Axisymmetric Nose Inlet Effects on Supersonic Airloads

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Effects of axisymmetric nose inlet airflow on pressures, normal force, and pitching moment of two missile inlets are examined. Static pressures were measured 45 deg from the windward and leeward directions of one model cowl at 0- and 5-deg angle of attack for Mach numbers from 1.8 to 3.0. Pressure differences due to model incidence, at weight flow ratios near 1, approximately agreed with those predicted by slender-body theory applied to the cowl with a faired-over inlet. Reducing the weight flow ratio to 0.75 caused loadings on the windward side to become about one-third larger than those predicted by slender-body theory for the faired-over inlet. This change in loading increased the cowl normal force. For missile nose inlet locations, the destabilizing pitching moment that must be resisted by tail surfaces would also increase. Forces and moments were measured on another model at Mach numbers of 3.0 and 3.5 with the internal duct port cover both closed and fully open. There were no significant effects of duct flow on body normal force or pitching moment. These quantities were closely predicted by use of an available data correlation for ogive-cylinder bodies.

Nomenclature

C_m	= pitching moment coefficient about apex, nondimensionalized relative to SD
C_N	= normal force coefficient, nondimensionalized relative to S
C_P	= pressure coefficient
D	= inlet cowl maximum diameter
r	= inlet cowl external surface local radius
S	= inlet cowl maximum cross-sectional area, $(\pi/4)D^2$
WR	= ratio of inlet weight flow to that of a freestream streamtube with radius equal to inlet capture radius
X	= axial distance from cowl apex
α	= fuselage angle of attack
ΔC_p	= difference between pressure coefficient at a given cowl location and Mach number at actual and zero angle of attack
θ	= azimuth angle from cowl windward meridian

Introduction

LARGE tactical supersonic missiles with airbreathing propulsion and high cruise altitude generally[1] have inlets located beneath the fuselage at midlength or chin position. Thrust control by modulating the inlet weight flow may affect the inlet shock wave system. Resulting changes of static pressure distribution on the fuselage lower surface may change the airframe normal force and pitching moment. Integral rocket ramjets, with inlet duct airflow obstructed by a port cover during boost, will undergo quasisteady changes of inlet detached shock wave position with Mach number. Also, the duct pressures and shock wave position may undergo organ-pipe oscillations with time. For chin inlet locations, the resulting changes[2] of airframe steady and unsteady pitching moment may be excessive.

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Smaller tactical missiles, flying at lower altitudes or requiring less stringent maneuvers, may be best packaged[3] with axisymmetric nose inlets. Payloads usually placed in the missile forebody may fit equally well within the inlet spike or diffuser centerbody. Changes in the external shock wave system due to inlet duct flow should then be approximately axisymmetric, with less effect on missile airloads.

Static pressure data were available for a range of axial locations on the external cowl surface of a projectile axisymmetric nose inlet. Those data were originally taken to determine cowl external pressure drag at zero incidence. Static pressures also had been measured over a range of weight flow ratios at nonzero incidence. Weight flows were varied as a means of thrust control. It was recognized that the additional data could be utilized to determine cowl external airloads due to incidence. These could be compared with aerodynamic predictions for the equivalent sharp-nosed body obtained by fairing a smooth curve from the apex to the cowl lip. Additional unpublished data from another configuration have been utilized to extend the range of Mach number.

Models and Test Conditions

Wind Tunnel and Models

All tests were conducted in the Vought Corporation, Systems Division, 4×4-ft High-Speed Wind Tunnel. The tunnel is an intermittent flow, blowdown to atmosphere facility. Its supersonic test section, used in both test programs, has a flexible-wall two-dimensional nozzle. The wall contour is adjusted by hydraulic jacks to provide the appropriate freestream Mach number.

One axisymmetric nose inlet model, sketched in Fig. 1, was a full-scale model of the AIFS ramjet[3] inlet and air induction system. The cowl had nine static pressure taps on its external surface. These taps were located in a plane rotated 45 deg to the plane in which the model centerline was pitched. Five taps were on the windward and four on the leeward sides. Axial locations were at the centroid of frontal areas such that the product of pressure coefficient and frontal area would be constant at zero incidence. That is, all taps would measure equal contributions to cowl pressure drag. The model also was extensively instrumented to determine internal duct total pressure profiles and internal surface static pressure distributions.

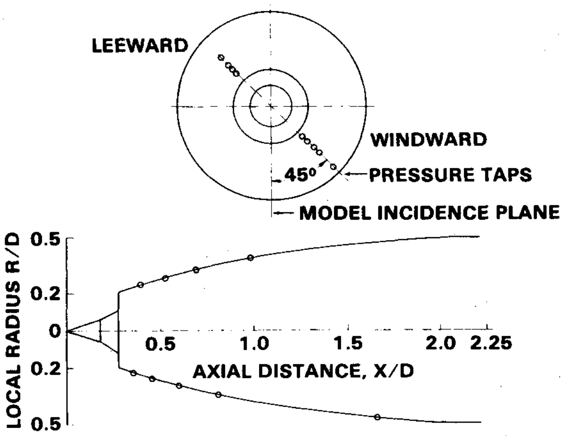

Fig. 1 Axisymmetric nose inlet model with cowl static pressure taps.

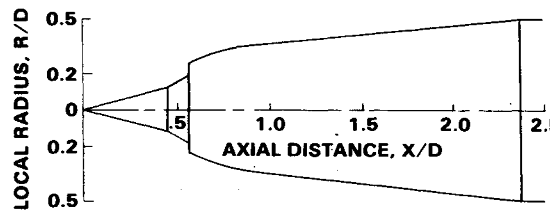

Fig. 2 Axisymmetric nose inlet body model used in force-balance tests.

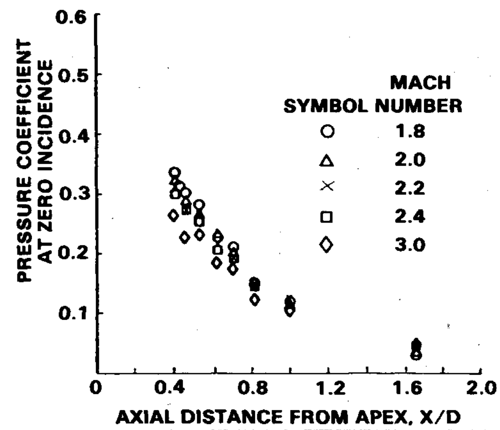

Fig. 3 Variation of cowl external surface pressure coefficient with axial distance at zero incidence and a weight flow ratio of 1.

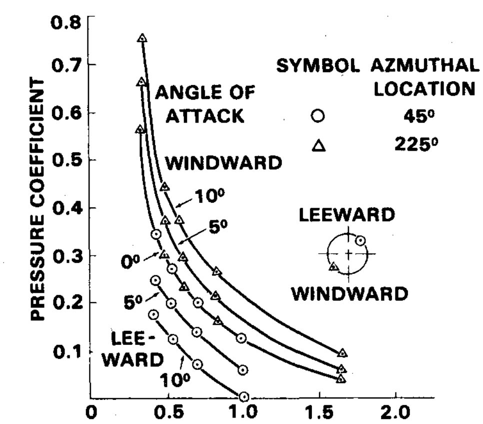

Fig. 4 Inlet external cowl pressure coefficients measured at a Mach number of 2.0 and a weight flow ratio of 1.

A cowl nominal maximum outer surface diameter of 7.96 in. was reached at 18.00 in. downstream of the centerbody apex. The cowl was a basic elliptical shape with its lip located 2.187 in. downstream of the apex. The lip had a nominal 0.005 in. leading edge radius and the initial external wedge angle was 20 deg. Its inner surface was aligned with the local inviscid conical flow direction of 17 deg at zero incidence and a Mach number of 2.0. A nominal cowl diameter of 3.20 in. at the inlet lip provided a capture area equal to 16% of the reference frontal area.

The double cone centerbody was designed using inviscid flow theory. At zero incidence and the design shock-on-lip Mach number of 2.0, both the initial conical shock wave and the shock from the second cone intersect the cowl lip.

The other axisymmetric nose inlet model had a flow-through duct. A six-component internal strain gage balance was contained in the centerbody. The model had a 3.25-in. maximum outside diameter. Its cowl, sketched in Fig. 2, was 7.66 in. long and was followed by a cylindrical afterbody to produce a total fineness ratio of 10. The 0.013-in.-diam cowl lip was 1.79 in. downstream of the apex. A cowl inlet lip diameter of 1.562 in. provided a capture area equal to 23% of the maximum fruntal area. The shock-on-lip design Mach number was 3.6. The cowl external contour (Fig. 2) was an initial curved region followed by an approximately 6-deg half-angle cone frustum. This model also was tested with several sizes and shapes of stabilizing tail fins and simulated telemetry antennas (not shown).

Test Conditions and Procedures

The model having cowl static pressure taps was tested at 0-, 5, and 10-deg angles of attack at Mach numbers 1.8, 2.0, and 2.2, respectively. Data were taken at 0 and 5 deg at Mach numbers 2.4 and 3.0, respectively. Reynolds numbers ranged from 4.6 to 8×10^6 based on maximum diameter.

This model was firmly mounted on a hollow support sting connected to the facility suction supply through a computer-controlled throttle plug. Sting angle of attack was controlled by the same computer. At each Mach number, the wind tunnel was started at zero angle of attack and maximum weight flow throttle position. Pressure data were then recorded at preselected throttle settings as the throttle was stepped through its programmed range. The throttle was then opened to the maximum weight flow position. The model was rapidly pitched to its next angle of attack, and this procedure was repeated.

The force-balance model was slowly pitched from −2- to 5-deg angle of attack at constant Mach number. Some runs were conducted with a closed port cover within the inlet duct 10.0 in. downstream of the apex. The configuration then simulated an integral rocket ramjet during rocket boost, with all the approaching airflow spilled around the inlet. Test conditions with the port cover both closed and open overlapped only at Mach numbers of 3.0 and 3.5. Nominal Reynolds numbers were about 3×10^6 based on maximum diameter.

Analytical Prediction Methods

Effects of incidence angle on pressure coefficients on an axisymmetric body without an inlet can be predicted from several analytical methods. The simplest of these methods is the slender-body approximation to linearized supersonic theory.[4] This method should be reasonably accurate for slender inlet cowls at low subsonic cross-flow Mach numbers $M\sin\alpha$. As given by this method, the change in pressure coefficient at axial position X and azimuthal angle θ from the leeward direction, owing to a small incidence angle α, is

$$\Delta C_p = -4 \sin\alpha\cos\theta \frac{\mathrm{d}r}{\mathrm{d}X}$$

where r is the local radius of the cowl surface. Although the pressure coefficient at each axial station at zero incidence is a function of the Mach number, the incremental change due to angle of attack is predicted to be independent of the Mach number.

For larger supersonic Mach numbers, the second-order shock-expansion method[5] can be used. Local loading is predicted to vary with the cosine of the azimuth angle, with an amplitude that depends on the local Mach number and normal force coefficient slope of the local tangent cone. The major difference between loadings predicted by these two methods occurs on the nearly constant radius aft portion of the cowl and on the cylindrical afterbody. Loading calculated from the supersonic slender-body theory approaches zero at the cowl-cylinder junction and is zero along the cylinder. Loading calculated from the second-order shock-expansion method is nonzero at that junction and exponentially approaches zero with increasing downstream distance.

If only the normal force coefficient slope and center of pressure are of interest, rather than the spatial distribution of local loading, data correlations can be used. A convenient correlation is available[6] for ogive-cylinder bodies over a range of forebody and afterbody fineness ratios at Mach numbers to 4.5. This was used for comparison with force-balance data for the inlet spike, axisymmetric cowl, and cylinder body with and without inlet flow at Mach numbers 3.0 and 3.5.

Discussion of Pressures and Loading

Measured axial variations of pressure coefficient on the inlet cowl at Mach numbers from 1.8 to 3.0 are plotted in Fig. 3 for zero incidence and the weight flow ratio closest to 1. The pressure coefficient at the most forward pressure tap (near the cowl lip) was close to that which would be predicted for two-dimensional flow deflection through the local surface slope angle. Measured pressure coefficients decreased with increasing axial distance and increased Mach number. They decreased slightly (not shown in Fig. 3) as the weight flow ratio was reduced.

Pressure coefficients measured on the cowl 45-deg windward and leeward meridians at a Mach number of 2.0 and weight flow ratio of approximately 1 are given in Fig. 4 for 0-, 5-, and 10-deg angles of attack. The inlet apex shock wave is predicted to intersect the cowl lip for this Mach number and weight flow ratio at zero angle of attack. Absolute values of the difference between pressure coefficient measured at each pressure tap at zero and at nonzero angles of attack were obtained from the data tabulation for comparison with predictions.

Measured local loadings at the five windward and four leeward pressure taps are plotted as symbols in Fig. 5 for a weight flow ratio near 1. Separate symbols are shown for the windward and leeward sides at each of the five test Mach numbers. Shown for comparison are the curves predicted by use of slender-body theory for this inlet with a smooth solid surface faired from the apex to the cowl lip. These predicted curves are independent of the Mach number, and have the same magnitude for windward and leeward positions.

Measured loadings generally agreed with the prediction except at the most forward pressure tap. This simple theory would not be expected to apply at that position near the cowl lip. Data were approximately the same for both the windward and leeward sides, as is predicted by the linearized inviscid flow theory. Loadings at axial distances within 0.8 diameter of the apex generally were, at most, 15% larger than those predicted by slender-body theory. Larger differences occurred for the two rearmost axial positions. These amplitudes approximately doubled when the angle of attack was doubled, as would be predicted from an inviscid flow analysis.

Decreasing the weight flow ratio decreased the cowl surface static pressures. This effect became smaller as the Mach number was increased. The decrease on the leeward side was roughly as large as that measured at zero incidence. Smaller decreases occurred on the windward side. The resulting axial distribution of loading at 5 deg incidence and the weight flow ratio closest to 0.75 for each of the five test Mach numbers is given in Fig. 6. Loadings were very large near the windward lip. These large loadings came from a small decrease of static pressure at the windward pressure tap, accompanied by a large decrease for that tap at the reference zero-incidence condition. Loadings were larger on the windward side than those measured at a weight flow ratio of 1, and were about 50% larger than the predicted curve. This difference became smaller with increased Mach number. In contrast, loadings measured on the leeward side at this reduced weight flow ratio remained close to the prediction for all but the lowest Mach number.

Axial distribution of the local contribution to normal force and pitching moment along the cowl outer surface therefore generally agreed with predicted levels at a weight flow ratio near 1. Reducing the weight flow ratio to 0.75 by throttling the inlet duct flow, as might be done for thrust control, increased these contributions. A missile's center of gravity would be located aft of the nose inlet cowl. For a ramjet powered missile flying near zero incidence, thrust control by throttling the inlet weight flow increases the fuselage contribution to destabilizing pitching moment. Larger tail fins would be needed to provide the desired static margin. For missiles flying at nonzero trimmed lift, such thrust control would alter the required tail trim control deflection. These disadvantages can be avoided by use of inlet duct bypass bleed to modulate air weight flow into the combustor.

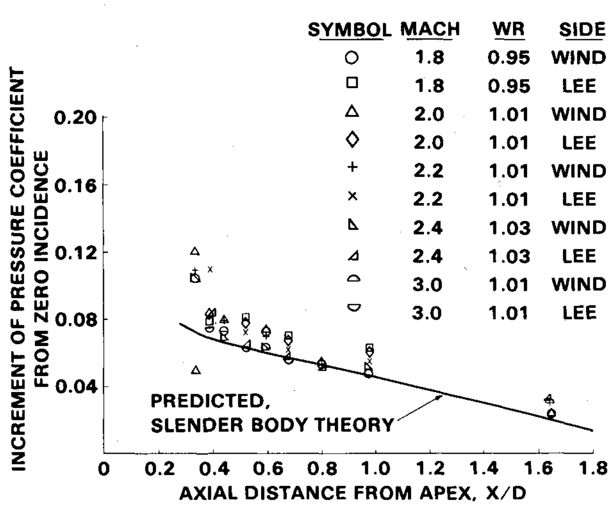

Fig. 5 Measured and predicted loading at 5 deg incidence at a weight flow ratio of 1.

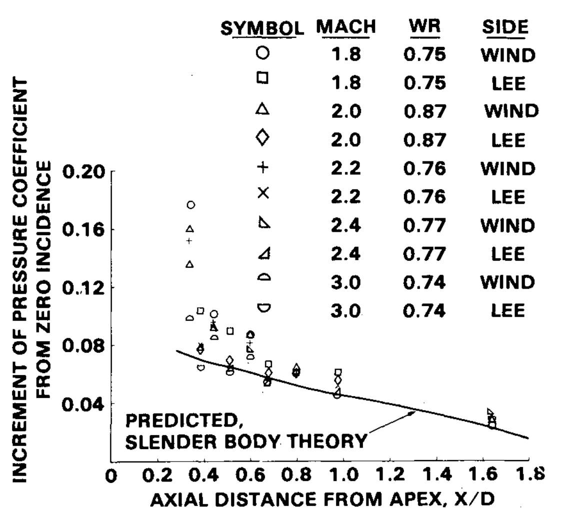

Fig. 6 Measured and predicted loading at 5 deg incidence at a weight flow ratio near 0.75.

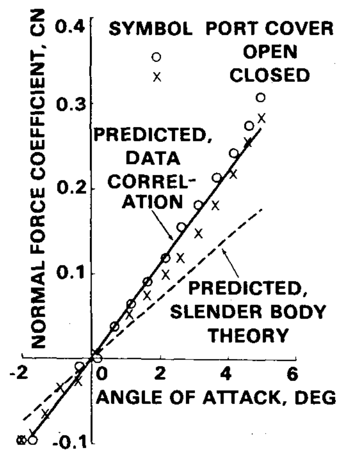

Fig. 7 Variation of normal force coefficient with angle of attack for inlet body at a Mach number of 3.0.

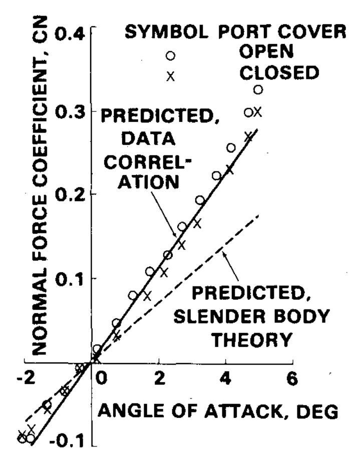

Fig. 8 Variation of normal force coefficient with angle of attack for inlet body at a Mach number of 3.5.

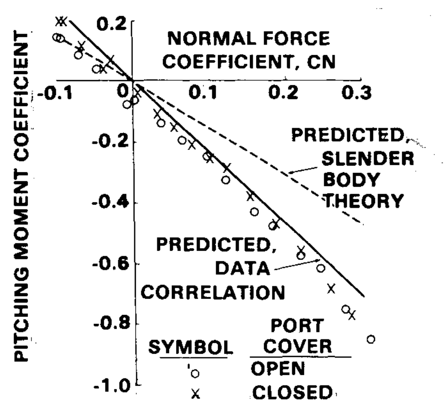

Fig. 9 Variation of pitching moment with normal force for inlet body at a Mach number of 3.0.

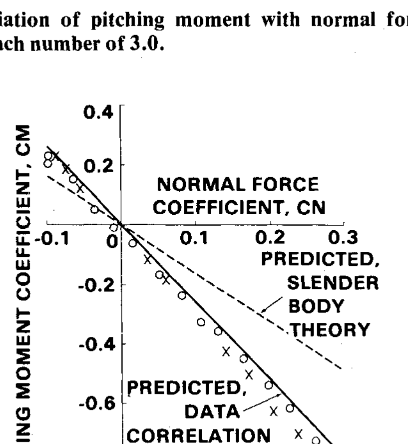

Fig. 10 Variation of pitching moment with normal force for inlet body at a Mach number of 3.5.

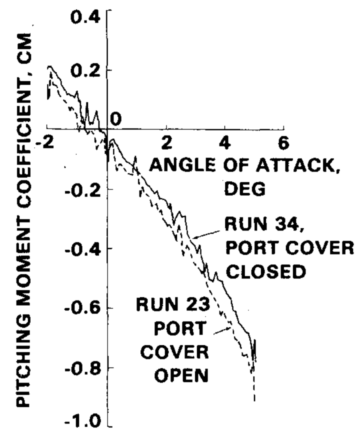

Fig. 11 Detailed variation of pitching moment coefficient with angle of attack for inlet body at a Mach number of 3.0.

Discussion of Total Forces

Measured variations of the normal force coefficient with angle of attack for the axisymmetric inlet body at Mach numbers 3.0 and 3.5 are given in Figs. 7 and 8. The open circles are data obtained with the port cover open, so that air flowed through the inlet and internal duct. The × symbols are data with the port cover closed so that air spilled around the sharp cowl lip. Measured normal force coefficients were about 50% larger than those predicted by slender-body theory, which omits lift generated on the cylindrical portion of the body. An available data correlation[6] for ogive-cylinder bodies generally matched these data for the inlet body with or without flow. Opening the port cover caused a small increase of normal force coefficient. This increase agrees with the expected normal component of nondimensional inlet air momentum (0.008/deg) given by the product of the capture area ratio, weight flow ratio, and slender-body normal force coefficient slope.

Corresponding variations of the pitching moment coefficient about the apex with normal force coefficient are plotted in Figs. 9 and 10. Closing the port cover had essentially no effect on the data curves. Although normal force and pitching moment were reduced slightly by eliminating the inlet flow, there was no change in center of pressure.

The axial force coefficient near zero incidence was increased from about 0.35 to 0.51 by closing the port cover. This increase is what would be expected if flow that passed through the inlet apex conical shock wave was then reduced to pitot-pressure conditions by a locally normal shock wave.

Static stability of this inlet fuselage model also was measured with stabilizing tail fins. Eliminating the inlet flow had no effect on the airframe center of pressure.

The detailed variations of pitching moment coefficient with angle of attack, and therefore with time, during the two test runs at a Mach number of 3.0 are plotted in Fig. 11. Neither the data trace with the port cover closed nor that with it open was perfectly smooth, because neither the tunnel airflow nor the angle-of-attack sector motion is perfectly steady. However, data were equally unsteady with the port cover closed or open. The detached shock wave ahead of the inlet cowl with the port cover closed may have oscillated axially with time, but such oscillation apparently did not cause fluctuations of pitching moment. Such oscillations apparently have occurred[2] for a chin inlet configuration during boost with the port cover closed.

Conclusions

Changes of axisymmetric nose inlet cowl external surface static pressures with incidence, at an inlet weight flow ratio of one, agree with slender-body predictions. Reducing the weight flow ratio to 0.75 by throttling the inlet duct flow for thrust control increased the cowl lift. This effect decreased as Mach number was increased. For a fuselage nose inlet, this change of cowl lift would increase the destabilizing pitching moment that must be overcome by tail fins.

Closing off the internal flow by closing the port cover at higher Mach numbers caused a small reduction of lift and no effect on center of pressure. Tail fins designed to stabilize the axisymmetric fuselage with faired-over inlet will be adequate for boost and sustain flight.

Acknowledgments

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