Intake Lip separation control using Plasma Actuators

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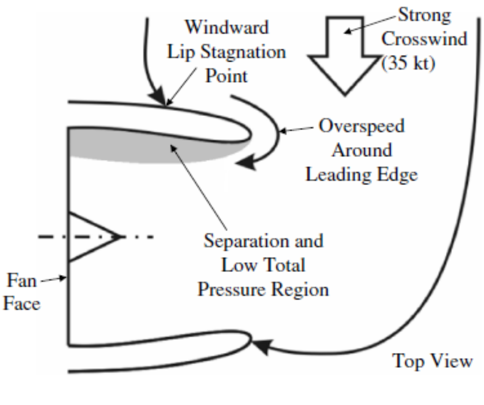
Long Abstract

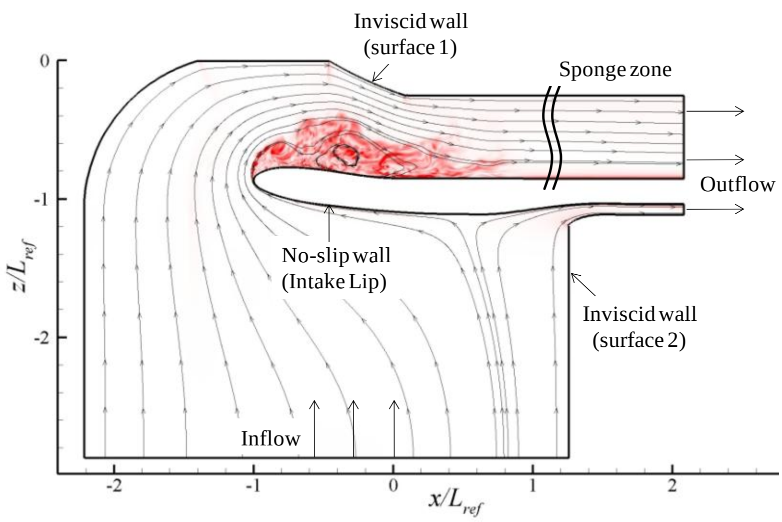
Introduction

The next-generation aircraft engines operate at a high bypass and low fan pressure ratios. Such modern architectures will have the key benefits of improving the fuel burn and reducing the emissions and noise. With increasing bypass ratio, the diameter of the engine inlet increases and shorter intakes (with as small an outer diameter as possible) are required to compensate for the subsequent increase in the weight and drag. However, the sharper lips of shorter intakes have a reduced incidence tolerance and the flow is prone to: rapid acceleration around the intake lip, relaminarization, flow separation and transition to turbulence specifically under off-design conditions like high incidence/crosswinds (see Figure 1(a)).

The current study aims to capture the flow separation over the intake-lip under crosswinds using eddy resolving simulations. Subsequently, the effect of plasma flow control will be investigated. These devices can either induce additional disturbances or inject momentum into the separated shear layer depending on their orientation. It helps in suppressing separation thereby improving the performance of the intakes.



(a)



(b)

Figure 1: a) Schematic showing typical off-design crosswind condition [1] b) Computational domain and boundary conditions (contour of vorticity magnitude and streamlines are shown to highlight the separated region around the intake lip)

1. Computational Domain and Numerical Methodology

Figure 1(b) shows the computational domain used in the current simulations, which is in accordance with the low-speed experiments performed by Wakelam et. al. [1]. Surfaces 1 and 2 are inviscid and are solely meant to impose a pressure distribution over the intake lip, thereby minimizing the grid requirements in these regions. Spanwise width of around 20% of the lip length is chosen for the simulations, which is long enough to accommodate all the dominant flow features formed during the flow transitioning to turbulence. A sponge zone is specified at the exit to damp out the vortical disturbances exiting, and the acoustic waves reflected from the domain exit. It should be noted that the vortex generating jets (VGJs) were employed in the experiments to suppress separation over an annular intake sector [1]. However, the current simulations were carried out on an extruded intake section (unlike an annular sector) using plasma flow control.

Simulations are performed using an in-house high-order structured code, COMP-SQUARE. Three dimensional compressible Navier-Stokes equations are solved in generalized curvilinear coordinate system. Fourth order compact finite-difference schemes are used to spatially discretize the inviscid, viscous fluxes and the metric terms. Time integration is carried out using an explicit four-stage fourth order Runge-Kutta (RK) scheme. The numerical instabilities arising due to the non-dissipative nature of the high-order compact schemes are eliminated by filtering the conservative variables. For this purpose, 8^{th} order low pass Pade-type non-dispersive filter is employed at each RK stage. The code utilizes MPI message passing system for parallelization on distributed memory platforms. Mach number and Reynolds number are set to 0.11 and 10^5 respectively. Reynolds number is based on the fan-face diameter and the simulated crosswind speed. Around 12M nodes were used for the coarse mesh simulations discussed in this abstract.

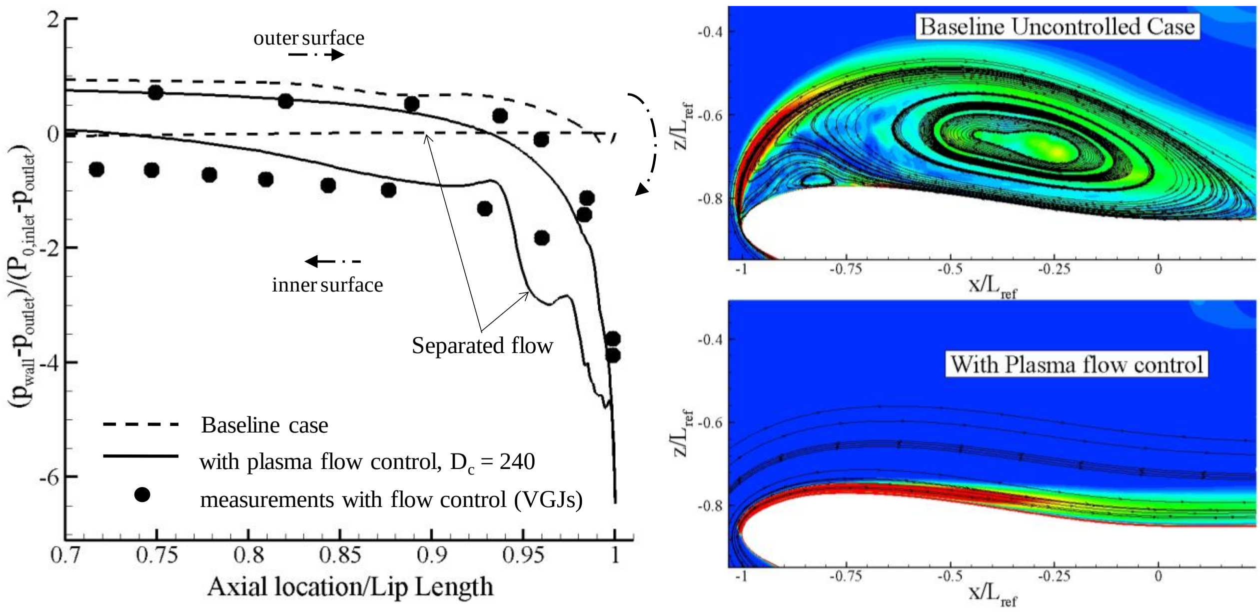
Following Rizetta et. al. [2], the effect of plasma actuator for the test cases with flow control is replicated using an empirical approach. In this model (originally proposed by Shyy *et al*. [3]), a linear body force term given by $D_c q_c \boldsymbol{S}$ is added to the momentum and energy equations. Here, D_c is a dimensionless number representing the ratio of electrical to inertial forces, q_c is the charge density, $\boldsymbol{S} = \{0, E_x, E_y, E_z, uE_x+vE_y+wE_z\}$ is the source vector where $\boldsymbol{E} = (E_x, E_y, E_z)$ and $\boldsymbol{U} = \{u, v, w\}$ are the non-dimensional electric and velocity field vectors respectively. This model has been successfully applied to the flow control on wings, high-lift aerofoils and cavities (see Rizetta et. al. [2] and Gaitonde et. al [4])

2. Results

Figure 2(a) compares the non-dimensional pressure distribution over an intake lip for both the baseline and controlled cases. The arrows indicate the direction of the flow. Figure 2(b) shows the corresponding contours of the time-averaged vorticity magnitude with streamlines overlaid. It is evident from the plots that the flow is largely separated over the intake lip for the uncontrolled case. This is also manifested as a plateau in the pressure distribution. The extent of separation has been effectively suppressed using plasma flow control (with D_C = 240) resulting in a rapid pressure recovery. However, a small separation is still evident between x/L = 0.94-0.98.

For the controlled case, comparisons against the measurements of Wakelam *et al* [1] are also shown in the figure. Although the results agree favourably with the measurements; discrepancies can be spotted in the pressure distribution over the inner surface of the intake. As reported in the previous section, this discrepancy is attributed to the differences in the modelling strategy employed in the simulations when compared to the experiments; the intake being modelled as an extruded 2D strip with plasma flow control rather than as an annular sector with VGJs.

Figures 3(a) and 3(b) compare the iso-surfaces of *Q* contoured with axial velocity for both the cases. Since the plasma has been operated in a co-flow mode (i.e. the plasma force and the flow are in the same direction) a high speed jet is generated close to the wall. The additional momentum induced by the wall-jet has effectively eliminated the separation.



(a) (b)

Figure 2: (a) Non-dimensional pressure distribution over the intake lip (b) Contours of vorticity magnitude for the baseline case and with plasma actuator, D_c = 240

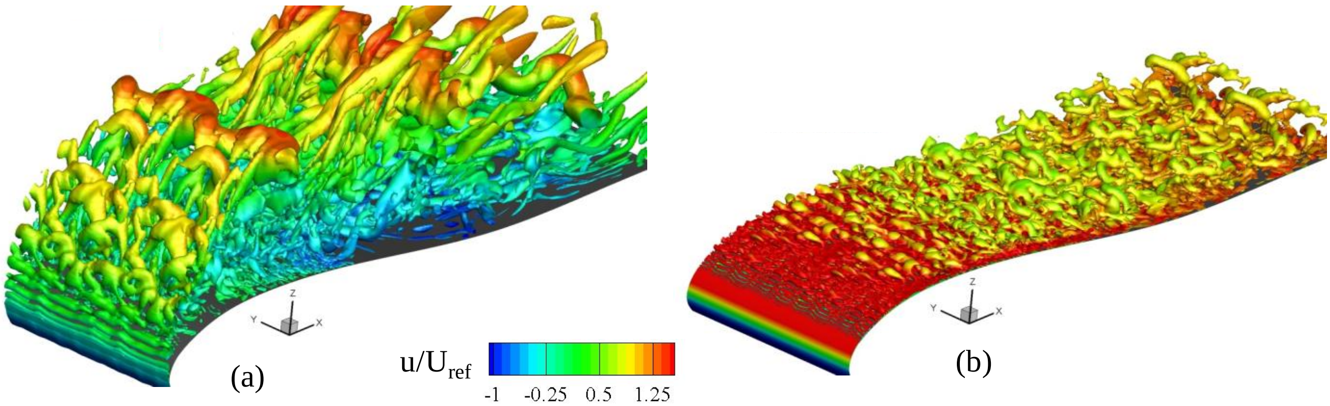


Figure 3: Iso-surfaces of Q contoured with axial velocity a) for the baseline case and b) with plasma actuator, D_c = 240

Following Rizetta *et. al.* [2] and Gaitonde *et. al.* [4], the effectiveness of the pulsed mode and counter-flow actuation of plasmas in suppressing the separation over intakes is also under investigation. Detailed comparison of the skin friction coefficient, Reynolds stresses, etc will be presented at the conference.

References

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[2] Rizzetta, D. P., Visbal, M. R., & Morgan, P. E. (2008) “A high-order compact finite-difference scheme for large-eddy simulation of active flow control,” Progress in Aerospace Sciences, 44(6), 397-426.

[3] Shyy, W., Jayaraman, B., & Andersson, A. (2002) “Modelling of glow discharge-induced fluid dynamics, ” Journal of applied physics, 92(11), 6434-6443.

[4] Gaitonde, D. V., Visbal, M. R., & Roy, S. (2005), “Control of flow past a wing section with plasma-based body forces,” AIAA paper, 2005-5302.