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Investigation of Unswept Normal Shock Wave/Turbulent-Boundary-Layer Interaction Control

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An analytical model for the unswept normal shock wave/turbulent-boundary-layer interaction control using an upstream and downstream unimorph piezoelectric flap actuator has been proposed. The amount of flap deflection controls the bleed/suction rate through a plenum chamber. The cavity allows rapid thickening of the boundary layer approaching a normal shock wave, which splits into a series of weaker shocks forming a lambda shock foot, leading to a reduction in the wave drag. The analysis provides an understanding of the control influences produced in an experimental investigation of an unswept normal shock wave/turbulent-boundary-layer interaction at a Mach number of 1.5. It has also been validated by application to the normal shock wave/boundary-layer interaction control system using mesoflaps for aeroelastic transpiration described in previous transonic/supersonic shock wave/boundary-layer interaction studies.

I. Introduction

THE interaction of a shock wave with a boundary layer is a classic viscous/inviscid interaction problem that occurs over a wide range of high-speed aerodynamic flows, such as on transonic wings, in supersonic air intakes, at control surface deflections, and propelling nozzles at off-design conditions, just to name a few. On an aerofoil in transonic flow, for instance, when the nearly normal shock wave interacts with a boundary layer, phenomena ranging from a mild increase in section drag to flow separation, eventually leading to buffeting, can occur, depending on the strength of the shock and the state of the boundary layer.

Herein, we address the problem of controlling the interaction of a normal shock wave with a turbulent boundary layer such as that which occurs on the rear of a transonic aerofoil. However, the approach is equally applicable to the control of any interaction wherein the shock wave, either normal or oblique, meets with a turbulent boundary layer.

In view of the adverse effects, such as flow separation and drag increase as a consequence of shock wave/boundary-layer interaction, a number of methods have been explored to control the interaction. However, in general, they have not been very successful, mainly because the drag reduction achieved has been negated by the attendant increase in power expended in removing or energizing, for example, the boundary-layer mass by suction or injection, or, in the case of vortex generators, drag created by their addition alone.

Passive control of the interaction, wherein the boundary layer on a porous surface covering a plenum chamber, as shown in Fig. 1, is interacting with a shock, has shown that considerable wave drag reductions can be achieved in principle. However, in most instances, the skin friction component of the drag over a porous (rough) surface is unacceptable and the overall drag reduction becomes insignificant. Secondly, passive control may result in an increase in skin friction drag in the absence of a shock or when the shock location is outside of the control region as can happen at off-design conditions. Then, there is also the constraint that it is not easily possible to switch on or off the passive control technique. Passive techniques of shock wave/boundary-layer interaction (SBLI) control have been analyzed and studied for many years, for example, see Nagamatsu et al. [1], Raghunathan [2], Gibson et al. [3], and Delery and Bur [4].

In recent years, a novel method of passive control of SBLI using mesoflaps has been proposed by the researchers at the University of Illinois at Urbana–Champaign [5–7]. In this method, termed mesoflaps for aeroelastic transpiration (MART), an array of aeroelastically tailored flaps are placed underneath the shock foot covering the recirculation cavity. The flaps remain closed in the absence of the shock but deflect due to pressure difference across when a shock wave is present, thereby creating a flow circulation that controls the shock. In particular, the flaps downstream of the shock deflect down due to the pressure increase downstream of the shock. Upstream of the shock, the flaps deflect upward as a consequence of the pressures being lower than in the cavity. The flow circulation across the shock so set up energizes the low-momentum upstream boundary layer and spreads the shock foot, thus avoiding flow separation and increase in viscous and wave drag. Thus, the advantage of such flaps is that, not only is there no increase in the drag in the absence of the shock, because with the flaps closed, the surface is smooth and behaves as a solid wall, but also the bleed flow is nearly *tangential* both upstream and downstream of the shock, leading to smaller losses.

The present paper reports an investigation of an SBLI control system, which can be considered a variant of the MART system. In this system, piezoelectrically controlled flap actuators are used to control the SBLI. The actuators are designed using PZT-5H piezoelectric material to control bleed/suction rate. The flaps are made up of unimorph construction wherein the piezoelectric ceramic is bonded to an inert substrate and applying an electric field to the piezoelectric ceramic will induce deflection [8–11]. The flaps would thus deflect, firstly, due to pressure difference created by the pressure rise across the shock, and secondly, due to piezoelectrically induced strains. In this respect, the flaps can be considered smart and the control "active" in a broad sense because they can be activated to control the recirculation rate or can be switched off, leaving the recirculation rate uncontrolled. The piezoelectric material was selected for flap construction due to its bipolar nature, which is the ability to produce positive or negative strain. This bipolar characteristic enables it to assist the flap's aeroelastic deflection up or down to control the mass transfer. Full details of structural analysis of unimorph flap actuators and the evaluation of their performance is given in [2,11]. Figure 2 illustrates the schematic arrangement of the system.

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