Shock Impingement Caused by Boundary-Layer Separation Ahead of Blunt Fins

LOUIS G. KAUFMAN II*

Grumman Aerospace Corporation, Bethpage, N.Y.

AND

ROBERT H. KORKEGI† AND LT. COL. LEO C. MORTON (USAF)‡

Aerospace Research Laboratories, Wright-Patterson Air Force Base, Ohio

Theme

HIGH-SPEED flow past a protuberance from a surface results in a complex, three-dimensional, inviscid-viscid interaction flowfield, such as that sketched in Fig. 1. Such interactions magnify the heating rate and pressure loads in local regions on the protuberance and adjacent surface, and have been responsible for in-flight structural failures.[1] We conducted several experiments and examined results from many other sources in order to understand better these types of interactions and establish a reliable flow model. Our purpose here is to describe the flow and methods for estimating the effects of the interactions.

Contents

The pressure rise across a blunt-fin bow-shock causes the boundary layer to separate from the adjacent surface ahead of the fin. The separated flow region is composed of horseshoe shaped vortices that scavenge part of the oncoming stream flow and spiral downstream very rapidly. Shock waves emanate from the separation location and impinge on the fin bow shock, resulting in a lambda-type shock interaction pattern in the plane of symmetry. The major effects of the interaction are an increased load on the surface adjacent to the fin, and intense pressures and heating rates in small regions on the surface immediately ahead of the fin and on the fin leading edge.

Separated flows ahead of fins are very unsteady; we attribute this intrinsic oscillatory behavior to a pulsating, scavenging action of the horseshoe vortices. The oscillation of the separation point about its mean position, and the fluctuating pressures ahead of the fin, are an order of magnitude larger than for comparable two-dimensional flows.[2] The amplitude of the movement of the separation point is particularly large when separation occurs in the vicinity of the transition location for the undisturbed boundary layer on the surface.

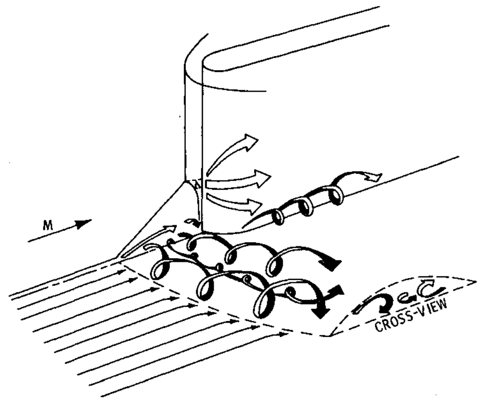

Fig. 1 Sketch of interaction flowfield.

Separation lines, scaled from oil film flow photographs, are shown in Fig. 2 for boundary layers that were fully turbulent upstream of separation. Within the natural oscillation of the separation location, these traces may be used in estimating the region of increased load on the surface adjacent to the fin. Examination of results from many sources shows that turbulent boundary-layer separation occurs approximately two diameters ahead of the fin and is insensitive to Mach number, Reynolds number, and boundary-layer thickness for a very wide range of test conditions (Mach numbers from 1.2 to 21), as long as the fin is larger (thicker and higher) than the undisturbed boundary-layer thickness. Laminar boundary-layer separation is much

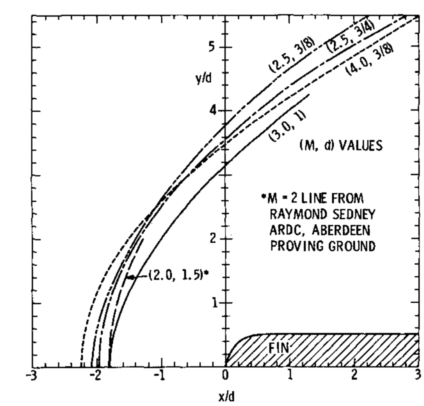

Fig. 2 Separation line locations on flat plate surface.

Presented as Paper 73-236 at the AIAA 11th Aerospace Sciences Meeting, Washington, D.C., January 10–12, 1973; submitted February 20, 1973; synoptic received April 24, 1973. Full paper available from National Technical Information Service, Springfield, Va. 22151 as N73-17274 at the standard price (available upon request).

Index categories: Supersonic and Hypersonic Flow; Jets, Wakes, and Viscid-Inviscid Flow Interactions; Airplane and Component Aerodynamics.

* Staff Scientist, Research Department; presently NASA/Grumman Research Associate at Langley Research Center, Hampton, Va. Member AIAA.

† Director, Hypersonic Research Laboratory. Associate Fellow AIAA.

‡ Deputy Director, Hypersonic Research Laboratory; presently Deputy Chief, Electronics Accessory Division, Headquarters, Ogden Air Materiel Area, Hill Air Force Base, Utah. Member AIAA.

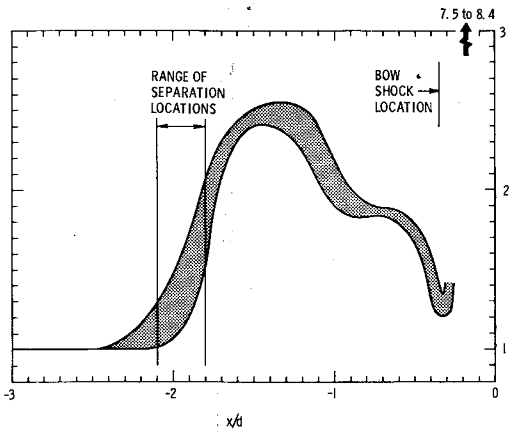

Fig. 3 Range of separation locations and centerline pressure distributions ahead of fin for $M = 3$.

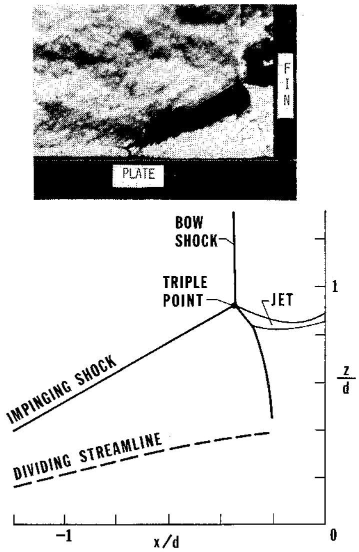

Fig. 4 Schlieren and sketch of interaction flow in centerplane ahead of fin for $M = 3$.

more extensive than turbulent separation. Although laminar separation also scales with fin diameter, it depends on both Mach and Reynolds numbers; there are no reliable methods for estimating its extent.

The pressure rises on the surface centerline ahead of the fin (Fig. 3) are similar to those ahead of forward facing steps and approach the two-dimensional laminar plateau or turbulent peak pressure values

laminar

$$p_{\text{plat}}/p_1 = 1 + 1.22M^2[(M^2-1)Rey_{\text{sep}}]^{-1/4} \tag{1a}$$

turbulent

$$p_{\text{peak}}/p_1 = \begin{cases} 1+2.24M^2/[8+(M-1)^2] & \text{for} \quad M < 3.4 \\ 0.091M^2 - 0.05 + 6.37/M & \text{for} \quad M > 3.4 \end{cases} \tag{1b}$$

where p_1 and M are the undisturbed static pressure and Mach number, and Rey_{sep} is the Reynolds number based on undisturbed flow conditions and streamwise distance to the separation location. Turbulent peak pressures ahead of fins agree well with the two-dimensional values for $M < 2.2$; for $M > 2.5$, the peak pressures are about 10% less than given by Eqs. (1).[3] The laminar plateau pressures are well approximated using Eqs. (1) for all Mach numbers. The preceding can be used to estimate the free interaction pressure rise on the centerline ahead of the fin (well within the "scatter" caused by the unsteadiness of the flow). Outboard of the centerline, the peak pressures diminish and move aft.

The vortices comprising the separated flow bring high-energy stream flow into close proximity with the surface, resulting in extremely high pressures and heating rates on the surface in the immediate vicinity of the fin leading edge. In this small region, surface pressures approaching the pitot pressure of the free-stream flow, and heating rates exceeding 10 times the undisturbed surface values, have been measured.

Self-induced shock impingement, caused by turbulent boundary-layer separation ahead of unswept fins, generally results in the type of interaction (Edney Type IV)[4] that leads to the greatest pressure and heat transfer rate amplifications on the fin leading edge. The amplification depends strongly on Mach number and local flow conditions.

The location of the shock impingement "triple point" (Fig. 4), may be estimated using the pressure rise ahead of the fin and oblique shock relations to determine the impinging shock wave angle. Oblique shock relations can then be solved iteratively to calculate the initial conditions of the comparatively high energy "jet" flow. The maximum attainable peak pressure on the fin leading edge can be calculated simply assuming the jet flow stagnates isentropically. However, particularly for hypersonic flows, this is a very crude upper limit (overly conservative). For supersonic jet flows, characteristics can be used to obtain more realistic values for the peak pressure on the fin.[4] However, the width of the jet is not determinable by the analysis. The dividing streamline is slightly curved, allowing the flow above it to expand. This correction, and the displacement growth of the free shear layer along the slip line from the triple point, should be included in calculating the jet flow conditions.

Fin sweep changes the character of the shock impingement and greatly alleviates the peak pressure and heating rates. Thick boundary layers, in comparison to the fin height or diameter, mask shock impingement effects and reduce the peak values.

References

[1] Korkegi, R. H., "Survey of Viscous Interactions Associated with High Mach Number Flight," *AIAA Journal*, Vol. 9, No. 5, May 1971, pp. 771–784.

[2] Robertson, J., "Fluctuating Pressures Induced by Three Dimensional Protuberances," WR-70-10, April 1970, Wyle Labs., Huntsville, Ala.

[3] Lucero, E., "Turbulent Boundary Layer Separation Induced by Three Dimensional Protuberances," APL Rept. TG-1094, Jan. 1970, Johns Hopkins Univ., Silver Spring, Md.

[4] Hains, F. D. and Keyes, J. W., "Shock Interference Heating in Hypersonic Flows," *AIAA Journal*, Vol. 10, No. 11, Nov. 1972, pp. 1441–1447.