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The near wall effect of synthetic jets in a boundary layer

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Abstract

An experimental investigation to analyse the qualitative near wall effect of synthetic jets in a laminar boundary layer has been undertaken for the purpose of identifying the types of vortical structures likely to have delayed separation on a 2D circular cylinder model described in this paper. In the first instance, dye visualisation of the synthetic jet was facilitated in conjunction with a stereoscopic imaging system to provide a unique quasi three-dimensional identification of the vortical structures. Secondly, the impact of synthetic jet structures along the wall was analysed using a thermochromic liquid crystal-based convective heat transfer sensing system in which, liquid crystals change colour in response to the thermal footprints of a passing flow structure. Of the different vortical structures produced as a result of varying actuator operating and freestream conditions, the footprints of hairpin vortices and stretched vortex rings revealed a marked similarity with the oil flow pattern of a vortex pair interacting with the separation line on the cylinder hence suggesting that either of these structures was responsible in delaying separation. Conditions were established for the formation of the different synthetic jet structures in non-dimensional parameter space.

Keywords: Synthetic jets; Boundary layer; Flow separation control; Vortex structures

1. Introduction

Synthetic jet actuators (SJA) provide a novel means of applying flow control and their potential application for the effective delay of boundary layer separation on aircraft has been the focus of intense research in recent years (Smith and Glezer, 1998; Crook and Wood, 2001; Gilarranz and Rediniotis, 2001; Glezer and Amitay, 2002). One of the reasons for this is due to their unique ability to impart additional momentum on a fluid region from which it was originally synthesised without a net mass addition, therefore requiring no bleed air supply and complex piping. In addition, the oscillatory nature of synthetic jets has been observed to offer greater entrainment of fluid in the near field compared to their continuous counterparts (James et al., 1996; Cater and Soria, 2002).

It is believed that the interaction of the discrete trains of vortices formed out of a SJA (Fig. 1) with a local boundary layer produces streamwise vortical structures, which are capable of delaying flow separation by entraining faster moving fluid from the freestream to the near wall region. Crook and Wood (2001) investigated the flow control effectiveness of an array of SJAs implemented flush to the surface of a circular cylinder upstream of its separation line in a turbulent boundary layer. From Fig. 2, surface oil patterns showed that with the actuators active, the separation line was pushed downstream noticeably. In particular, the oil flow revealed the footprints of a well defined streamwise vortex pair immediately downstream of each SJA orifice that appeared to persist for a long distance downstream and interact with the separated flow. Subsequent dye visualisation by Zhong et al. (2005) has shown that the interaction between a synthetic jet and a boundary layer is complex, varying from hairpin vortices that remain near to the wall to tilted vortex rings that penetrate the boundary layer as the jet-to-freestream velocity ratio increases. It

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Nomenclature

c_f	skin friction coefficient
d	boundary layer thickness to orifice diameter ratio
D	diameter of cavity or orifice, mm
f	diaphragm oscillation frequency, Hz
h	orifice depth, mm
H	cavity height, mm
L	dimensionless stroke length
Re	Reynolds number
S	Stokes number
St	Strouhal number
T	time period of a diaphragm oscillation cycle, s
u	instantaneous velocity, m/s
U	characteristic velocity, m/s
VR	jet-to-freestream velocity ratio
x	streamwise distance from orifice exit, mm
y	normal distance from orifice exit, mm

Greek symbols

Γ	vortex circulation, m^2/s
δ	boundary layer thickness, mm
Δ	peak-to-peak displacement at the diaphragm centre, mm
ρ	fluid density, kg/m^3
τ	surface shear stress, N/m^2
v	molecular kinematic viscosity, m^2/s

Superscripts

–	time average
∼	space average

Subscripts

c	cavity value
j	jet value
o	orifice value
w	wall value
∞	freestream value

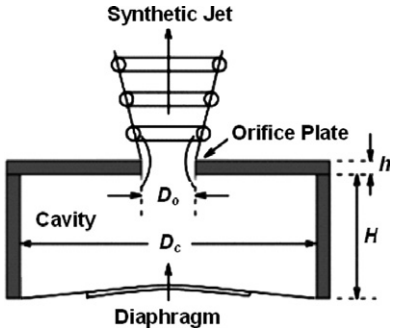

Fig. 1. Schematic of a SJA.

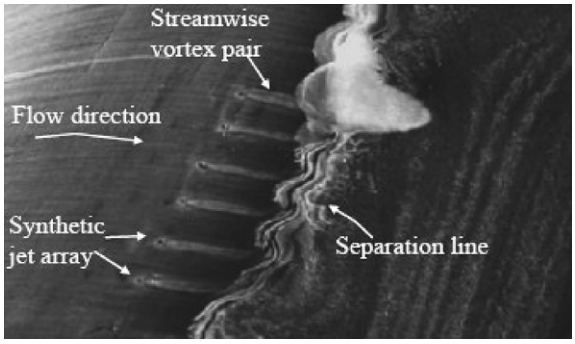

Fig. 2. Demonstration of flow separation control (Crook and Wood, 2001).

has been hypothesised (Zhong et al., 2005) that the hairpin vortices may have been responsible for the formation of the streamwise vortex pair that interacted with the separation line on the circular cylinder, however, further evidence is still to be sought.

In this paper, the results of a qualitative study of the interaction of a synthetic jet with the near wall region of a laminar boundary layer are presented. As a continuation of the aforementioned investigation, the purpose of the work described herein is to identify the likely type of vortical structures responsible for the delayed separation on the circular cylinder and to establish the conditions that ensure the formation of such structures in non-dimensional parameter space. To this end, the nature of vortical structures produced under a range of actuator and freestream conditions are to be investigated with a view to analysing their respective near wall effects where flow control is ultimately desired. The use of a laminar flow provides a logical first step into visualising and understanding the basic mechanism of synthetic jet boundary layer interaction, which would otherwise be difficult to achieve for a turbulent boundary layer. Furthermore, it is believed by the authors that the type of vortical structures produced should essentially be the same as that for a synthetic jet issuing into a turbulent flow with the main difference being in the dissipation rate of the ejected structures near the wall. This study is therefore applicable to turbulent flows, as in the case of the cylinder model described herein.

Realisation of the aims of this study is to be made primarliy through the application of two qualitative visualisation techniques, which are novel to this area of research. In the first instance, dye visualisation of the synthetic jet structures was facilitated in conjunction with a stereoscopic imaging system to allow simultaneous side and surface views. The technique provides a unique quasi three-dimensional identification of the vortical structures produced by the synthetic jet. Secondly, the impact of