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Experimental investigation on supersonic boundary layer transition induced by single/multi- roughness elements

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Abstract

Supersonic boundary layer transition is of significance theoretically and in engineering applications due to the great differences in wall friction drag and wall heat flux between laminar boundary layer and turbulent boundary layer. As a typical passive flow control technique, although a lot of roughness-induced transitions of supersonic/hypersonic boundary layers have been investigated numerically and experimentally, the characteristics of transitions induced by single/multi- roughness elements still remain blank. Based on novel nanoparticle-based planar laser scattering (NPLS) technique, this paper conducts experimental investigations on various arrangements of roughness elements induced transitions in a Ma 2.95 wind tunnel. For single roughness, a stable shear layer is maintained at the ranges of x= [2.5, 16] mm, and then gradually developed into the hairpin vortex structures. The occurrence of near-wall secondary instability is resulted by the interaction between destabilized hairpin vortices and horseshoe vortices and is a key factor in inducing boundary layer transition downstream. For two adjacent roughness elements, as the latter roughness is right located in the end part of shear layer formed by the former, the destabilization of the shear layer is suppressed. Thus, the flow is maintained laminar. For three elements, the laminar flow elongates to x=27mm. This indicates that the onset of supersonic boundary layer transition may be delayed by arranging arrays of roughness elements.

Keywords: boundary layer transition; supersonic flow; roughness; NPLS

1. Introduction

Higher, faster and farther has always been the pursuit of human beings. The emergence and development of hypersonic vehicles fit this demand of human beings. Hypersonic vehicle technology is a new commanding point in the field of aerospace technology in the 21st century. However, there are many difficulties in the development of hypersonic vehicles. For example, the US hypersonic vehicle (HTV-2) failed in two flight tests in April 2010 and August 2011. Chris Schulz, director of HTV-2 program, said: "under the flight condition of Mach 20, there is still a blind spot in our understanding of Aircraft Aerodynamics" [1]. Boundary layer transition and turbulence problems are one of the inevitable blind areas in hypersonic field, which lead to major accidents such as the failure of HTV-2 flight test and the crash of space shuttle Columbia.

Boundary layer transition usually refers to the process of boundary layer flow developing from laminar flow to turbulent flow. It is a strong nonlinear complex flow physical phenomenon influenced by multi factor coupling. The transition problem is one of the few basic scientific problems left over by classical mechanics, and together with the turbulence problem, it is known as the "Century (or century) problem" [2]. As the boundary layer transition is very easy to occur in the range of altitude, velocity and Reynolds number of hypersonic vehicles, hypersonic boundary layer transition has always been a key basic problem restricting the design of aircraft, and also a key research topic of great Aerospace powers. In the national hypersonic basic research program (NHFRP) of the United States, hypersonic boundary layer control is definitely included in the medium and long-term key plan. The U.S. Air Force Scientific Research Office (AROSR) has launched the hypersonic boundary layer transition flight test program (BOLT). NASA's "CFD 2030 vision" even listed transition as the first kind of physical model problem to be solved urgently [4]. The "global engineering frontier 2019" and "global engineering frontier 2020" published by the strategic consulting center of Chinese

Academy of Engineering respectively ranked "Research on drag and heat reduction in supersonic flow" and "thermal protection technology for hypersonic aircraft" in the forefront of engineering development in the field of mechanical and transportation engineering for the third and eighth. In 2020, the National Natural Science Foundation of China will take "the mechanism and method of high-speed flow and control" as one of the priority development fields of the Ministry of mathematics and physics, and take "the turbulence mechanism and control method related to the flow of high-speed aerospace vehicles and marine vehicles and multiphase complex flow" as the main research direction.

In the case of hypersonic flow, the wall friction and heat flux of turbulent boundary layer are usually 3-5 times higher than that of laminar boundary layer [5]. It is very important to predict and control boundary layer transition accurately. Previous studies have shown that the weight of the thermal protection system of full laminar flow and full turbulence can be about 4 times different, the total resistance of full laminar flow can be reduced by about 30% compared with that of full turbulence [6], and the payload of full laminar flow is twice that of full turbulence [7]. It can be seen that the delay of hypersonic boundary layer transition can effectively reduce heat and drag, and ensure that the hypersonic vehicle "carries more, flies farther and safer".

The application of rough element in hypersonic boundary layer transition control has been started since 1950s. Rough elements can be divided into two types, namely isolated and distributed [8,9]. Height and position are important sensitive parameters of rough element control. The effect of different position and height of rough element on boundary layer transition control may be opposite. The research of rough element in transition promotion is more common. Schneider et al. [10] have carried out a lot of work on transition promotion, but there are few studies on transition delaying. Sterrett and Holloway et al. [11] were the first to find that the roughness element suppressed the transition phenomenon in wind tunnel experiments. When the height of the isolated roughness element was 0.76 and 1.26 times that of the local boundary layer, they observed that the boundary layer transition was delayed, which was attributed to the laminar separation zone near the roughness element. In the subsequent wind tunnel test, it was found that a hemispherical roughness element installed on the plate could also push the transition position downstream [12].

Based on the stability theory, the sensitivity problem caused by the scattering of two-dimensional rough elements in the hypersonic boundary layer is studied by Fedorov. It is found that the direction of the two-dimensional roughness element is the key to the influence of the second modal wave. When the two-dimensional rough element is arranged near the synchronous point of the slow mode and the fast mode interaction, the amplitude of the corresponding second mode wave is the strongest [13]. Marxen et al. [14] found that the two-dimensional roughness element had different effects on the second mode waves in different frequency ranges, and the disturbance to some frequencies could be amplified and the disturbance of certain frequencies could be suppressed. They think that the role of rough element is actually equivalent to a "low frequency amplifier". The study of Duan and Zhong [15-17] shows that when the rough element is placed upstream of the branch point of slow mode and fast mode interaction, the second mode wave is hardly affected by the roughness element. When the rough element is placed near or downstream of the branch point, the amplitude of the second mode wave will be suppressed by the two-dimensional rough element. Fong [18, 19] also found that the relative positions of the synchronization points of fast mode and slow mode in the rough element and the boundary layer are very important for the development of the disturbance wave. If the rough element is installed behind (in front of) the resonance point, the slow mode will be suppressed (amplified). Li Hui [20] studied the evolution of disturbances in a flat plate boundary layer with a bulge and Mach number of 4.5 and a flight altitude of 30km, and found that the rough element can promote the growth of some frequency disturbances and restrain others. In a word, the influence of rough elements on the disturbance wave depends on the installation position: under the condition of given disturbance wave frequency, the roughness element before the resonance point is limited or helpful to the second mode image. If it is installed at resonance point, it will inhibit the second mode. If it is installed near the resonance point, it is easy to excite the second mode. Because the resonance points of the disturbance waves with different frequencies are different, the disturbance waves with lower resonance frequency than the installation position will be amplified, while the disturbance waves with higher resonance frequency will be suppressed.

The reasonable arrangement of rough elements to excite the band with finite amplitude [21,22] has gradually attracted attention in the aspect of transition suppression. The mechanism of the finite amplitude band delayed transition is that the correction effect of the band on the boundary layer makes the boundary layer fuller and the flow more stable, but its control premise is that the strength of the band cannot exceed the critical strength of the secondary instability [23]. In the wind tunnel test of Fransson in 2006, the coarse micro elements with equal spacing distribution in spanwise direction were used to generate the strip structure, which suppressed the growth of T-S wave in the boundary layer and delayed the transition. The first mock exam and second mode interaction of K type and G type bands are studied in the Ma4.5 and Ma6 conditions. When the amplitude of the strip is within the proper range (i.e., enough to control the boundary layer without triggering two instabilities), the first mode and the second mode will be suppressed [24]. Paredes et al. [25, 26] studied the transition control of a 7-degree conical boundary layer with rough elements under the condition of ma 5.3 by using PSE. In their experiments, a single group of rough elements brings about 17% transition delay effect. If two groups of rough elements are used to control alternately (that is, the latter is used to suppress the instability induced by the former group of rough elements), It can achieve 40% delay control effect.

However, the control effect of rough element is very sensitive to the flow parameters. For example, only 6 of 112 flight experiments of 30 degree swept wing in Chapter observed that the boundary layer transition was obviously delayed, and the transition may be advanced under inappropriate fluid conditions [27]. It can be seen that there are still many challenges for rough element and strip control to move from wind tunnel experiment to actual flight. More explanation about roughness induced/delayed transition can be found in [28].

This paper investigates the roughness induced transition experimentally using NPLS technique. Different number of roughness are tested to compare the control effect.

2. Experimental setup

The whole experiments are conducted in a *Ma* 2.95 wind tunnel with its turbulence intensity lower than 1%. Laminar-turbulent transition do not occur within the streamwise distance of 300mm. The dimensions of the test section are 400mm in length, 200mm in height and width respectively. Total pressure and stagnation temperature of the free stream flow are P0=0.1MPa and T0=300K. The unit Reynolds number is 7.49×10^6/m.

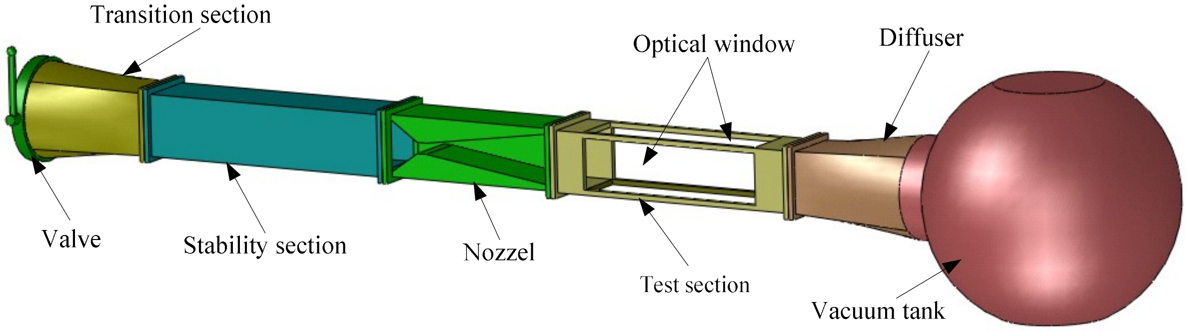

Figure 1 –Wind tunnel schematic.

Table 1 Parameters of wind tunnel.

Ma	P_0/MPa	T_0/K	$Re/10^6\times m^{-1}$	t/s
2.95	0.1	300	7.49	>10

NPLS is a new kind of flow visualization technique with a high temporal and spatial resolution for the fine supersonic/hypersonic flow measurement. TiO_2 is adapted as the tracing particle to capture the fine flow structures, with an average diameter less than 50 nm. As shown in Fig.2, the NPLS system is composed of a computer, a CCD camera, a synchronizer and a dual-cavity Nd: YAG laser. The region of the test section of interest is illuminated by a laser sheet with a wavelength of 532 nm, and Rayleigh scattering signals of particle are recorded by a CCD camera fixed perpendicular to the laser sheet. The synchronizer is used to make the laser and the CCD camera work cooperatively. The laser has a pulse time of 6 ns and a maximum pulse energy of 350 mJ. The thinnest part of the laser sheet is less than 0.5 mm. The image size is 2048×2048 pixels with a gray level of 4096. More detailed information about NPLS technique and its performance can be found in reference [29].

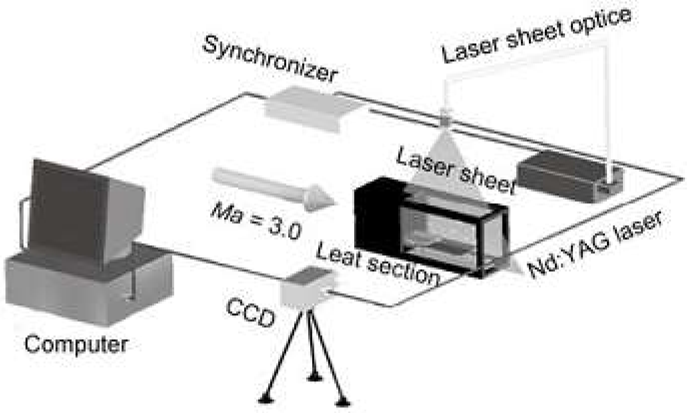

Figure 2 –The schematic of NPLS system [29].

The cylindrical roughness element is 5mm in diameter, 1mm in height ($2\delta_{0.99}$). The center of the first element is defined as the coordinate origin and locates 122.5mm downstream from the leading edge of the flat-plate. The distance between each element is 7.5mm. Here, for convenience, the leading edge of the first roughness is defined as the origin of coordinates, as shown in the following.

3. Results

The basic principle of NPLS technique in that the gray scale of the images is proportional to the density of density of flow field. As the inner part of boundary layer is lower than that of the outer mainflow, the black part in the images corresponds to the boundary layer. For streamwise images, the spatial resolution of the images is 57.9 μm/pixel, while for spanwise ones, it is 44.6 μm/pixel. With a minimum of 6-ns time interval, NPLS image pairs have the advantage of high temporal-spatial resolutions.

Fig. 3 shows the transient NPLS image pair with a 5 μs delay of the streamwise flowfields of single roughness and Fig.4 gives the corresponding spanwise image. For single roughness, a stable shear layer is maintained at the ranges of x= [2.5, 16] mm, and then gradually developed into the hairpin vortex structures. The occurrence of near-wall secondary instability is resulted by the interaction between destabilized hairpin vortices and horseshoe vortices and is a key factor in inducing boundary layer transition downstream. Right after the roughness, the flow still maintains a laminar state elongating to about x=16mm. And then, due to the strong Kelvin-Helmholtz (K-H) instability in the roughness-induced shear layer, the flow begins to destabilize and breakdown into small scale coherent structures suddenly. Ultimately, the flow become completely turbulent, presenting obvious intermittence.

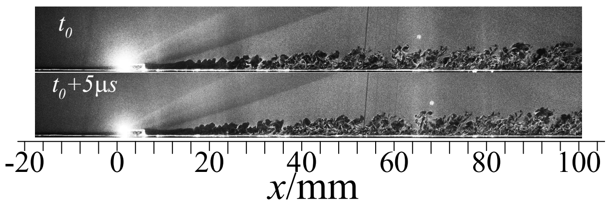

Figure 3 –Transient NPLS image pair with a 5 μs delay of the streamwise flowfields: single roughness.

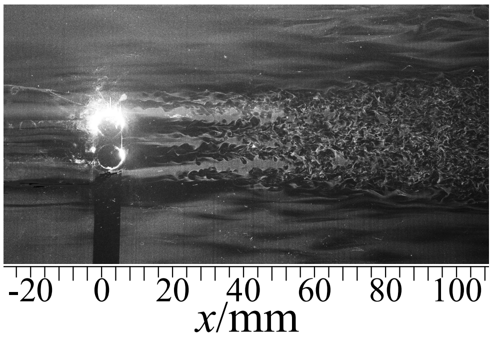

Figure 4 –Transient NPLS image of the spanwise flowfields: single roughness.

Fig. 5 and Fig. 6 gives the transient NPLS image pair with a 5 μs delay of the streamwise flowfields for double and triple roughness, respectively. Fig. 7 presents corresponding spanwise viewpoints. The flow field around the rough element is very disordered. This is due to the wake vortex formed in the flow field behind the three-dimensional rough element, which causes the strong disturbance and shear effect in the plate boundary layer and makes the laminar boundary layer transition to turbulence. Fig. 8 gives a comparison between single/multi- roughness elements induced transition in streamwise direction. For two adjacent roughness elements, as the latter roughness is right located in the end part of shear layer formed by the former, the destabilization of the shear layer is suppressed. Thus, the flow is maintained laminar. For three elements, the laminar flow elongates to x=27mm. This indicates that the onset of supersonic boundary layer transition may be delayed by arranging arrays of roughness elements.

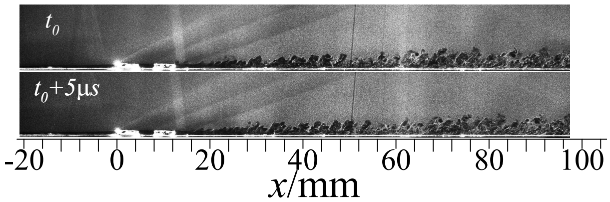

Figure 5 –Transient NPLS image pair with a 5 μs delay of the streamwise flowfields: double roughness.

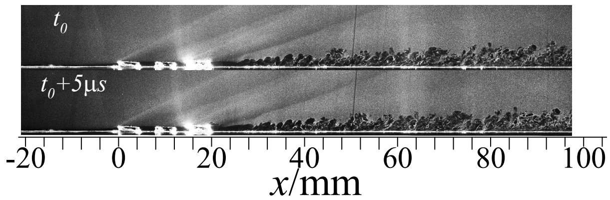

Figure 6 –Transient NPLS image pair with a 5 μs delay of the streamwise flowfields: triple roughness.

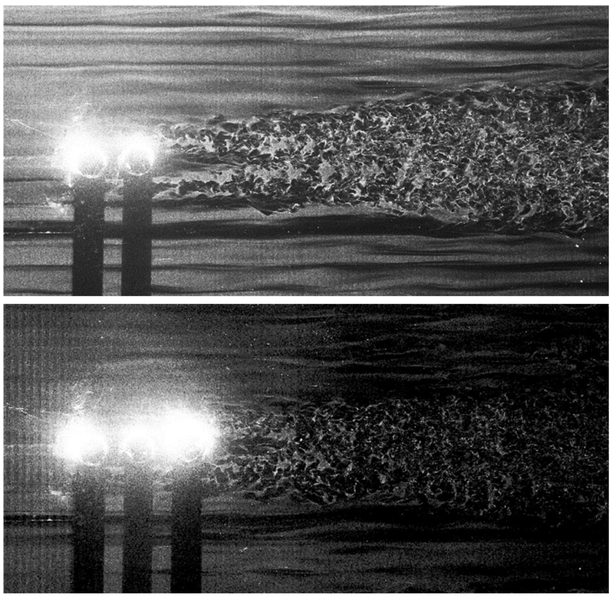

Figure 7 –Transient NPLS images of the spanwise flowfields: double and triple roughness.

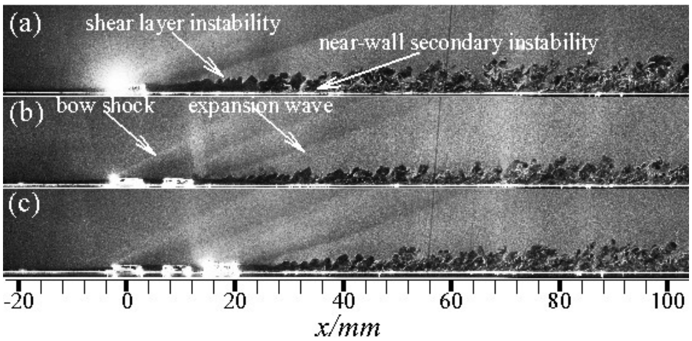

Figure 8 –Comparison between single/multi- roughness elements induced transition in streamwise direction.

4. Conclusion

Generally, the rough element will produce wake vortex with streamwise vorticity in the supersonic boundary layer, and the rough element with enough height will produce shock wave. The effect of wake vortex and shock wave will increase the instability in the boundary layer. However, as the latter roughness is right located in the end part of shear layer induced by the former, the destabilization of the shear layer will be suppressed. Thus, the flow is maintained laminar. This indicates that the onset of supersonic boundary layer transition may be delayed by arranging arrays of roughness elements.

Copyright Statement

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