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Aero-Optical Diagnostic Technique for the Hypersonic Boundary Layer Transition on a Flat Plate

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Abstract: A new cross disciplinary conception of transitional aero-optics is built up during analyzing and measuring the linkage between the hypersonic boundary layer transition on a flat plate and the jittering characteristics of the small-aperture beam through that boundary layer. Based on that conception, the Small-Aperture Beam Technique (SABT) and high-speed Imaging Camera System (ICS) used in aero-optical studies are considered as new techniques for the assessment of the hypersonic transition in the boundary layer on a flat plate. In the FD-20 gun tunnel, for the free stream parameters with Mach number of 8 and unit Reynolds number of 1×10^7 (1/m), those two optical techniques are used to measure the jitter of the small-aperture beam. At the same free stream parameters, the distribution of the heat transfer along the centerline of the flat plate is also measured by the thin film resistance gauge technique. The results show the similarity of the increase trend between the heat transfer and the jitter of the small-aperture beam in the transitional region. It helps us to surmise that it may be feasible to diagnose the transition in a hypersonic boundary layer on a flat plate by means of those above optical techniques.

Key Words : Small-aperture beam, Imaging Camera System, Transition, Boundary layer, Aero-optics

1. Introduction

When one light beam propagates through a flow field with the inhomogeneous distribution of density, the speed and direction of that beam will be affected by the variations of the index of refraction in the flow field [1]. After the beam shoots out of the flow field, compared with the beam's initial state, the image of the beam by the camera will be leaded to an aberration. The cross disciplinary study on those aberrations, such as deflection, blur and jitter of that beam, is referred to as "aero-optics", which is of relatively short propagation length in the near field of the optical system, or is usually termed as "atmospheric propagation" [2,3].

The aero-optics on the turbulent flow field in the boundary layer could be commenced from the Liepmann's analysis in 1952 [4]. In 1969, Sutton first considered the problem of the effect of near-field phase aberrations due to the propagation of a large aperture, single wave length beam through a turbulent flow field [3]. In 1979, the first conference on aero-optics sponsored by American Air Force Weapons Laboratory and NASA Ames Research Center was held at Ames Research Center in California [5]. Aerodynamicists, physicists, opticians and instrumentation engineers were involved in data acquisition and analysis in this conference to establish an extensive data base, and a basic research program known as the Aero-Optical Program was also started in this conference, which

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indicated that the conception of aero-optics was generated.

In a symposium on aero-optics held in 1982 [6], Otten and Kelsall gave out two contrary viewpoints for the aero-optical investigation. In 1985, Sutton [1] advanced a possible reconciliation of those two statements, and introduced the aspects of the aero-optical investigation and classified those contents into five cases. In 1997, the past investigations on the aero-optics from 1950s to 1990s were summarized by Jumper and a four-level viewpoint was suggested in that review paper [7]. Remarkably, his review mainly involved the aero-optical effects of the turbulent boundary layer with relative low speed of no more than Mach number of 3, Jet or shear layer, and no detailed flow field of the boundary layer, especially the hypersonic transitional boundary layer, was regarded.

Since 1990s, the aero-optical investigations have been comprehensively and deeply advanced. Yanta et al. experimentally measured the aero-optic effects of the hypersonic boundary layer on a plate by the WFS (Wave Front Sensor) and ICS (Imaging Camera System) techniques [8]. Jumper et al. theoretically demonstrated the consistency between the Linking equation of Sutton and the Liepmann's equation [9]. Gordeyev et al. [10], Bucker et al. [11] and Wyckham et al. [12] experimentally gave out the complex form of the linking equation in the subsonic and hypersonic turbulent boundary layer. After several years' work, Yin, X. L., wrote an important book [13] to introduce their theoretical, experimental and numerical achievements and to build up the foundation of the aero-optical investigations in China. Shi, K. T., et al. theoretically analyzed the aero-optical effects in a flow field with Mach number of 2~5 [14], Yan, M., et al. discussed the application of RANS method in aero-optics [15].

There are two main clues in the development of boundary-layer aero-optics, one is the linking equation and the other is the four-level viewpoint of Jumper. Whereas, the past aero-optical works related to the boundary layer are mainly focused on only the optics in aero-optics or aero-optical effects of only the turbulent boundary layer. The reason that the aero-optical effects resulted from the hypersonic boundary-layer transitional flow field have not been enough regarded and investigated may be the complexity and difficulty of the hypersonic boundary-layer transition.

The relative analysis shows that there should be a certain linkage between the aero-optical and aerothermodynamic phenomena resulted from the hypersonic transitional boundary layer in this paper, and the aero-optical measurements by SABT and ICS are compared with the distribution of the heat transfer and statistically analyzed to reveal that the function of the transitional boundary layer to the beam jittering. Then, an aero-optical diagnostic technique for the hypersonic boundary layer transition on a flat plate may be advanced.

2. Propagation of SAB in a Boundary Layer

In aero-optics, the Gladstone-Dale law could be described as the following:

$$n = 1 + K_{GD} \cdot \rho \qquad (1)$$

Where n is the refraction rate, ρ is the density and K_{GD} is the Gladstone-Dale constant.

If we replace the gas density ρ in above equation (1) by the ideal gas state equation and the derivation of refraction rate could be written as:

$$dn = \frac{K_{GD}}{RT}dp - \frac{K_{GD} \cdot p}{RT^2}dT \qquad (2)$$

Where p is the pressure, T is the temperature and R is a gas state constant. Note that the change of the pressure in the boundary layer is less in the vertical direction (also the incident direction of the small-aperture beam) and could be neglected, thus:

$$dn = -\frac{K_{GD} \cdot p}{RT^2}dT \qquad (3)$$

Based on the Newton's heat transfer equation:

$$q = h(T - T_w) \qquad (4)$$

where q is the heat transfer, T_w is the temperature on the surface of the flat plate and h is heat exchange coefficient. (4) could be derived as:

$$q = -\frac{hRT^2}{K_{GD} \cdot p}dn \qquad (5)$$

Equation (5) could show that the heat transfer is direct proportion to the gradient of the refraction rate, and in a boundary layer, the refraction rate is the function of the Reynolds number, that is, $q \propto f_1(Re_x)$, where x is the streamwise coordinate. From the view of optics, the distortion of the small aperture beam when it goes through the hypersonic boundary layer is caused by the change of the refraction rate. For example, the streamwise deflection angle of the small aperture beam could be written as:

$$\theta_x = \frac{\partial}{\partial x}\int_0^{\delta}(n - n_0)dz \tag{6}$$

where Θ_x is the streamwise deflection angle, n_0 is the refraction rate of the null flow field, δ is the thickness of the boundary layer, and z is the vertical direction of the flat plate and is also the incident direction of the small-aperture beam. For the streamwise deflection angle, $\langle\theta_x\rangle$ represents the change of the total refraction rate along the vertical direction, and could also be written as $\langle\theta_x\rangle \propto f_2(Re_x)$.

Then,

$$\frac{\langle\theta_x\rangle}{q} \propto \frac{f_2(Re_x)}{f_1(Re_x)} = g(Re_x) \tag{7}$$

Based on the view of the aero-optics, the density distribution of the flow structures could affect the refraction rate, and further result in the distortion of the small aperture beam. And from the sense of the aerothermodynamics, the heat transfer is resulted from the unsteady exchange of the heat between the flow structure and the wall. So the similarity of the heat transfer to the standard deviation of the streamwise deflection angle in the transitional boundary layer could be assumed to be a constant:

$$\left(\frac{\langle\theta_x\rangle}{q}\right)_{\text{in transition region}} = \text{const} \tag{8}$$

3. Experimental Results

The experiments including heat transfer measurement and the laser spot jittering measurement are both performed in the FD-20 gun tunnel in China Academy of Aerospace Aerodynamics (CAAA). The free stream Mach number is 8 and unit Reynolds number is 1.0×10^7 (1/m). There are two plate models with the length of 459 mm and the width of 300 mm. One is for the heat transfer measurement by thin film resistance technique and a row of sensor holes are arranged in the centerline of this plate model, the other one is for the laser spot jittering measurement by ICS technique and three optic windows with the area of 50 mm × 50 mm and the distance from theirs centre to the front edge of 193 mm, 283mm and 411mm are embedded in the plate model. In the optic tests, the laser beam is generated by the He-Ne laser generator with the wavelength of 632.8 nm, the power of 2 mW and the exit diameter of 1 mm. The photos are recorded by a CMOS camera produced by Mega Speed Corp. in Canada. The speed of the camera could reach 1000 fps as its resolution rate is adjusted at the largest value of 1280 × 1024. Actually, during the tests, the speed is set up to 2000 fps with the resolution rate of 600 × 500.

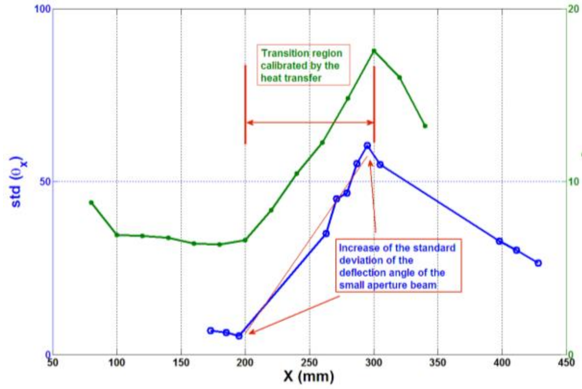

Fig. 1 The comparison of the heat transfer and the standard deviation of the deflection angle in transition region

The spot images in the null flow field and runs could be obtained by ICS to calculate the time series of the streamwise deflection angle by the estimation of the change of the spot centroid that represents the jitter of SAB. And the distribution of heat transfer along the centerline on a flat plate is also measured by thin film resistance gauge. The measurements of the standard deviation of the streamwise deflection angle and the heat transfer are both shown in Fig. 1, and the transition region calibrated by the heat transfer curve is from 200 mm to 300 mm. In that region, the standard deviation of the streamwise deflection angle has a same increase trend. If the equation (8) could be related to those two curves in the Fig. 1, the constant in the transitional region may be about 5.0194 (μrad·m^2/kW).

4. Conclusions

The complexity and difficulty of the transition in a hypersonic boundary layer restrain the investigations on its aero-optical effects, so the analysis and measurement shown above may be the first time to regard that problem. Though the measurements are required to be validated by more data in more cases of free stream, the similarity of the increase trend between the heat transfer and the jitter of the small-aperture beam in the transitional region could be preliminarily proved to be right. Thus, the SABT and HICS could be considered as a set of feasible techniques to diagnose the transition in a hypersonic boundary layer on a flat plate.

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