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Toward Understanding and Optimizing Separation Control Using Microjets

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Flow separation in engine inlets and diffuser ducts and over external aerodynamic surfaces such as wings can significantly compromise performance. In a previous experimental study, we demonstrated the value of microjets for separation control. In this paper, we significantly broaden the range of conditions and parameters to explore the effects of microjet control on the efficiency of separation control over a backward-facing ramp. The parameters explored include the following: the freestream velocity, the ramp angle of attack, and the microjet pressure, location, and injection angle. Detailed velocity field investigations and unsteady pressure measurements have been conducted to study the effect of flow control over this parametric space. The results indicate that, by activating the actuator arrays in the immediate vicinity of the separation location, the control efficiency can be greatly enhanced, reducing the actuator mass flow needed dramatically. By correlating the unsteady surface pressure measurements with the measured velocity field, we demonstrate that, at least in the present geometry, the unsteady pressure alone can be used to 1) detect separation and hence identify which actuator(s) to activate, and 2) estimate the effect of control on a separated flowfield. Finally, based on the response of the flowfield to actuation, we propose some simple scaling laws for detecting and implementing separation control.

Nomenclature

C_μ = steady momentum coefficient
d_{Mj} = microjet diameter
H = ramp height
$\dot{m}_{in}$ = rate of mass flux supplied through microjets
N = number of microjets
P_{rms} = rms value for unsteady pressure
U_j = microjet velocity
U_∞ = freestream velocity
w = width of the model
X_{Mj} = microjet location
X_s = separation location
X_T = unsteady pressure transducer location
δ = boundary-layer height
ρ_∞ = freestream density
Ψ_P = $(P_{\mathrm{rms,baseline}} - P_{\mathrm{rms,control}})/P_{\mathrm{rms,baseline}}$
$\Psi_P(L)$ = scaling factor for the effect of microjet location on P_{rms}
$\Psi_P(P)$ = scaling factor for the effect of microjet pressure on P_{rms}
ω_z = streamwise vorticity

I. Introduction

FLOW separation and its control are of considerable interest both from fundamental fluid dynamics and practical perspectives. Flow separation occurs when fluid already decelerated by frictional forces is unable to overcome the increasing pressure forces when exposed to an adverse pressure gradient. It can lead to significant reductions in performance for both internal and external flows, such as lift loss, increase in drag, buffeting, and pressure recovery losses (in engine inlet and transmission ducts), among others. As an example, inlet ducts [1] used in a blended wing body [2] (BWB) configuration are located on the aft end to reduce the size of aircraft and to diminish radar signatures from the engines. In commercial aircraft, the use of these inlets makes the BWB aircraft significantly lighter with the additional advantage of a higher lift-to-drag ratio [3]. The placement of serpentine inlet ducts, however, requires ingestion of a thick boundary layer developed over the aircraft surface. This thick boundary layer is much more susceptible to separation when it encounters adverse pressure gradients in the inlet/diffuser ducts. The pressure loss due to this separation reduces the overall system efficiency. Moreover, flow distortion and unsteadiness created due to this separation can result in aerodynamic stall and surge of the compressor and the fan blades [4,5]. Therefore, it is highly desirable to avoid boundary-layer separation as it can significantly compromise the performance of aircraft propulsion systems.

Numerous techniques [6–20] have been explored to control flow separation. These range from the use of passive devices such as vortex generators in the form of vanes and bumps [11,12], etc., to the use of flexible walls [13], synthetic jets [7,14], and acoustic excitation [8,9] as active control devices. However, to date, the performance of most of these techniques has been somewhat limited, although work continues to further increase the efficiency of the more promising approaches [17,21–23]. For example, passive devices such as vortex generators have been found to be effective in controlling separation. However, they need to be optimized for their location, size, and other parameters for a wider range of operating conditions and may induce parasitic drag when not needed. As a result, active flow control devices have been suggested as an alternative control technique. Some of these active control devices, such as synthetic jets, have been explored by Amitay et al. [7] and Smith and Swift [14] for separation control. A comprehensive review of synthetic jets can be found in Glezer and Amitay [24].

Similar control devices (piezoelectric synthetic jets) were also employed by Jenkins et al. [25] over a Stratford ramp. Based on their results, Jenkins et al. concluded that synthetic jets did not have sufficient velocity/momentum to provide effective control. The use of flexible walls [13] has also been attempted for separation control; however, it adds mechanical complexity to the system. In addition, the system is dependent on the combination of the membrane tension

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