AN EXPERIMENT INVESTIGATION ON SHOCK-INDUCED TURBULENT BOUNDARY LAYER SEPARATION FLOW-FIELD

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Abstract

High-speed flow past a blunt fin on a surface results in a interaction flow-field. And the fin shock causes the boundary layer to separate ahead of the fin. The interaction flow-field includes horseshoe vortices near the surface and a lambda-type shock pattern in the plane of symmetry ahead of the fin. To understanding the interaction flow field, Pressure Sensitive Paint has been made to study the flow-field induced by blunt fin turbulent boundary layer interactions at Mach 5. The experiments were carried out with a model comprising a flat plate with a single blunt fin. PSP was sprayed on the flat plate and the blunt fin surface, which was illuminated by a high power UV light. And a high-speed camera was used during the experiments to measure the luminescence. After image processing, the pressure distributions on the blunt fin were obtained.

1 General Introduction

Flow separation induced by shock wave/turbulent boundary layer interaction can play significant difficulties in the design of hypersonic transport system ［1］. The shock wave boundary layer interaction is one of the many aerodynamic problems associated with supersonic and hypersonic flows around complex airframe geometries. Such an interaction can be generated by a large number of configurations including wing-body junctions, inlets, or deflected control surfaces. The aerothermodynamics problems associated with the interactions include very high amplitude unsteady pressure loading and intense local heating rates. As with most separated flows, shock wave turbulent boundary layer interactions also degrade performance, whether it be due to added drag in external flows or decreased engine efficiency in internal flows.

Boundary layer separation upstream of semi-infinite blunt fins in supersonic flows has been a subject of research in aerodynamics for more than thirty years. Early work concentrating on laminar boundary layer separation induced by blunt fins indicated that the process was steady. An equally intriguing problem with more practical applications is the separation of supersonic turbulent boundary layers upstream of blunt fins.

Fundamental to progress in high-speed aerodynamics is our understanding of shock wave/turbulent boundary layer interactions. Shock wave/turbulent boundary layer interactions are responsible for generating excessive heating rates and fluctuating surface pressures that in turn are critical total prediction of aero acoustic loads and structural fatigue. In order to optimize aerodynamic design of high-speed aircraft, an understanding of the shock wave/turbulent boundary layer interaction is essential.

Significant progress has been made toward understanding the time-averaged aspects of shock wave/turbulent boundary layer interactions, through both experimental and computational means. Computational fluid dynamics has contributed considerably to our understanding of time averaged flow structure, but there are still aspects of the flow that computational methods do not predict well (i.e., fluctuating loads, heat transfer) ［3］.

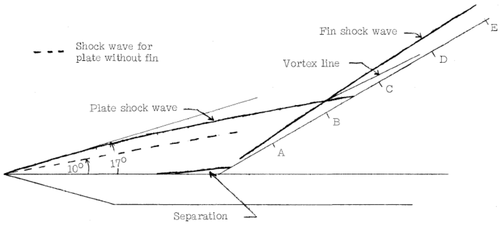

Figure 1. General Characteristics of Fin-Induced Sketch of schlieren photograph (Robert, 1964)

The interaction study, which is experimental, concentrates on the blunt fin-induced shock wave turbulent boundary layer interaction, which most closely resembles that occurring at a wing-body intersection on an aircraft. In such an interaction a large-scale, three-dimensional, separated flow region is generated whose scales are controlled, to first order, by the fin thickness, d [4]-[7]. Figure 1 shows some of the salient features of this interaction. The bow shock formed in front of the fin is bifurcated and has the characteristic " λ -foot" shape. Separation noted by the line marked 'S' and 'U' is the upstream influence line, the upstream limit of the unsteady separation shock foot travel. The distance between these two lines is the intermittent region length, so named because of the intermittent nature of fluctuating pressures measured there[8]-[12].

The current experiment was designed to determine the flow of the interaction with oil film and pressure sensitive paint method. By comparing the two methods in visualization studies on determining he upstream influence and separation line locations, it can be drawn that PSP is an available method in interaction flow visualization at hypersonic condition.

2 Wind Tunnel and the Model

2.1 The Hypersonic Wind Tunnel

The tests were conducted at Mach 5 in FD-03 blow down hypersonic wind tunnel in China Academy of Aerospace Aerodynamics (CAAA). This wind tunnel is transient, and blow down free jet one whose nozzle outlet size is 170mmx170mm. The test section size is 1000mm×500mm×500mm. And the section side wall has square window to detect the model inside. The Mach number extends from 5 to 10; every Mach number has a corresponding nozzle that can be changed to change the Mach numbers.

The air is heated by a two stage electric storage heaters upstream of the settling chamber. The first stage heater can heat the air to 573K, and then the flow passes by second stage heater can heat the air to 1000K.

Also there are two 300mm square optical glass windows on the test section side wall to view the schlieren flow field. The hypersonic wind tunnel flow total pressure, total temperature and the balance out data were acquired by SYSTEM8400 electric scan pressure system and NEFF470 data acquisition system whose sampling rate is 10000 points/sec. Before the data were acquired, we used the HBM amplifier to filter and amplify. Filter can get rid of the wind tunnel fixed frequency and other disturbed wave effects. When the data signals were amplified 10000 times, we could obtain the high precision data.

Data acquisition system uses DT9806 data acquisition board produced by American Data-Translation Company. This acquisition board has built-in CJC cold temperature compensate. It can acquire 7-channel thermocouple temperature data, and the acquisition frequency is 50K samples per second.

2.2 The Model

The test model used in the tests was a flat plate with a single blunt fin. The size of the flat plate is 330mmx200mm.

Two blunt fins were used to get the shock wave/boundary layer interactions. The fin's diameter D is 10mm and 19mm. And the height h is 105mm. The fin is mounted vertical to the plate. Marker points were added on the paint surface manually for image registration as shown in Figure. 2.

Figure 2. The flat plate with blunt fin model fixed in the wind tunnel test section

2.3 Instruments and Measurement Precision

A 8400 pressure scan valve was used to get the pressure data of the pressure taps. It's accuracy is ±0.05% F.S. Three PT100 temperature transducer were set under the plate to measure the model temperature during the wind tunnel test. It's accuracy is ±0.2%F.S

3 PSP Measurement Techniques

3.1 Pressure Sensitive Paint

Pressure sensitive paint is a molecular sensor based on oxygen quenching of its luminescence. Luminescence intensity from luminophore is varied by the environmental oxygen partial pressure. Conventional PSP, which consist of luminophore and polymer binder, have their typical response time of order 1 second. For unsteady PSP measurement, it is necessary to use much faster PSP.

Various PSP formulations are under continuous development in cooperation between CAAA and Institute of Chemistry, Chinese Academy of Science. CAAA has developed high porosity paints where the luminescent dyes can be incorporated into a highly porous polymer. The emission spectrum of the fast response PSP is shown in Fig. 3. This paint uses PtTFPP as luminophore, which is relatively photo-stable: the decay of luminescent intensity with continuous illumination is 1.5 percent/h. This paint is able to prayable on any model surfaces. It is durable enough to withstand the aerodynamic forces. The response time of the high porosity paint is less than 1 millisecond.

3.2 Pressure-sensitivity Calibration

The Static calibration device is shown in Fig.4. Porous PSP samples were installed in a pressure chamber in which both the pressure and temperature can be set. The sample was excited by UV light and its photoluminescence was detected by a CCD digital camera. Pressure range was 10-100 KPa and calibration temperature are 25°C,30°C and 35°C. As we can see from Fig .4, PSP characteristic tend to between pressure and luminescence intensity.

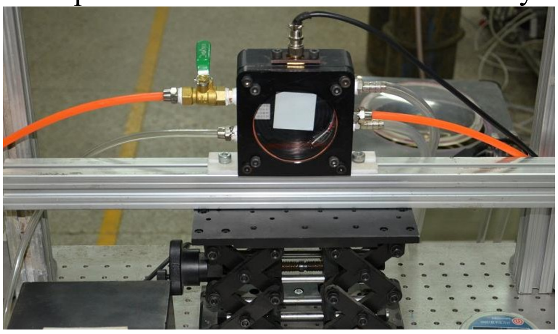

Figure 3. Static calibration device

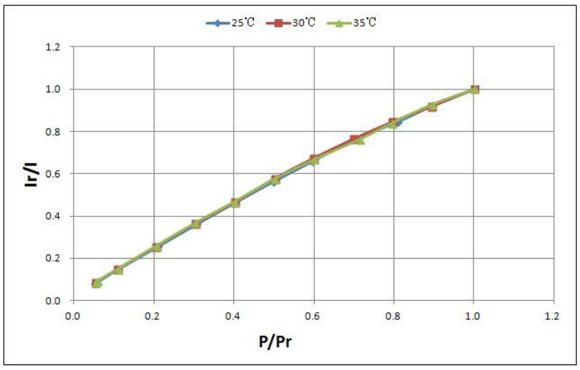

Figure 4. Calibration of PSP

3.3 Experimental Setup

To demonstrate the capability of porous PSP for pressure measurements in hypersonic wind tunnel, a cylinder mounted on a flat plate was tested in a Mach 5 hypersonic wind tunnel. The experiment was conducted in the blow down hypersonic wind tunnel FD-03 of China Academy of Aerospace Aerodynamics (CAAA). The Cylinder/flat plate model is shown in Fig.2, the diameter of circular cylinder is 25mm. The flat plate is mounted to the floor of the nozzle. The pressure on the plate surface was measuring by several pressure taps simultaneously. The temperature of the model was detected by three PT100 temperature sensors in real time. Painted Cylinder/flat plate was mounted in the hypersonic wind tunnel as shown in Fig.9. Optical access was gained through a 200-mm-diameter observation window on the ceiling. A 450-W xenon lamp with a bandpass filter (365±10 nm) was used for excitation light. The emission from the PSP was detected by Photron Highspeed Camera SA5 with 12-bit intensity resolution. A bandpass filter (650±10 nm) was placed in front of the camera lens.

3.4 PSP Measurement System

Unsteady PSP measurement system includes a high-speed camera, two high-power illumination light sources, and optical apparatus. The detail of the components of the unsteady PSP system is described followings.

High-Speed Camera

The high-speed camera in this system was the Photron high-speed Camera SA5, which has 12bit depth A/D resolution. Its ISO photosensitivity was 4000 on catalogue. High-photosensitivity of the high-speed camera is great merit for short exposure measurements like unsteady PSP measurement. The Photron SA5's maximum spatial resolution is 1024×1024 pixels at 7k (fps) frame rate. The measurement configuration in this study was 1024×1024 pixels spatial resolution at 250 fps with 4 ms exposure time. In this study, 50 wind-off and 1,000 wind-on images were captured for each test cases. Measured images were at first stored in the camera memory and then transferred to a control PC. Data transfer used the 1GB Ethernet. Another test using pressure transducers were conducted at the same time.

The camera lens, Nikon 50mm F1.4S, was installed at the high-speed camera. Its iris was set open to collect largest PSP luminescence. A bandpass optical filter was set in front of the camera lens to get the PSP signal from 640nm to 660nm and cut the illumination light component of UV light.

To compensate small exposure time, high-power illumination light source was one of the key components to increase PSP luminescence. The 400W high-power UV light, INTELLIRAY 400, was used as the illumination light source in this study. Its wavelength is from 300nm to 500nm; hence a filter is needed to get the 365nm UV light. Its total illumination power is 400W at maximum. The intensity can be adjusted from 50% to 100%. Typical instability is less than 1%, and it is air-cooling.

3.5 PSP Data Processing

As the pressure calculation process of PSP measurement, there are two types of acquired images, reference and wind-on ones, which are time-series images acquired by a high-speed camera. Reference images are PSP intensity images under atmospheric pressure around 100 KPa. Wind-on images are test data. Both images are subtracted dark component. Then, reference images are averaged to single reference image, Iref. Wind-on images keep time-series images. Time series Iref/I ratio images are calculated using the reference image and time-series wind-on images. The test model deformation is small, image registration between reference and wind-on image was not necessary on present data processing. Finally, Iref/I ratio images are processed to time-series pressure images using the relation between Iref/I and pressure and PSP characteristics provided from calibration. Theoretically the relation between Iref/I and pressure is represented by following Stern-Volmer relation;

$$\frac{I_{ref}}{I} = A + B\frac{P}{P_{ref}} \qquad \text{.............................(1)}$$

In this study, the second order expression as following was appropriate to fit the relationship between pressure and luminescence intensity.

$$\frac{I_{ref}}{I} = A + B\frac{P}{P_{ref}} + C\left(\frac{P}{P_{ref}}\right)^2 \qquad \text{..................(2)}$$

A,B,C are the constant and is determined through calibration process described above. The quantitative pressure value was calculated using this equation (2) in this study.

4 Experiment Results

Figure 5 showed the PSP measurements results of the 72° blunt fin. According to pressure distribution, it was obvious that the windward of blunt fin is the high pressure area which was caused by the bow shock. It was the red part in the image. After the bow shock effect, the pressure decrease, it appeared in the image as yellow and green area. The dark blue color was the lowest pressure area, which was the separation area. The pressure distribution results were agreed with the oil film results.

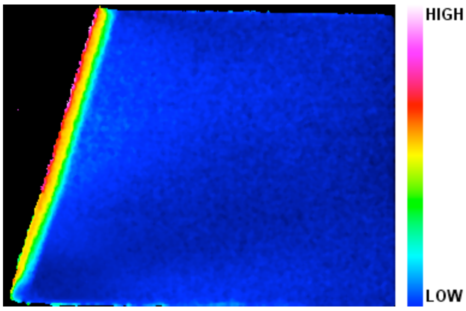

Figure 5. Pressure distribution on the blunt fin (72°)

Figure 6 showed the PSP results of the 45° blunt fin. On the top the 45° blunt fin, the bow shock effects dominated the pressure distribution. And it was the high pressure area which appeared as green part on the top of the fin. At the fin root, the vortex was still the dominant flow condition, so the separation area was the low pressure area. In the image it was the blue area.

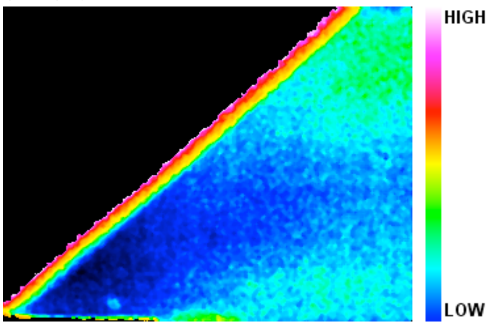

Figure 6. Pressure distribution on the blunt fin (45°)

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