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Influence of vortex generator on cylindrical protrusion aerodynamics at various Mach numbers

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ABSTRACT

Effects of vortex generator on the flow field around vertically wall mounted cylindrical protrusion were carried out computationally at different Mach numbers. The flow field around cylindrical protrusion of three different heights with a ramp type vortex generator is analyzed. Three dimensional steady implicit formulation with standard k-ω turbulence model is used. Results obtained through present computation are validated with the existing experimental results at Mach 2.0. Good agreement between computation and experimental result has been achieved. Present result indicates that the presence of vortex generator will alter the flow field around cylindrical protrusion. It is observed that the vortex generator can also help in reduction of aerodynamic drag acting on cylindrical protrusion at various Mach numbers.

1. Introduction

Supersonic flow around any protruded objects or excrescences will normally lead to Shock Boundary Layer Interaction (SWBLI). The presence of protrusion in supersonic flow alters the pressure distribution on the skin as well as increases the overall drag [1]. SWBLI causes the flow to separate ahead of protrusion creating a dead air region. This flow separation depends upon protrusion height when compared with the flow boundary layer thickness. During manufacturing process, most of these excrescences are unavoidable, at the same time not all excrescences are disadvantageous to the aerodynamic characteristics of the vehicle. Some are like vortex generator (VG), which helps in delaying the separation of boundary layer by energizing it and in high speed flow these help in the control of shock wave boundary layer interaction as one of the main passive control methods.

The drag of several types of excrescences including two dimensional steps and ridges circular cylinders, holes and fairings immersed in turbulent boundary layer for a wide range of Mach numbers and Reynolds number were measured by Gaudet and Winter [2]. Estimation of drag on several circular cylinders for different Mach numbers and Reynolds numbers was investigated by Gowen and Perkins [3] and they reported that for supersonic speeds, the effect of Reynolds number is negligible. To study the effects of surface irregularities and to estimate the drag due to surface roughness, experiments on two-dimensional cylinders and a finite cylinder fully and partially submerged into turbulent boundary layer were conducted by Young and Paterson [4]. Surface irregularities and imperfections are formed when the flap deflects from the main airfoil. Considering this, Higazy and Cockrell [5] using pressure distribution technique determined the drag of small backward-facing steps. The variation in length of separation zone as a function of cylinder diameter for a cylinder of infinite height has been investigated experimentally at Mach number 2.5 and Reynolds number of 1.85×10^7 by D.M. Voitenko et al. [6]. Empirical relation for the separation distance ahead of cylindrical protrusion (S/D) and height to diameter ratio (H_C/D) and method to determine the angle of the oblique shock wave caused by the separation was proposed by Westkaemper [1]. Sedney [7–9] and Mashburn [10] conducted experiments using optical indicator method for surface flow visualization around the cylindrical protrusion and proposed a correlation on separation distance ahead of protuberances at different Mach numbers for different height and diameter. The presence of 3-dimensional complex flow field around rectangular and cylindrical protuberances of height of the order of turbulent boundary layer thickness was described by Su-Xun Li et al. [11]. Fig. 1(a) shows schematic of flow field around short cylindrical protrusion.

Several researchers have attempted to control SWBLI using vortex generator located upstream of the interaction region. Vortex generator (VG) introduces stream wise vortices into a flow field which helps in delaying the flow separation. The smaller VGs are characterized by heights less than or equal to the flow boundary layer thickness and have been referred to as "low-profile" or

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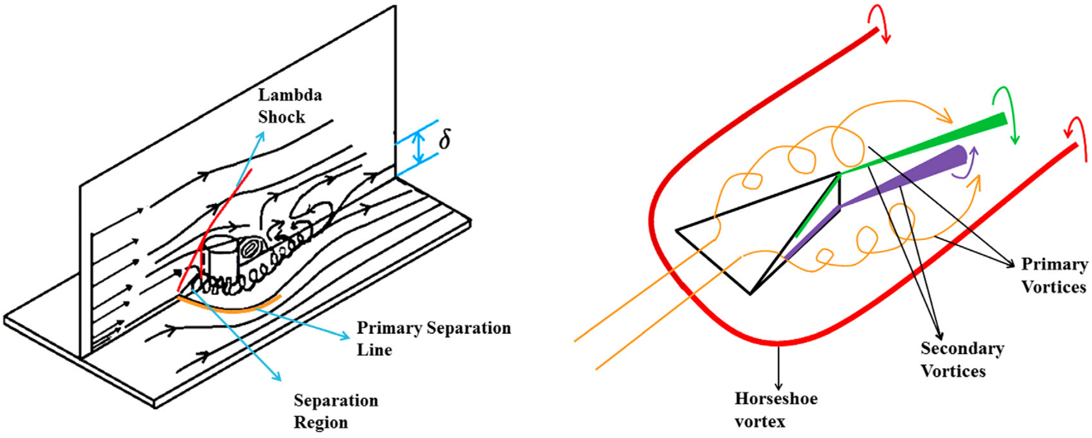


(a) (b)

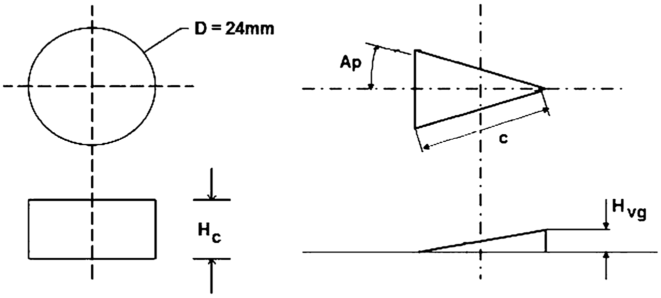
Fig. 1. Schematic of flow field around a) cylindrical protrusion, b) VG.

“micro” VGs, particularly, micro-vanes and micro-ramps. Control of SWBLI using an array of micro-vanes and micro-ramps was reported by Anderson et al. [12]. They also demonstrated that the Response surface Methodology (RSM) can be able to determine the optimal designs of micro-array actuation for controlling the SWBLI. Experimental surface separation pattern is obtained by the experiments of Babinsky [13], in which a series of distinct accumulated oil lines mark the location of separation lines. According to his experimental results of flow separation, a vortex model has been derived. The vortex system around VG consists of 4 pairs of vortices, i.e., the horseshoe vortex due to the leading edge separation of VG, the primary vortex by VG, two secondary vortices under the primary vortex – one lies on the bottom of the plate, the other lies at the side of VG. Fig. 1(b) shows schematic of vortices emanating from VG. Lu et al. [14] have reported experimental and numerical investigation on several types of micro-VG at supersonic speed. Detailed study of flow interactions with micro-ramps on a supersonic boundary layer at $M = 3.0$ using monotone integrated Large Eddy Simulation (MILES) and Reynolds Averaged Navier–Stokes (RANS) has been carried out by Loth and Lee [15]. Ramp induced interaction studies were carried out using micro-vortex generators by Pierce et al. [16] who studied the flow features of micro-VG with 1-inch diameter circular cylinder by conducting fluorescence surface flow visualization. J.C. Lin [17] studied low profile vortex generator and reported that it is more suitable for separated flows. Galbraith [18] investigated the control of shock wave boundary layer interaction using multi row micro-ramp actuators and showed that it is able to improve the boundary layer health downstream of the separation.

Previous study has been made to see the height (H_C) effect of cylindrical protrusion at Mach number 2.0, with the objective of reduction of aerodynamic drag due to cylindrical protrusion. Micro vortex generator which is cost effective, physically robust and a passive device to control the shock boundary layer interaction is widely used in supersonic inlets to energize the boundary layer. To study the effect of vortex generator on cylindrical protrusion, a detailed experimental and computational study of cylindrical protrusion with VG at Mach 2.0 was undertaken [19, 20]. In the present study, an attempt has been made to study the advantage of adopting vortex generator ahead of cylindrical protrusion at different Mach numbers with the consideration of reduction of aerodynamic drag acting on cylindrical protrusion and influence of vortex generator around the cylindrical protrusion.

Table 1
Summary of test cases.

Model	Cases	H_C, mm	D, mm	H_C/D
Cylinder	Case 1	3	24	0.125
	Case 2	6	24	0.250
	Case 3	9	24	0.375
VG	Case 4	$H_{vg} = 3$ mm	$c = 12$ mm	$Ap = 12°$



(a) (b)

Fig. 2. Geometric details of model: a) cylinder, b) vortex generator.

2. Computational methodology

Tests were made on cylindrical protrusions of different heights and with vortex generator. The diameter (D) of cylindrical protrusion is 24 mm and different heights (H_C) of 3 mm, 6 mm and 9 mm are used in the present work. The vortex generator model has a height (H_{vg}) of 3 mm which is of the order of flow boundary layer thickness (δ), chord length (c) of 12 mm, and ramp angle (Ap) of 12° were chosen from the basic model of Anderson et al. [12], which is appropriate to use along with the cylindrical protrusion. The summary of test cases is tabulated in Table 1. The geometrical details of cylindrical protrusions and vortex generator are presented in Fig. 2. The schematic of CFD domain along with boundary condition is shown in Fig. 3.

The dimensions of the grid are based on the diameter of the cylinder (D). The length, width and height of the domain are 35D, 12.5D and 12.5D respectively. The close up view of grid over model is shown in Fig. 4. The origin is fixed at the center of the cylinder. Although the vortex generator geometry is simple, the computational grid, which fills the immediate surrounding volume, can be challenging to build, especially for one using a conventional structured hexahedral grid generator. The triangular shapes and sharp corners can lead to highly skewed cells adjacent to the device. In addition, the oblique induced shock can be difficult to resolve be-