BOUNDARY LAYER TRANSITION IN HYPERSONIC BOUNDARY LAYER

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Summary Flow visualization and wall pressure measurement were used to study the transition of a flared cone in our newly established Mach 6 quiet tunnel. In comparison with the previous visual results, the images show the clear evolution of the flow structure. Our results show that each second-mode wave generates one Mach wave and there is a quiet zone before breakdown stage. Transition trigged by the second mode wave seems not as complex as that generated by the first mode [1].

Because the differences in skin friction and heat transfer between laminar and turbulent flow are large enough to alter radically the performance of hypersonic vehicles, the transition problem in hypersonic flow has for a long time attracted attention. Most of previous hypersonic stability experiments have been conducted in conventional wind tunnels where relatively large freestream disturbances occur. To reduce the disturbance, we have developed a Mach 6 quiet tunnel (M6QT) in Peking University. Following the successes of the M6QT, a flared cone was tested for its transition experiments. Second-mode instability waves are phenomena that occur in the transition region in certain hypersonic boundary layers [2]. However, information in regard to the development of these instability waves is not well understood. In this paper, we report the performance of the newly developed M6QT in Peking University and our experimental investigations of hypersonic boundary-layer stability on a flared cone with zero angle of attack.

To assess the quiet flow performance of the tunnel, a series of Pitot pressure fluctuations were measured by high-frequency dynamic pressure transducers located on the nozzle centerline. Sensors used were XCE-062-25A models manufactured by Kulite Semiconductor. A Kulite Pitot Pressure trace with observed quiet flow is presented in Figure 1. For this run, the total pressure was 0.35MPa and total temperature was 410K. The Kulite sensor head was located at the nozzle exit. With the bleed valve open, the nominal RMS Pitot pressure fluctuation is observed to be $P'_0/P_0=0.20\%$, which is essentially the sensor's electronic noise floor under no-flow conditions. Nevertheless, this has the same order of magnitude as the generally-accepted 0.10% threshold for flow considered quiet. The level may be less than 0.10% by using more sensitive sensors. With the bleed valve closed, the RMS pressure fluctuation level is approximately 2.5%.

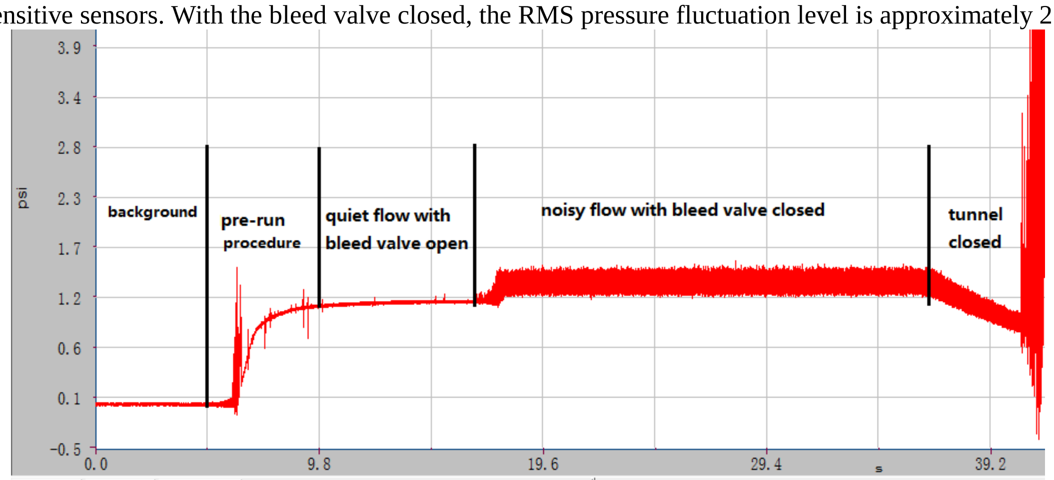

Figure 1. Kulite Pitot pressure trace

The M6QT is a long-duration blow-down hypersonic facility that provides a Mach 6 air flow through an axisymmetric contour nozzle, with a 120-mm exit diameter. To induce transition on the model, a flared cone was tested in this study. The cone has a straight 5° half angle for the first 100mm of axial distance which tangentially merges into a flared region of radius 930.71mm for the remaining 160mm. Second-mode waves were measured using PCB132A31 pressure transducers. Such sensors were first used to measure second-mode waves by Fujii[3]. The sensors were placed at distances of 100mm, 170mm, and 240mm from the nose tip of the model. The pulsed schlieren diagnostic was used to image second-mode waves. All images were taken using pulsed xenon lamp as a light source. The CCD exposure time was 2-μs. To get the whole picture of the transition process, the cone was studied under noisy flow.

Figure 2 shows second mode waves indicated by PCB132A31 power spectral densities (PSD) with unit Reynolds number of $5.3\text{x}10^6$/m. Second-mode waves are not seen at x=100mm. At x=170mm and x=240mm, the second-mode waves can be seen centered at around 280 kHz. In addition, the second-mode waves can be visualized in Figure 3 using schlieren techniques. The field-of-view is approximately 108 x 38 mm^2. The flow goes from left to right. Some faint waves intermittently appear on the left side. As they progress downstream, the second-mode waves become distinct until they become weak and hard to see again just before the breakdown stage. The wavelength of these waves is measured to be approximately 2mm. Figure 3 also shows the strong Mach waves radiated from the edge of boundary layer. The Mach waves develop and form a set of small shock waves with the amplitude increase of the second-mode wave.

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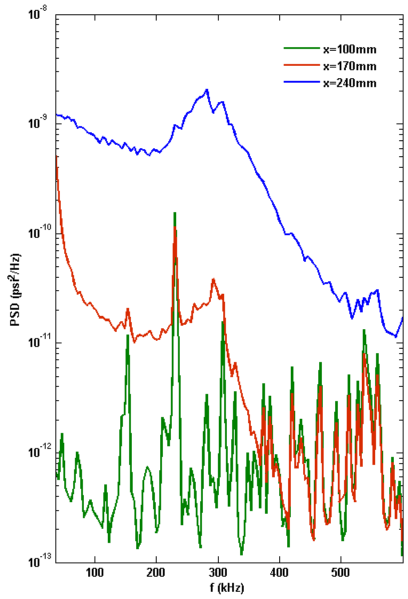


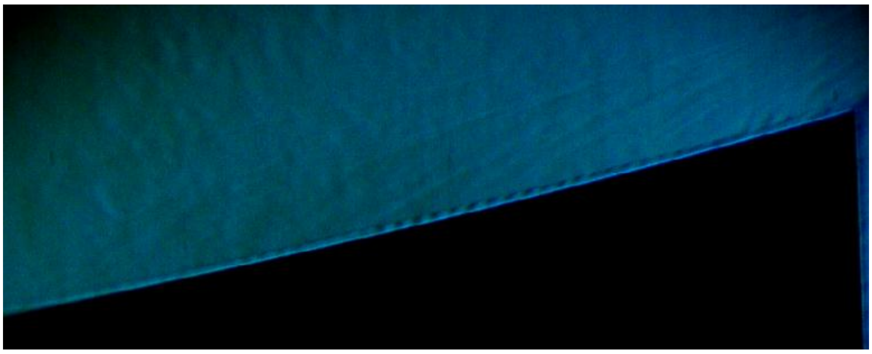
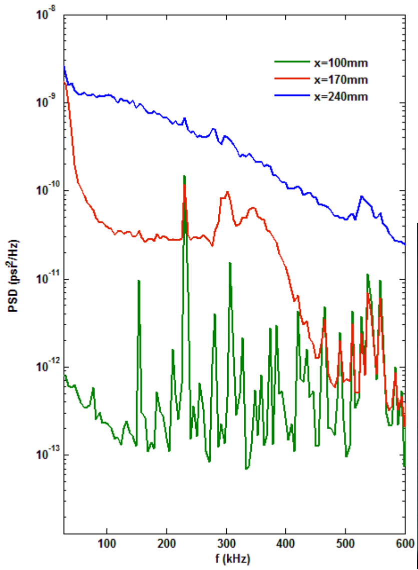


Figure 2. PSD at Re/m=5.3×10^6 Figure 3. Schlieren image at Re/m=5.3×10^6

Figure 4 shows PCB132A31 power spectral densities under transitional flow for Re/m=8.5×10^6. The PCB at x=100mm shows no indication of second-mode waves. At this location, the boundary layer is laminar. A second-mode wave with a peak frequency around 340 kHz can be seen at x=170mm. However, at x=240mm，the second-mode waves have broken down and are no longer visible. The boundary layer breakdown occurs at this location. Second-mode waves are also imaged in Figure 5. In the upstream portion of the cone, the second-mode waves are remarkably in appearance. Then the second-mode waves become weak but are still visible just before the breakdown stage. After the quiet zone, the second-mode waves break down and disappear. Li et al. [4] also mentioned that the boundary layer becomes quiet before the breakdown stage in their DNS results. To our knowledge, the existence of the quiet zone in the hypersonic transitional flow is first found in experiments.



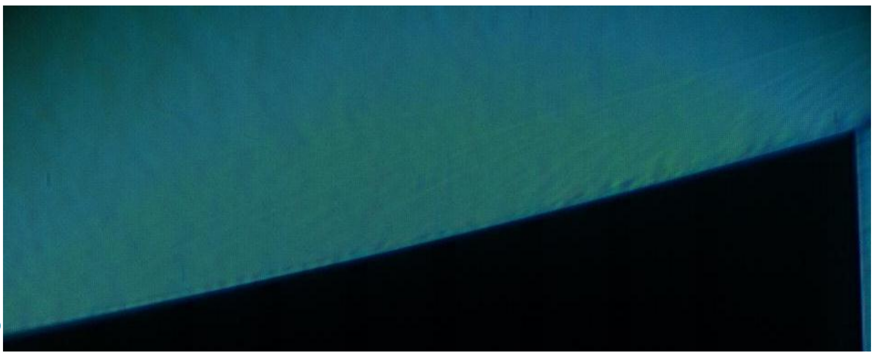


Figure 4. PSD at Re/m=8.5×10^6 Figure 5. Schlieren image at Re/m=8.5×10^6

In this paper, growth rate of second-mode wave was obtained both from pressure fluctuation measurement and the flow visualization. The present work shows clear pictures of the generation and development of the second mode instability waves. The pictures also show a series of Mach waves induced by the second mode waves. We find that there is a quiet zone before the breakdown stage, which is not reported in previous experiments. Transition trigged by the second mode wave seems not as complex as that in low speed flow.

References

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