EFFECT OF FREESTREAM DISTURBANCES ON BOUNDARY LAYER TRANSITION IN HYPERSONIC WIND TUNNEL

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Abstract

The freestream disturbance has a direct influence on hypersonic boundary layer transition. Compared with the atmospheric environment, the level of freestream disturbance in conventional hypersonic wind tunnels is 1-2 orders of magnitude higher, which leads to a large difference in transition phenomena between wind tunnel experiments and real flight. Therefore, quantifying the level of wind tunnel freestream disturbance and its effect on transition is of great significance for predicting the real transition data of hypersonic vehicles. In the present work, an experimental investigation on freestream disturbance and transition measurement was carried out based on two hypersonic wind tunnels (FL-63 and FL-64) in AVIC Aerodynamics Research Institute (AVIC ARI). The level of freestream disturbance was measured and evaluated by Focused Laser Differential Interferometry and pressure probes. The transition position of hypersonic model (HIFiRE-5) was measured by temperature sensitive paint. The results show that Focused Laser Differential Interferometry can quantitatively characterize the level of freestream disturbance in hypersonic wind tunnel, and a high level of freestream disturbance will make boundary layer transition more forward.

Keywords: hypersonic, boundary layer transition, freestream disturbance, wind tunnel test

1. General Introduction

Boundary layer transition has an important effect on the force/thermal performance of hypersonic vehicles. Previous studies have shown that the friction drag and heat flux of turbulent boundary layers are 3-5 times greater than that of laminar boundary layers [1]. So accurate prediction of boundary layer transition is of great significance for hypersonic vehicle design. At present, numerical calculation, wind tunnel test and flight test are the three main methods for transition prediction. Among them, wind tunnel test is widely used and trusted due to its low cost, high efficiency and relative reality. However, in wind tunnel tests, a significant problem is that the disturbance level of the freestream is much higher than that of the atmospheric environment, which makes the ground results different from the flight results. Therefore, how to quantify the level of freestream disturbance becomes the focus of concern.

In the past, disturbance measurement techniques mainly relied on pitot tubes and hot-wire anemometers. The pitot tube measures the total pressure fluctuation after the shock wave, which cannot represent the pressure fluctuation in the real freestream. The hot wire probe can acquire the total temperature and mass flux fluctuations of freestream, but it's very easy to be damaged in hypersonic flow field. In recent years, a non-intrusive optical measurement technique called Focused Laser Differential Interferometry (FLDI) has been developed for the acquisition of density fluctuations in hypersonic flow fields, and shows a good application prospect. By optical focusing, the "probe" is placed at the measuring point in a non-intrusive way, which avoids the destruction of the flow field by the measurement itself, and can obtain the real information. At the same time, FLDI has extremely high spatial and temporal resolution, and the response frequency of the optical path can reach 100 MHz, which can easily capture the high-frequency mode disturbance of the hypersonic flow field. More importantly, FLDI can be used in more demanding test environments, such as high enthalpy wind tunnels with total temperatures up to several thousand Kelvin, without the risk of probe damage.

A lot of research has been carried out on the measurement of wind tunnel freestream disturbance by FLDI. Parziale measured the density disturbances in the freestream of T5, the reflected shock tunnel at Caltech. The results showed that the root-mean-square (rms) of density fluctuation for Mach number 5.5 is less than 0.75% [2-3]. Fulghum modified the traditional FLDI optical path system and tested it in the Penn State University Supersonic Wind Tunnel and USAF AEDC Hypervelocity Tunnel 9. The data showed that the density fluctuation level for Mach number 3 in PSUSWT is about 0.3%, and that for Mach number 10 in AEDC Hypervelocity Tunnel 9 is about 7.7% [4]. Birch used the same FLDI optical path system as Fulghum to measure the freestream density disturbances in the Mach 6 wind tunnel at the University of Southern Queensland. In the experiment, the contact between the FLDI optical path and the turbulent shear layer of the nozzle was isolated by the shield, and the contribution of the turbulent shear layer to the whole FLDI signal was eliminated to a large extent, thus significantly improving the measurement [5]. Ceruzzi used the two-point FLDI system at UTSI Mach 4 Ludwieg tube and AEDC T9 Mach 18 freestream, to obtain convection velocity and wave-number spectra [6]. Houpt developed cylindrical focused laser differential Interferometry (CFLDI) and measured the freestream disturbance s in the wall boundary layer and core region of the supersonic wind tunnel at the University of Notre Dame. The results showed that the disturbance level in the boundary layer is higher at all measured frequencies compared to the core region [7].

The present work is to evaluate the level of freestream disturbance in two hypersonic wind tunnels (FL-63 and FL-64) in AVIC ARI and investigate the transition difference of the same configuration in two wind tunnels.

2. Experimental Setup Details

2.1 Facility Description

FL-63 wind tunnel is a combined pulsed high-enthalpy facility newly built by AVIC ARI, as shown in Figure 1. The tunnel operates in a combination of two modes with a wide Mach number simulation capability. At Mach 3.0-4.5, the Ludwieg tube operation mode is adopted, the nozzle diameter is 300mm, the effective running time is greater than 150ms, and the maximum total temperature is 900K. While at Mach 5.0-10.0, the shock tube operation mode is adopted, the nozzle diameter is 500mm, the effective running time is greater than 20ms, and the maximum total temperature is 1200K.

(a) Ludwieg tube

(b) Shock tube

Figure 1. Photograph of FL-63 wind tunnel

FL-64 hypersonic wind tunnel is a large blowdown free jet type facility newly built by AVIC ARI, as shown in Figure 2. It adopts the blowing type operation mode, at the same time, considering the test requirements of low dynamic pressure, a vacuum exhaust system is also equipped. The nozzle diameter is 1.0m, the range of Mach number is 4.0-8.0, the total pressure range of the settling chamber is 0.1-8.0 MPa, the total temperature range of the settling chamber is 300-900K, and the effective operating time is greater than 30 s.

Figure 2. Photograph of FL-64 wind tunnel

2.2 Model Description

The model used in the experiments is HIFiRE-5 elliptic cone. It is a 38.1% scale model of the flight vehicle. The model length is 328mm long, the base semi-major axis is 82 mm, the base semi-minor axis is 41 mm, and the nosetip radius along the minor axis is 0.95 mm. Figure 3 shows the geometry of the model. The reason for choosing this model is that it’s an internationally recognized hypersonic transition model, and there are a lot of experimental data and flight data that can be compared. Moreover, the second mode and the crossflow mode in this model are the common transition patterns for hypersonic aircraft.

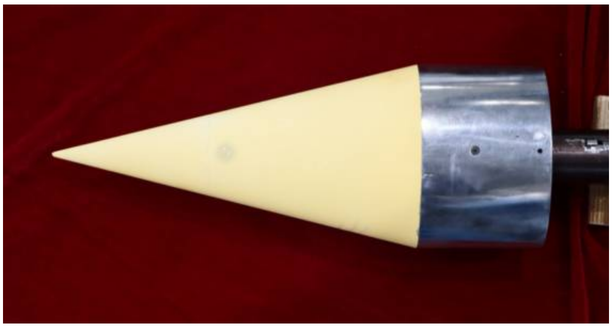

Figure 3. Photograph of HIFiRE-5 model with TSP

2.3 Test Techniques

2.3.1 Focused Laser Differential Interferometry (FLDI)

The optical path diagram of a typical FLDI system is shown in Figure 4. The parallel beam (linear polarized light) emitted by the laser becomes a divergent conical beam after passing through the concave lens (C1), and then the light perpendicular to the polarization is filtered through the polarizer (P1), and a beam with the same polarization direction is obtained. Wollaston prism (W1) divides the beam into two linear polarized beams with equal intensity, perpendicular polarization directions and a certain separation Angle (o light and e light). After passing through convex lens (C2), the two beams converge at the focusing region (A), forming two separate focal points. It’s in this small focal area that the measurement is very sensitive to the optical path difference caused by density fluctuations. Outside of the focus area, the two beams of light pass almost the same path, causing no optical path difference, and therefore no impact on the measurement signal. After the beam passes through the focusing region (A), the divergent beam will be converged through the convex lens (C3). The Wollaston prism (W2) recombines the two linear polarized beams with a certain separation angle into one beam, and then the light perpendicular to the polarization is filtered through the polarizer (P2) to obtain a beam with the same polarization direction. Finally, it is received by the photodetector at the focal point of the beam and converted into a voltage signal. The relationship between the output signal of the photodetector and the density fluctuation of the measuring point is shown in formula (1).

$$\frac{\Delta\rho}{\rho_L} = \frac{\lambda_0}{2\pi L K \rho_L} \arcsin\left(\frac{V}{V_0} - 1\right) \tag{1}$$

where $\Delta\rho$ is the density fluctuation, ρ_L is the local density, λ_0 is the wavelength of the laser, L is the optical path length of the focused area, K is the Gladstone–Dale constant, V is the output voltage amplitude of the photodetector in the experiment, and V_0 is voltage amplitude without flow influence.

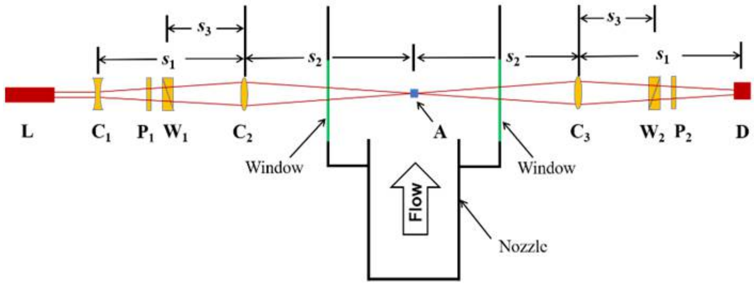

Figure 4. Schematic diagram of the FLDI system optical path

According to the characteristics of wind tunnels and the needs of measurement, a FLDI system with adjustable horizontal position and height was built, as shown in Figure 5. The laser is a stable He-Ne laser with 633nm wavelength, 1000:1 linear polarization ratio, 1.2mW output power and power fluctuation less than 0.1%. The laser has excellent stability and ensures very low base noise of the measured signal. At the same time, in order to avoid the back-reflected light of the optical lens entering the laser aperture and weakening the stability of the laser, an optical isolator with a wavelength of 633 nm is placed at the laser outlet. The focal length of the selected concave lens is 60mm, the focal length of the convex lens is 630mm, and the separation Angle of the Wollaston prism is 3.3 arc minutes. The polarization direction of the light is adjusted to 45 degree through the polarizer. The photodetector is a silicon detector with adjustable gain and 12MHz bandwidth, and the base noise is less than 0.3mV. The data acquisition system sets the sampling frequency to 1MHz.

(a) Emitting optical path (b) Receiving optical path

Figure 5. Photograph of FLDI system

2.3.2 Pressure Probe

A freestream disturbance comprehensive measurement device is designed, as shown in Figure 6. The device is equipped with pressure probes and hot wire. High-frequency Kulite dynamic pressure sensor (XCQ-062-50A) is used to measure the pitot pressure. The total pressure fluctuation after the shock wave can be obtained by the pitot pressure and used to estimate the noise level of wind tunnels. Because the hot wire was damaged in the experiment, no effective data was obtained, so it's not introduced.

It should be noted that the FLDI and the pressure probe do not measure the same area and the same physical parameter, so how the data are related to each other is still unclear. At present, the data are analyzed separately.

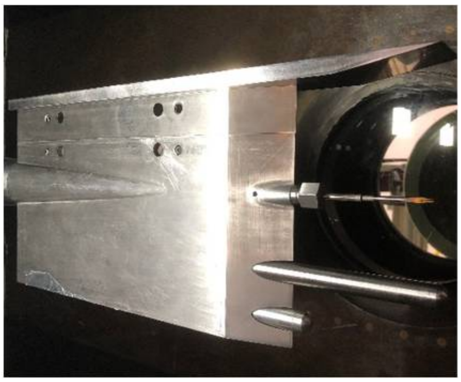

Figure 6. Freestream disturbance measurement device

2.3.3 Temperature Sensitive Paint (TSP)

TSP technology is a surface temperature measurement technology. It establishes a relationship between fluorescence intensity and local ambient temperature through the fluorescence temperature quenching effect of probe molecules. As we know, the heat exchange coefficient in laminar flow region is smaller than that in turbulent flow region. When there is a temperature difference between the airflow and the model, there is a temperature difference between the laminar flow region and the turbulent flow region on the model surface due to the difference in the heat exchange rate. TSP can determine the transition location by measuring this temperature difference. At high Mach number, significant temperature difference can be generated between laminar flow region and turbulent flow region on the model surface due to heat generation by friction.

The TSP system used in the test mainly includes LED light source, PCO1600 CCD camera and corresponding components. The central wavelength of LED light source is 400nm, which is used for fluorescence excitation of TSP coating, and PCO1600 camera is used for fluorescence image acquisition of TSP coating. In order to prevent the interference of LED light and other ambient stray light on the test data, the CCD camera is equipped with a filter in front of the mirror head. As shown in Figure 7, the camera is positioned directly above the model with a good viewing Angle.

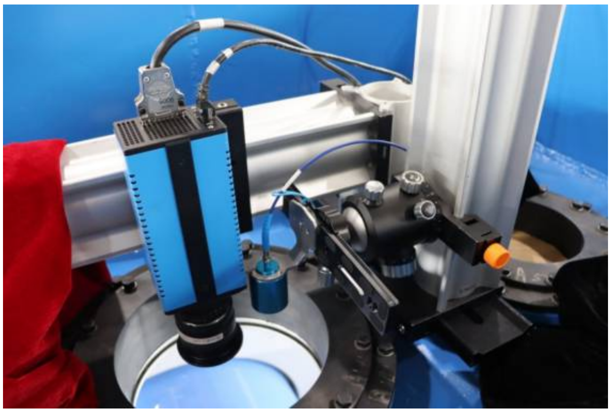

Figure 7. Viewing angle of TSP camera

2.3.4 Infrared Thermography (IR)

Similar to TSP, IR is also an absolute temperature measurement technique. The difference is that it establishes a relationship between the intensity of infrared radiation and the local temperature. The transition location is determined by visualizing the temperature difference between laminar and turbulent regions. The advantage of IR is its high temperature resolution (about 0.025K).

In the FL-64 wind tunnel, transition was measured by both IR and TSP. The infrared camera was mounted in a protective cover inside the wind tunnel test section and photographed the model from below, as shown in Figure 8. A heat map of the model surface was obtained using the FLIR A655sc camera, which has a pixel resolution of 640×480, a temperature resolution of 35mK, and a sampling frame rate of 50Hz. While in the FL-63 wind tunnel, the effective running time of 20ms and the camera frame rate of 50Hz are limited, so only TSP can be used for measurement.

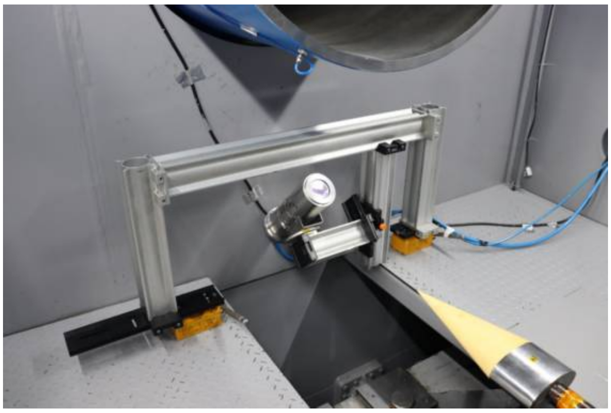

Figure 8. Viewing angle of IR camera

3. Results

3.1 Freestream Disturbance Level

3.1.1 FLDI signal characteristics

Figure 9 shows the FLDI output signal during the operation of the FL-64 wind tunnel. Before the wind tunnel starts, the overall voltage fluctuation is very small, only 0.2 mV. When the running is started, the shock waves sweep through the measuring point, and the fluctuation suddenly increases. After the stable hypersonic flow is established, the fluctuation will decrease compared with the start-up stage, but is still obvious compared to before running. The fluctuation of voltage amplitude is about 0.6 mV. When the blow is over, the low-pressure environment in the wind tunnel is re-balanced to atmospheric pressure, and the loud noise makes the fluctuation increase sharply. As this process progresses, the fluctuation will gradually return to the state before the experiment. It can be seen that the FLDI system is very sensitive to changes in the flow and can reflect the entire process of wind tunnel start-up - stabilization – closure. Figure 10 shows the results of converting the voltage signal into density fluctuations during the experiment. The maximum fluctuation of $\Delta\rho/\rho_L$ does not exceed 0.2%, and the root-mean-square value of $\Delta\rho/\rho_L$ is 0.05%. Figure 11 shows the spectrum analysis of FLDI signal when the flow field is stable. The black line is the power spectrum density of the original signal, and the red line is the result after smoothing. In the spectrum bandwidth of 10kHz -500kHz, there is a slow downward trend. There were several peaks between 40kHz and 100kHz, and initial speculation was that external factors such as the laser might be the cause, rather than the flow field itself. Further investigation will be carried out.

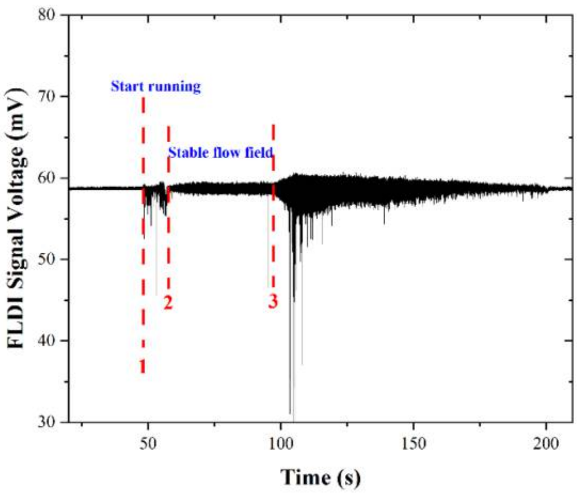

Figure 9. The voltage signal of the whole experiment process

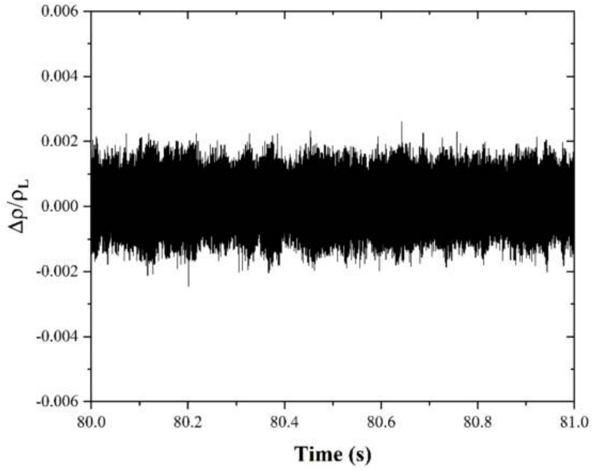

Figure 10. Results of density fluctuation measurement when the flow field is stable

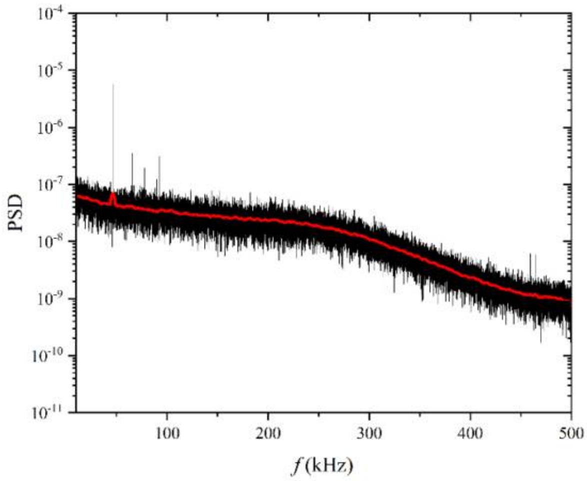

Figure 11. Power spectral density of FLDI signal when the flow field is stable

3.1.2 Repeatability at Mach 6.0

Figure 12 shows the results of repeated measurements of freestream disturbances in the FL-64 wind tunnel at Mach 6.0. Data were collected from a total of seven experiments. Each experiment maintained the same flow conditions. The root-mean-square of density fluctuation is obtained by selecting the voltage signal after the flow field is stabilized. It can be seen that the root-mean-square of density fluctuation has little change and remains around 0.1%. This indicates that the freestream in the wind tunnel has a low disturbance level, and the flow field has a good repeatability.

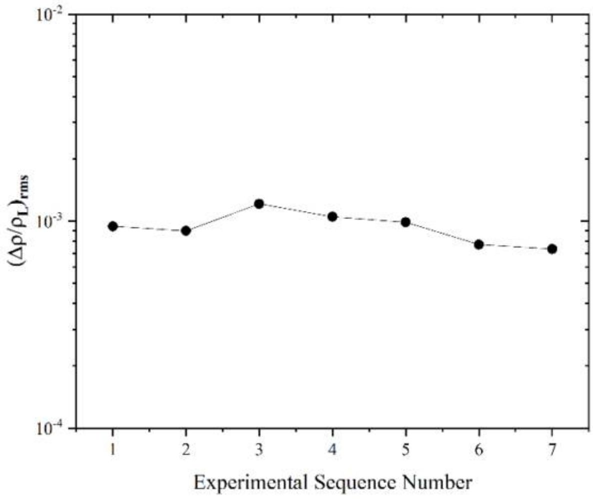

Figure 12. Multiple test results

3.1.3 Density Fluctuations at Different Mach Numbers

Table 1 gives the measurement results of freestream density fluctuation at Mach number 6.0, 7.0 and 8.0. Before the running, the density fluctuations of different Mach numbers are basically the same. However, during the running, the density fluctuations of different Mach numbers are somewhat different. Freestream fluctuations at Mach 6.0 and 8.0 are greater than that at Mach 7.0. If the airflow is considered to be basically static in the test section before running, the fluctuation can be attributed to the base noise of the FLDI system. The fluctuation caused by the airflow is 3-4 times greater than the base noise. This value is not high due to the low base noise and the low level of freestream disturbance. When the flow field is unstable, this value will be much larger.

Table 1. Freestream density fluctuation at different Mach numbers

Mach number	Unit Reynolds number $\times 10^6$/m	Before the running $(\Delta\rho/\rho_L)_{rms} \times 10^{-4}$	During the running $(\Delta\rho/\rho_L)_{rms} \times 10^{-4}$
6.0	12.6	2.21	9.42
7.0	14.4	1.76	5.16
8.0	11.4	1.83	8.33

3.2 Transition Position

Figure 13 and Figure 14 show the transition positions of the windward surface at different angles of attack and Reynolds numbers. It can be seen that the two measurement techniques, IR and TSP, have a good consistency. As the angle of attack increases, the transition position moves backwards and the flow on the windward side tends to be stable. According to the studies of Borg [8] and Schneider [9-10] et al., the transition at the center line of the HIFiRE-5 model is caused by the streamwise unstable mode, while the transition in the region between the center line and the leading-edge line is caused by the crossflow unstable mode. When the angle of attack increases, the pressure gradient between the leading-edge line and the center line decreases, so the crossflow intensity weakens. The transition on the center line is a little too far forward and seems to be influenced by the front screw. Although the hole caused by the screw was filled in before the experiment, the surface was not smooth enough and affected the transition process. Therefore, the main concern of this study is the transition between the center line and the leading-edge line caused by crossflow instability. After increasing the unit Reynolds number, the transition position moves forward and the turbulent area becomes larger.

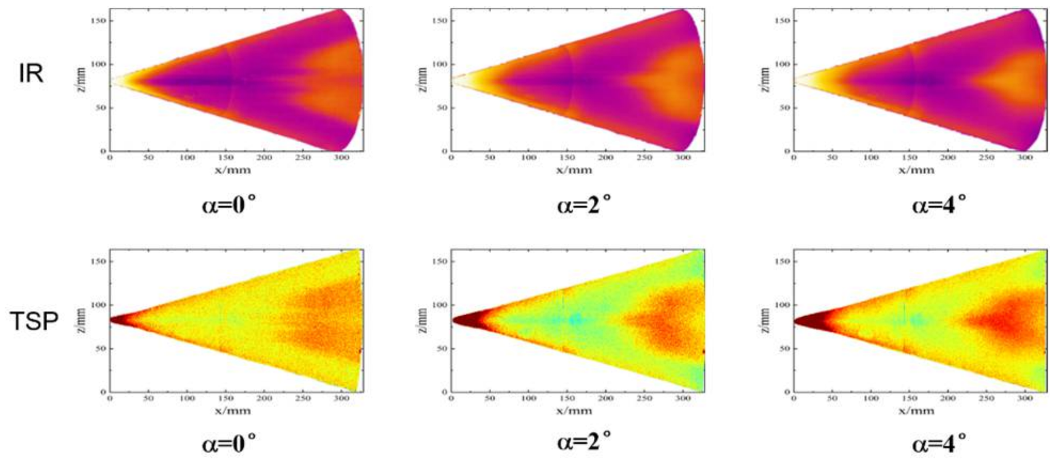

Figure 13. Results of transition position (M = 6.0, Re = 8.1$\times 10^6$ /m)

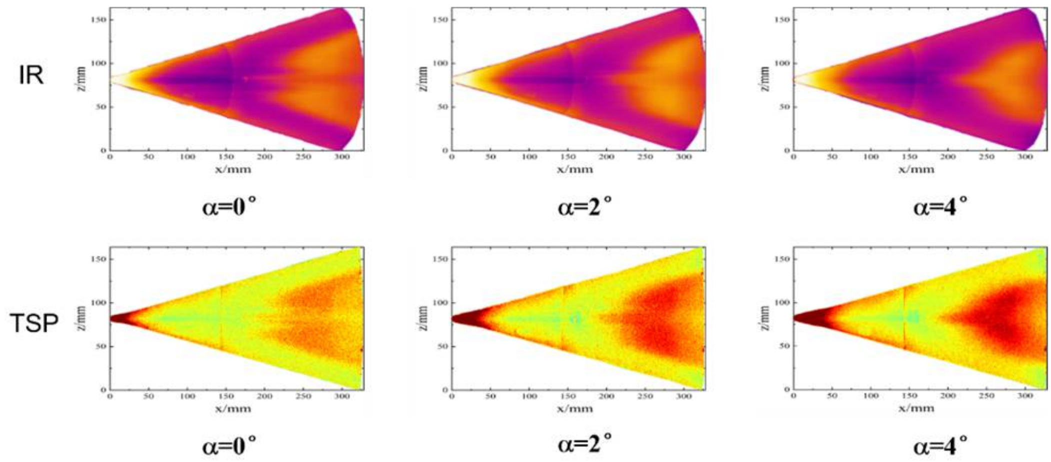

Figure 14. Results of transition position (M = 6.0, Re = 10.2×10^6 /m)

3.3 The Effects of Different Disturbance Levels

The current data comes from experiments in the FL-64 wind tunnel. Due to wind tunnel planning, the experiment in FL-63 wind tunnel is scheduled to take place in July, so the relevant data will be available later. Nevertheless, we can compare our data to that of Schneider et al. [9-10], and analyze the differences. Because the model, the angle of attack, the Mach number, and the Reynolds number are the same, except for the level of wind tunnel disturbance. Their research was carried out in the BAM6QT at Purdue University. For consistency, Pitot pressure data are used to characterize noise levels. The BAM6QT wind tunnel has two operating modes corresponding to different disturbance levels. While running quietly, the noise level is less than 0.05%, and it increases to about 3% when noisy. The transition data at Ma = 6.0 and α = 0° are selected here for comparison. For quiet freestream in the BAM6QT, no transition occurs and the boundary layer is all laminar flow at Re = 8.1×10^6 /m; while at Re = 10.2×10^6 /m, the transition occurs at x=289 mm. For noisy freestream in the BAM6QT, at Re = 8.1×10^6 /m, the transition occurs at x=193 mm; at Re = 10.2×10^6 /m, the transition occurs at x=161 mm. In the flow field of the FL-64 wind tunnel, the noise level at Mach 6.0 was 0.9%-1.0% according to the measurements of the pressure probe. At Re = 8.1×10^6 /m, the transition occurs at x=216 mm; at Re = 10.2×10^6 /m, the transition occurs at x=183 mm. It can be easily found that the higher the level of freestream disturbance, the more forward the transition occurs. Moreover, at the same Mach number and Reynolds number, the transition position is significantly different in two wind tunnels. For noisy flow of BAM6QT and freestream of FL-64 wind tunnel, at Re = 8.1×10^6 /m and 10.2×10^6 /m, the transition position is different by about 23 mm. For quiet flow of BAM6QT and freestream of FL-64 wind tunnel, at Re = 10.2×10^6 /m, the transition position is different by about 106 mm. This indicates that hypersonic boundary layer transition is very sensitive to freestream disturbance. After completing the experiment in FL-63 wind tunnel, FLDI data can be compared and analyzed in more detail to establish a deeper understanding.

4. Conclusions

In this work, FLDI is used to measure the level of freestream disturbance in hypersonic wind tunnel, TSP and IR are used to measure the transition position of HIFiRE-5 model. The results show that FLDI can quantitatively characterize the level of freestream disturbance in wind tunnel. Based on FLDI data, the relative level of freestream disturbance can be compared, and its influence on transition can be studied. At the same Mach number and Reynolds number, the transition position is significantly different in two wind tunnels. The higher the level of freestream disturbance, the more forward the transition occurs.

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6. Copyright Statement

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