Bow-Shock Instability and its Control in front of Hemispherical Concave Shell at Hypersonic Mach Number 7

By Ashish VASHISHTHA,1) Yasumasa WATANABE2) and Kojiro SUZUKI1)

1)Department of Advanced Energy, The University of Tokyo, Kashiwa, Japan
2)Department of Aeronautics and Astronautics, The University of Tokyo, Tokyo, Japan

(Received July 31st, 2015)

In this study, effectiveness of vortex manipulation by using passive control methods at hypersonic flows have been studied to control the bow-shock instabilities in front of negative curvature (concave) hemispherical shell. The force measurement and unsteady center pressure measurements were performed for hemispherical shell with no control and with three kind of passive controls such as spike at the center of cavity, breathing holes at the curved surface and crosswire along the diameter of hemisphere. The flow visualization for shock instability in front of all four geometries were performed using twin mirror Schlieren system and high-speed camera with 10,000 fps, which were synchronized with pressure measurements. The fluctuations in bow-shock were computed in time resolved manner by image processing methods and compared with pressure data. It is found that drag coefficient does not change significantly by using the different control methods, which were studied. The time resolved Schlieren image processing method is reliable in providing the information of shock fluctuations and the crosswire control method is most effective in subsiding the large shock deformation in the current study.

Key Words: Unsteady Measurement, Hypersonic, Bow-Shock, Shock Instability, Image Processing

Nomenclature

- $C_D$: Drag Coefficient
- $C_L$: Lift Coefficient
- $C_S$: Side Force Coefficient
- $P$: Pressure
- $\rho$: Density
- $U$: Velocity
- $t$: Time
- $\delta_Z$: Shock Displacement

Subscripts

- $\infty$: freestream
- $A$: Upper
- $B$: Center
- $C$: Lower

1. Introduction

The blunt nose shapes have great influence on drag of moving object in hypersonic flow-field because of detached bow-shock formation in front of the body. For the same reference area, the positive curvature (convex) nose shape can have smaller drag coefficient than the zero curvature (flat) and negative curvature (concave) blunt nose shape.1) In the supersonic and hypersonic flow-field, a detached bow-shock formed in front of blunt nose shape, can be observed as steady in uniform flow of wind tunnel test-sections by using Schlieren method and normal video camera (25~30 fps). By using high-speed cameras, the fluctuations in bow-shock have been observed in front of concave hemispherical shell at supersonic speeds higher than Mach 3 and mechanism of bow-shock instabilities has been discussed by assuming the density disturbance in the cavity by Mizukaki et.al.2) Further large bow-shock instabilities have been observed in front of finite length concave cylindrical arc at hypersonic speed of Mach 7.3) However, for positive radius of curvature with high bluntness, the high-frequency oscillations in bow-shock in hypersonic flow, have been observed with high-speed camera by Fujii et.al.4) But, for the negative radius of curvature hemispherical shell, these bow-shock oscillations can become so large in amplitude, that it can be observed even with normal digital camera. Although, for analyzing, the bow-shock instabilities, it is required to use high-speed cameras. The mechanism of bow-shock instabilities in front of highly blunt body or concave shape geometry is still not completely understood. There can be many possible reasons, for instabilities in bow-shock e.g. flow non-uniformity, structural oscillations, particle induced instability or aerodynamic instability (bow-shock/cavity-vortex interaction). The random particle induced instabilities can be identified by shock interactions between bow-shock and shock in front of particle.3)

The motivation of this study is to utilize the high drag configuration of concave shaped blunt nose as decelerator in high-speed flows. However, the unstable bow-shock around the concave shape geometry can influence the force experienced by the body as well as heat transfer in hypersonic flow-field. Hence, to utilize concave shape as decelerator, the flow-field around the concave shape geometry should be stable. The main objective of this study is to investigate the effectiveness of different passive flow control methods for bow-shock instabilities in front of concave shaped blunt nose. Passive control methods have been advantageous over the active control methods because it requires only geometrical modifications and no requirement of external energy source. The energy required for the flow control is directly drawn from the flow-field. Various types of passive control methods have been studied by many researchers, according to flow control requirement of particular study. In this study, three types of passive flow control methods have been studied for concave shape hemispherical shell as spike, breathing holes and crosswire. To reduce the drag for lifting body configuration, application of aero-spikes have
been studied by Khurana et al.\(^5\) The effectiveness of breathing blunt nose (BBN) concept for drag control in hypersonic flows was demonstrated by Imamura et al.\(^6\). Further the effectiveness of BBN on drag reduction has been studied at supersonic speed by Ashish et al.\(^7\). The performance of disk-band-gap parachute model has been studied by Wernet et al.\(^8\) for supersonic parachute model. The disk-gap works similar to breathing flow-control device, which allows flow to pass through the side gaps. The jet control method in form of crosswire as limiting length of the tabs at the exit of supersonic nozzle have been studied by Rathakrishnan,\(^9\) for promoting mixing and noise control in supersonic jets. The limiting length of tabs as radius of the nozzle exit area, which found to be effective for mixing promotion and noise reduction by Rathakrishnan,\(^9\) is termed as Rathakrishnan limit.

These three passive control methods were also selected to make an attempt to understand the bow-shock instability phenomenon in front of concave hemispherical shell by studying the effect of these controls. These different passive control methods have their different effectiveness of vortex manipulation in the flow-field to get desired flow control. In case of hemispherical shell studied in hypersonic flow field, spike at the center of concave shell can reduce the size of the cavity vortex in comparison to no flow control concave shell. The breathing hole at the curved surface of hemispherical shell can reduce the strength of vortex inside the cavity by allowing high pressure flow to pass through the base. Although, the amount of vortex strength reduction in the cavity depends on the hole size and environment pressure at the base of concave shell as it will be always choked in hypersonic environment. The crosswire can increase the mixing in the cavity by shedding small eddies from its surface into the cavity to control the vortex size in the cavity as well as it can produce hindrance to disturbance waves going into and coming out from the cavity.

In this study, the effectiveness of passive flow control methods was studied by force measurement and unsteady pressure measurement along with synchronized time-resolved flow visualization using high speed camera. The Schlieren video was captured with high speed camera and further shock instabilities were studied by digital image processing method.

2. Experimental Method

2.1. Hypersonic Wind Tunnel

The high speed experiments were conducted at Kashiwa Hypersonic and High Temperature Wind Tunnel,\(^10\) at Graduate School of Frontier Sciences, The University of Tokyo. The wind tunnel test-section is designed for Mach 7 flow field with uniform core of 120 mm diameter. The maximum stagnation pressure and temperature for the wind tunnel are 950 kPa and 1000 K, respectively. The specifications of hypersonic wind tunnel are mentioned in Table 1. Although the stagnation pressure was kept approximately 958 kPa for all the experiments, the stagnation temperature varies from 450 K to 600 K. Total number of 8 runs of wind tunnel were carried out for force and pressure measurements separately.

2.2. Experimental Models

The experimental models used during experiments as concave hemispherical shell with no control and with spike, breathing holes and crosswire controls are shown in Fig. 1. The base hemisphere geometry have outer diameter of 30 mm and thickness of 3 mm (Fig. 1a). The hemisphere with spike geometry have spike at the center with 3 mm diameter (Fig. 1b). The location of spike end is 1 mm outside the cavity so that the disturbance waves should interact with spike first at the center before entering the cavity and spike should not be too long to work as drag reduction device. The hemisphere with breathing holes has four identical holes of 3 mm diameter. The four number of holes were chosen so that these can be placed at symmetric locations and the placement of holes do not affect the lift and side force during measurements. The 3 mm size of the holes was chosen to have the similar size of all the control methods.
studied in this study. The holes were drilled perpendicular to the surface of hemisphere at four diametric opposite locations with center lies on the periphery of the circle of 18 mm diameter (Fig. 1c). The hemisphere with crosswire geometry was made by attaching 3 mm diameter cylindrical rod at the groove made at the diametrically opposite edges of hemispherical shell (Fig. 1d). The reference coordinate system for each geometry is shown in Fig. 1. The Z-direction is assumed in the flow direction. The two sets of experimental models for each geometry have been fabricated for force and pressure measurements which are shown in Fig. 2. The pressure measurement model have been attached with 1 mm outer diameter pressure tube at the diametric opposite location, with center at X = ±13.5 mm. It is to note here the center pressure tube is flush mounted at the center of the cavity for no control, breathing control and crosswire control geometries, while for spike control, it is flush mounted at edge of the spike (Fig. 1b). As the main objective of this study is to demonstrate the effectiveness of different passive control methods, the experimental models are designed with same size of different control methods as 3 mm. However, the parametric study of different sizes of control methods can be performed in future by using numerical methods.

2.3. Measurements and Flow Visualization

The force measurement was done using six component force balance system. As the sensitivity of force balance system is low, force data was acquired with 20 Hz low pass filter for 20 seconds (30 seconds in case of crosswire control) using data logger to avoid noise. The experimental models were mounted with force balance on the moving arm in the wind tunnel test-section, which was inserted in the established hypersonic flow-field and retracted after measurement time. The first four experiments were done for only force measurements. The pressure measurement was done using two kind of kulete pressure sensor. For center pressure, highly accurate, amplified version of pressure sensor Kulite ETL 76M-190 was used, which has full scale output of ±5 V. For edge pressure, two Kulite XCEL-152 pressure sensor were used, which has full scale output of ±100 mV. The pressure signals were recorded with 10 kHz frequency using data logger during the experiments. The flow visualization was done using twin mirror Schlieren system with sodium lamp as light source. The Schlieren system was combined with high speed camera Phantom Miro M310 and high resolution lens system. The frame size captured was 640 × 480 pixels around the geometry in test-section. The frame rate was used as 10000 fps with exposure time of 99.569 μsec. The Schlieren video was captured along with pressure measurement and camera was triggered manually during the experiment. This trigger signal was recorded along with pressure sensor data and have been used to synchronize the pressure data and Schlieren video. The Schlieren video was captured in X-Z plane for all the four geometries. Due to internal memory of camera, the Schlieren video was recorded for 1.37 s.

2.4. Pressure Data and Image Processing

Pressure data measured during the experiments have been synchronized with the Schlieren video. As the edge pressure sensor XCL-152 had very low full scale output (±100 mV) and recorded as it is without any conditioning, it exhibits very low S/N ratio as there are many sources of noise in the wind tunnel system. Hence, pressure data at the edges have not been taken into account for current study. The center pressure($P_b$), which was measured using ETL-76M-190 sensor, with 10 kHz sampling rate, have been non-dimensionalized by freestream dynamic pressure (($\rho_\infty U^2_\infty$)/2). A 4th order low-pass Butterworth filter with cut-off frequency ratio ($f_c/f_s$) of 0.3 has been applied to reduce the high frequency fluctuations.

The shock displacements were computed from Schlieren video recorded during the experiments. The OpenCV library, was utilized to capture the frames from the video and process them to extract the shock fluctuation information. The method for image processing is shown in Fig. 3 with different steps taken after the original frame extraction. The canny edge detection method was utilized which was found useful by Estruch et.al for studying unsteadiness in shock-wave/turbulent boundary layer. Figure 3a shows the cropped original grayscale image frame of 300 × 300 pixels, captured from high speed camera. The image frame further processed by histogram equalization (Fig. 3b) and binary threshold with median blur filter to reduce the noise in the image (Fig. 3c). The canny edge detection method was applied further to capture the edges based on intensity gradient (Fig. 3d). The contours were drawn from the output image from edge detection (Fig. 3e). These contours have some noise in form of small contours at the left corner, which were reduced by using contour isolation based on area and length and the final image as (Fig. 3f) has been obtained which has shock and geometry outline. Further, three locations on the outer edge of shock has been computed as shown in (Fig. 3g). The upper edge and lower edge lines were placed at the location of pressure tube used in pressure measurement.
model. The shock displacement was calculated as horizontal distance between the location of computed pixel (A, B and C) and the center pixel of geometry. The shock displacements have been non-dimensionalized by the size of the geometry and referred as $\delta_{ZA}$, $\delta_{ZB}$ and $\delta_{ZC}$ for upper edge, centerline and lower edge, respectively. These non-dimensionalized shock displacements were calculated for all the image frames of Schlieren video for 1 s. The accuracy of shock displacement calculation depends on resolution of image frame, applied filter kernel sizes and noise present in the captured original image. The non-dimensionalized pressure data was also analyzed for 1 s time interval starting from the trigger location.

3. Results and Discussion

3.1. Force Coefficients

The force measurement experiments were conducted for all four geometries by using six-component force balance system. Further, the measured drag, lift and side forces were non-dimensionalized by using freestream dynamics pressure ($\rho_{\infty}U_{\infty}^2/2$) and maximum projection area of concave geometry. Figure 4 shows the time history of drag, lift and side force coefficients for all four geometries. The force coefficients were measured for 20 s (30 s in case of crosswire control), while the model was inserted in the steady hypersonic flow-field for 15 s (25 s in case of crosswire control) by moving arm inside the test-section. Table 2 shows the time-averaged force coefficients for 10 s (between 5 s to 15 s) for all four geometries.

### Table 2. Time-averaged Force Coefficients between 5 s to 15 s.

<table>
<thead>
<tr>
<th>Geometry</th>
<th>$C_D$</th>
<th>$C_L$</th>
<th>$C_S$</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Control</td>
<td>1.71</td>
<td>-0.024</td>
<td>-0.048</td>
</tr>
<tr>
<td>Spike Control</td>
<td>1.73</td>
<td>0.036</td>
<td>0.001</td>
</tr>
<tr>
<td>Breathing Control</td>
<td>1.73</td>
<td>0.007</td>
<td>-0.031</td>
</tr>
<tr>
<td>Crosswire Control</td>
<td>1.72</td>
<td>0.021</td>
<td>-0.012</td>
</tr>
</tbody>
</table>

Figure 4a shows the time history of drag coefficient ($C_D$) for no control, spike control, breathing control and crosswire control. It is interesting to note that there is no significant effects on time history of drag coefficients by using different control methods. The time-averaged drag coefficient is also approximately similar for all the geometries. The fluctuations in time history of lift and side force coefficients in Fig. 4b and 4c reflects the unsteadiness of flow-field around the geometries. In these figures, it can be seen that no control and breathing control for concave hemispherical shell geometries show high fluctuations in lift and side force coefficient, while spike control and crosswire control geometries have relatively stable lift and side force coefficients during the measurement. The time-averaged values of lift and side force coefficients are slightly offset from zero, which can be because of uncertainty in angle of attack during measurement. From the fluctuations in lift and side force coefficients, it can be clearly seen that spike and crosswire controls are very much effective in controlling the bow-shock unsteadiness.

The plot between lift and side force can provide information regarding the flow motion around and inside the cavity. Ideally, the vortical motion in cavity can represent circle in lift and side force plot, while back and forth motion of flow can represent as straight line. Hence, the lift and side force coefficient are plotted for time between 5 s to 15 s. In Fig. 5. The offset from zero can be seen for all the cases, which is because of uncertainty in measurement of angle of attack in the experimental set-up. For no control, the locus of lift and side force shows very wide spread and not a perfect circle or straight line. It can be said that the it
is because of the combination of both kind of flow motion inside the cavity, vortical as well as back and forth. For breathing control, the spread of locus of lift and side force coefficient become slightly lesser than compare to no control, hence, it can be concluded that the breathing can reduce the fluctuation in flow-field slightly. For spike and crosswire control, spread of the plot is significantly reduced. It can be deduced that spike and crosswire works as better control for reducing bow-shock instability by stopping the flow disturbances traveling inside the cavity. It is also interesting to note that spike can stop the disturbances at center of the cavity, while crosswire is mounted in Y direction, still both shows effective control on flow-field unsteadiness in three dimension. To further understand the flow-field around the concave hemispherical shell with no control and with different controls, it is required to study flow visualization images with high-speed camera as well as pressure fluctuations.

3.2. Bow-shock Instability for No Control

The unsteady pressure and shock displacement have been analyzed for 1 s duration and have been synchronized. To understand the bow-shock instability phenomenon and to analyze the reliability of image processing method for shock displacement, a short time duration window of 30 ms. starting from \( t_0 = 0.34 \) s has been analyzed in detail for no control geometry. The non-dimensionalized shock displacement \((\delta_Z)\) has been plotted for center line (Location B), upper line (Location A) and lower line (Location C) in Fig. 6 for 30 ms. Along with shock displacement, non-dimensionalized center pressure also have been plotted for 30 ms starting from \( t_0 = 0.34 \) s. Both these plots were marked with 6 time locations as \( t_1 = t_0 + 2.1 \) ms where the shock displacements for all three locations are close to each other, \( t_2 = t_0 + 5 \) ms just before starting of instability, \( t_3 = t_0 + 6.9 \) ms when the peak was attained for lower edge displacement, \( t_4 = t_0 + 18 \) ms just before drop in shock displacement for all the three locations, \( t_5 = t_0 + 19.9 \) ms peaks are attained for upper edge and center location, and \( t_6 = t_0 + 21 \) ms, again at the end of instability pattern. The center pressure data was also referred for the same time. The corresponding Schlieren image at the same time locations were shown in Fig. 7.

The shock displacement fluctuations in Fig. 6 are corresponding to one large shock deformation observed for concave hemispherical shell with no control. The shock outer edge varies upto approximately 0.6 which is corresponding to 18 mm horizontal distance from the edge of 30 mm diameter concave shell. During the over all shock deformation, the center shock displacement \((\delta_Z)\) and lower edge shock displacement \((\delta_{ZC})\) has shown significant fluctuations after time \( t_3 \) up to approximately \( t_6 \), while the shock displacement fluctuations for upper edge \( \delta_{ZA} \) are near 0.2. However, after time \( t_4 \), \( \delta_{ZA} \) and \( \delta_{ZB} \) attains one peak, while \( \delta_{ZC} \) become almost stable. It can be deduced from only shock displacement plot that in this shock deformation, first the shock from the center to the lower edge is deformed significantly, while shock at the upper edge in intact to the body. Just before attaining stable shock position, shock deformed at upper edge for very short time. Hence, from only shock displacement \( \delta_Z \) plot the unsteady shock instabilities can be analyzed clearly.

From the non-dimensionlized center pressure fluctuations during this time window it can be seen that the center pressure ratio \((P_B/P_\infty)\) has increased from 2.0 to 2.1, which correlates to pressure rise of approximately 790 Pa during the shock movement and center pressure ratio further reduced after shock moved back to stable location. Hence, the rise in center pressure can be explained from the Schlieren images. The center pressure ratio crosses the 2.1 value at time \( t_1 \) the corresponding Schlieren image in Fig. 7 shows the kink near the center, where the bow-shock is deformed in two shocks one at the edge and other one moved upstream, and they interact each other near the center. In subsequent images at \( t_4 \) and \( t_5 \) also exhibits that bow-shock has been deformed in two interacting shocks. Figure 7 shows the different stages of bow-shock deformation during the window time of 30 ms. At time \( t_1 \), the bow-shock is well placed in front of concave hemispherical shell and Fig. 6 also shows the shock displacement for \( \delta_{ZA} \) and \( \delta_{ZB} \) and \( \delta_{ZC} \) are close to 0.2. Although center pressure has increased slightly and fluctuates between \( t_1 \) and \( t_2 \). When \( t_2 \), the shock instability has initiated from the center and moved towards the lower edge, it can be reflected in center pressure ratio plot as sharp increase.
At time $t_3$, shock displacement at lower edge has peak as Fig. 6 shows the large deformation in bow-shock in Schlieren image at the lower edge. The bow-shock has transformed in kind of two interacting shock and the interaction point is near the center. At time $t_4$, just before the drop in shock displacement, the interaction point of two different shocks has reached at the upper edge, and shock displacement at upper edge shows the rapid decrease. The secondary shock is very close to upper edge and covering the cavity, hence, there is no significant change in center pressure ratio from $t_4$ to $t_5$. At time $t_5$, the bow-shock deformed from the upper edge while having the interaction with the secondary shock at the lower edge, it shown peaks in shock displacement plots for $\delta_{ZA}$ and $\delta_{ZB}$. As the secondary shock is still covering the cavity but from the lower edge side, no significant changes observed in center pressure ratio. At time $t_6$, the Schlieren image shows the stable position of bow-shock. Hence the deformation from the upper edge sustained less than 2 ms.

It can be concluded from this discussion the image processing method adopted to analyze the shock displacement, provides reliable information for shock deformations during the shock instability, which can be related to center pressure data and Schlieren images to have better understanding of flow behavior during particular shock instability.

### 3.3. Bow-shock Instabilities with Controls

The image processing method, discussed in previous section has been utilized to study the effectiveness of passive flow control methods. Figure 8 shows the bow-shock displacement at the centerline $\delta_{ZB}$ of concave hemispherical cavity for no control, spike control, breathing control and crosswire control for time period of 1 s from the starting of the trigger location. The concave hemispherical shell without any control shows significant fluctuations up to $\delta_{ZB} = 0.6$. These random fluctuations show the unsteadiness of bow-shock in front of concave blunt nose. The center shock displacement for concave hemisphere with spike control shows significant reduction in the fluctuations of center shock displacement ($\delta_{ZB}$). But still there are some instants, where the shock movement has crossed $\delta_{ZB} = 0.4$. The shock displacement with breathing control plot has also shown reduction in shock fluctuations for some intermittent time intervals, but it has violent movements of bow-shock at many intervals. The center line shock displacement with crosswire control plot shows best effectiveness of flow control and had reduced shock oscillations significantly, except at few time locations. Figure 9 shows the power spectrum diagram for centerline (at $X = 0$) shock displacement ($\delta_{ZB}$), upper edge (at $X = 13.5$ mm) shock displacement ($\delta_{ZA}$) and lower edge (at $X = -13.5$ mm) shock displacement ($\delta_{ZC}$) for concave hemispherical shell with no controls and with spike, breathing and crosswire controls. The continuous peaks in fluctuations of bow-shock displacement have been seen for most of the frequency range.
A. VASHISHTHA et al.: Bow-Shock Instability and its Control in front of Hemispherical Concave Shell at Hypersonic Mach Number 7

The spike at the center of concave hemispherical shell can reduce the bow-shock instability initialization at the center, which starts from center and move towards the lower or upper edge. As the end of spike is 1 mm ahead from the cavity, which may not disturb the bow-shock in front of cavity but it can cut the disturbance waves traveling in and out of the cavity at the center. However, spike at the center can only disrupt the initiation of bow-shock instability at the center, still the instability initialization can shift off-center (Fig. 9 for δZC). The breathing mechanism controls the fluctuations inside the cavity and release some of the mass entrained in the cavity towards the base. Although, the static pressure outside can be very low and the cavity pressure can be very high, the breathing holes will be choked and can allow only maximum mass to pass through base, hence can delay the shock instability, which reflects in the centerline shock displacement plot in (Fig. 8). However, the crosswire can control of bow-shock instability initialization along the diametrical line and also control the disturbance wave moving in and out of the cavity. Along with that the vortex shedding from the cylindrical cross section can promote the mixing with small eddies for mass entrained inside the cavity. Hence, crosswire control has best effectiveness among the control methods studied. From this explanation, it can also be deduced that in case of shorter crosswire (in form of diametrically opposite tabs) with length less than radius of hemispherical shell may not be as much effective, as crosswire because there will be no control for shock initialization at the center. To have effective control, the maximum length can be provided as crosswire along the complete diameter, which is consistent with the Rathakrishnan Limit defined in case of jet control. 9)

3.4. Center Pressure Analysis

It is to note that the center pressure tubes are flush mounted at the center of the cavity surface for no control, breathing control and crosswire control, but located at the spike end for spike control geometry (Fig. 1). The non-dimensionalized center pressure (Pc/P∞) has been plotted for 1 s time duration in Fig. 10, which is synchronized with the shock displacement plot (Fig. 8). The center pressure ratio can be related with the large deformation of bow-shock as explained in section 3.2. It can also provide the information of flow structure inside the cavity. The center pressure ratio oscillations for concave hemisphere with no control (Fig. 10) have shown many peaks above the value 2.0, which explains many large deformations in bow-shock for no control (Fig. 8). For spike control in Fig. 10, the center pressure ratio has shown many low peaks, as the pressure measurement location is just behind the shock, these low peaks can be related with any disturbance at the center location of bow-shock. For breathing control the center pressure ratio has shown again oscillatory behavior as in case of no control, but the number of high peaks have been reduced for the analysis time of 1 s. It can be deduced from that the large deformation are delayed in case of breathing control mechanism. For the crosswire control in Fig. 10 the center pressure ratio is almost below value of 2.0 except for some peaks, which can be related with the centerline bow-shock displacement plot for crosswire control (Fig. 8). It can also be observed that the response of center pressure variation is slower than the shock displacements measured by Schlieren images because of the location of center pressure tube and the disturbances in bow-shock may take sometime to reach the center. However, in future, by improving the pressure measurement method, shock displacements and corresponding pressure fluctuations can be studied together to extract more information regarding the flow-field around the concave hemispherical shell.

4. Conclusions

The time averaged drag coefficients does not significantly change for concave hemisphere with or with out control methods studied. However, the locus of lift and side force coefficients provide information about the effectiveness of spike and crosswire control in comparison to breathing and no control geometries. The adopted method of image processing for shock displacement study, have been found reliable in providing information of shock movement with respect to measured unsteady center pressure data and flow structure in the Schlieren images. It is concluded that crosswire control have been most effective to reduce the large deformation of bow-shockwave in front of concave hemispherical shell. The center pressure data also have been helpful to provide information for bow-shock fluctuations. In future, center pressure along with edge pressure data and Schlieren images combined may be useful for further understanding of flow physics of instability phenomenon.

Acknowledgments

The author would like to acknowledge the Ministry of Education, Science and Technology (MEXT), Government of Japan
to provide financial support for carrying out doctoral research at The University of Tokyo.

References