Microelectrical Mechanical Systems Flow Control Used to Manage Engine Face Distortion in Compact Inlet Systems

Turbofan engine-face flow distortion is one of the most troublesome and least understood problems for designers of modern engine inlet systems (refs. 1 and 2). One concern is that there are numerous sources of flow-field distortion that are ingested by the inlet or generated within the inlet duct itself. Among these are (1) flow separation at the cowl lip during in-flight maneuvering, (2) flow separation on the compression surfaces due to shock-wave/boundary layer interactions, (3) spillage of the fuselage boundary layer into the inlet duct, (4) ingestion of aircraft vortices and wakes emanating from upstream disturbances, and (5) strong secondary flow gradients and flow separation induced by wall curvature within the inlet duct itself. Most developing aircraft (including the B70, F-111, F-14, Mig-25, Tornado, and Airbus A300) have experienced one or more of these types of problems, particularly at high Mach numbers and/or extreme maneuver conditions when flow distortion at the engine face exceeded the allowable limits of the engine.

Using vane vortex generators to "locally" control the effects of separation has been the most common method of flow control in inlet ducts. Low- and high-momentum regions are mixed locally in the flow to effectively spread out the lower momentum fluid and suppress flow separation from the wall. However, in advanced, inlet serpentine S-duct configurations, this method often does not achieve significant control and reduction in engine face distortion. Furthermore, locally used vortex generators can control separation at one flow condition only (usually the cruise condition)--all other flow conditions are off-design.

In this study at the NASA Lewis Research Center, vortex generators were used in an entirely different manner. They were used to "globally" restructure secondary flow to increase inlet total pressure recovery and decrease engine face distortion (as first proposed in refs. 3 and 4). Such vortex generator installations can be optimized for optimum system levels of the inlet total pressure recovery and engine face distortion level over a wide range of inlet operating conditions. Thus, flow separation is not prevented unless this improves the overall inlet system as measured by engine face flow characteristics. With this global method, computational fluid dynamics (CFD) and design of experiments (DOE) optimization procedures can be used to design vortex generator installations that encompass a wide variety of inlet operating conditions.

Work done under the NASA/MOD cooperative Joint Aeronautical Program (refs. 5 and 6) led to an equivalency-of-flow principle: It does not matter how vorticity is produced; all that matters is the overall vorticity strength and distribution and how it interacts with the inlet secondary flow field. Consequently, inlet flow-control research shifted from concerns for vane generator geometry and preventing flow separation to establishing the proper overall vorticity signature to maximize inlet total pressure recovery and minimize engine face distortion. This equivalency principle simplifies the modeling of vortex generators by full Navier-Stokes CFD analyses, and it gives excellent performance comparisons with experimental data even for coarse grid calculations (ref. 7).

The current development strategy for combat aircraft emphasizes reducing life-cycle cost without compromising aircraft performance and survivability. Because this strategy has been extended to the component level, advanced S-duct inlet configurations are being made more compact (or shorter) to reduce weight and volume (and life-cycle cost). However, these compact S-ducts are typified by high distortion and low pressure recovery because of the extreme wall curvature and strong secondary flow gradients. Flow-control methods are being developed for these compact ducts to improve their performance. In addition, microelectrical mechanical systems (or MEMS-based) actuators are being evaluated as minimally intrusive, lightweight, controllable flow-control effectors to replace fixed-vane vortex generators. However, before MEMS technology can manage inlet flow fields successfully, much basic and applied aerodynamic research must be done.

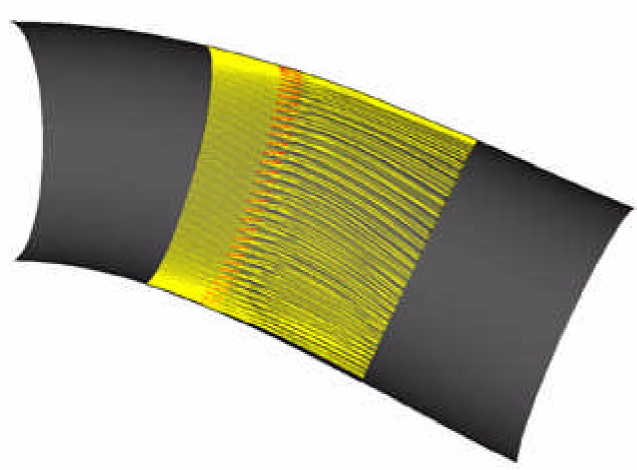
This study used a full Navier-Stokes analysis to examine MEMS flow control of compact inlets, focusing on developing a workable installation. Instead of examining a particular MEMS device, it defined a device that could manage the entire inlet flow field effectively. This reference MEMS device has a vane height between 2 and 4 mm above the duct walls (about the height of the boundary layer momentum thickness). The objectives of this study were to

1. Enable the MEMS reference vane generator installations to manage the entire inlet flow field by controlling the secondary flow in the thin layer adjacent to the wall.

2. Use DOE procedures and full Navier-Stokes analysis to determine design rules for the MEMS installations, where the grid defines the individual vanes.

3. Validate that CFD modeling can be used effectively to design MEMS installations by using a full Navier-Stokes analysis to repeat the DOE design matrix, where the individual vanes are modeled.

   These CFD experiments were conducted using the Defense Evaluation Research Agency DERA/M2129 inlet S-duct (ref. 8) and the Lockheed Martin Tactical Aircraft Systems (LMTAS) full Navier-Stokes FALCON code (ref. 7), which includes a vortex generator model. In part, this study, which is part of The Technical Cooperative Program (TTCP), is a validation of the vortex generator model in the FALCON code.



Particle traces showing the secondary flow field induced by the MEMS-scale reference generator installation.

The figure shows particle traces emanating just below the height of the MEMS reference vane generator installation, a co-rotating installation. Co-rotating installations interact to create vortices that merge quickly to form an overall single secondary flow pattern that remains in the wall boundary layer. This induced flow pattern prevents pairs of counter-rotating vortices from forming in the S-duct and, consequently, prevents the damaging effects of vortex lift-off (separation) on engine face distortion.

References

0. Advisory Group for Aerospace Research and Development (AGARD): Engine Response to Distorted Inflow Conditions. AGARD CP-400, 1987.

1. E.L. Goldsmith and J. Seddon, eds.: Practical Intake Aerodynamic Design. Blackwell Scientific Publications, Oxford, 1993.

2. Anderson, B.H., et al.: Study of Vortex Flow Control of Inlet Distortion. J. Propuls. Pow., vol. 8, no. 6, Nov.-Dec. 1992, pp. 1266-1272.

3. Anderson, B.H.; and Gibb, J.: Study on Vortex Generator Flow Control for the Management of Inlet Distortion. J. Propuls. Pow., vol. 9, no. 3, May-June 1993, pp. 420-430.

4. Anderson, B.; and Gibb, J.: Vortex-Generator Installation Studies on Steady-State and Dynamic Distortion. AIAA Paper 96-3279, 1996.

5. Gibb, J.; and Anderson, B.H.: Vortex Flow Control Applied to Aircraft Intake Ducts. Proceedings of the High Lift and Separation Control Conference, Royal Aeronautical Society, U.K., 1995, pp. 14.1 to 14.11.

6. Bender, E.E.; Anderson, B.H.; and Yagle, P.T: Vortex Generator

Modeling for Navier-Stokes Codes. Proposed paper for the Symposium on Flow Control of Wall Bounded and Free Shear Flow, 1999 Joint ASME/JSME Fluids Engineering Conference, ASME Paper FEDSM99-6919, 1999.

7. Willmer, A.C.; Brown, T.W.; and Goldsmith, E.L.: Effects of Intake Geometry on Circular Pitot Intake Performance at Zero and Low Forward Speeds. Aerodynamics of Power Plant Installation, AGARD CP-301, Paper 5, 1981, pp. 51-56.

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