8th. World Congress on Computational Mechanics (WCCM8)
5th. European Congress on Computational Methods in Applied Sciences and Engineering (ECCOMAS 2008)
June 30 – July 5, 2008
Venice, Italy

The design, numerical modelling and validation of microfabricated pulsed airjet actuators for flow separation control

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Key Words: *Multiphysics Problems, Applications, Computing Methods, Pulsed Jets, Flow Control.*

ABSTRACT

Flying vehicles of the future could benefit significantly from the application of aerodynamic flow control, which offers not only improvements in absolute performance (flying faster or slower, increased agility, reduced fuel burn) but also the potential to reduce vehicle size, weight and cost. Controlling a practical aerodynamic flow to achieve a desired effect such as drag reduction or lift enhancement is often a very difficult task. Passive technologies, while always preferable, are generally limited in their utility. The "brute force" suppression or manipulation, via active, energy-consuming control devices is always possible, but the penalty for doing so often exceeds any potential savings. The challenge is to actively achieve a desired effect with a minimum of energy expenditure. Traditional methods of flow control have generally been of the passive or "brute force" type. It is only during the last decade or so that new advanced technologies such as "Microfabricated-Electro-Mechanical Systems" (MEMS) have emerged, opening up the possibility for step changes in aerodynamic performance.

Boundary-layer separation entails significant energy loss, increases flow unsteadiness and limits the performance of many flow devices. Not surprisingly, a substantial amount of research aimed at controlling boundary-layer separation has been conducted. Traditionally, the following approaches have been applied: a) tangential blowing to energize directly the low-momentum region near the wall; b) wall suction to remove the low-momentum region; c) vortex generators (VGs and micro VGs) in the form of vanes and bumps and d) forced excitation devices, for example, acoustic excitation and synthetic jets. Tangential blowing and suction are very effective in controlling separation. However, they have the parasitic cost associated with high-pressure (mass flux) sources and are infrequently used. VGs are among the most widely examined flow-control methods, where VGs of various shapes and sizes have been used to control boundary-layer separation. Although the mechanism is still not fully understood VGs produce strong streamwise vortices, which enhance the mixing between the high-momentum core flow and the low-momentum boundary-layer flow, thus energizing the boundary-layer fluid. However, the performance of these VGs, which are passive in nature, has been somewhat limited; usually there is a need to optimize their location, size, and other parameters to achieve optimal performance for specific operating conditions. In addition, they have an associated parasitic drag. Other active flow control devices, such as synthetic jets have also been examined for separation-control applications.

The term MEMS embodies an area of technology that has emerged over the last two decades in which very small sensors, actuators and electronics may be manufactured on a common substrate using integrated-circuit fabrication techniques and compatible bulk and surface micro-machining processes. MEMS devices, including micro-sensors and micro-actuators, are attractive because they can be made small (tens or hundreds of microns), be produced in large numbers, include electronics for complex functionality, and be inexpensive. Their application in everyday use is increasing, for example, in the form of ink-jet printer heads and sensors for applications such as the accelerometers used in triggering

automotive airbags, small, solid-state gyroscopes for angular rate sensing and miniature pressure sensors for use in medical applications. One potential future application for MEMS technology is the control of fluid flows through the reactive manipulation of the turbulence structures within the thin boundary layer flow that develops in the region of the interface between a solid boundary and the fluid. It has long been known that the aerodynamic performance of an aircraft or a turbomachine is directly linked to the condition of the boundary layers forming over their surfaces and that the modification of these boundary layers can lead to significant improvements in performance. Substantial reductions in drag and increases in lift are possible together with the potential for controlling flow separation and buffet.

The application of MEMS for active reduction of turbulent skin friction drag is still at a very immature level with most activity still being undertaken in university laboratories or by numerical simulation. However, for the case of flow-separation control the technology is at a more mature level. Many studies have been undertaken to demonstrate the application of MEMS technology to the control of flow separation but often at sub-scale laboratory conditions. In contrast the European Aeromems I and Aeromems II projects are good examples of programmes that have demonstrated concepts and technologies at close to full-scale conditions. These recently completed projects have resulted in the demonstration of practical flow separation control technologies based on the use of microfabricated sub-boundary-layer-scale actuators at close to flight-scale conditions (Mach number, Reynolds number and scale).

This paper details the activities undertaken within, and subsequent to, the aforementioned Aeromems II project to develop and demonstrate a practical actuator for flow-separation control suitable for full-scale application to a medium/large air vehicle. This paper presents the design and validation of a microfabricated pulsed air-jet actuator for practical application to flow-separation control at full-scale operating conditions on a medium/large air vehicle. The actuator device is designed to generate streamwise vortices within the boundary layer and comprises a pitched and skewed orifice of 200 µm diameter through which a high velocity (200-300 m/s) jet of air can be modulated by operation of a piezoelectric microvalve. This paper describes the overall design and manufacture of the actuator device with particular reference to the impact of fluid dynamic effects on the design and operation determined through the application of Computational Fluid Dynamic (CFD) analysis tools. Key results obtained from both static and dynamic tests of a prototype device are presented and compared with original predictions obtained from CFD analysis. It is shown that the device that was developed and tested fulfils all the original design requirements with regard to size, jet velocity and operating frequency. It is also shown that the device has a measured performance that is within approximately 5% of that predicted by the design analysis process. The developed device has dimensions of approximately 5 mm x 2 mm in the plane of the aerodynamic surface in which it is imbedded and a thickness of 1 mm. Peak jet velocities in excess of 300 m/s through a 200 µm diameter orifice at 500 Hz have been demonstrated with peak driving voltages of 90 V and a nominal electrical power consumption of 50 mW.