VISUALIZATION OF UNSTEADY SHOCK WAVE OSCILLATIONS BY HIGH SPEED SCHLIEREN PHOTOGRAPHY

J.K. Ma, S.X. Li, Y.F. Liu

China Academy of Aerospace Aerodynamics
100074, Beijing, China

Abstract

An experimental study of interaction flow induced by a swept blunt fin was presented. The tests were carried out in a hypersonic gun tunnel with freestream Mach number of 6 or 8. High speed schlieren photography was used to show the unsteady features of the interactive flow. Different features of laminar and turbulent interactive flowfield are presented. The separation region extent of turbulent interaction is much smaller than the laminar flow. Unsteady oscillations of separated flowfield can be shown by schlieren photos. The oscillating frequency is less than 1 kHz.

Key words: hypersonic flow; separated flow; blunt fin; unsteady oscillations

1. Introduction

Shock wave/boundary layer interaction, which often accompanied by separation, is a commonly feature of high speed flow over flight vehicles. Extensive work has been done over the past 50 years [1–5]. Most of the work has been done in fully-developed turbulent flows as the most applications in the past were at transonic and supersonic speeds, where the Reynolds numbers are large and the flow status is turbulent. Recently many countries are interesting in the plans of developing hypersonic vehicles which fly in near space (20 ~ 100 km). In this flight range laminar flow is also very important. But unfortunately the research work of laminar interactions are relative rare, especially lacking the detailed experimental measurements and observations of unsteady flow characteristics in hypersonic flow.

Previous research results [6–10] show that flow separation is highly unsteady and large fluctuating pressure loads up to 185db or more occur in the interaction region. The oscillating characteristic frequencies are very close to the resonant frequencies of vehicle structural components. Additionally, high heating rate can further threaten the structural integrity of the vehicle. These flow features are corresponding some new problems for the design of vehicle structure, thermal protection system and noise reduction.

The unsteadiness observed in the interactions spans a wide range of frequencies and scales. It has been observed that the dominant frequency range that characterizing the motion of the separated shock is at least an order of magnitude lower than the nominal boundary layer frequency based on the free stream velocity and boundary layer thickness. The low frequency of the shock foot seems to be related to the low-frequency motion of the separated flow.

In spite of the increasing interest in the unsteady flow, we are despairing to say that our current understanding of unsteady flow induced by shock wave boundary layer interaction is plain. The experimental data from past study is very limited.

This study aims to investigate the steady and dynamic characteristics of the hypersonic separated flowfield induced by a swept blunt fin. The primary diagnostics used are high speed schlieren photography. The objective of the current work is to study the different features between the laminar separated flowfield and turbulent separated flowfield and show the dominant frequency of these flows.

In this paper to investigate the laminar separated flow upstream of a blunt fin, schlieren photography is used. The research work has been performed in hypersonic gun tunnel FD-20 in China Academy of Aerospace Aerodynamics, with stable flow time is over 20ms. The model consists of two parts: (a) the flat plate with sharp leading edge; (b) the fin, sweep angle \( \Lambda = 45^\circ \), as shown in Figure 1. The dimensions for the flat plate are 680 mm×380 mm and the sharp leading
edge angle is 10°. The fin has the leading edge diameter $D = 25$ mm and the sweep angle of $\Lambda = 45^\circ$. The distance between leading edge of the flat plate and the fin is 432.5 mm. High speed schlieren photos with 2000 frames per second have been taken to visualize the time-varying structure of separated flow.

2. Experimental procedure

The experiments have been performed in FD-20 hypersonic light piston gun tunnel of China Academy of Aerospace Aerodynamics (CAAA), in which the nozzle exit is $\Phi 480$ mm and $\Phi 400$ mm. Freestream Mach number is set with different Laval contour nozzles from 5 to 15. The typical stable flow period is about 20 milliseconds. In present study Mach number is set to 8.0 for turbulent flow and 8.0 for laminar flow.

The model consists of two parts: (a) the flat plate with sharp leading edge; (b) the fin, sweep angle $\Lambda = 45^\circ$, as shown in Figure 1(a). The dimensions for the flat plate are 680 mm×380 mm and the sharp leading edge angle is 10°. The fin has the leading edge diameter $D = 25$ mm and the sweep angle of $\Lambda = 45^\circ$. The distance between leading edge of the flat plate and the fin is 432.5 mm. The origin of the coordinate system is located in the intersection point of the leading edge of the fin and the centerline of the flat plate, as shown in Figure 1(b). OX axis points to downstream along the centerline of the flat plate. OS axis points to the top of the fin along the leading edge of the fin. The model was supported by a sting in the test section.

During the tests two models have been used in this study: flat plate without fin and flat plate with fin, sweep angle $\Lambda=45^\circ$. The dimensions for the flat plate are 680 × 380 mm and the sharp leading edge angle is 10°. A blunt fin is mounted on another plate with the same dimensions. The fin has the leading edge diameter $D = 25$ mm and sweep angle of $\Lambda=45^\circ$. The distance between leading edge of the flat plate and the fin is 432.5 mm.

![Model Setup](image1.jpg)  
(a) model setup Flat plate with fin, sweep angle $\Lambda=45^\circ$  

![Coordinate System](image2.jpg)  
(b) coordinate system

Fig. 1. The test model and coordinate system

High speed black white schlieren photos with 2000 frames per second were taken by the Mega Speed camera to visualize the time-varying structure of separated flow. Heat flux measurements have also been made along the flat plate centerline upstream of the blunt fin and the centerline of fin leading edge with high frequency responding and spatial resolution thin film transducers. In this paper only the visualizations of schlieren photography were shown.

The experimental conditions are shown in Table 1. Under these conditions, it is known from the previous study [7] that at freestream Mach number 8.0, the status of boundary layer on the plate ahead of the fin is laminar and at freestream Mach number 6.0, the status of boundary layer is turbulent.
The distance between two transducers is 2.5 mm. 20 transducers or 39 transducers are integrated on a single element. Using those integrated elements more detailed and credible data are obtained compared with using isolated transducers before.

Output from the heat flux transducers is first amplified by DH3480V amplifiers, and then low-pass filtered using three order Butterworth analog filters. Filter cut-off frequencies are set at 10 kHz or 1 kHz. Filtered signals are then acquired with 25 kHz sampling rates and downloaded to an HC1210 work station.

High speed schlieren photos with 2000 frames per second are also taken to visualize the time-varying structure of separated flow.

3. Discussion of results

3.1 Structure of flow field

The typical flowfield of blunt fin induced separated flow is visualized by the schlieren photography as shown in Figure 2. An upstream shock wave is formed induced by the blunt fin. It brings the converse pressure gradient. Disturbance transfers upstreamwise through the subsonic region of the boundary layer, which causes flow separated. The oblique separation shock eventually connects with the detached shock wave of the fin, and forms complex $\lambda$ shock wave systems. An oscillating separation shock can be observed from the schlieren video. The laminar boundary layer separation occurs earlier and the separation region is more extensive. Based on the scale calibration of the schlieren photo, it can be estimated that: (1) the laminar boundary layer separation started on the upstream of fin at about X/D $\approx$ –2.0 (on the plate), the laminar reattached point was at about S/D $\approx$ 0.38~0.5. (2) for turbulent case, X/D $\approx$ –0.4 and S/D $\approx$ 0.38 respectively.

![Fig. 2. The typical structure of the interactive flow](image)

3.2 Unsteady features of the flowfield

Six typical sequential schlieren photos of laminar flow, turbulent flow are shown in Figures 3, 4. The unsteady flow characteristics are very obvious and the separation shock moves upstream and downstream at different time. The detailed flow figures around the fin root are extracted and

<table>
<thead>
<tr>
<th>No.</th>
<th>$M_\infty$</th>
<th>$P_0$ (MPa)</th>
<th>$T_0$ (K)</th>
<th>Re×10$^7$ (m$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1235</td>
<td>8.0</td>
<td>7.47</td>
<td>1093</td>
<td>0.89</td>
</tr>
<tr>
<td>1236</td>
<td>8.0</td>
<td>7.46</td>
<td>1093</td>
<td>0.89</td>
</tr>
<tr>
<td>1238</td>
<td>8.0</td>
<td>6.9</td>
<td>1093</td>
<td>0.82</td>
</tr>
<tr>
<td>1243</td>
<td>6.0</td>
<td>11.59</td>
<td>900</td>
<td>3.86</td>
</tr>
<tr>
<td>1245</td>
<td>6.0</td>
<td>11.08</td>
<td>900</td>
<td>3.69</td>
</tr>
<tr>
<td>1248</td>
<td>6.0</td>
<td>12.15</td>
<td>900</td>
<td>4.04</td>
</tr>
</tbody>
</table>
amplified, as shown in Figures 5, 6. We can see that positions of the oscillated separated shock wave foot have been changed with different times.

Mean separated shock wave oscillating frequency is obtained by counting schlieren photos. We also obtain another oscillating frequency by heat-transfer rate signal which has the cut-off filter frequency 1 kHz at X/D = −0.2 [9]. Tables 2 and 3 show the results. We can see that separated shock wave and heat flux signals in separated region both oscillate under 1 kHz, the two approaches have the similar result.

**Table 2. Oscillating frequencies**

<table>
<thead>
<tr>
<th>No.</th>
<th>Oscillating frequencies (Hz)</th>
<th>schlieren photos</th>
<th>signals</th>
</tr>
</thead>
<tbody>
<tr>
<td>1235</td>
<td>620</td>
<td>×</td>
<td></td>
</tr>
<tr>
<td>1236</td>
<td>570</td>
<td>×</td>
<td></td>
</tr>
<tr>
<td>1238</td>
<td>540</td>
<td>465</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 3. Six sequential schlieren photos of laminar flow
(a) $t_0$

(b) $t_0 + \Delta t$

(c) $t_0 + 2\Delta t$

(d) $t_0 + 3\Delta t$

(e) $t_0 + 4\Delta t$

(f) $t_0 + 5\Delta t$

Fig. 4. Six sequential schlieren photos of turbulent flow

Fig. 5. Six sequential schlieren photos around the fin root of laminar flow

Fig. 6. Six sequential schlieren photos around the fin root of turbulent flow

**Table 3.** Oscillating frequencies

<table>
<thead>
<tr>
<th>Flow regime</th>
<th>Schlieren Photography</th>
<th>Heat flux</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laminar</td>
<td>430 Hz</td>
<td>470 Hz</td>
</tr>
<tr>
<td>Turbulent</td>
<td>650 Hz</td>
<td>710 Hz</td>
</tr>
</tbody>
</table>
4. Summary

An experimental investigation of separated flow characteristics caused by a swept blunt fin on a flat plate in a hypersonic laminar flow has been carried out. Steady and unsteady flow characteristics are shown by heating flux measurement and the high speed schlieren visualization. The following conclusions have been reached:

- The existence of the fin changes flowfield significantly. There is a highly complex disturbance region upstream of fin.
- The boundary layer status has huge impact on the separation region of the interaction flowfield. The extent of separation region in laminar flow is broad than that in the turbulent flow. The disturbance resistance of the laminar boundary layer is poor than that of turbulent case. The laminar boundary layer can separation occurs easily and the separation region is more extensive., the model geometry, the Reynolds number and the Mach number. Both laminar and transition boundary layer were studied with both weak and strong interaction. Detailed information on the complex flow field around the root area of the blunt fin was obtained.
- Distributions of heat rates are changed obviously in distributed cases compared with undistributed cases. Upstream of separated regions there exists a region where heat flux is decreased. Schlieren photos can discover the unsteady features of the shock wave boundary layer interactions
- Oscillating frequencies obtained by high speed schlieren photos are lower than 1 kHz.
- Schlieren photos can discover the unsteady features of the shock wave boundary layer interactions.

5. Acknowledgements

The authors wish to acknowledge the support from the Key National Natural Science Foundation of China (No. 91116009 and No. 91216114). The support provided by the FD 20 wind tunnel staff is greatly appreciated.

REFERENCES