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An improved micro-vortex generator in supersonic flows

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ABSTRACT

The micro-vortex generator has currently received much attention as a passive flow control device in supersonic flow. This paper investigates the induced velocity and the trajectory of the vortices generated by micro-vortex generators by using the point vortex model. The analysis suggests that counter-rotating vortices could adversely affect each other and this effect depends on the distance of the counter-rotating vortices. A novel micro-ramp for boundary layer control, called dissymmetric micro-ramp, was put forward on the basis of this analysis. The effect the dissymmetric micro-ramp was numerically studied at a free stream Mach number of 2.5 via RANS simulations. The vortices generated by these devices have similar path and dissipation with the ones generated by traditional devices. There is a constant drop of vorticity in the development and dissipation of these vortices. The vorticity in dissymmetric micro-ramps is stronger than that in standard micro-ramp. On the other hand, the vortex height from wall in dissymmetric micro-ramps is smaller than in standard micro-ramp. This effect also suggests that vortex in dissymmetric micro-ramp is apt to maintain in boundary layer.

1. Introduction

The shock wave/boundary-layer interaction (SWBLI) is a common phenomenon in the supersonic flow field such as supersonic engine inlet and it has been a cause of concern to the aerospace industry. The interactions could change the shock wave structure and the strong adverse gradients induced by shock could accelerate the boundary layer developing. Interactions between boundary layer and shock waves also distort the velocity profile in boundary layer. These distortions increase the possibility of separation and reduce total pressure recovery. The use of boundary-layer suction is a traditional controlling technique and the low momentum fluid in boundary layer is removed by a suction system such as porous sections, slots, or scoops. These techniques have been proved to be effective, but result in reduced mass flow and increased system weight.

Vortex generators are particularly interesting among the multitude of flow control methods. Compared with suction system, vortex generators have the following advantages [1,2]. First, the vortex generators are passive control methods and no additional hardware is required. Second, the vortex generators will not cause a decrease in mass flow rate and additional performance penalty [3]. So, vortex generators have more potential than the suction system. Traditional vortex generators [4] which have the same order of magnitude with boundary layer thickness have been used in supersonic flow control for a long time. Researchers subsequently found that vortex generators which have smaller scale than boundary layer thickness have the advantage of smaller resistance while maintaining the ability of flow control [5,6]. In recent years, micro-vortex generators have obtained the full attention and development [7–9]. Anderson et al. [10] used Reynolds-averaged Navier–Stokes method to confirm that micro-vortex generators have the similar ability to suction system and also have the advantage of physical robustness. The vortices induced by micro-vortex generators were validated experimentally by Pitt-Ford and et al. [11]. The main function of these vortices is to accelerate the mixing effect between the higher-momentum external flow and the lower-momentum flow near the wall.

This paper presents a novel micro-ramp called dissymmetric micro-ramp, the vortex structure and the trajectory of the vortices generated by these two micro-ramps are compared. This investigation seeks to understand how the development of the vortices generated by different micro-ramps differs and gain more insight into the impact of vortices on the boundary layer. In addition, this paper estimates the influence of the two micro-ramps on the pressure distribution of the interaction zone and incompress-

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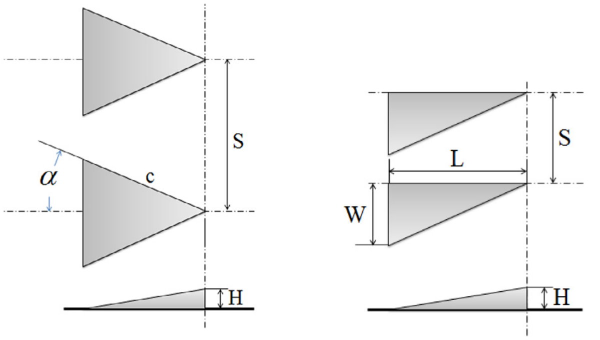
Nomenclature

α	micro-ramp angle of incidence
H	micro-ramp height
c	micro-ramp side length
S	micro-ramp spanwise spacing
L	dissymmetric micro-ramp length
w	micro-ramp spanwise width
H_i	boundary layer incompressible shape factor
Γ	circulation of vortex
W	complex velocity potential of vortex
Z	coordinate of vortex



(a)micro-ramp (b) dissymmetric micro-ramp

Fig. 1. 3D illustration of the micro-ramp and the dissymmetric micro-ramp.

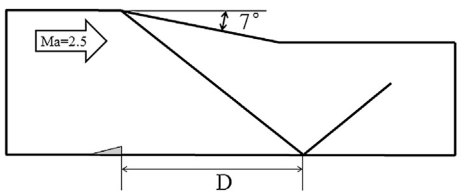


Fig. 2. Computational domain setup for shock wave/boundary layer interaction with micro-vortex generators control.

ible shape factor of boundary layer downstream the interaction zone.

2. Computational model and methodology

This paper is targeted at micro-ramps and dissymmetric micro-ramps, as shown in Fig. 1. There were three objects in this study, namely: (1) to present a new micro-vortex generator, (2) to investigate the flow characteristics of vorticity induced by micro-vortex generators, and (3) to evaluate the effectiveness of micro-vortex generator array flow control. The CFD solver used in the present study is commercial software CFX by solving the 3D compressible Reynolds-averaged Navier–Stokes equations. The governing equations are discretized using the finite element framework. The RANS closure used is Menter's hybrid $k-\omega/k-\varepsilon$ model [12] in its shear-stress transport forms. The simulated condition involving the effects of micro-vortex generators on shock interaction control have been shown in Fig. 2. A 7 degree wedge angle is setup to generate an oblique shock wave and a micro-vortex generator array is arranged upstream of the shock wave/boundary layer interaction zone. The height of the micro-vortex generator (H) is set to 70% of the boundary layer thickness (B) at the position of the micro-device. The distance of the micro-device and the shock wave/boundary layer interaction zone is 25 times of the boundary layer thickness B. A nominal Mach number of 2.5, a stagnation temperature of 280 K, a total pressure of 380 000 Pa, and a Reynolds number of 3×10^7 are taken as inlet conditions.

The flow field of shock wave/boundary layer interaction with micro-ramp is simulated by using CFX software. The simulated conditions are the same experimentally investigated by Babinsky in Ref. [1]. The numerical results are compared with the experimental data to invalidate the accuracy and reliability of the numerical methods in this paper. The computational mesh is generated by Gambit software, mesh refinement is processed besides the wall. The topological structure of mesh is shown in Fig. 3.

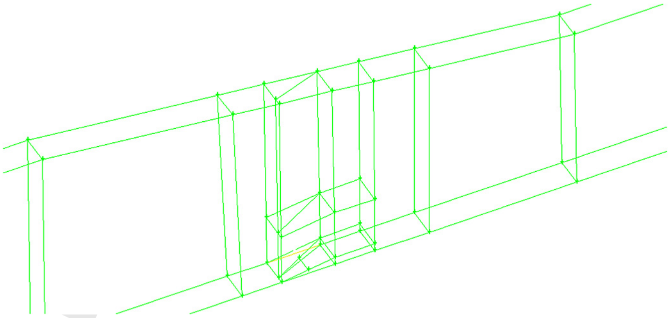


Fig. 3. Grid topology for the micro-ramp domain.

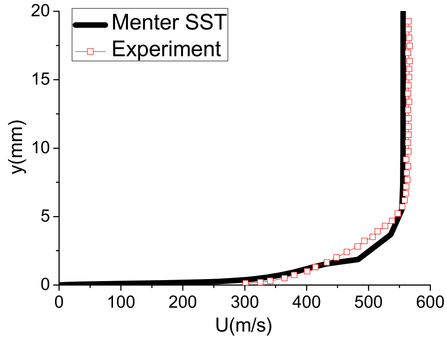


Fig. 4. Inflow boundary layer profile and comparison with simulation results.

Fig. 4 is the comparison of boundary layer internal velocity profile between simulation results and experimental values. It suggests that the simulation results are accordance with the experimental values. As shown in Fig. 5, the experimental values of near wall velocity distribution are compared with the simulation results. It suggests that the near wall velocity distribution of experimental values is approximately same with simulation results.

3. Results

3.1. Micro-vortex generator structure

Fig. 1(a) shows the micro-ramps device where the height of the device is given by h, the chord by c, and the half-angle of the span by α. The micro-ramp is scaled according to Anderson and et al. [10], the half-angle α is equal to 24 degrees, the side length c is 7.2 times of the device height h, and the span spacing s is 7.5 times of h. The novel dissymmetric micro-ramp is shown in Fig. 1(b), the length L is 7 times of the device height H, the span length W is 3 times of H, and the span spacing S is 7.5 times of H.

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