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Effects of Forebody Geometry on Subsonic Boundary-Layer Stability

S. S. Dodbele
Vigyan Research Associates, Inc.
Hampton, Virginia

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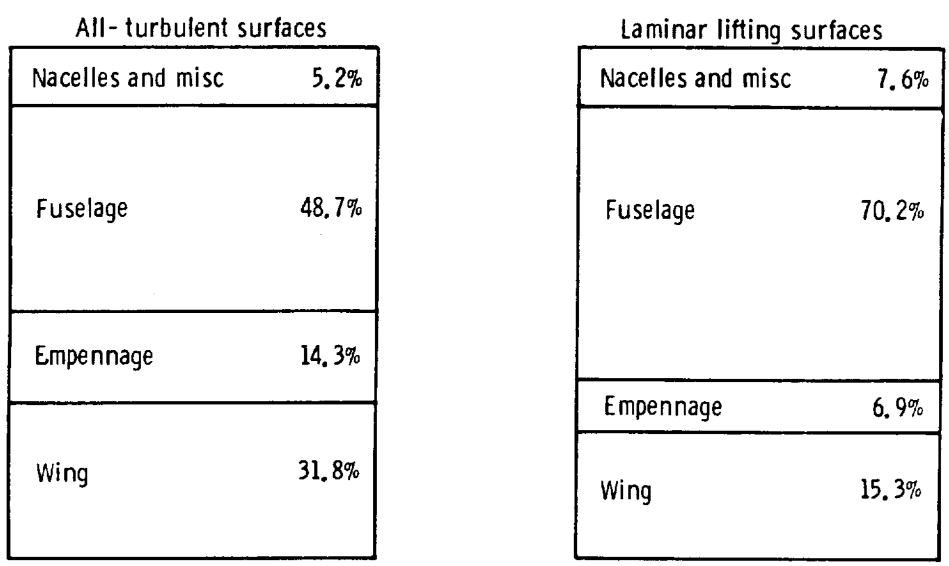
INTRODUCTION

Except for underwater bodies and a few sailplane fuselages, virtually all applied laminar flow research has been focused on airplane lifting surfaces, especially wings. Very little research has been conducted on the application of laminar flow technology on business and transport aircraft fuselages. In the past, the quality of production airframe surfaces was not smooth enough to permit laminar flow to persist over substantial lengths. Surface roughness typically took the form of steps and gaps at skin panel joints. Currently, subsonic and transonic aircraft wing surfaces can be manufactured to meet roughness and waviness criteria for laminar flow. Once laminar flow is applied on airplane lifting surfaces, the benefits of achieving laminar flow on other aircraft components, especially the fuselage, will become increasingly attractive from the point of view of drag reduction. Figure 1 illustrates



All-turbulent surfaces	
Nacelle and others	.0010
Fuselage	.0092
Empennage	.0027
Wing	.0060
Total profile C_D	.0189

Laminar lifting surfaces	
Nacelle and others	.0010
Fuselage	.0092
Empennage	.0009
Wing	.0020
Total profile C_D	.0131

Fig. 1. Viscous drag breakdown for a subsonic transport airplane with and without laminar flow over lifting surfaces (ref. 1).

the benefits of achieving laminar flow on various aircraft surfaces. The figure shows a breakdown of the total viscous drag contribution for a transport aircraft (ref. 1) illustrating that for the all-turbulent transport configuration the fuselage contributes nearly half of the viscous drag. The achievement of substantial amounts of natural laminar flow over the wing and the tail surfaces, as shown on the right, increases the relative contribution of the fuselage to more than 70% of the total profile drag.

Several technical issues remain to be resolved before practical engineering design guidance can be offered for laminarization of fuselages by shaping (pressure gradient) alone. These issues include the effects of forebody geometry on the stability of the laminar boundary layer, the significance of the favorable effects of compressibility on stability of laminar flow on fuselages, the effects of nonaxisymmetric fuselage shapes on laminar stability, the practical importance of insect contamination on fuselage noses, and manufacturing tolerances for surface imperfections on bodies.

This paper presents results of a theoretical analysis of the effect of forebody geometry on the stability of the laminar boundary layer for incompressible flow over axisymmetric body shapes at Reynolds numbers representative of business and commuter airplanes in cruise flight (unit Reynolds number of about one million per foot). The present investigation is part of an effort to design natural laminar flow fuselages by computer optimization.

NOMENCLATURE

C_p Pressure coefficient

f_r Fineness ratio, body length/maximum diameter

L	Body length, ft
NLF	Natural laminar flow
n	Logarithmic exponent of T-S wave growth ratio
r_N	Radius at the nose, ft
R	Body radius, ft
R_L	Reynolds number based on freestream conditions and body length
R_{TR}	Transition Reynolds number based on freestream conditions and transition length from nose
T-S	Tollmien-Schlichting waves
x	Axial coordinate, ft
x_{TR}	Axial coordinate of the onset of transition, ft
α	Angle of attack, deg

BACKGROUND

Past research on laminarization of three-dimensional bodies includes the wind tunnel and flight experiments by Boltz, et al. (ref. 2) and Groth (ref. 3). However, very few theoretical or experimental data have been published on the application of natural laminar flow (NLF) to fuselages of fineness ratios 5 to 9 at cruise length Reynolds numbers representative of business and commuter airplanes. Figure 2 summarizes most of the past unclassified experimental research on laminar flow on bodies (refs. 2 and 4-7). Most of the past research on the shaping of axisymmetric bodies for laminar flow has been focused on improving performance of underwater bodies and sailplane bodies. Power (ref. 8) investigated bodies of revolutions having vastly different forebody geometries and ranging from very fine to very blunt

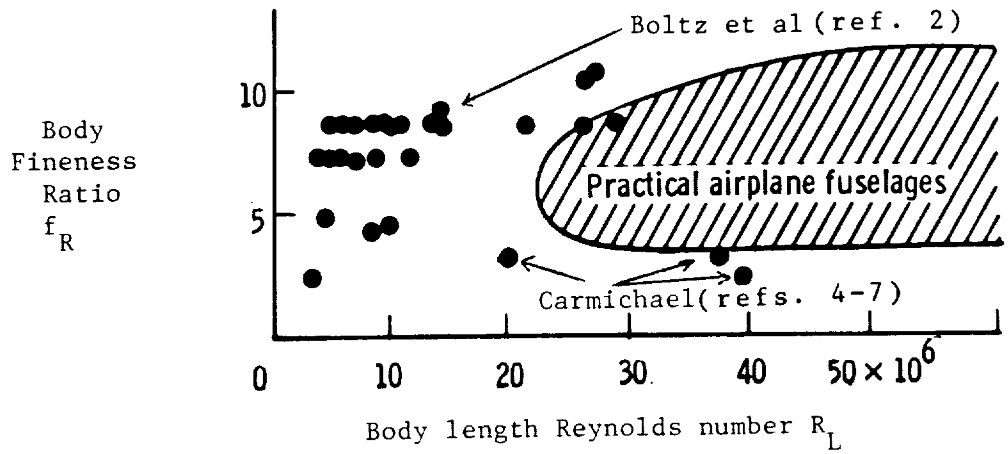


Fig. 2. Past experimental research on natural laminar flow on bodies.

profiles for underwater applications. Kuethe (ref. 9) has presented an approximate analysis indicating that on a blunt body the stretching of vortex filaments due to the change in cross-sectional area and the positive velocity gradient near the nose of the body is a destabilizing influence on the stability of the laminar flow. The drag-reduction potential of laminar hydrodynamic bodies was recognized by Carmichael (refs. 4-7) who designed low fineness-ratio axisymmetric bodies which were successfully tested underwater, achieving transition-length Reynolds numbers as high as 18 million at R_L = 38 million (ref. 6). In experimental investigations, Althaus (ref. 10) and Radespiel (ref. 11) have achieved significant reductions in viscous drag by modifying the body shape of sailplane fuselages. Hertel (refs. 12 and 13) studied the body shapes of fast and prolonged-cruising fishes such as tuna, shark, and dolphin, to learn the potential value of these shapes for low-drag transport fuselages. Meier and Kreplin (ref. 14) made detailed boundary-layer measurements over a range of incidence angles at a maximum length Reynolds number of 7.2 million on a prolate spheriod of fineness ratio 6. Parsons, et al. (ref. 15), Dalton and Zedan (ref. 16), Pinebrook and Dalton (ref. 17), and Dodbele, et al. (refs. 18 and 19) conducted numerical optimization studies to design axisymmetric bodies for minimum drag.

To design bodies for extensive regions of natural laminar flow, a reliable method to predict transition has to be used. The state-of-the-art in transition prediction on practical three-dimensional bodies of fineness ratios 4 to 10 (of interest for aircraft fuselages) is very poor. The adequacy of existing transition prediction methods such as empirical integral correlations and laminar stability theory applied to three-dimensional bodies is discussed in reference 18. The existing integral methods were shown to be poor predictors of transition on many body shapes. This is partly because the transition criteria are based on two-dimensional correlations and the criteria validated in a lower Reynolds number range are extrapolated into higher ranges. Particularly, experimental results used in correlations could be influenced by high turbulence levels and acoustic disturbances present in the wind tunnels. To provide useful methods for transition prediction on three-dimensional bodies in flight, methods must be developed to include compressibility effects, non-parallel boundary-layer effects, curvature effects, Tollmien-Schlichting wave stretching effects, and crossflow vorticity effects.

On axisymmetric bodies at zero angle of attack, Tollmien-Schlichting (T-S) wave amplifications are likely to be the cause of natural transition. The n-factor method, which is used in the present computations to predict transition, is based on the fact that a certain value of logarithmic disturbance amplitude ratio (maximum n-factor) correlates with the beginning of the transition process. Previous studies (refs. 20-23) have indicated that onset of transition due to T-S waves in low disturbance wind tunnels, generally correlates to an "n" in the range between 9 to 11. Values of "n" up to 15 have been observed to correlate with transition in flight experiments (ref. 24).

EFFECT OF FOREBODY SHAPE ON LAMINAR STABILITY

The steepness of the pressure gradient and the value of the minimum pressure govern the stability of laminar flow in incompressible flows.[i] An increase in flow acceleration increases laminar stability of the boundary layer by providing more fullness in the boundary-layer profiles. The pressure gradients over bodies of revolution are generally less favorable than over lifting surfaces. Figure 3 compares incompressible pressure distributions on an airfoil, a flow-through nacelle and an axisymmetric body. The airfoil, the nacelle outer surface, and the axisymmetric body have the same profiles. The figure shows that the maximum flow acceleration (minimum pressure) occurs on the airfoil. Relatively less flow acceleration occurs on the axisymmetric body. To achieve similar levels of laminar stability on an axisymmetric body as on an airfoil, the body would require smaller fineness ratio (more thickness) than the thickness ratio of the airfoil. Generally, the extent of laminar boundary-layer flow can be increased by pushing the minimum pressure point further aft. With a sufficiently strong pressure gradient, transition will occur downstream of the location of minimum pressure. But since the

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[i]There is a significant favorable influence of compressibility on the stability of laminar boundary layers. This effect is independent of favorable pressure gradient changes as speed increases. It was predicted in reference 25 that a body at compressible speed can sustain more laminar flow than the same body at low speeds.

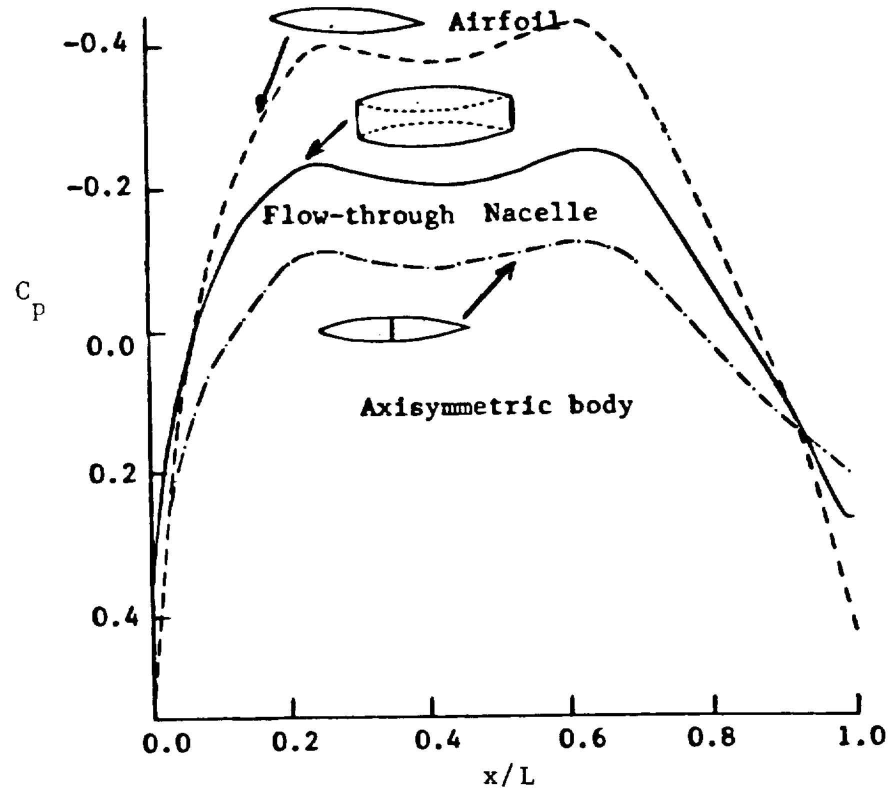


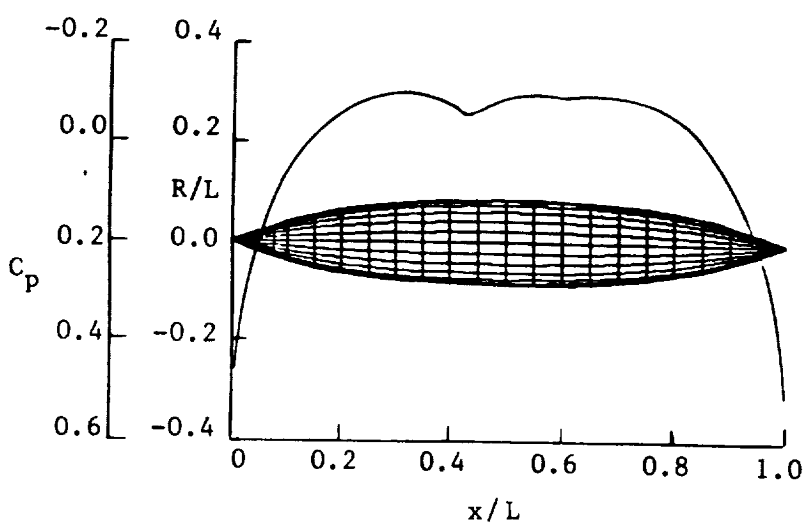
Fig. 3. Calculated pressure distributions over an airfoil, a flow through nacelle and a body of revolution of the same profile shape, VSAERO, α = 0 and incompressible conditions.

magnitude of the pressure coefficient is smaller on bodies than on airfoils of equivalent thickness, less favorable pressure gradients on bodies provide comparitively less stability of the laminar flow. Carmichael (refs. 6 and 7) obtained large amounts of laminar flow on the Dolphin bodies with fineness ratios 3 and 3.33. These Dolphin bodies had long runs of favorable pressure gradients followed by high pressure peaks. On these bodies boundary-layer transition occurred very near the location of the minimum pressure point.

The nose radius has a remarkable effect on the stability of the laminar boundary layer on the body. Small nose radii tend to keep the boundary layer laminar for longer distances. However, too small a nose radius generates vortex separation at off design conditions such as angles of attack. On bodies with large nose radii, pressure peaks occur due to centrifugal effects, resulting in very short stretches of laminar flows.

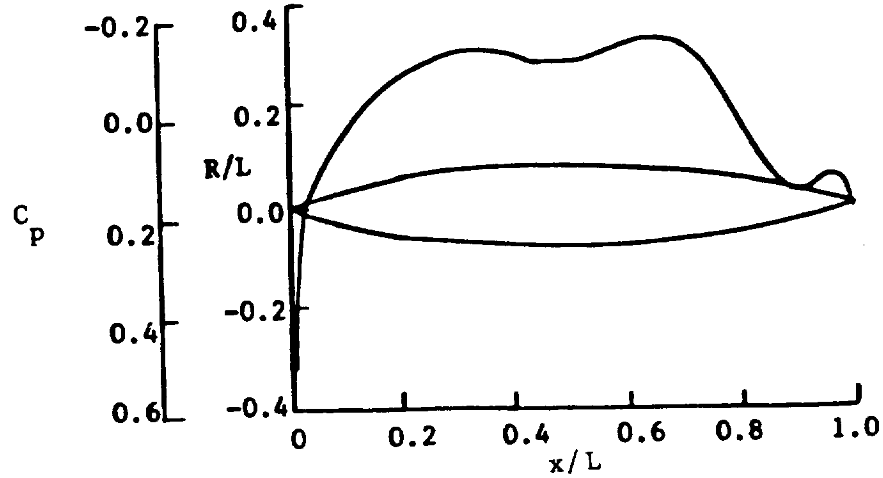
DISCUSSION OF LINEAR STABILITY ANALYSIS

In the present investigation, the effect of several different nose radii on the stability of the laminar boundary layer on axisymmetric bodies was investigated computationally. The comments made here generally apply for axisymmetric bodies of other fineness ratios and profile shapes, provided their shapes are within reasonable limits, representative of small and medium-sized aircraft fuselages. Four forebody shapes with different nondimensional nose radii and with the same body fineness ratio of 6.414 were selected for the analysis and are presented in Fig. 4 along with the corresponding pressure distributions. The pressure distributions on these bodies were obtained by

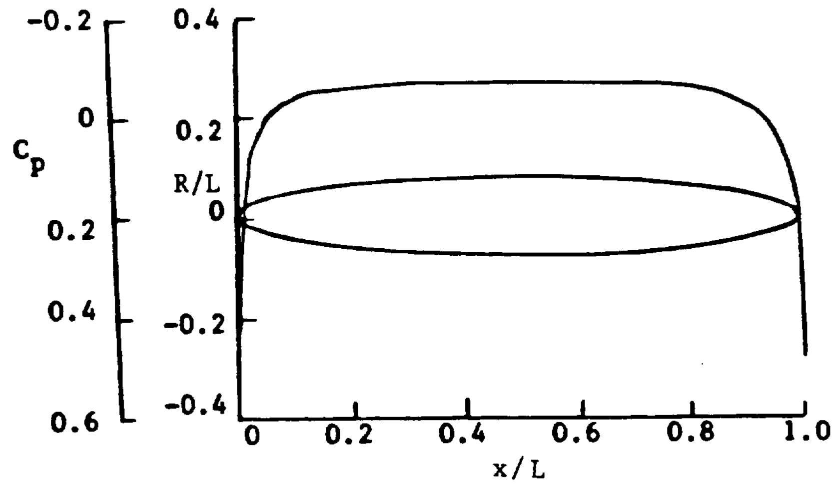


4(a) $r_n/L = .0006$

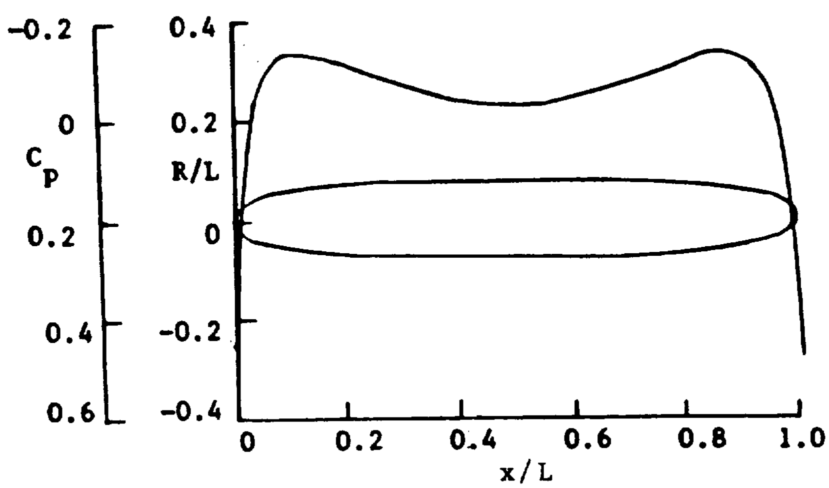
Fig. 4. Pressure distributions on bodies considered for stability analysis, incompressible conditions, $\alpha = 0$.



4(b) $r_n/L = .0028$



4(c) $r_n/L = .0126$



4(d) $r_n/L = .0247$

Fig. 4. (Concluded). Pressure distributions on bodies considered for stability analysis; incompressible conditions, $\alpha = 0$.

using the VSAERO - a low-order surface panel method (ref. 26). The body surface is divided into a number of quadrilateral panels on which piecewise constant doublet and source singularities are distributed. Source strengths are obtained by solving the external Neumann boundary-value problem which requires zero flow velocity normal to the surface. The strengths of the doublet singularities are obtained by imposing the internal Dirichlet boundary condition of zero pertubation velocity potential at the inner centers of the panels. The axisymmetric bodies were modeled by 32 panels in the longitudinal direction and 24 equally spaced panels in the circumferential direction. Panels were distributed densely in the nose region to obtain better resolution of the pressures near the stagnation point (see Fig. 4(a)). In reference 18 it was shown that a good agreement exists between measured and calculated (by VSAERO) surface pressure coefficients for several axisymmetric configurations.

Incompressible linear stability analysis was conducted using the SALLY code (ref. 27). The detailed boundary-layer profiles required for the stability analysis were generated using a modified version of the HARRIS finite difference boundary-layer code (ref. 28). The transverse curvature effects were included in the computation of laminar boundary-layer profiles.

Results of the linear stability analysis done on the body shown in Fig. 4(a) are presented in Fig. 5. In the figure, the logarithmic disturbance amplitude (n-factor) is plotted as a function of the nondimensional axial distance for different T-S frequencies ranging from 500 Hz to 3000 Hz. The envelope of these curves shows that for the axisymmetric body an n-factor of 9 is reached at $x/L = 0.21$ ($R_{TR} = 9.2 \times 10^6$) while an n-factor of 15 is attained at $x/L = 0.31$ ($R_{TR} = 12.4 \times 10^6$). Figure 6 presents the stability envelopes

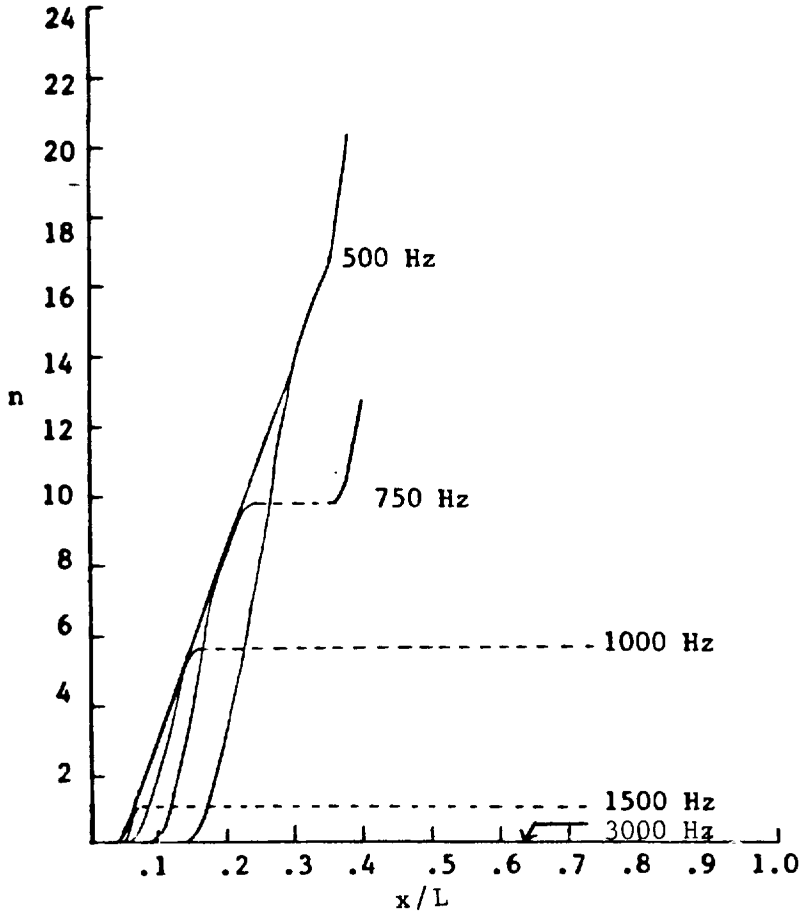


Fig. 5. Stability analysis of the axisymmetric body shown in Fig. 4(a); $\alpha = 0^{o}$, $R_L = 40.86 \times 10^{6}$, and incompressible flow.

obtained for T-S frequencies of 500 to 3000 Hz for the four bodies. The figure shows that an n-factor of 9 is reached farther downstream, that is, the laminar boundary layer is comparatively stable for a longer distance, on the body having the smallest nondimensional radius at the nose. From the computations it was found that on bodies with the larger nose radii, n-factor of 9 is attained near 12% of the length of the body from the nose (see Fig. 6).

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16. Abstract

As part of an effort to develop computational techniques for design of natural laminar flow fuselages, a computational study was made of the effect of forebody geometry on laminar boundary-layer stability on axisymmetric body shapes. The effects of nose radius on the stability of the incompressible laminar boundary layer was computationally investigated using linear stability theory for body length Reynolds numbers representative of small and medium-sized airplanes. The steepness of the pressure gradient and the value of the minimum pressure (both functions of fineness ratio) govern the stability of laminar flow possible on an axisymmetric body at a given Reynolds number. It was found that to keep the laminar boundary layer stable for extended lengths, it is important to have a small nose radius. However, nose shapes with extremely small nose radii produce large pressure peaks at off-design angles of attack and can produce vortices which would adversely affect transition.

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