Acta Astronautica 118 (2016) 199–209

Contents lists available at ScienceDirect

Acta Astronautica

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

A combined experimental and numerical investigation of roughness induced supersonic boundary layer transition

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ARTICLE INFO

Article history:
Received 29 June 2015
Received in revised form
28 September 2015
Accepted 12 October 2015
Available online 19 October 2015

Keywords:
Boundary layer transition
Surface roughness
Supersonic
Experiment
Numerical simulation

ABSTRACT

The effect of surface roughness on boundary layer transition is of great importance to hypersonic vehicles. In this paper, both experimental and numerical methods are used to investigate the laminar-turbulent transition of a Mach 3 flat-plate boundary layer induced by isolated roughness element. Good agreements are achieved between experimental data and high-order numerical simulations. It is observed that, with increasing height of roughness, the transition tends to move forward. Two different types of transition mechanisms are found according to the height of the roughness elements. For the smallest roughness height of $h=1$ mm, the shear layer instability in the wake region appears to be the leading mechanism for transition to turbulence. For two larger roughness elements of $h=2$ mm and $h=4$ mm, strong unsteadiness is developed from the upstream separation zone and transition is immediately accomplished, which indicates that the absolute instability in upstream separation zone dominates the transition.

1. Introduction

Laminar-turbulent transition is of great importance to the design of supersonic and hypersonic vehicles which can significantly affect vehicles' aerodynamic lift and drag, control and surface heat transfer. The effect of surface roughness on transition is one of the active research topics in recent years. For a reentry vehicle, the presence of three-dimensional surface roughness tends to accelerate the laminar-turbulent transition process, leading to dramatic increase in surface heating which directly impacts the vehicle's performance and safety [1,2]. In scramjet applications [3], artificial roughness elements are often employed by combustors inlet for hypersonic cruise vehicles to trip transition and prevent engine unstart. Despite its importance on the design and operation of hypersonic vehicles, the mechanisms by which roughness affects transition are at present poorly understood.

Surface roughness is often classified into isolated roughness element and distributed roughness [4]. Early experiments at low-speed [5,6] have provided a basic understanding of the physical mechanisms about isolated roughness induced transition. However, for hypersonic boundary layer, the studies are started considerably late due to limitations in high-speed experimental instruments and numerical methods. A recent review of this subject is given by Schneider [4], in which the complexities and difficulties at high-speed regime are discussed in-depth. One aspect of the complexity is the large amount of affecting factors. Different from transition in incompressible flow, besides Reynolds number and the shape and height of the roughness element, transition at supersonic and hypersonic speeds is also sensitive to the Mach number and acoustic disturbances. Experimental data collected by Schneider [4] shows that at higher Mach numbers, the critical Reynolds number increases remarkable. Meanwhile, many complex flow physics such as

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http://dx.doi.org/10.1016/j.actaastro.2015.10.008
0094-5765/

shock, shock-turbulence interaction, flow separation, unstable shear layer and multiple instability modes may occur when a large roughness element is placed in a hypersonic boundary layer. In Bartkowicz et al.'s [7] study, an unstable vortex-shock system creates disturbances that travel downstream and cause the Mach 6 boundary layer to transition. Redford et al. [8] results have highlighted the importance of the instabilities of the detached shear layer on the breakdown process when the convective Mach number varies. These studies have indicated that there probably exists a new class of instability mechanisms in high-speed flow which is different from that in incompressible cases. However, little is known in this aspect.

In recent years, with fast advances in numerical methods and computer technologies, high-order numerical simulations in discretizing compressible Navier–Stokes equations have become an effective research tool for supersonic/hypersonic boundary layer transition study. Zhong [9] presented a set of high-order upwind finite difference shock-fitting method for hypersonic boundary layer receptivity, instability, and transition simulation. The fifth-order shock-fitting scheme was adopt by Wang and Zhong [10] for investigating receptivity of a Mach 5.92 flat-plate boundary layer to three-dimensional surface roughness. Their results showed that counter-rotating streamwise vortices and transient growth were induced by surface roughness. The spanwise wave number of roughness had a strong effect on the excitation of transient growth. Bernardini et al. [11] performed DNS study of the compressibility effects on roughness induced boundary layer transition using a sixth-order central finite difference scheme. Based on large numbers of computations, a wall kinematic viscosity based, modified roughness Reynolds number was proposed as criterion for roughness-induced transition which incorporates the effect of compressibility. Many other recent computations can also be found in Marxen et al. [12], Iyer and Mahesh [13]. These latest high-order numerical researches have considerably extended our knowledge of flow physics by which roughness affects transition at high-speed.

Meanwhile, many high-accuracy experimental techniques have also been developed recently for supersonic/hypersonic boundary layer transition and turbulence measurements. For example, Danehy et al. [14] investigated the hypersonic transition over an isolated hemispherical roughness element in a Mach 10 wind tunnel at NASA Langley Research Center. Nitric oxide (NO) planar laser-induced fluorescence (PLIF) flow visualization method had been used to characterize the flow structures in the transitional wake region. It was found in the PLIF images that streamwise corkscrew-shaped structures appeared to be the leading mechanism for transition to turbulence in the flow field. Wheaton and Schneider [15] recently carried out experimental measurements of instability and transition in the wake of a cylindrical roughness within the laminar nozzle-wall boundary layer of the Purdue Mach-6 Quiet Tunnel. Under a controlled low-noise experiment environment, the dominant disturbance frequencies were identified, and streamwise evolution of these disturbances were also reported.

In present paper, we use both high-order numerical method and high-accuracy experimental technique to investigate the transition of a Mach 3 laminar flat-plate boundary layer induced by isolated cylindrical roughness element. While numerical simulation provides a detailed analysis of the entire flow field, experimental measurement discovers the real flow physics and confirms the results of the computation. For experiments, a nano-based planar laser scattering (NPLS) technique is adopted in current study. The NPLS is a novel flow visualization technique developed by Yi et al. [16] for measuring fine structures of supersonic/hypersonic flow, whose spatial resolution can reach the micron scale with a time resolution of 6 ns, and the temporal correlation resolution can reach 0.2 μs. For numerical simulations, a fifth-order weighted compact nonlinear scheme WCNS-E-5 [17] is utilized to discrete the compressible Navier–Stokes equations. The objective of this work is to combine the above experimental and numerical methods to investigate the flow phenomenon of supersonic boundary layer transition by a surface roughness element.

2. Experimental and numerical methods

2.1. Experimental methods

2.1.1. Supersonic wind tunnel and the testing model

The experiments are carried out in a Mach 3 low-noise wind tunnel which runs in an indraft mode. The total pressure and stagnation temperature of the incoming flow are $P_0 = 1$ atm and $T_0 = 300$ K, respectively. And other freestream flow parameters are listed in Table 1.

As shown in Fig. 1, a vitreous flat plate with sharp leading edge is used to generate laminar boundary layer in experiments. The distance between the upper surface of flat-plate and the ceiling of the testing chamber is 80 mm (the size of the cross section of the testing section was width 100 mm × height 120 mm), which ensures that the flat-plate is within the uniform flow region, thus a laminar supersonic boundary layer is formed on the upper surface of plate naturally. A three-dimensional cylindrical roughness element is located at a distance of 135 mm downstream from the leading edge of the flat plate, to trip the boundary layer transition. The undisturbed laminar boundary layer thickness tested at the location of roughness is $\delta = 1.2$ mm. In this paper, three different roughness height conditions of $h = 1$ mm, 2 mm and 4 mm are tested.

Table 1
Wind tunnel flow parameters.

Mach number (M)	Pressure (p)	Temperature (T)	Velocity (u)	Viscosity (μ)	Reynolds number (Re)
3	2750 Pa	107 K	622.5 m/s	7.43×10^{-6} Ns/m^2	7.5×10^6/m