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RAPID COMMUNICATION

Supersonic boundary layer transition induced by self-sustaining dual jets*

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To promote high-speed boundary layer transition, this paper proposes an active self-sustaining dual jets (SDJ) actuator utilizing the energy of supersonic mainflow. Employing the nanoparticle-based planar laser scattering (NPLS), supersonic flat-plate boundary layer transition induced by SDJ is experimentally investigated in an *Ma*-2.95 low-turbulence wind tunnel. Streamwise and spanwise NPLS images are obtained to analyze fine flow structures of the whole transition process. The results reveal the transition control mechanisms that on the one hand, the jet-induced shear layer produces unstable Kelvin–Helmholtz instabilities in the wake flow, on the other hand, the jets also generates an adverse pressure gradient in the boundary layer and induce unstable streak structures, which gradually break down into turbulence downstream. The paper provides a new method for transition control of high-speed boundary layer, and have prospect both in theory and engineering application.

Keywords: supersonic boundary layer transition, self-sustaining dual jets, nanoparticle-based planar laser scattering (NPLS), vortex structures

PACS: 47.85.ld, 47.40.Ki, 47.80.Jk, 47.27.De **DOI:** 10.1088/1674-1056/ab5ef7

The pursuit for hypersonic flight has been the dream for several decades but it has encountered many difficulties, among which boundary layer transition is of great importance. Laminar boundary layer has lower friction drag and heat flux. However, compared with laminar boundary layer, turbulent boundary layer has the superiority of stronger momentum transport and can effectively suppress flow separation in inlet and enhance mixing in combustor.[1] Thus, laminar–turbulent transition and the corresponding flow control have drawn much attention over the past several decades.[2] Flow control methods involve roughness,[3,4] vortex generator,[5] wall perturbation,[6] thermal bump,[7] blowing and suction,[8] and jet control.[9] These techniques have been widely studied by researchers. Considering additional drag and energy consumption, however, not all are so satisfactory. It is necessary to develop a new lower extra-drag and zero-energy-consumption method for transition control.

In this paper, an active self-sustaining dual jets (SDJ) is proposed based on traditional dual synthetic jet actuator.[10] Employing nanoparticle-based planar laser scattering (NPLS), fine flow structures of the whole supersonic boundary layer transition process are experimentally obtained. NPLS is a novel non-contacted flow visualization technique invented by Yi and Zhao.[11] It adopts nanoparticles — TiO_2, with average diameter less than 45 nm — as tracer particles to accurately track high-speed flows, and has been applied to supersonic mixing layer,[11] supersonic flow over a forward-facing step,[12] and over a double elliptic surface,[13] *etc*.

The whole experiments are conducted in an *Ma*-2.95 wind tunnel with its turbulence intensity lower than 1%. Laminar–turbulent transition does not occur within the streamwise distance of 300 mm. The dimensions of the test section are 400 mm in length, 200 mm in height and width respectively. Total pressure and stagnation temperature of the free stream flow are $P_0 = 0.1$ MPa and $T_0 = 300$ K. The unit Reynolds number is 7.49×10^6/m. Experiment system is shown in Fig. 1. The testing model is a flat plate with the dimensions as follows: the length 320 mm, the width 199 mm, and the angle of leading wedge is 15° (see Fig. 1(a)). As shown in Fig. 1(b), the SDJ actuator has two additional inlets compared with dual synthetic jet actuator. The basic idea of this design is that the vibrating diaphragm is too inefficient in low-pressure environment to form synthetic jet. Motivated by fluidic shock control technique[14] and based on the idea of making full use of incoming flow kinetic energy, two variable ram-air inlets are designed on the windward to collect incoming fluids. And then continuous jets eject from the outlet orifices. Thus, self-sustaining jets are formed. The

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jets strength can be controlled by adjusting the sizes of inlets. Its control ability has been confirmed in *Ma*-3 and *Ma*-5 supersonic/hypersonic wind tunnels, respectively.[15,16] In this paper, the sizes of the actuator inlets and the orifices are 1 mm × 1 mm and 20 mm × 2 mm respectively. The distance between two outlet orifices centers is 7 mm. The orifices of actuator locates 110-mm downstream from the leading edge of the flat plate. In numerical simulations, the average velocity of outlet orifices in this situation is 4.53 m/s.

Experimental setup is presented in Fig. 1(c). Laser sheet illustrates the area of interest along the central line of one orifice to get streamwise images (x–z plane). By transforming the position of camera and laser sheet, spanwise images (x–y plane) can be obtained. The size of the images is 4000 pixel×2672 pixel and the gray level is 4096. The synchronizer is used to adjust the time of laser, ensuring that CCD camera can capture two images accurately in the frames of dual exposure. The dual-cavity Nd:YAG laser has a pulse time of 6 ns and a maximum pulse energy of 350 mJ. More detailed information about NPLS technique can be founded in Ref. [11].

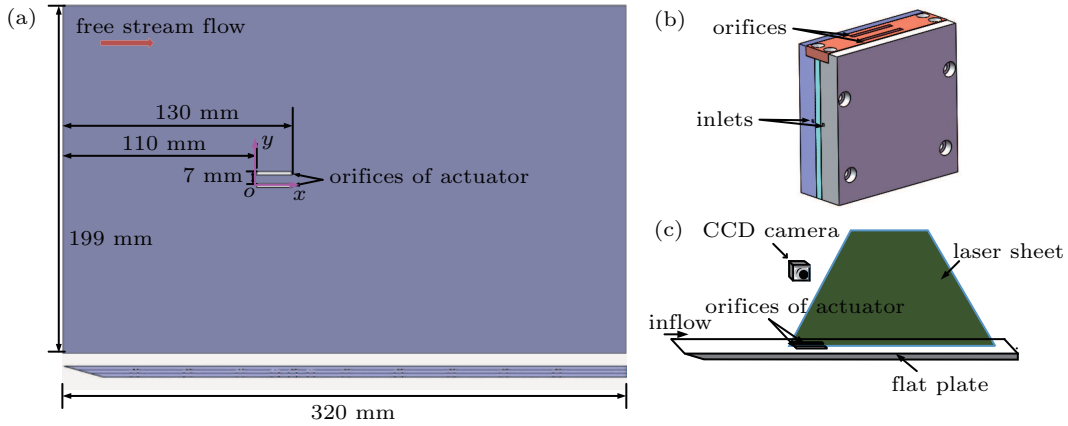


Fig. 1. Schematic diagram of experiment system, (a) testing model, (b) SDJ actuator, and (c) experimental setup.

The basic principle of NPLS technique is that the gray scale of the images is proportional to the 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.

Typical transient streamwise NPLS image pair with a 5-μs delay are shown in Fig. 2. The flow is from left to right. Laminar boundary layer is maintained well with its thickness gradually increases until upstream of the orifices. Above the orifices, the boundary layer thickness increases at a slope of 5°. Right after the orifices, the flow still maintains a laminar state elongating to about $x = 35$ mm. And then, due to the strong Kelvin–Helmholtz (KH) instabilities in the jet-induced shear layer, the flow begins to destabilize and breakdown into small scale coherent structures suddenly. Ultimately, the flow become turbulent completely, presenting obvious intermittence.

Compared with the image pair, we can find that although there are some changes in the coherent structures, they are aligned and translated in the streamwise direction. The vortex structures move downstream for about 2.9 mm in a 5-μs time interval, with the corresponding translating velocity of 580 m/s. They also rotate clockwise by a certain angle. Thereby, the coherent structures of the supersonic boundary layer has the characteristics of fast motion and slow deformation.

To some extent, the jets act like two bumps over the orifices. They generate a certain adverse pressure gradient (APG) to the boundary layer, compel the boundary layer thickness to increase and enhance the various instabilities of the original existing disturbances. The difference is that the jets can also introduce many kinds of disturbances, such as acoustic waves, entropy waves, and vorticity waves, directly into the boundary layer.

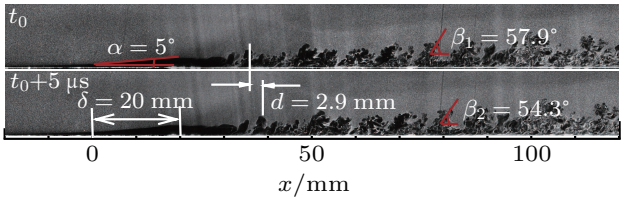


Fig. 2. Transient streamwise NPLS image pair with a 5-μs delay.

For boundary layer flow, the unstable streaks gradually break down into irregular small-scale structures and present an irregular curve due to the density difference between mainflow and boundary layer. Fractal dimension is a geometric quantity describing the degree of an irregular curve and has been applied to analyze the turbulent flow since 1980s.[17] Figure 3 demonstrates the fractal characteristics of supersonic boundary layer. Since the former part is not exacted clearly, only areas after $x = 20$ mm are valid. The fractal dimension increases

at first along the streamwise direction and then reaches to a fixed value at about $x = 100$ mm. It indicates that the streamwise vortex structures produced by the jets gradually become unstable and breakdown into turbulence finally. The fragmentation degree of the whole supersonic boundary layer transition process increases with the scale contraction of coherent structures.

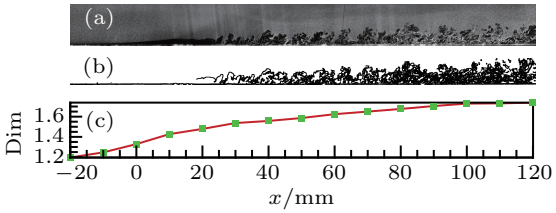


Fig. 3. Fractal characteristics of supersonic boundary layer, (a) NPLS images, (b) the curves of the edge detection, and (c) the curve of the fractal dimension.

Unlike streamwise ones, spanwise flow fields have more complex vortex structures due to the three-dimensional characteristic of boundary layer flow, which can demonstrate transition process more intuitively. By analyzing the spatially developing supersonic turbulent boundary and incompressible turbulent boundary, Pirozzoli[18] and Yoshikawa[19] concluded that the large-scale structures, such as hairpin vortices and hair packets, were the main compositions of outer layer while the inner layer was composed of quasi-streamwise vortices, respectively. He confirmed this phenomenon directly by NPLS experiments.[20] This paper also gives the spanwise NPLS images of supersonic boundary layer transition controlled by SDJ.

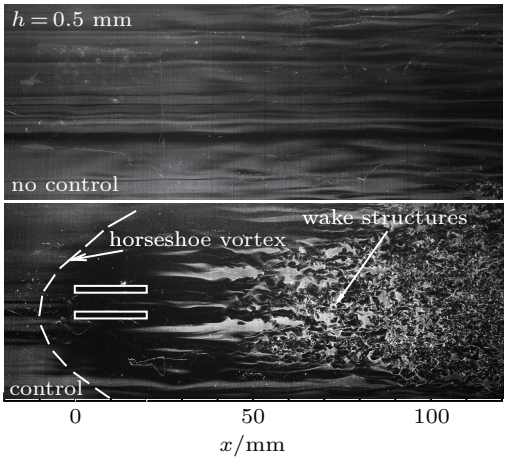


Fig. 4. Comparison between uncontrolled/controlled spanwise NPLS images at the height of 0.5 mm.

Figure 4 presents transient spanwise NPLS images at the height of 0.5 mm. For the purpose of comparison, an uncontrolled image is given. For the uncontrolled flowfield, the whole flow maintains laminar and only some long streaks can be observed. While for the boundary layer with SDJ control, the flow structure can hardly be observed in the upstream region of the images, indicating that the boundary layer is laminar. Due to the obstacle of adverse pressure gradient induced by SDJ, however, horseshoe vortex systems form upstream of the jet orifices.[21] Right after the horseshoe vortexes, several streamwise streaks (presented in dark color) appear. It is observed that downstream of the horseshoe vortex, these streak structures become organized and alternate in spanwise direction, and the scale in flow direction is much larger than that of spanwise. In fact, boundary layer transition is just accompanied by these streak structures. From the point view of dynamics, these streak structures continue to twist and twist in the process of propagation downstream, and bifurcate to derive new streaks after they move to a certain distance of flow direction. Actually, this also corresponds to the self-sustaining mechanism of turbulence, which indicates that turbulence is self-generated. Downstream, the streak structures gradually lose their stabilities and breakdown into turbulence finally.

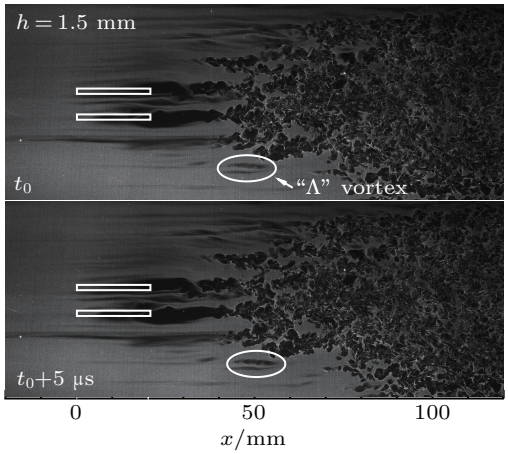


Fig. 5. Transient spanwise NPLS image pair with a 5-μs delay at the height of 1.5 mm.

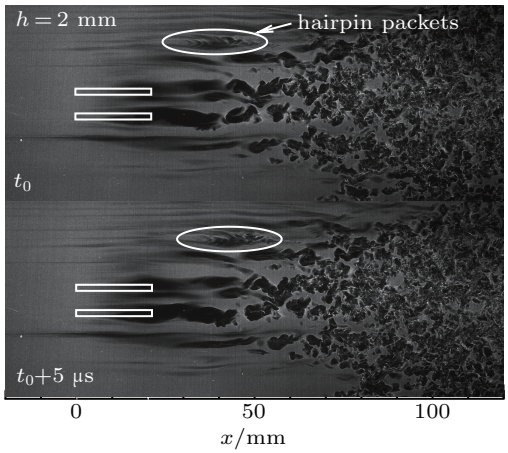


Fig. 6. Transient spanwise NPLS image pair with a 5-μs delay at the height of 2 mm.

Figures 5 and 6 give transient spanwise NPLS image pair with a 5-μs delay at the height of 1.5 mm and 2 mm, respectively. At this time, the streaks are no longer very clear. Only in the turbulent region downstream, with the increase of the boundary layer thickness, some irregular coherent structures can be observed. In Fig. 5, a typical “Λ” vortex is observed with its head facing to flow direction and the feet pointing to

the upstream. The strengths of its two legs are not inconsistent. In fact, the probability of this inconsistence is quite high in the boundary layer. A bunch of hairpin packets are also observed in Fig. 6. These coherent structures are located in the outer layer of boundary layer and move together at essentially the same convective velocity. This phenomenon confirms the conclusions in incompressible experiments conducted by Adrian and Christensen.[22,23] As the flow is unsteady, however, these coherent structures are not always visible or fixed in a certain position.

This letter proposes an active transition control technique-SDJ, and experimentally investigates its performance on supersonic flat plate boundary layer in an *Ma*-2.95 low-turbulence wind tunnel. The actuator makes full of the kinetic energy of mainflow without any energy-consumption. Fine flow structures in both streamwise and spanwise planes are obtained based on NPLS technique. The interactions between primary jet-induced streaks and the mainflow generate shear layers and bring the KH instabilities to the boundary layer. Meanwhile, the horseshoe vortex induced by adverse pressure gradient also introduces several unstable streak structures. The interactions between the two types of the streaks in the process of downstream movement bifurcate and derive new streaks and breakdown into turbulence finally.

References

[1] Fedorov A 2011 *Ann. Rev. Fluid Mech.* **43** 79
[2] Zhong X L and Wang X W 2012 *Ann. Rev. Fluid Mech.* **44** 527
[3] Fong K D, Wang X W and Zhong X L 2014 *Comput. Fluids* **96** 350
[4] Tang Q, Zhu Y D, Chen X and Lee C B 2015 *Phys. Fluids* **27** 064105
[5] Berry S A, Nowak R J and Horvath T J 2004 34*th AIAA Fluid Dynamics Conference*, 28 June–1 July, 2004, Oregon, Portland, p. 2246
[6] Wang X W and Zhong X L 2009 *Phys. Fluids* **21** 044101
[7] Yan H and Gaitonde D 2010 *Phys. Fluids* **22** 064101
[8] Wang X W and Zhong X L 2008 38*th Fluid Dynamics Conference and Exhibit*, 23–26 June, 2008, Washinfton, USA, p. 3731
[9] André T, Durant A and Fedioun I 2017 *AIAA J.* **55** 1
[10] Luo Z B, Xia Z X and Liu B 2006 *AIAA J.* **44** 2418
[11] Zhao Y X, Yi S H, Tian L F and Cheng Z Y 2009 *Sci. Chin. Ser. E-Tech.* **52** 3640
[12] Zhang Q H, Zhu T, Yi S H and Wu A P 2016 *Chin. Phys. B* **25** 054701
[13] Zhang Q H, Yi S H, He L, Zhu Y Z and Chen Z 2013 *Chin. Phys. B* **22** 114703
[14] Richard G H, Jeff S N and Russell L D 2001 *J. Spacecr. Rockets* **38** 51
[15] Liu Q, Luo Z B, Deng X, Wang D P, Wang L, Zhou Y and Cheng P 2019 *Acta Astronau.* **164** 262
[16] Yang S K, Luo Z B, Deng X, Liu Q and Wang L 2017 *Proceeding of APCATS* 2017 *& AJSAE* 2017, 20–23 November, 2017, Beijing, China, p. 387
[17] Sreenivasan K R 1991 *Ann. Rev. Fluid Mech.* **23** 539
[18] Pirozzoli S, Bernardini M and Grasso F 2008 *J. Fluid Mech.* **613** 205
[19] Yoshikawa J, Nishio Y, Izawa S and Fukunishi Y 2018 *Phys. Rev. Fluids* **3** 013904
[20] He L, Yi S H, Zhao Y X, Tian L F and Chen Z 2011 *Chin. Sci. Bull.* **56** 489
[21] Kelso R M and Smits A J 1995 *Phys. Fluids* **7** 153
[22] Adrian R J, Meinhart C D and Tomkins C D 2000 *J. Fluid Mech.* **422** 1
[23] Christensen K T and Adrian R J 2001 *J. Fluid Mech.* **431** 433