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Side-Force Alleviation on Slender, Pointed Forebodies at High Angles of Attack

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A new concept for alleviating the high angle-of-attack asymmetry on slender, pointed forebodies has been proposed and tested. A pair of helical trips are used to force nonuniform crossflow separation from the forebody to disrupt the formation of concentrated leeside vortices. Subsonic wind-tunnel measurements on bodies with circular and noncircular cross sections and an aircraft-type configuration at up to 55 deg angle of attack showed that the device was highly effective in suppressing the side force. Water-tunnel flow visualizations confirmed that the helical trips rapidly diffused the forebody vortices and prevented wake asymmetry.

Nomenclature†

C_D = drag coefficient
C_L = lift coefficient
C_Y = side-force coefficient
C_l = rolling moment coefficient (body axis)
C_m = pitching moment coefficient
C_n = yawing moment coefficient (body axis)
C_{l_β} = rolling moment due to sideslip, per deg
C_{n_β} = yawing moment due to sideslip, per deg
α = angle of attack, deg
β = angle of sideslip, deg

Introduction

COMBAT agility requirements in the new generation of fighter aircraft have emphasized the need for controlled flight capability to increasingly high angles of attack. Such aircraft commonly employ pointed forebody shapes, which characteristically experience abrupt and relatively large out-of-plane aerodynamic loads when pitched to high angles. With degraded control effectiveness also encountered under such conditions, serious handling difficulties can result. Alleviation of the forebody side force (and related yawing moment) has therefore become important in the current efforts to evolve aerodynamic configurations for improved controllability at extreme nose-high attitudes.

This paper describes a new device for side-force alleviation and presents the results of a preliminary wind-tunnel evaluation on a variety of forebodies of circular and noncircular cross sections and on a wing-fuselage combination. Supplementary water-tunnel flow visualization studies were carried out to observe the operation of the device in modifying the leeward vortex wake.

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†Coefficients for bodies based on forebody base area and body length; for wing-fuselage, on wing area and wingspan. Moment reference station: at nosetip for bodies, and as indicated in Fig. 1 for wing-fuselage.

Background

The out-of-plane force arising from asymmetrical development of the leeward vortex wake of slender, lifting bodies has attracted increasing attention in recent years (see Ref. 1 for a recent summary and additional references). In this research, the two-dimensional impulsive flow analogy has provided a useful conceptual and analytical framework for modeling the vortex asymmetry over long cylindrical bodies. This analogy however, does not account for the nosetip effect. Recent experimental results[1,2] have emphasized the influence of the nose shape on the onset and buildup of side force. From these and many similar studies, it is clear that any attempt at reducing the side-force problem on fuselage forebodies by aerodynamic means will have to pay special attention to the nose region.

A variety of devices for side-force attenuation have been proposed and wind-tunnel tested, with varying degrees of success. Of these, perhaps the most practical as well as effective are the nose strakes. These short, sharp-edged side projections attached close to the nosetip generate a pair of relatively small but intense, free-trailing, contrarotating vortices at high angles of attack. These shed vortices (unlike vortices connected to feeding sheets) apparently have a strong tendency to remain symmetrical with respect to the pitch plane and thus seem to have a stabilizing influence on the leeward wake.

In practical application, however, nose strakes have certain disadvantages. Their optimum size, shape and location appear to be critically dependent on the forebody geometry, requiring a certain amount of trial and error in order to develop an effective design for each case (see Ref. 3). If too large, they may contribute pitching instability. Also to be considered is the possibility of adverse interference of the strake vortices with downstream components such as air intakes and tail controls. Further, strakes mounted on nose radomes may be a potential source of disturbance in radar operation. Keeping these considerations in view, an alternative approach for overcoming the asymmetry problem was proposed.

The present device was conceived as a logical extension of previous work with vortex-wake suppression on cylinders in two-dimensional flow (for example, to prevent the destructive wind-induced oscillation of tall chimney stacks). The principle of interfering with classical vortex shedding phenomenon is shown in Fig. 1 (taken from Ref. 4). Essentially, the cylinder boundary layers are forced to separate at varying peripheral locations (and so at varying local flow velocity) along the cylinder length. Since the vorticity flux into the wake is a function of the velocity at separation, the free shear layers are rendered highly nonuniform in the spanwise direction.

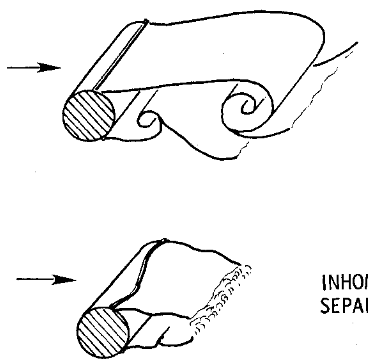

Fig. 1 Two-dimensional cylinder vortex wake.

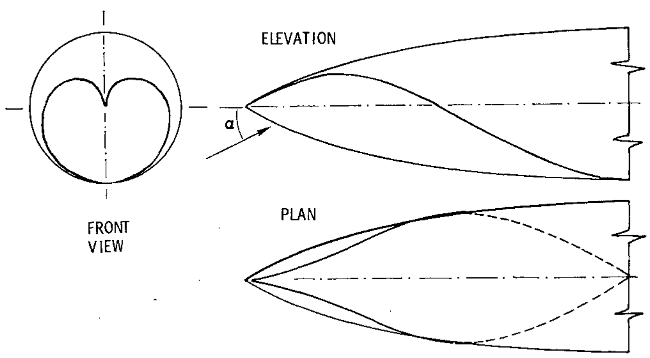

Fig. 2 The helical trip concept.

Consequently, the formation of discrete two-dimensional vortex cores is disrupted, and thus the possibility of vortex asymmetry is removed at source. Experiments[4] have shown that the periodic oscillatory wake of a two-dimensional cylinder can be changed into random turbulence and the rms cross-force greatly reduced, by means of a variety of separation trip arrangements designed to introduce the required three-dimensionality in separation.

Applying this principle to the forebody basically requires a trip arrangement to force crossflow separation at varying meridional position along the forebody length, symmetrically disposed with respect to the pitch plane. The proposed helical-trip device is illustrated in Fig. 2. The trips are so oriented (i.e., running from top at the nosetip to bottom at the rear) as to insure effectiveness in separating the boundary layer which is generally flowing upwards (i.e., from windward to leeward) on the forebody at angle of attack.

Experimental Evaluations

Wind-Tunnel Tests

Proof-of-concept tests of the helical trips were carried out on a series of force models in the NASA Langley 7×10 ft wind tunnel. The models are illustrated in Fig. 3 and described as follows:

1) Pointed axisymmetrical bodies: a 10 deg semi-angle cone-cylinder and an ogive-cylinder.

2) General research fuselage: This two-part model was mounted on a dual-balance arrangement which allowed the forebody loads to be measured separately from the total model loads. The oval cross-section of the fuselage enabled two different section shapes to be simulated (relative to the crossflow) by orienting the model successively at 0 deg and 90 deg roll.

3) Fuselage-wing combination, obtained by mounting a swept wing in the mid-position on the general research fuselage (the fuselage being in the 0 deg roll orientation). During sideslip tests, a central vertical tail was added to this combination.

The models were supported on a straight sting of adequate length. It is believed that the leeside flow was not significantly influenced by the support system.

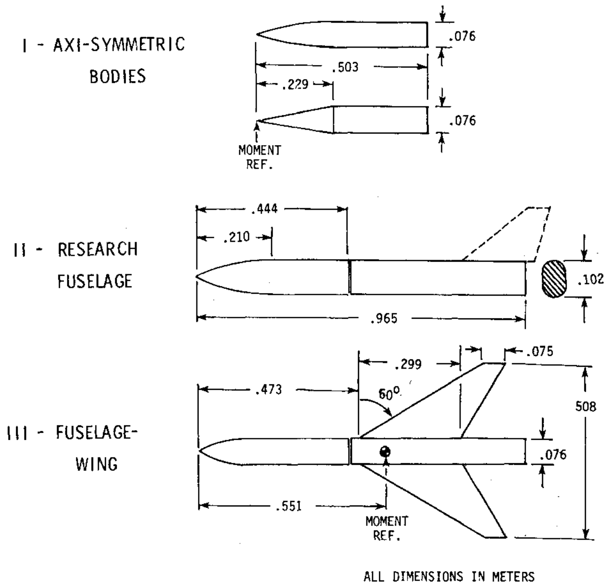

Fig. 3 Geometry and dimensions of wind-tunnel models.

The trips were made of solder wire (3.18 mm or 1.59 mm diam) attached to the forebody by means of epoxy cement. Any cement appearing on the upstream side of the wires was trimmed away to insure that a discontinuous trip protrusion would be encountered by the boundary layer.

The freestream conditions throughout the tests were maintained nominally constant at Mach 0.3 and Reynolds number 6.2×10^6 per meter. Except where otherwise indicated, the tests were done at zero sideslip.

Water-Tunnel Flow Visualization

To assist in a qualitative understanding of the effect of helical trips on the leeside vortices, visualization experiments were run in Northrop Corporation (Aircraft Division) 16×24-in. water-tunnel facility. The following models were tested: 1) ogive-cylinder, 2) general research fuselage, and 3) complete aircraft configuration (Northrop F5-F at 1/40 scale).

These sting-supported models were provided with separate internal channels to facilitate injection of dye in two colors, through orifices strategically located on either side of the windward meridian near the nosetip. When emitted in a controlled manner, the dye solution was entrained into the forebody vortex cores and so provided a color-differentiated visualization of the vortex paths and the breakdown phenomenon. Color photographs were taken in the side and plan views at various angles of attack spanning the symmetrical and the asymmetrical vortex regimes, with and without helical trips on the models.

Discussion of Results

Axisymmetrical Bodies

Side-force and yawing-moment measurements on the bodies with and without helical trips are compared in Fig. 4. On the cone-cylinder, two pairs of helical trips were first tested, one over the forebody and the other covering the cylindrical afterbody. This was followed by a further test with the afterbody trips removed. The data show that the forebody helical trips by themselves were capable of eliminating the side force.

Both the axisymmetrical models without trips developed a severe lateral oscillation at some angle of attack (marked "Buffet") beyond side-force onset, requiring termination of the test for safety reasons. In a striking demonstration of the helical trip effectiveness, this dynamic behavior was totally

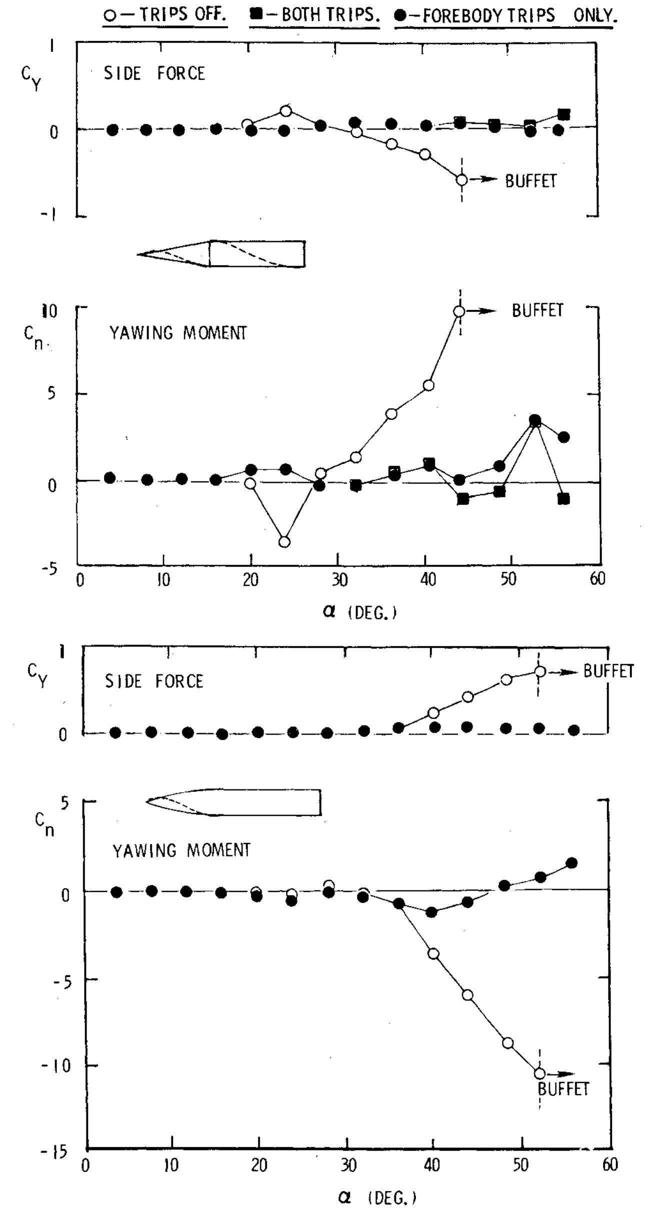

Fig. 4 Axisymmetric bodies: side force and yawing moment vs angle of attack.

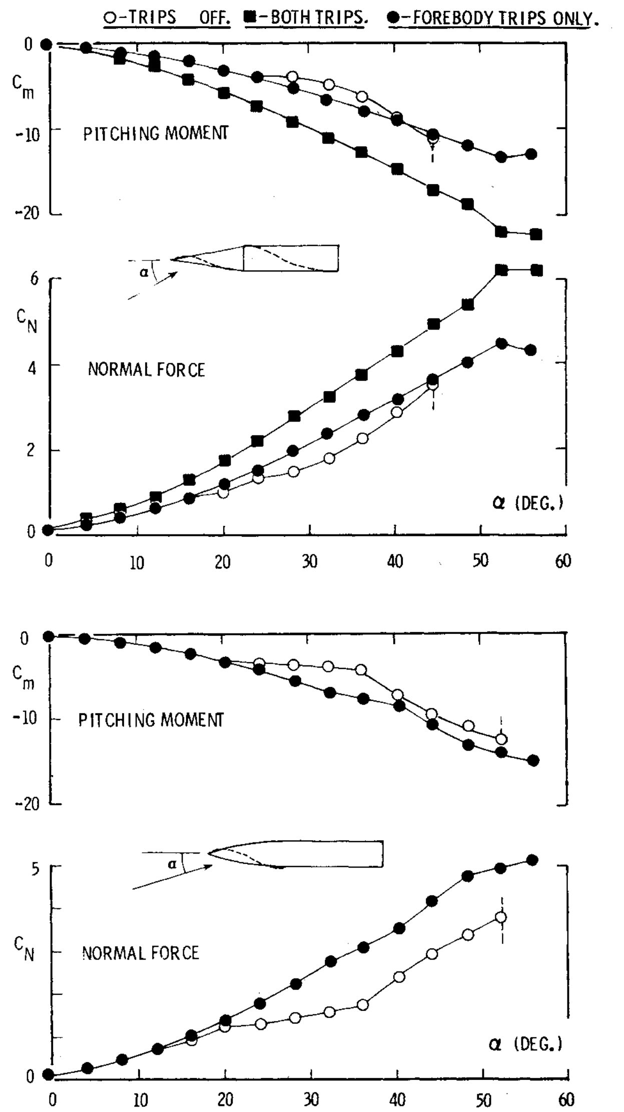

Fig. 5 Axisymmetric bodies: pitching moment and normal force vs angle of attack.

suppressed with the trips and the test carried on to the full angle-of-attack limit.

The effect of helical trips on the longitudinal characteristics of axisymmetrical models is shown in Fig. 5. The presence of trips is hardly noticeable on pitching moment and normal force up to nearly 20 deg angle of attack. At higher angles, the variation of these characteristics with angle of attack is considerably smoothed by the trips.

General Research Fuselage, 0 Deg Roll

A number of trip variations were tested on the fuselage model. The forebody side-force measurements of this test series are summarized in Fig. 6. (Yawing-moment data showed similar trends.) Starting at the top, trip-off data showed onset of asymmetry at about 30 deg angle of attack. Comparison with earlier measurements in the same tunnel showed good repeatability of the asymmetry characteristics.

The first trip arrangement was a pair of straight wires affixed along the side meridians of the forebody. The results confirmed that insuring symmetrical separation did not necessarily cure the asymmetry problem.

When the same wire material was formed into a helical trip, however the side force was practically eliminated, as shown by the third set of data. The degree of side-force suppression appeared to be limited only by the precision of symmetry in the trip pair; installation at the tunnel site without the aid of normal shop facilities led to some unavoidable asymmetry in the trips. Nevertheless, the side-force data were within the estimated accuracy of the balance, viz ±0.5% of side-force capacity.

In the next test of the series, the fuselage with helical trips was rolled through 180 deg. At positive angles of attack, this reversed orientation (wires running windward to leeward meridian) would place the trips generally along the boundary-layer flow direction, making them far less effective in forcing separation. The results verify the anticipated loss of side-force alleviation capability of the helical trips in this orientation.

The model was then returned to 0 deg roll and the trips cut back approximately 2 cm from the forward junction. This portion of the trip was thought to be mostly submerged in separated flow at high angles of attack, and its removal was therefore not expected to significantly reduce the trip effectiveness. The measurements appeared to support this reasoning. Since the forward portion of the device may be undesirable on a nose radome, further work to optimize trip truncation is probably worthwhile.

Finally, thinner helical trips (of half the wire diameter previously used) were tested to obtain some indication of the size effect. In this case, loss of trip effectiveness appeared after 40 deg angle of attack. The minimum trip height to insure separation would be expected to depend on the local boundary-layer thickness. However, the boundary layer not only is variable along the trip length but will change considerably with the flight parameters including angle of attack and Reynolds number, and also have a highly three-dimensional structure. Under these conditions the minimum trip size for separation cannot be precisely calculated. From the limited wind-tunnel data available, a trip height of about 2% of the maximum forebody diameter may be taken as a starting point for further refinement (preferably through flight testing) to arrive at the optimum size for a particular full-scale vehicle.

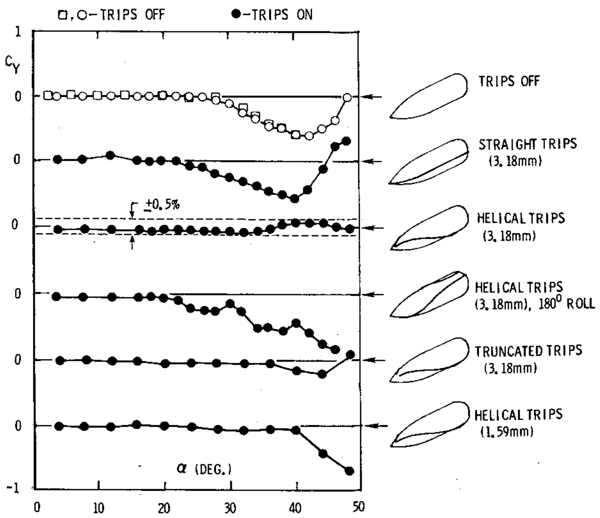

Fig. 6 Fuselage model in 0 deg roll orientation: forebody side force vs angle of attack for various trip arrangements.

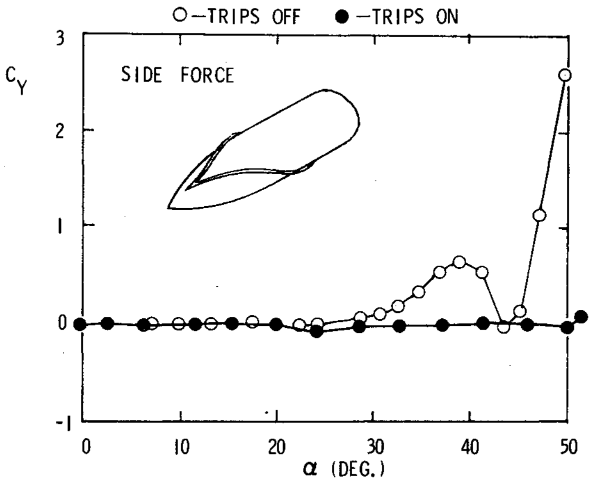

Fig. 7 Fuselage model in 90 deg roll orientation: forebody side force vs angle of attack.

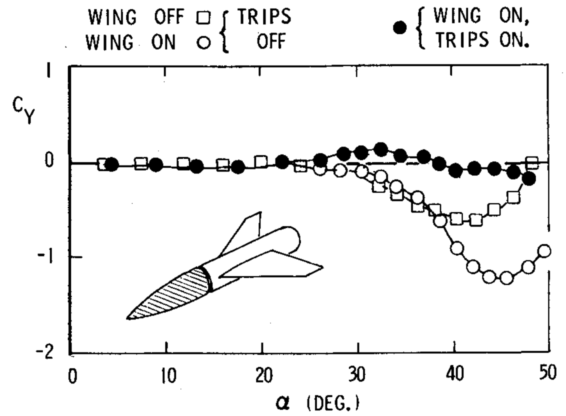

Fig. 8 Wing-fuselage model: forebody side force vs angle of attack.

General Research Fuselage, 90 Deg Roll

In this roll orientation the crossflow is incident on the flat side of the oval cross section. As shown by data in Fig. 7 a rapid buildup of side force occurred at angles of attack greater than 45 deg. Once again, installation of helical trips suppressed the side force up to the highest angle of attack.

Wing-Fuselage Combination

With the addition of wing-to-fuselage afterbody, the peak level of forebody side force was almost doubled, presumably due to the wing upwash effect (Fig. 8). This accentuated side-force characteristic of the wing-fuselage model was equally well suppressed by means of helical trips attached to the forebody.

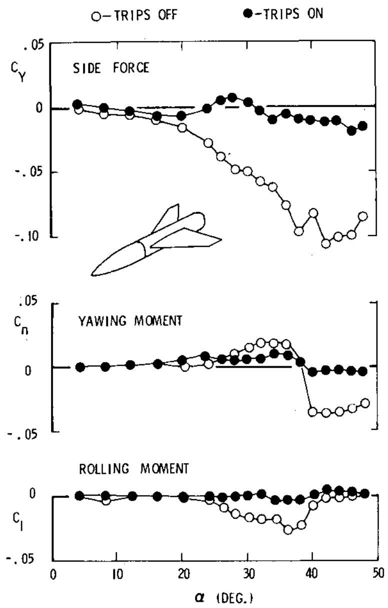

Fig. 9 Wing-fuselage model: total side force, yawing moment and rolling moment.

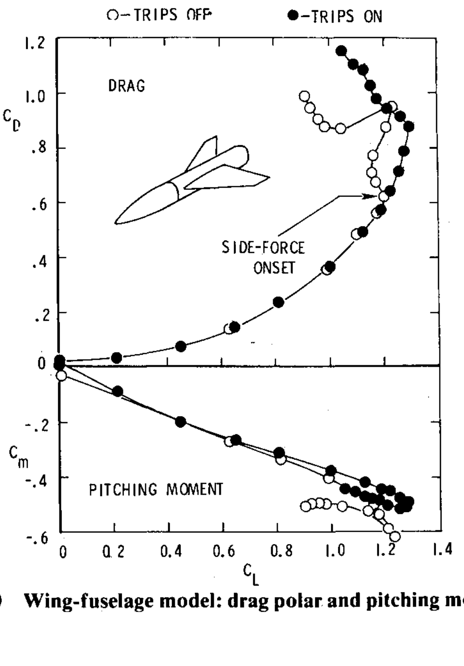

Fig. 10 Wing-fuselage model: drag polar and pitching moment.

The lateral-directional characteristics at zero sideslip (measured by the main balance) of the wing-fuselage combination are shown in Fig. 9. The helical trips alleviated not only the side force and yawing moment, but also the rolling moment apparently caused by an asymmetrical forebody wake acting on the wing flowfield.

The longitudinal characteristics of the wing-fuselage model are shown in Fig. 10. The effect of helical trips was barely noticeable in the drag and pitching moment up to the angle of attack corresponding to onset of asymmetry on the model without trips. At higher angles, the erratic nature of the "clean" model drag polar was markedly improved by the trips.

A brief investigation of the helical trip effects on directional stability was conducted with the wing-fuselage-vertical tail combination at 10 deg sideslip angle. As shown in Fig. 11, the trips added to the instability of the forebody, increasingly with angle of attack. The data suggest that the adverse effect arose from the increased crossflow drag of the forebody due to trips, probably magnified in this case due to the relatively large trip size used (3.6% of body diameter).

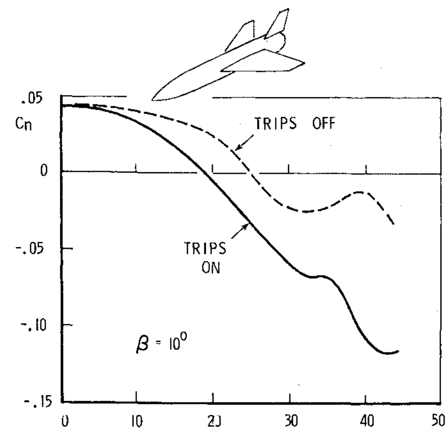

Fig. 11 Wing-fuselage-vertical tail model: yawing moment at sideslip vs angle of attack.

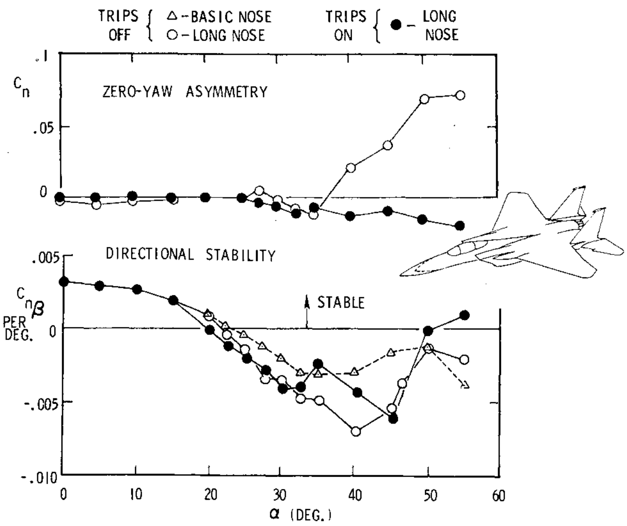

Fig. 12 Fighter configuration: zero sideslip yawing moment and directional stability derivative vs angle of attack.

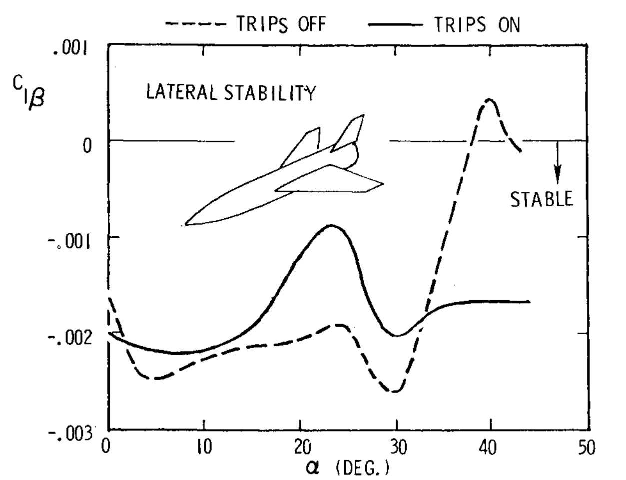

Fig. 13 Wing-fuselage-vertical tail model: lateral stability derivative vs angle of attack.

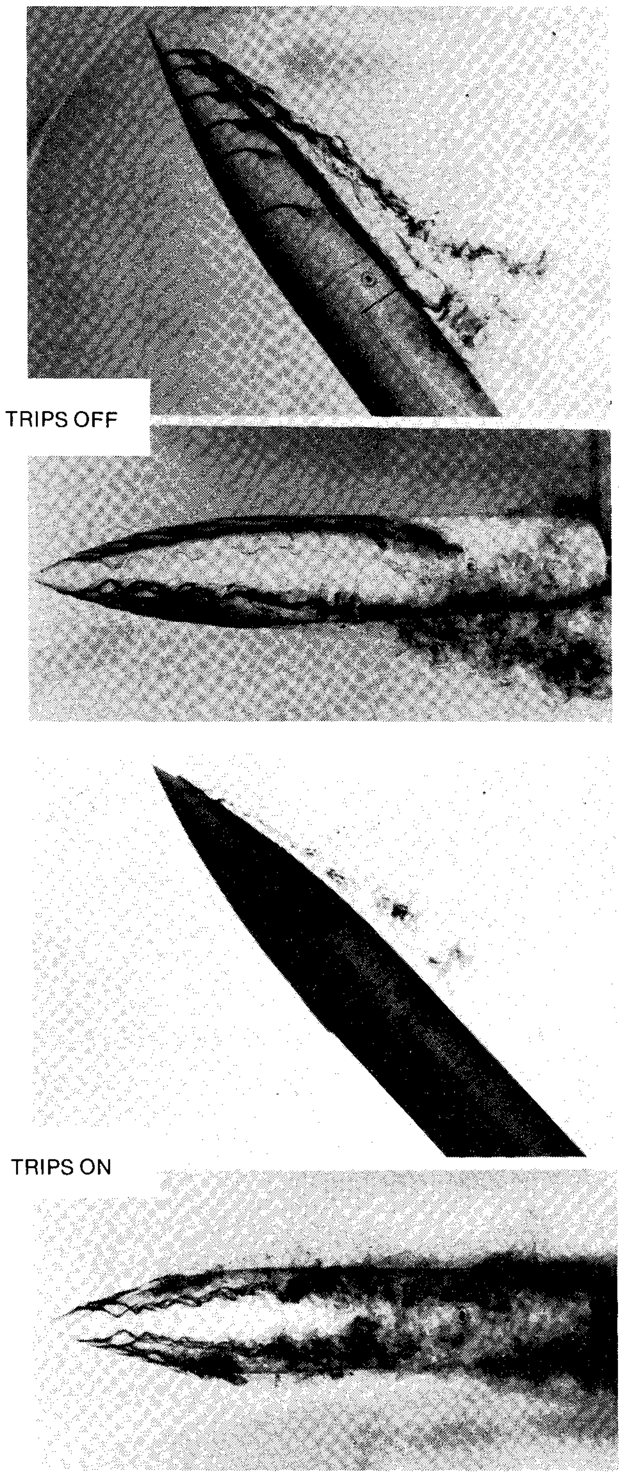

Fig. 14 Water-tunnel flow visualization on ogive-cylinder at 50 deg angle of attack.

For comparison, results of an unpublished wind-tunnel test at NASA Langley on a contemporary twin-tail fighter configuration, with lengthened forebody, are presented in Fig. 12. Application of helical trips of 2.8% body diameter to the forebody, yielded a marked reduction in the yawing moment at zero sideslip, without penalizing the directional stability characteristics.

These contrasting examples suggest that the influence of helical trips on directional stability is configuration dependent, and that on sensitive configurations the use of minimum-size trips will be helpful in reducing adverse effects.

Lateral stability measurements on the fuselage-wing-tail model are shown in Fig. 13. Without trips, the model showed a rapid decline in stability at about 30 deg angle of attack (coincidental with asymmetry onset). Helical trips were successful in overcoming this sudden loss of lateral stability and maintained it up to the angle-of-attack limit.

Flow Visualization

A representative set of photographs reproduced in Fig. 14 illustrates the results obtained in the water-tunnel tests. Leeside vortex patterns on the ogive-cylinder at 50 deg angle of attack (well above the asymmetry onset on the clean model) are shown in the side and top views. Without trips the primary vortices initially grew symmetrically but began to drift off to a side about halfway down the forebody. Consequently, a pronounced asymmetry developed in the wake which would be associated with a side force on the body. With helical trips attached, the vortices were seen to diffuse rapidly while still symmetrical, producing a turbulent wake which also remained symmetrical as far downstream of the model as it could be traced.

Conclusion

A new device conceived for alleviation of side force (and related yawing moment) on slender, pointed forebodies was experimentally evaluated. Subsonic wind-tunnel force tests up to 55 deg angle of attack on models with circular and noncircular forebody cross sections showed that the helical trip device was highly effective in reducing the side force. Water-tunnel flow visualization confirmed that the success of helical trips was related to their ability to disrupt the forebody vortices, as hypothesized. This unique feature has significant implications with regard to the vortex flowfield interference with downstream components, tail surfaces in particular. The helical trips did not noticeably disturb the longitudinal aerodynamic coefficients at the low angles of attack appropriate to cruise.

The efficacy of helical trips apparently is independent of forebody geometry, which offers the possibility of forebody design free from high angle-of-attack asymmetry considerations. It also is relatively insensitive to the precise trajectory of the trips. These features make the device particularly suited for retrofitting existing aircraft.

Although originally conceived with fighter applications in mind, the helical trips (or their adaptations) would be equally effective for bank-to-turn missiles. They may also be considered for use on commercial aircraft for alleviation of adverse fuselage vortex effects on directional stability and control during approach and near stall.

Acknowledgments

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