International Journal of Heat and Fluid Flow 45 (2014) 53–71

Contents lists available at ScienceDirect

International Journal of Heat and Fluid Flow

journal homepage: www.elsevier.com/locate/ijhff

Effect of trailing edge ramp on cavity flow structures and pressure drag

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ARTICLE INFO

Article history:
Received 27 February 2013
Received in revised form 30 November 2013
Accepted 30 November 2013
Available online 27 December 2013

Keywords:
Cavity flow
Trailing edge ramps
Particle image velocimetry
Proper Orthogonal Decomposition
Pressure drag reduction

ABSTRACT

The effects of trailing edge ramp modifications on time-averaged velocity and pressure distributions within a cavity with a length to depth ratio of 2, at a speed of 15 m/s were investigated. The ramp angles were varied at 30°, 45° and 60° and ramp heights were varied at 0.25 times and 0.5 times of cavity depth. The mean flow within the cavity differed significantly from the baseline case when ramp angle was 30° and 45° with ramp height 0.5 times of cavity depth. At these 2 configurations, moment about the center of the cavity floor was reduced significantly. These could be attributed to the more steady flow within the cavity as compared to the baseline case. Spatial correlation of velocity in the cavity of ramp angle 30° showed that internal cavity flow was less sensitive to flow changes in the shear layer as compared to the baseline case. In the same cavity, snapshot Proper Orthogonal Decomposition revealed a redistribution of energy content where energetic structures exist only in the shear layer as opposed to energetic structures in both the shear layer and internal cavity for the baseline case. A reduction of pressure drag was also observed as the gentle ramp angle of 30° guides the flow smoothly out of the cavity and reduces trailing edge impingement.

1. Introduction

Study of flow over cavities is motivated by its phenomena found in many areas such as in solar cells, slots between movable parts of ships, tandem arrangements of bluff bodies such as adjacent tall buildings or tractor–trailer combinations, gas dynamic lasers, hydraulic gates, control valves, landing gears of aircrafts, sunroofs or windows in automobiles (Gharib and Roshko, 1987; Kook et al., 1997). Though geometrically simple, these cavities are associated with complex phenomenon. When exposed to freestream, the cavities experience unsteady flow around them. At a fixed freestream Mach number, fixed shear layer thickness at leading edge and fixed depth of cavity, the onset of unsteady flow begins when cavity length (relative to the upstream boundary layer thickness) exceeds a certain value (Karamcheti, 1956; Rockwell and Naudascher, 1978; Sarohia, 1975). Below the minimum cavity length, the shear layer bridges smoothly over the cavity with no distinct oscillation in it (Gharib, 1983). Beyond that, the disturbance can undergo a minimum integrated amplification between separation and impingement. This allows the flow to transit into a shear-layer mode where self sustained oscillations occur (Rossiter, 1964). This is the regime usually seen in experiments. However, as the length of the cavity continues to increase, a loss of coherence in the oscillation will eventually occur. This is replaced by large scale shedding with Strouhal number independent of Mach number, an indication of the transition of shear layer mode into wake mode (Gharib and Roshko, 1987; Rowley et al., 2002).

In the shear layer mode, the self sustaining oscillations impinge on the trailing edge of the cavity to produce large pressure fluctuations and high pressure drag. In order to suppress these loads, flow control methods must be employed. A review of the flow control studies in the open literature found most work to focus on the suppression of the pressure fluctuations, with little emphasis on the drag considerations. The successful reduction in pressure fluctuations alone may reduce the overall drag (McGregor and White, 1970), but the device used for suppression will most probably have some adverse effects on drag. Since the interest is to reduce pressure drag using trailing edge ramps, a short review of the frequently used passive control methods and their effectiveness in suppressing pressure oscillations and reducing pressure drag in cavities will be presented here.

Common passive methods used in cavity flow control by researchers include spoilers, vortex generators and front and rear wall geometry changes. Spoilers and vortex generators introduce 3-dimensional disturbances into the shear layer which helps improve stability characteristics and disrupt coherence of turbulent structures. A spoiler and vortex generator height equivalent to the boundary layer thickness is usually used for pressure oscillations suppression (Dix and Bauer, 2000; Stanek et al., 2002; Ukeiley et al., 2004). The deployed spoilers are likely incur a drag penalty,

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0142-727X/$ - see front matter © 2013 Elsevier Inc. All rights reserved.
http://dx.doi.org/10.1016/j.ijheatfluidflow.2013.11.008

Nomenclature

C_{Dp}	drag coefficient per unit length, calculated from integration of pressure
Cp	pressure coefficient
D	depth of cavity (mm)
L	length of cavity (mm)
L_e	extended length of cavity (mm)
P_c	static pressure within cavity (Pa)
P_∞	freestream pressure (Pa)
R_{uu}	spatial correlation coefficient in u
R_{vv}	spatial correlation coefficient in v
Re_D	Reynolds number based on cavity depth
U	instantaneous velocity in the x direction (m/s)
$\overline{U}$	mean velocity of U (m/s)
U_∞	freestream velocity (m/s)
V	instantaneous velocity in the y direction (m/s)
$\overline{V}$	mean velocity of V (m/s)
W	width of cavity (mm)
h_{ramp}	height of ramp (mm)
u'	fluctuation of U (m/s)
$\overline{u'}$	root mean square of u' (m/s)
v'	fluctuation of V (m/s)
$\overline{v'}$	root mean square of v' (m/s)
$\overline{u'v'}$	Reynolds shear stress $(m/s)^2$
$\delta_{0.95}$	boundary layer thickness at leading edge of cavity, based on 95% of freestream velocity (mm)
ρ_∞	freestream density (kg/m^3)
θ_{ramp}	ramp angle (°)
θ_o	momentum thickness at leading edge of cavity (mm)

but there is an absence of data to confirm this. For the vortex generators, a comprehensive series of tests done at high subsonic and supersonic speeds has found the angle (with respect to horizontal), to influence the suppression effectiveness, with angles between 45° and 90° to be optimum (Heller and Bliss, 1975). The same study included some drag measurements in a small-scale wall-jet facility where there was a pair of triangular vane-type vortex generators set at 35°. Drag measured using low friction rails reveal an increase in drag of about 30% at Mach numbers up to 0.5.

Front wall geometry changes that were found to be effective in pressure oscillations suppression include the addition of ramps or steps (Doran, 2006; Zhang et al., 1999). Ramps have the same aim as spoiler while the aim of steps is to force the shear layer to separate ahead of front wall, in order to prevent interaction between returning pressure waves within the cavity and the separating shear layer, thereby weakening the effect on shear layer instability. Other front wall modifications include lip rounding (Clark, 1975; Tan et al., 2005), wall grooving and venting (Perng and Dolling, 2001), full height, full-width lateral sweep of the front wall, or part-width sweep through the insertion of full-height chevrons (Doran, 2006) or triangular corner blocks (Plentovich, 1992). These modifications were disappointing with either little improvements or resulted in worse fluctuating pressure. With regards to pressure drag, front wall modifications involving circular arc ramps at Mach number of 1.5 and 2.5 all gave drag increases (Zhang et al., 1999). This could be accounted for by the deflection of the shear layer into the cavity, which promotes full impact on the rear wall, thus increasing pressure drag drastically.

Rear wall geometry changes have the primary objective of varying the downstream location of the shear layer impact area throughout the oscillation cycle. A series of tests on rear wall ramps with ramp angles of 45° has been carried out previously (Heller and Bliss, 1975). In these tests, the ramps were extended above the aft horizontal surface by 2 in. before returning to the surface aft of the trailing wall. At a Mach number of 0.8, a cavity with $L/D = 2.25$ and $h_{ramp}/D = 0.375$ achieved reduced Sound Pressure Level in the frequency range of 31.5 Hz to 8000 Hz, while a cavity with $L/D = 5.14$ and $h_{ramp}/D = 0.857$ achieved reduced Sound Pressure Level in the frequency range of 31.5 Hz to about 700 Hz. In another experiment done on cavity with a 45° ramp and $h_{ramp}/D = 0.5$, it was found that the rear wall ramp was moderately successful in noise reduction (Lavoix, 2004). Other forms of trailing edge modifications include vented walls, slotted walls, slanted walls, beak walls, valley walls, rounded trailing edges, nosed-like trailing edges and grooved walls (Heller and Bliss, 1975; Pereira and Sousa, 1994; Perng and Dolling, 2001; Soemarwoto and Kok, 2001; Vikramaditya and Kurian, 2009). Through these studies, the slanted wall has been found to be one of the most effective ways to reduce pressure oscillations. To the author's knowledge, the very few drag studies available for cavity trailing wall modifications include (1) the use of a 45° rear wall ramp, where the drag was increased by 5% compared to the baseline case, for Mach numbers up to about 0.5 (Heller and Bliss, 1975), and (2) the 2D CFD simulations of rear wall slant angles of 22.5° and 45° and three circular arc rear wall ramps at Mach number of 1.5, where drag reductions were achieved compared to the baseline value (Zhang et al., 1998).

The brief review above has found most studies to focus on high subsonic and supersonic flows with emphasis on instantaneous pressure fluctuations and Sound Pressure Levels. There is a lack of experimental studies to investigate the effect of passive control methods on the pressure drag of cavities. Similarly, there also appears to be a lack of velocity measurements to study the cavity flow when the passive controls are in place, particularly in the subsonic regime. These measurements could give good insights into how flow responds to the controls and hence the resulting pressure changes.

The focus of this study is to investigate how the baseline cavity centreline flow responds to trailing edge ramps. Prior to this, a preliminary study based on 2 different trailing edge ramp configurations has revealed potential in reducing pressure drag (Pey et al., 2012). The ramps were both kept at 45° with ramp heights varied at 0.25 times and 0.5 times of cavity depth. The current study aims to extend the work by carrying out a more in-depth investigation through including a larger range of ramp angles as well as utilizing correlation and decomposition methods. A total of 6 trailing edge ramps with varying combinations of ramp heights and ramp angles were employed to study the sensitivity of cavity mean flow and pressure drag to these parameters. Spatial correlations of velocity fluctuations within the baseline case and the modified case that changed the baseline flow most significantly were presented to give an insight, and comparison, of the different instantaneous cavity flow physics for the 2 cases. In addition, Snapshot Proper Orthogonal Decomposition (POD) was applied to these 2 configurations to reveal the redistribution of energetic structures in the presence of the trailing edge ramp.

2. Experimental arrangements

2.1. Wind tunnel facility

An open loop wind tunnel with a test section size of 220 cm (length) by 40 cm (width) by 40 cm (height) and a turbulence intensity of less than 1% at 15 m/s was used in this study.