Hypersonic vortex wake behind the wing and its interaction with shock waves

Andrey Shevchenko, Anatoly Kharitonov, Andrey Shmakov
Khristianovich Institute of Theoretical and Applied Mechanics
Institutskaya 4/1, 630090 Novosibirsk, Russia

Shock/Vortex interaction is one of the fundamental problems of aerogasdynamics [1, 2]. The absence of numerical and experimental data for hypersonic velocities should be specially noted. Obtaining results for this range of velocities is extremely important for the development of promising flying vehicles (avoiding of catastrophic operation regimes of a hypersonic inlet and improvement of mixing in the combustor). Earlier studies [3] were found principal differences in unsteady regimes during the interaction at Mach numbers of 2–4 and at $M = 6$. Therefore three sets of experiments were performed to study of a free vortex wake behind a wing and an unsteady nature of a wing wake / shock wave interaction at Mach number of 6.

The experiments were conducted in the hypersonic wind tunnel T-326 of ITAM SB RAS. A wing-tip vortex was generated by an unswept semispan slender wing. Experiments performed with bow shock in front of the cylinder with flat end and with oblique shock in front of wedge with a sharp leading edge. Complex of experimental techniques included a high–speed shadow visualization, a laser–sheet imaging technique, Pitot pressure and total temperature measurements in the vortex wake. The fast-response pressure transducers were used to measure of pressure pulsation on the face of the cylinder. Experimental equipment and flow visualization system allows obtain shadowgraphs and simultaneously record the pressure pulsation data. Time-averaged pressure distribution on shock wave generators were measured as well. Experimental data were obtained for wing angles of attack (α) up to 20 deg.

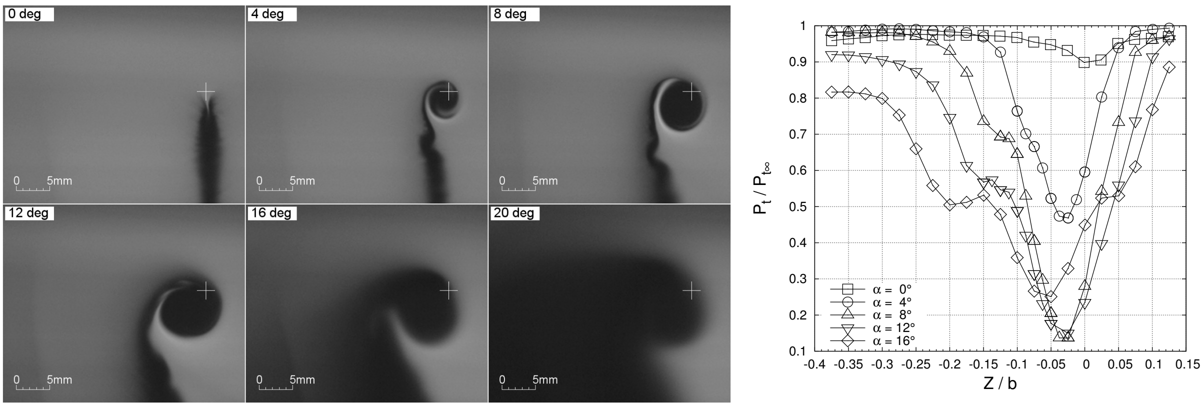
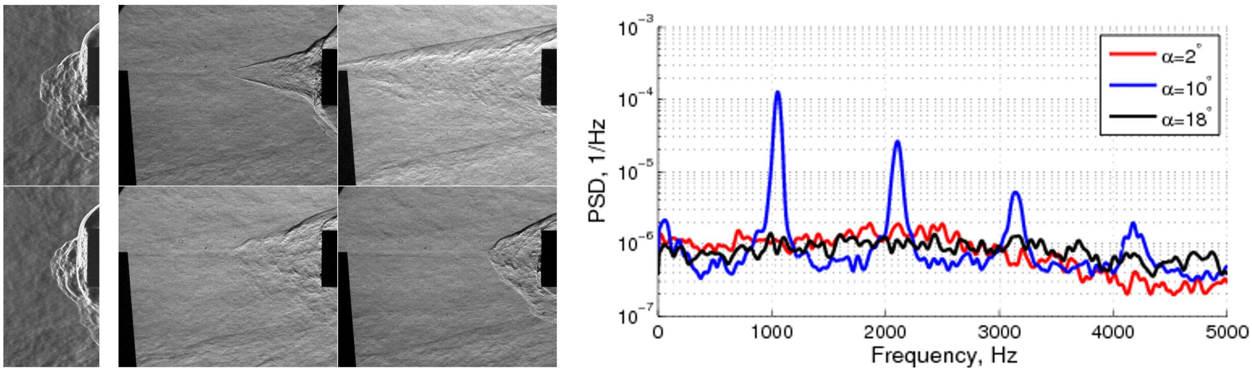


Figure 1: Free vortex wake data: laser–sheet images (left) and Pitot pressure distribution across the vortex core (right)

In the free vortex wake experiments the sizes of the vortex core for different angles of attack were determined. Both Pitot pressure and the stagnation temperature distributions were obtained. It was obtained that the vortex wake is characterized by a strong decrease in the total pressure and by nonuniformity of the stagnation temperature. In the near wake directly behind the wing, a single vortex wake is formed, where a decrease in the total pressure up to 4% of the free-stream total pressure and a decrease in the stagnation temperature by 10% were observed. The flow parameters change weakly in the spanwise direction. The minimum values of the total pressure and stagnation temperature decrease with increasing angle of attack. A vortex core is formed downstream from the wing. The decrease in the total pressure and temperature in the vortex core is appreciably greater than in the wake, which shows that the vortex core dissipate slower than the vortex wake. The decrease in the minimum values of the stagnation pressure and temperature is enhanced with increasing angle of attack. At angles of attack $\alpha \geqslant 16°$, the vortex core is destroyed, which is accompanied by an increase in the stagnation pressure and temperature.



(a) (b) (c)

Figure 2: Vortex wake / bow shock interaction regimes: (a) - pulsing mode at $\alpha = 2°$ (top) and at $\alpha = 18°$ (bottom); (b) - self-oscillations mode at $\alpha = 10°$; (c) - pressure pulsations power spectra density distribution

Depending on the distance between the wing and the bow shock wave generator (cylinder with a flat frontal face), flows similar to the flow in the free cavity of the open or closed type are formed. The pressure on the frontal face of the cylinder is lower and the pressure fluctuations are more intense than in the undisturbed flow around the cylinder. In the first case (open type), the interaction region extends upstream from the cylinder up to the vortex generator. The pressure in the central part of the cylinder is independent of the angle of attack of the wing. At $\alpha \geqslant 10°$, there arise self-sustained oscillations, and the interaction region extends upstream from the cylinder up to the vortex generator. As the distance between the vortex generator and the cylinder increases, flow reconstruction occurs, and a flow similar to the flow in a free cavity (closed type) is formed. At $\alpha = 8 \div 16°$, self-sustained fluctuations of the mass flow arises, and the interaction region extends upstream from the cylinder up to the vortex generator. The mean level of pressure decreases, and the amplitude of pressure fluctuations increases. The self-sustained oscillations are induced by the specific character of the pressure distribution in the core of the streamwise vortex, i.e., by a decrease in pressure at the center of the vortex core when approaching the vortex generator. At $\alpha \geqslant 16°$, the self–oscillations disappear, and the pulsed regime of interaction is reconstructed. The mean pressure at the cylinder center somewhat increases, and the pressure fluctuations become less intense. The reason for the recovery of the pulsed flow regime is the vortex breakdown.

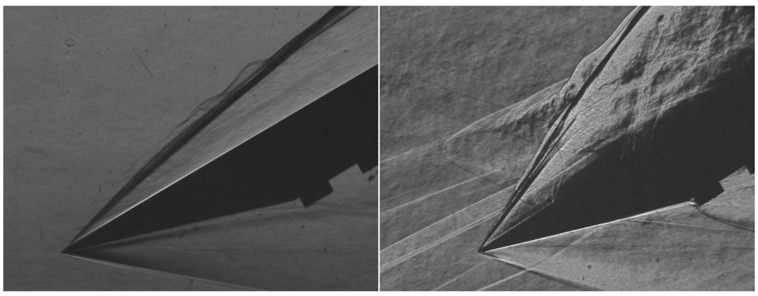


Figure 3: Vortex wake / oblique shock interaction regimes: $M = 6$ (left) and $M = 3$ (right)

During the vortex wake / oblique shock wave interaction at the Mach number $M = 6$ and angles of flow deflection up to 30° (which corresponds to the oblique shock intensity $p_2/p_1 = 17.8$), the regime of strong interaction with formation of a reverse flow region was not observed. The streamwise vortex passes through the shock wave without being destroyed and induces regions of reduced pressure on the surface of the shock wave generator. This shows that the total pressure in the vortex core is higher than the static pressure behind the oblique shock wave, i.e., the shock intensity is insufficient for vortex breakdown. At $M = 3$, moderate and strong interaction modes were observed, depending on the shock intensity. The strong interaction mode with vortex breakdown and formation of a reverse flow region occurs at flow deflection angles greater than 18° ($p_2/p_1 \geqslant 10$).

Acknowledgements:

The work was supported by the Russian Foundation for Basic Research (grant No. 12-01-00806)

References

[1] Delery J.M. (1994) Aspects of vortex breakdown. *Prog. in Aerospace Sciences*, **30**, pp. 1–59.

[2] Kalkhoran I. and Smart M. (2000) Aspects of shock wave-induced vortex breakdown. *Prog. in Aerospace Sciences*, **36**, pp 63–95.

[3] Shevchenko A.M., Shmakov A.S.: Experimental techniques and results of investigations of an unsteady flowfield in wing wakes / bow shock wave interactions. In: *Proc. at XIV Int. Conference for Aerospace Sci., Novosibirsk, June 30 – July 6, 2008*, ISBN 978-5-98901-040-0, Section 4, 10 p.