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Aerodynamic Flow Control over an Unconventional Airfoil Using Synthetic Jet Actuators

Michael Amitay*
Georgia Tech Research Institute, Smyrna, Georgia 30080
Douglas R. Smith†
University of Wyoming, Laramie, Wyoming 82071-3295
Valdis Kibens‡
The Boeing Company, St. Louis, Missouri 63166
David E. Parekh§
Georgia Tech Research Institute, Smyrna, Georgia 30080
and
Ari Glezer¶
Georgia Institute of Technology, Atlanta, Georgia 30332-0405

Control of flow separation on an unconventional symmetric airfoil using synthetic (zero net mass flux) jet actuators is investigated in a series of wind tunnel tests. The symmetric airfoil comprises the aft portion of a NACA four-digit series airfoil and a leading edge section that is one-half of a round cylinder. The experiments are conducted over a range of Reynolds numbers between 3.1×10^5 and 7.25×10^5. In this range, the flow separates near the leading edge at angles of attack exceeding 5 deg. When synthetic jet control is applied near the leading edge, upstream of the separation point, the separated flow reattaches completely for angles of attack up to 17.5 deg and partially for higher angles of attack. The effect of the actuation frequency, actuator location, and momentum coefficient is investigated for different angles of attack. The momentum coefficient required to reattach the separated flow decreases as the actuators are placed closer to the separation point. In some cases, reattachment is also achieved when the actuators are placed downstream of the stagnation point on the pressure side of the airfoil. Control effectiveness is distinctly different for low and high actuation frequencies and is influenced by the disparity of the characteristic timescale of the actuation.

I. Introduction

OPTIMUM aerodynamic performance that avoids flow separation on wing surfaces has been traditionally achieved by appropriate aerodynamic design of the airfoil section. However, when the wing design is driven by nonaerodynamic constrains, stealth, for example, the lift and drag performance of the resulting unconventional airfoil shape may be severely diminished, and either active or passive flow control is necessary to maintain aerodynamic performance throughout the normal flight envelope.

The present work is part of a series of related studies[1,2] that have explored the utilization of synthetic (zero net mass flux) jet flow control for the modification of the lift and drag characteristics of bluff bodies. The current contribution focuses on improving the aerodynamic performance of unconventional airfoil shapes whose designs emphasize optimization of mission objectives at the cost of vehicle aerodynamics.

Although passive control devices, for example, vortex generators, have proven to be quite effective in delaying flow separation, under some conditions, they afford no proportional control and introduce a drag penalty when the flow does not separate. In contrast, active control approaches enable coupling of the control input to flow instabilities that are associated with flow separation and, thus, may enable substantial control authority at low actuation levels. Furthermore, active actuation is largely innocuous except when activated and has the potential for delivering variable power.

In previous studies, active control efforts have employed a variety of techniques including external and internal acoustic excitation,[3,4] vibrating ribbons or flaps,[5] and steady and unsteady blowing/bleed.[6] Various degrees of separation control were achieved by manipulating the unstable separated free shear layer leading to a complete or a partial reattachment of the separated flow. External acoustic excitation for separation control on an airfoil was investigated by Ahuja and Burrin[3] and Zaman et al.,[4] who exploited the acoustic resonance in the wind-tunnel test section to induce cross-stream velocity perturbations. Zaman et al.[4] noted that the introduction of oscillatory cross-stream velocity perturbations by other means might be more viable for excitation of separated airfoil flows.

Internal acoustic excitation for separation control was first investigated by Huang et al.[5] and Hsiao et al.,[6] who used an acoustically driven cavity within a NACA 63_3-018 airfoil to excite the boundary layer through a small rectangular orifice placed near the leading edge of the airfoil. Both studies used the sound pressure level (SPL) above the orifice to characterize the control input. Whereas the work of Huang et al.[5] was limited to the shedding frequency of the airfoil, that is, dimensionless frequency $F^+ \sim 1$, Hsiao et al.[6] investigated a broader range of actuation frequencies up to $F^+ \sim 20$. These authors achieved a 40% increment in the lift coefficient at poststall angles of attack. In a later study on the effects of internal excitation on flow separation from a circular cylinder, Williams et al.[7] noted that the correct measure of the actuation amplitude is the unsteady velocity at the orifice rather than the SPL. In the subsequent work of Chang et al.[8] on a two-dimensional airfoil (NACA 63_3-018), the orifice velocity was calibrated with respect to frequency, and the authors were able to demonstrate the effect of frequency on separation control at low poststall angles of attack ($15 < \alpha < 20$ deg) at $Re_c = 3 \times 10^5$. For small levels of momentum coefficient $C_\mu < 10^{-4}$ (computed based on the amplitude of the velocity oscillations), separation control correlated strongly with the frequency of the shear

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*Research Engineer, Aerospace, Transportation and Advanced Systems Laboratory. Member AIAA.

†Assistant Professor, Mechanical Engineering Department. Member AIAA.

‡Associate Technical Fellow, Phantom Works. Associate Fellow AIAA.

§Director, Aerospace, Transportation and Advanced Systems Laboratory. Associate Fellow AIAA.

¶Professor, School of Mechanical Engineering. Member AIAA.