Aerodynamics of Pointed Forebodies at High Angles of Attack

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Aerodynamics of circular cylinders with conical shaped pointed forebodies is studied experimentally at a subcritical Reynolds number of around 10^5 Attention is focused primarily on the side force coefficient at high angles of attack which has a maximum value comparable to that of lift and drag The main objective is to minimize the side force, which may lead to a large undesirable yawing moment Effectiveness of several procedures such as surface roughness helical strakes modified tip geometries, and tip rotation is assessed Results suggest nose boom and tip rotation to be promising in achieving this objective

Nomenclature

A	= cyclinder cross sectional area $\pi d^2/4$
C_D	= drag coefficient $D/\frac{1}{2}\rho V^2 A$
C_L	= lift coefficient $L/\frac{1}{2}\rho V^2 A$
C_S	= side force coefficient $S/\frac{1}{2}\rho V^2 A$
D	= drag
d	= cylinder diameter
d_t	= diameter of trip wire
L	= lift
L_1 L_2 L_3	= height of conical sections (Fig 1)
Re	= Reynolds number $\rho V d/\mu$
S	= side force
V	= freestream velocity
α	= angle of attack
α_1 α_2 α_3	= apex angles of conical forebodies (Fig 1)
μ	= viscosity of air
ρ	= density of air
ω	= angular velocity of conical tip

Introduction

COMBAT agility requirements for present and next generation fighter aircrafts have emphasized the need for controlled flight capability to increasingly high angles of attack V/Stol type airplane configurations under study for intercity commuter traffic also use high attitude takeoff and descent Such aircraft commonly employ pointed forebody fuselage The asymmetric helical boundary layer separation has often led to an undesirable side force and the associated yawing moment

Fluid dynamics of slender bodies at high angles of attack has been a topic of long standing interest to fluid dynamicists Earlier investigations (1951 1976) were primarily based on the so called ' impulse analogy'' which describes the development of the wake along the body in terms of the flow behind a two dimensional cylinder started impulsively from rest Thomson and Morrison[1] have reviewed this literature quite effectively in their thorough study of spacing position and strength of vortices associated with slender cylindrical bodies at large incidence Most of the earlier efforts were primarily con cerned with the in plane force (force in the plane of the in clination) normal to the axis of the body

The out of plane force at times referred to as side force does not exist on bodies of commonly encountered fineness ratio until fairly high angles of inclination are reached and has received attention relatively recently Most investigations during the period 1971 1976 focused attention on obtaining experimental data for overall forces associated with bodies of specific geometry A notable exception is the detailed study by Lamont and Hunt [2] who beside reviewing the literature in this period have reported an experimental investigation of surface pressure on a cylindrical body of circular cross section fitted with various nose shapes for angle of inclination up to 90 deg The main emphasis is on the side force distribution along the axis of the body and its interpretation in terms of the impulse analogy Both the time averaged as well as the time dependent data were presented and the reason for the unsteadiness was examined In this context Wang's[3] review of the literature on separation of three dimensional flows which cites 61 references is also relevant

The tempo of research activities in the area has shown a marked increase since 1976 with a number of excellent papers touching upon different aspects of the problem, including the side force during ablation [4] pressure and force field distribution [5 11] wake structure and the process of vortex breakdown [12 14] flow visualization studies [15 19] and above all mechanisms for alleviation of the side force [20 24] Three ex cellent papers by Ericsson and Reding[25 27] go a long way in briefing an interested researcher about the current status of the subject

This paper briefly describes a systematic program in progress for the past two years aimed at measurement and alleviation of side force on a circular cylindrical body fitted with a family of nose geometries at subsonic speeds (Fig 1) In the beginning details of the models used the wind tunnel test program and associated instrumentation are explained This is followed by a description of efforts at affecting coherence of shedding vortices and evaluation of their merit Next results of experiments aimed at assessing the effect of tip geometries are presented Finally preliminary data showing the effect of the tip geometries and rotation are recorded Qualitative flow visualization results (not presented here) obtained in a liquid solution tunnel complemented the wind tunnel test program

Models and Test Arrangement

Four models with the same cylindrical base but different conical forebodies were constructed from aluminum as shown in Fig 1 The surface of the models was polished smooth Model A with a hemispherical forebody was tested only to provide reference information As model D with the sharpest forebody (smallest apex angle of 20 deg) resulted in the highest side force the attention was directed primarily at it during the force alleviation studies

The models were tested in a closed circuit laminar flow wind tunnel with a test section of 0 69×0 91×2 44 m The tunnel is able to produce a stable flow with velocity ranging

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from 0 3 to 30 m/s at a turbulence level of less than 0 1% The rectangular cross section 0 69 × 0 91 m is provided with 45 deg corner fillets which vary from 15 25 × 15 25 cm to 12 1 × 12 1 cm to partially compensate for the boundary layer growth The air velocity is measured by a Betz manometer with an accuracy of 0 02 mm of water The spatial variation of mean velocity in the test section was observed to be less than 0 25% The tunnel is powered by a 15 hp (11 2 kW) dc motor driving a commercial axial flow fan with a Ward Leonard system of speed control

Each of the models was supported on a bar and connected through a bracket to a six component strain gage balance The support platform can be rotated in the horizontal plane to vary the angle of attack over a ±90 deg range (Fig 2)

Results and Discussion

The amount of information obtained through a systematic test program involving four basic models and their numerous variations through add on devices is rather extensive For conciseness, only a few of the typical results useful in establishing trends are recorded here

Aerodynamic Coefficients

Variation of lift and drag coefficients with the angle of attack for the four models is shown in Fig 3 Note the maximum lift coefficient of about 3 6 is associated with the forebody having the smallest cone angle (model D) and occurs at $\alpha \simeq 55$ deg; the corresponding $C_D \simeq 4\ 6$ It is significant that the same model experienced the maximum side force ($C_S = 3\ 95$) as evident from Fig 4 The test emphasized several important aspects concerning aerodynamic behavior of this class of bodies at subcritical Reynolds numbers:

1) Cylindrical shaped bodies with pointed geometry may experience substantial side force at relatively large angles of attack

2) The side force coefficient reaches a maximum in the angle of attack range of 30 55 deg, depending upon the apex angle For $\alpha > 60$ deg C_S is relatively small

3) The side force exhibits bistable behavior The direction is decided perhaps by the character of freestream turbulence and tip condition Although direction of the force during a given wind tunnel run remained stable, restarting the tunnel with the same model condition did not guarantee the same direction

4) For the models tested, the maximum side force coef ficient was found to be associated with the conical forebody having the smallest apex angle (model D)

5) The maximum side force and lift coefficients have the same order of magnitude In fact for models C and D $[C_S]_{max}$ was found to be greater than the corresponding maximum lift coefficient values

Strategies Aimed at Alleviation of Side Force

Experiments were carried out with a variety of add on devices to assess their effectiveness in reducing the side force The procedures included: surface roughness, helical trip, modifications in nose geometry and rotation of the tip

Surface Roughness

It is generally accepted that, for subsonic flows past pointed forebodies at relatively high angles of attack separation of

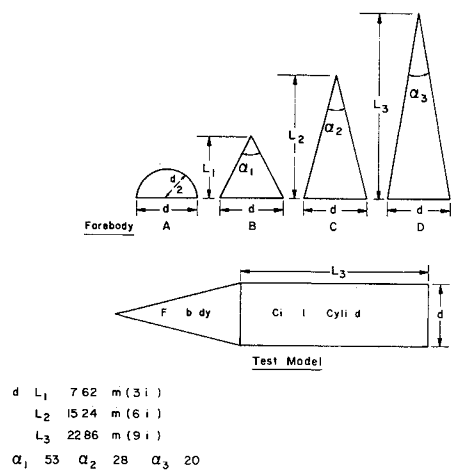

Fig 1 Geometry of models

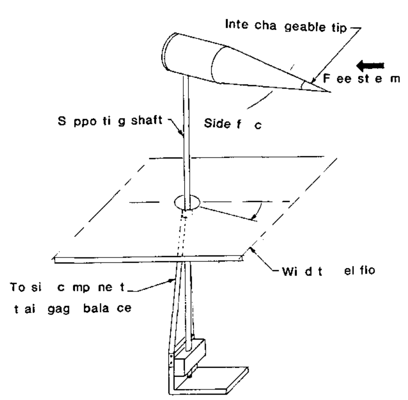

Fig 2 Model support system

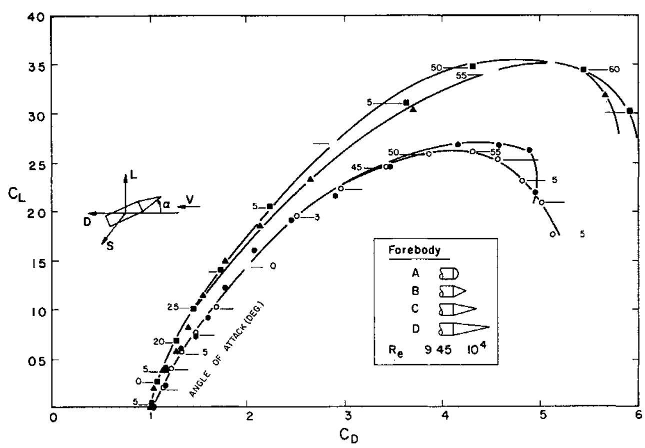

Fig 3 Variation of the lift and total drag coefficients as functions of angle of attack for the four models

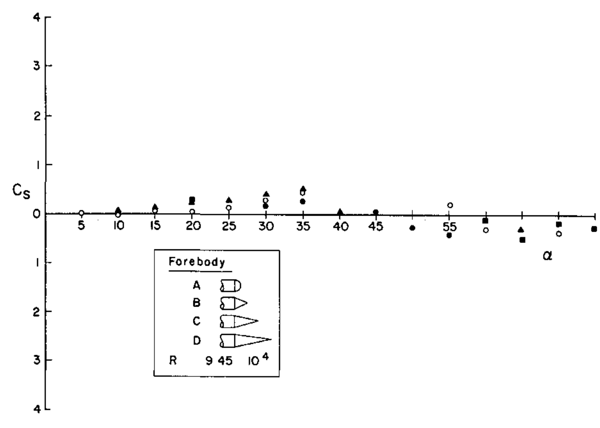

Fig 4 Variation of the side force coefficient with the angle of attack (Note the change in sign)

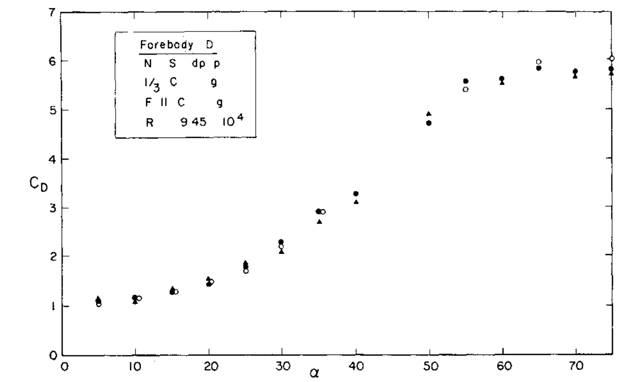

Fig 5 Effect of the sandpaper roughness on the variation of drag Note, in general the effect of roughness is negligible except at higher angles of attack where it shows a slight reduction in C_D

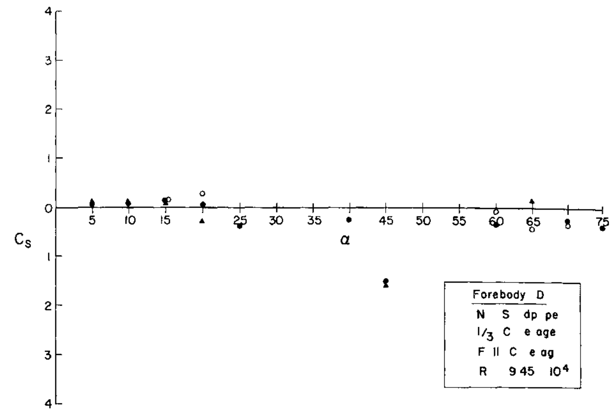

Fig 6 Effect of the forebody roughness on the side force coefficient Note that there is some reduction ($\approx$36%) in the peak value

boundary layer occurs due to adverse pressure gradients on the leeward side The separated boundary layer then rolls up to form a pair of vortex sheets Asymmetric evolution of the wake on the leeward side is held responsible for the presence of the side force The onset of asymmetry typically occurs when the forebody angle of attack exceeds 2 or 3 times the apex angle [28] The presence of asymmetry itself is attributed to freestream turbulence and surface roughness [2] Krouse[29] has effectively shown the side force to be associated with the asymmetry of circumferential pressure distribution and the vortex sheet separation The direction of the side force is governed by the initial development of asymmetry in the vortex flow which, in turn, is related to the instability of the velocity profile in the vicinity of the enclosing saddle singular point [22]

It was thought appropriate to evaluate effectiveness of the surface roughness in destroying coherence of the vortex sheets through promotion of turbulence by covering the conical forebody with sandpaper Two configurations were tested: full coverage and one third coverage with the sand paper (3M Co grade 40) The change in drag coefficient was essentially negligible and even slightly favorable particularly at high angles of attach ($\alpha \approx 40$ deg Fig 5) The peak value of the side force did show a reduction of as much as 36% for the case of full coverage as indicated in Fig 6

Helical Trip

Use of the helical trip first suggested by Scruton and Walsh [30] has been used rather successfully in vortex induced instability of structures susceptible to wind excited oscil lations The principle of operation is rather simple Essen tially, the flow is forced to separate at varying peripheral locations along the length of the body This results in a vorticity flux variation along the length preventing the shed vorticity from concentrating into discrete two dimensional cores The Kármán vortex street is now replaced by an in coherent wake and the alternating crossforce is suppressed

Figure 7 shows effectiveness of the helical trip with several different values of pitch applied to the pointed forebody section of model D A reduction in the side force coefficent by as much as 60% is unmistakable Extensive experimentation with different values of d_t/d pitch and starting position of single or twin trip configurations did not result in any sub stantial further reduction in C_S This is in contrast to the observation made by Rao [20]

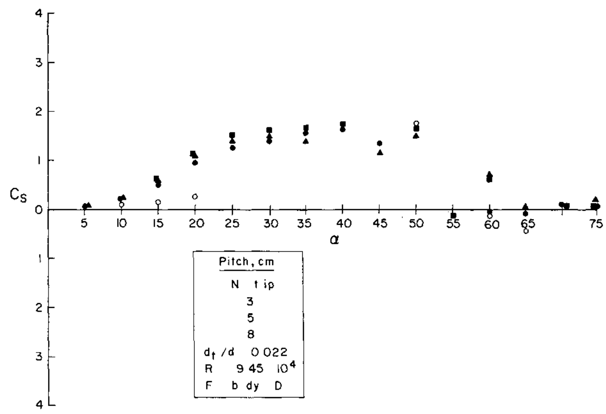

Fig 7 Effect of the helical trip wire on the side force d_t refers to diameter of the wire Note a consistent reduction in the side force of as much as 60%; however, it was never suppressed completely as suggested by Rao [20]

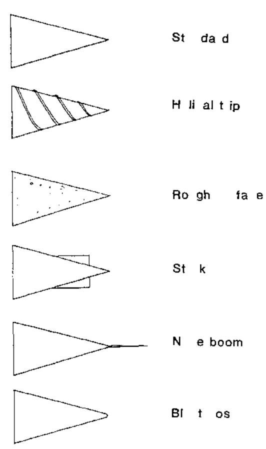

Fig 8 Tip geometries used in the test program

Modifications in Nose Geometry

As the side force is quite sensitive to the tip condition the efforts were now directed to assess the effect of modifications in the nose geometry Several tip geometries were used in the test program (Fig 8) Some of the results are plotted in Fig 9 Nose boom proved to be the most successful with a reduction in the side force coefficient of about 44%

Rotation of the Tip

Several authors have reported cyclic variation of the side force with the roll angle [31 32] Even rolling the nosetip alone has produced the same effect [32] The cyclic character of the side force variation with the roll angle suggests that the tip rotation at an appropriate rate should subject the body to the time average of the force Experiments by Fidler[21] using the tip with several grid patterns found the concept encouraging in reducing the side force

Since the wake vortices receive their vorticity from the separating boundary layer any reduction in the vorticity shed should reflect in reduced vortex strength as well as the related

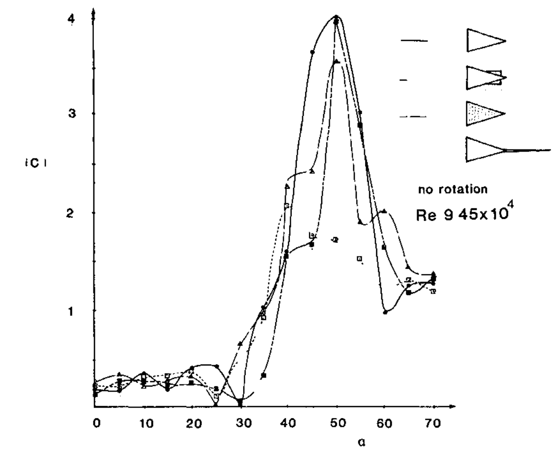

Fig 9 Effect of the forebody tip geometry on the side force coefficient in the absence of rotation

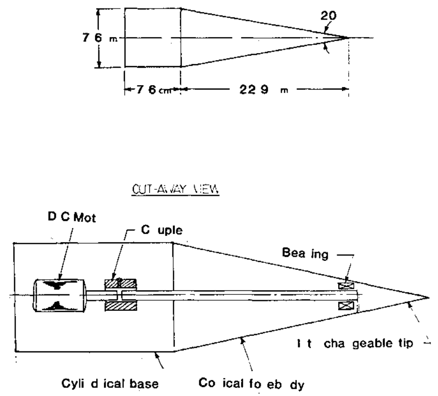

Fig 10 A schematic diagram of the modified model with a rotatable tip connected to a variable-speed dc motor

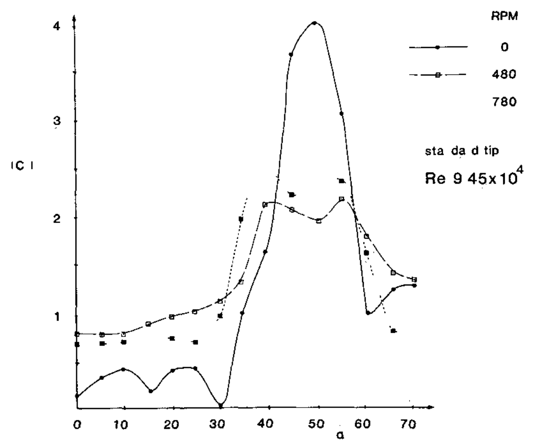

Fig 11 Effect of rotation on the side force coefficient for the conical forebody with the standard tip (model D)

forces and moments Furthermore, with rotation of the tip the vortices may not have enough time to fully develop their flowfield before switching to a new pattern In fact, Kruse[33] observed the side force on a spinning cone to reduce with an increase in the angular velocity up to around 8 rps

To assess validity of the concept and the effect of tip geometry during rotation model D was modified as shown in Fig 10 The interchangeable tips were now attached to a shaft supported by a self aligning bearing and connected through a

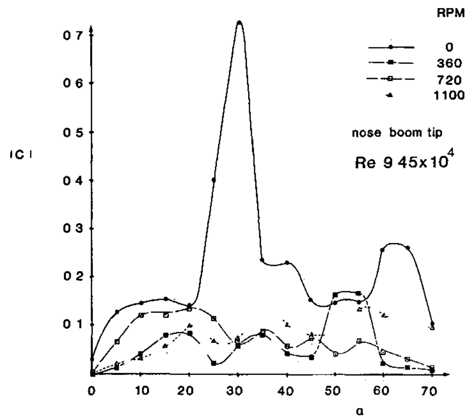

Fig 12 Plots showing substantial reduction in the side force coefficient with rotation of the forebody having a nose boom tip

flexible coupling to a variable speed dc motor Results with the standard tip and nose boom are presented in Figs 11 and 12, respectively Limited space within the model restricted the size of the motor (and, hence, its power) therefore the minimum attainable stable speed was 360 rpm The nose boom configuration reduced the side force coefficient to approximately 0 08 a 98% reduction!

Concluding Remarks

Based on the test results at subcritical Reynolds numbers the following general conclusions can be made

1) The side force coefficient associated with a cylindrical base and a pointed conical forebody can be as large as the lift coefficient

2) Direction of the side force is sensitive to the character of the freestream and tip geometry

3) Although surface roughness and helical strake proved successful in lowering the side force coefficient, the reduction was only modest (35 60%)

4) Among the various tip geometries tried nose boom showed the maximum promise Further tests with nose booms of different aspect ratios and surface conditions should provide useful information

5) Rotation of the tip resulted in a dramatic reduction in the side force coefficient A detailed study of the surface pressure distribution forces moment and wake structure at low revolutions per minute should prove helpful in better understanding of this intriguing problem

Acknowledgments

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