analysis of aircraft configurations at different asymmetric propeller thrust settings, with different rudder deflections each, are carried out in the present work. The aim is to find the available restoring moment at each rudder deflection and subsequently rudder deflection required to achieve trim condition with each asymmetric thrust setting. The open source multi-physics Partial Differential Equations (PDE) solver suite, Stanford University Unstructured (SU^2), is used in the current study with actuator disc capability.

Key words: Aerodynamic analysis, Actuator disc model, Asymmetric trust, One-engine-inoperative, ROE scheme, Second order, Open source, SU^2.

1 Introduction

One-engine-inoperative flight test (FAA, Section 91.611) is a vital test case for certification of aircraft having more than one engine. In such a scenario the aircraft should be controlled with rudder deflection. Similar situation may also arise during engine relight, or when one engine can only deliver partial thrust due to certain conditions prevailing during flight, like unable to run at full thrust due to engine oil temperature increase, propeller problem, etc. The flight tests for such scenarios are very critical & dangerous and must be carried out with utmost care by experienced pilots. Hence designers resort to use CFD simulations to convince certifying agencies to get approval for such flight tests. Now, in the present work few such scenarios are simulated with CFD to find the rudder deflection required to generate adequate restoring moment to trim a typical turbo-prop transport aircraft. The open source software suite, SU^2, is employed for simulation purpose. Actuator disc module of SU^2 suite is used to simulate propeller effects at few asymmetric thrust settings with different rudder deflection angles each. The restoring moment available at each case is calculated and the rudder deflection required for trimming the aircraft is predicted.

2 SU^2 Solver

The Stanford University Unstructured (SU^2) software suite is a multi-physics PDE solver based on cell volume Finite Volume Method (FVM) approach along with integrated PDE constrained optimizer based on adjoint methods [1]. The solver is very well verified & validated for compressible, 2-D & 3-D turbulent flows over wide range of Mach numbers relating to aerospace engineering [2]. SU^2 solver was used for aerodynamic shape optimization of large scale trisonic aircraft, the NASA CRM, with the continuous adjoint methodology available in SU^2 suit [3].

3 Computational grid

Unstructured grids on aircraft configurations are generated using the commercial tool, Pointwise V18.0R3 [4]. A total of 7 configurations are considered with different rudder deflection angles. Initially the surface grid on rudder is generated at 0^o deflection angle along with remaining surfaces and then the rudder surface grid at other deflections angles are generated automatically by using the glyph capability of Pointwise. Once the surface grid is ready, generation of volume grid needs minimum manual intervention.

Figure 1 shows the surface grid on rudder at 0^o deflection angle along with geometric model of rudder at 25^o deflection. A slice of volume mesh of vertical tail is also given, which shows the grid generated in the gap between vertical tail & rudder and rudder & trim tab along with prism layers in wall normal direction to resolve boundary layer.

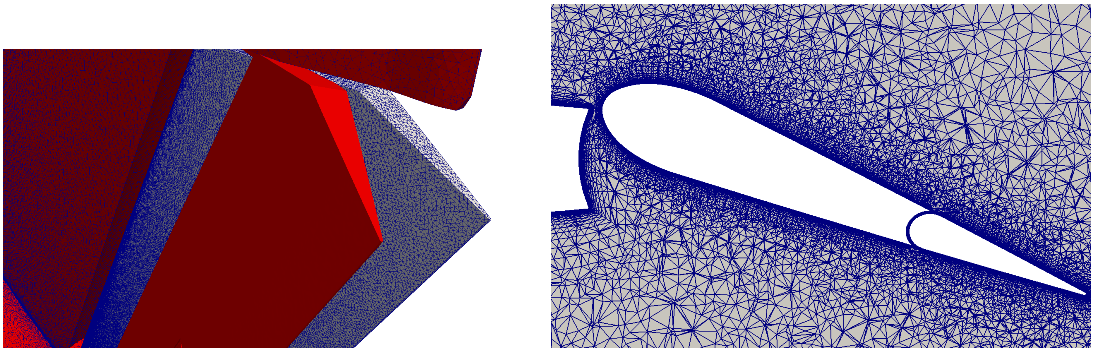

Figure 1: Surface mesh on rudder at 0^o deflection angle along with rudder at 25^o deflection in solid colour and a slice of volume mesh near vertical tail

4 Problem set-up

Steady Reynolds Averaged Navier Stokes(RANS) solver of SU^2 with Spalart-Allmaras (SA) turbulence closure scheme is used for the current study. Governing equations are discretized using finite volume method . The convective fluxes are discretized using Roe scheme with second order limiter method and for time integration, first order accurate Euler implicit method is used. Multi-grid capability is used for convergence acceleration with 2 level V-cycle option. Differential pressure and temperature corresponding to various propeller thrust are prescribed as a boundary condition (actuator disc with variable jump option) to simulate the effect of propellers.

5 Test conditions and cases

A total of 5 thrust settings are considered in the present study as shown in Table 1, with 4 cases of asymmetry in the engine torque between LH & RH sides. And case of zero torque on both LH & RH sides $(Test\ case\ No.:\ V)$ is also considered for reference purpose. RANS simulations are performed with deflected rudder at angles in steps of 5 degrees for each case of above thrust setting.

Simulations are carried out at an angle of attack of 7^o with free-stream Mach number of 0.21, Reynolds number of 8.0 million and a free-stream temperature of 287.15 Kelvin.

Table 1: Test matrix

Case Set	LH Torque (%)	RH Torque (%)	Degree of asymmetry (%)
I	100	0	100
II	100	20	80
III	100	40	60
IV	100	60	40
V	0	0	0

6 Results and discussion

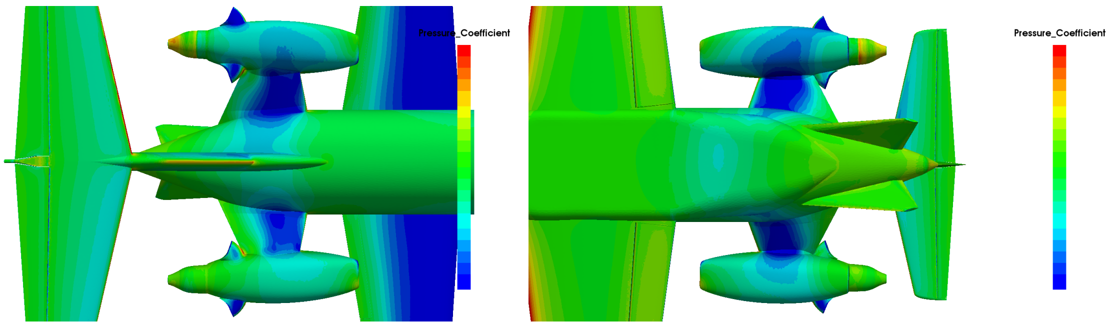

Figure 2: Surface pressure distribution with zero rudder deflection and with 100% torque on left propeller & zero torque on right propeller in top view (left) and bottom view (right)

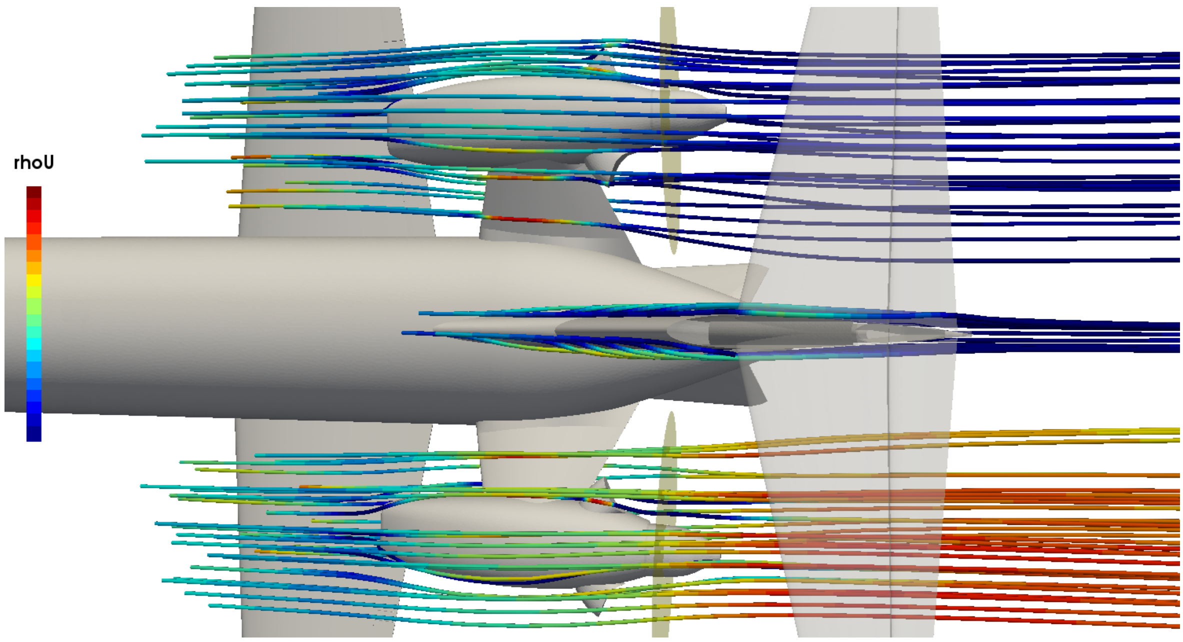

Figure 3: Volume streamlines with zero rudder deflection and with 100% torque on left propeller & zero torque on right propeller

The surface pressure distribution near nacelle and stubwing is shown in top & bottom views in Figure 2 for *Test case I*, with LH and RH propellers set at respectively full and zero torque without any rudder deflection. The asymmetry can be seen very clearly in C_p contours between LH & RH sides. More suction region is seen on LH side stubwing & nacelle ahead of propeller compared to RH side since LH propeller is running with full torque. Extent of suction region is even more on LH lower surface of nacelle compared to LH upper surface. This asymmetry produces net aerodynamic moment about $Z-axis$ i.e. yawing moment, which should be balanced by producing restoring moment through rudder deflection. The volumetric streamlines near stubwing, nacelle and empanage are shown in Figure 3, which clearly shows the smooth conversion of imparted momentum by propeller torque in to fluid acceleration in the disc normal direction can be seen very clearly as the stream lines are coloured with streamwise velocity. Being the LH propeller is in 100% torque setting the near by fluid acceleration is maximum, where as on RH side fluid slightly accelerated on nacelle surface and then retarded because that propeller is in 0% torque setting.

Figure 4 gives the C_p distribution on upper surface of stubwing and nacelle in left half and that of on lower surface in right half for $Test\ case\ I$ at a rudder deflection angle of 25^o. It is evident that the asymmetry in pressure distribution between LH & RH sides is very minimum than that of zero rudder deflection as shown in Figure 2. This suggests that the rudder deflection required for trim condition is nearer to 25^o. Figure 5 shows the volumetric streamlines for this case, where the turning of stream lines due to rudder deflection can be seen clearly.

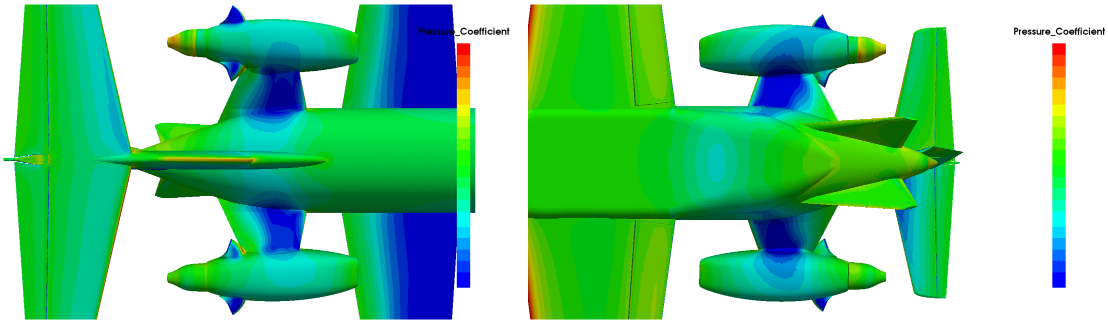

Figure 4: Surface pressure distribution with a rudder deflection of 25 degrees and with 100% torque on left propeller & zero torque on right propeller in top view (left) and bottom view (right)

Actuator disc model of SU^2 solver is able to apply jump in pressure with a little deviation of $\pm 1 - 2\%$ per iteration with an average corresponds to the specified thrust in all the cases. Hence all the integrated quantities are taken by averaging over last 1000 iterations.

The aerodynamic restoring moment (C_{M_z}) available with each rudder deflection of each test case are plotted against the rudder deflection angle in Figure 6 with solid lines. The variation is almost linear in the range considered and the lines are almost parallel to each other. At a given rudder deflection, $case\ I$ is producing minimum aerodynamic restoring moment and $case\ V$ is producing maximum with almost zero at no rudder deflection. The reason behind reduction of restoring moment is due to variation in fluid velocities on the either side of vertical tail, which increases with degree of asymmetry. The more variation in fluid velocities results in more drop in pressure difference then there is more reduction in restoring moment available. The dashed lines shows the moment being produced due to asymmetric thrust between propellers alone, which is maximum for $case\ I$, being the case with maximum degree of asymmetry. The point of intersection of solid lines and dashed lines gives the trim position of rudder, where the net moment is zero. The rudder deflection required for trim condition increases with degree of asymmetry as expected.

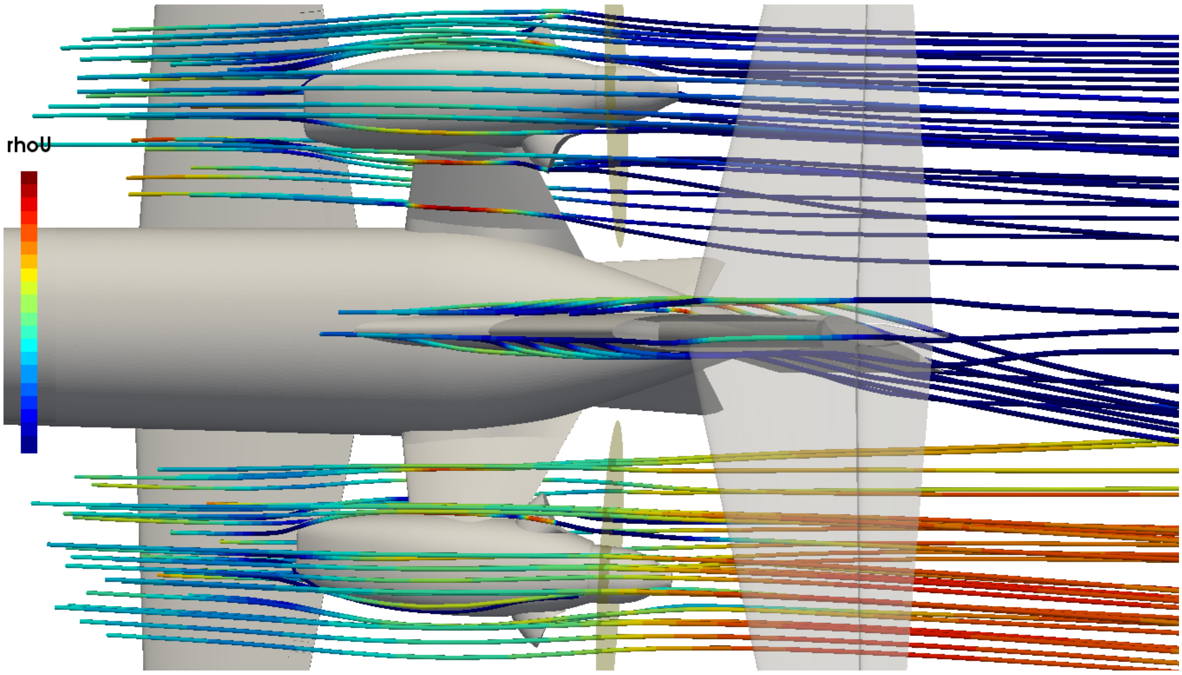

Figure 5: Volume streamlines with a rudder deflection of 25 degrees and with 100% torque on left propeller & zero torque on right propeller

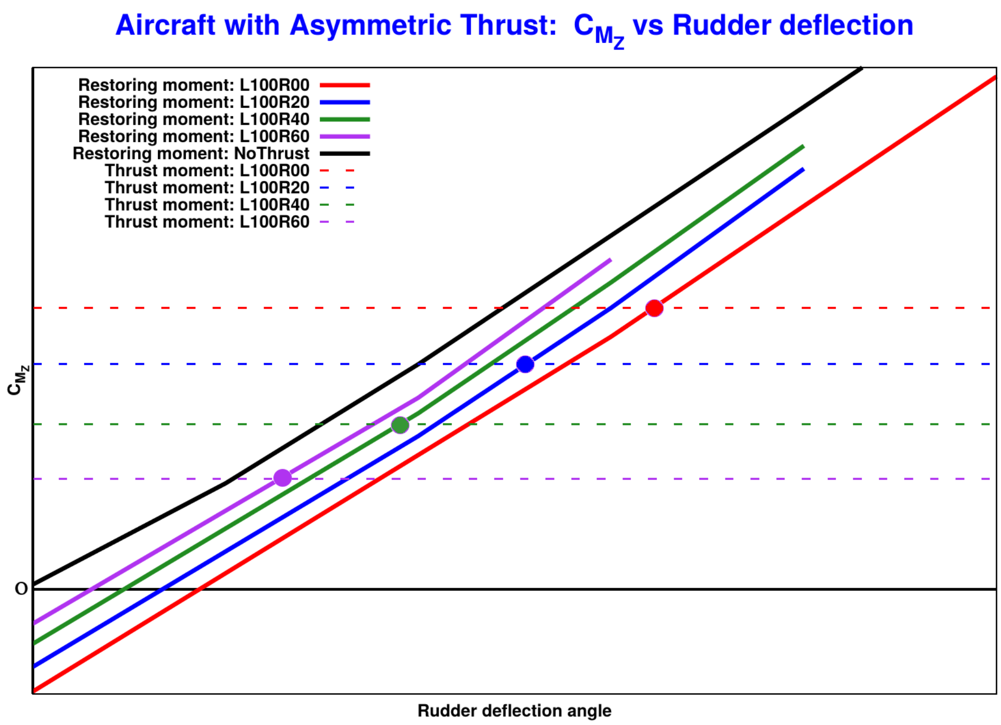

Figure 6: Variation of C_{M_z} against rudder deflection angle at different thrust settings

7 Conclusions

Aerodynamic analysis of aircraft with different asymmetric thrust settings between LH & RH propellers at different rudder angles is preformed successfully with SU^2, CFD tool by using actuator disc capability. These simulations are challenging as fine grids are required with rudder deflections and the asymmetric power has implications for convergence. The main observations are as follows:

- There is smooth variation in fluid velocity across the actuator disc in normal direction
- For a given asymmetry in thrust, the variation in available restoring moment is almost linear with rudder deflection angle in the range considered and the slope is almost constant for any symmetric thrust setting
- At a given rudder deflection angle, more asymmetric thrust produces less restoring moment. This is an indirect aerodynamic effect which has been captured in this study.
- The rudder deflection required for trim condition increases with degree of asymmetry. The variation is non-linear due to the indirect aerodynamic power effect.

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