Technical Notes

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Effect of Boundary-Layer Transition on Center-of-Pressure of Conical Bodies

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THE design of re-entry vehicles is dependent upon reasonable estimates of the location of transition on the body because transition affects 1) aerodynamic heating, 2) flowfield observables, and 3) vehicle dynamics.[1] It is the purpose of this Note to present some wind-tunnel measurements that demonstrate the effect that transition can have upon the static stability of a 5-deg half-angle cone in hypersonic flow. This information may help to explain some of the trajectory perturbations that have been observed in the region where transition occurs, as noted in Ref. 1.

Analyses of force and moment measurements obtained with six component strain gage balances in hypersonic wind tunnels have shown that the center-of-pressure location is sensitive to small changes in model configuration and also to changes in the flow over the model. The static force and moment measurements discussed herein were obtained in the Arnold Engineering Development Center (AEDC), von Kármán Gas Dynamics Facility (VKF) Hypersonic Tunnel (B).[2] Sharp and blunt 5-deg half-angle cones have been tested at $M_\infty \approx 6$ at Reynolds numbers per meter ranging from 0.3 to 1.5×10^6. These measurements have been made under conditions of natural transition and where fully turbulent flow over the entire body has been insured by placing boundary-layer trips close to the nose.

The measurements for both sharp and blunt cones are summarized in Fig. 1. On the basis of extensive transition location studies by Pate,[3] it can be assumed that as the Reynolds number per meter increases from 1 to 5×10^6, the transition front moves forward on the body. For the blunt cone (Fig. 1a), at ± 2 deg angles of attack as the transition front location moves from the base of the body to a location of $X_T/L \approx 0.72$, there is forward movement in the center-of-pressure location. For a Reynolds number per meter of 1.3×10^6 boundary-layer trips positioned close to the nose of the body have insured fully turbulent flow over almost the entire body. Under these conditions (Fig. 1a), the inviscid[4] and experimental values of center-of-pressure location are almost the same. For angles of attack greater than ± 4 deg, the center-of-pressure location is essentially independent of Reynolds number (Fig. 1a).

Measurements obtained with the sharp cone (Fig. 1b) show that, for constant values of Reynolds number, center-of-pressure location is a strong function of angle of attack for $-2 \leq \alpha \leq 2$ deg. For example, for a Reynolds number per meter of 0.3×10^6 as the angle of attack changes from 0 to ± 1 deg, the center-of-pressure location changes from 0.673 to

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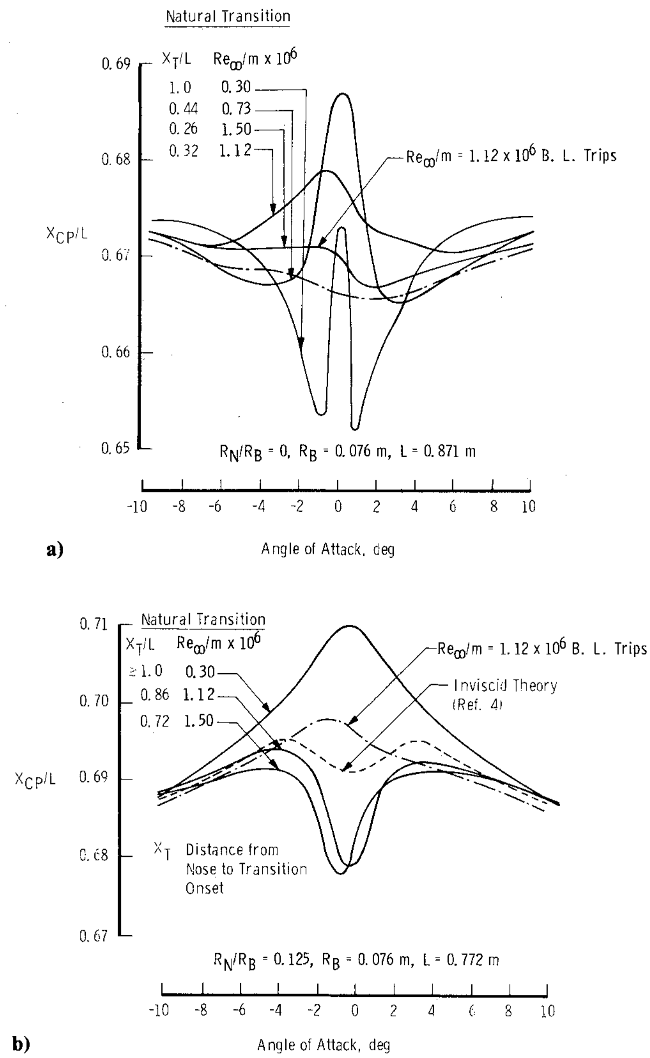

Fig. 1 Effect of transition front location on center of pressure, 5 deg half angle cone, $M_\infty = 5.95$: a) blunt cone; b) sharp cone.

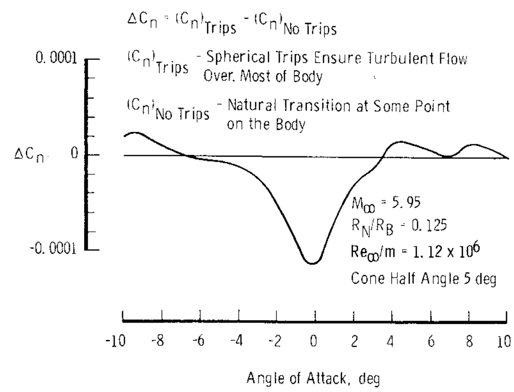

Fig. 2 Incremental yawing moment with natural transition.

0.652. When fully turbulent flow (resulting from boundary-layer trips or natural transition) exists over large portions of the body, center-of-pressure location is no longer a strong function of angle of attack (Fig. 1b).

It is of interest to note that the above changes in center-of-pressure location are associated with a yawing moment perturbation (Fig. 2). Presumably such a perturbation arises from an asymmetry in the transition front at small angles of attack.

Acknowledgments

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Breakdown Condition of an Axisymmetric Swirling Flow

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Introduction

MANY explanations have been proposed for vortex breakdowns of swirling flows, such as finite transition theory by Benjamine,[1] instability theory by Ludvieg,[2] etc. Quite recently Tsai and Widnall[3] reported a group velocity criterion for vortex flow.

On the other hand, one method for prediction and explanation of vortex breakdown using a simple axial velocity profile has been proposed by the author.[4] The principle underlying this method is to find solutions which approximately satisfy the Navier-Stokes equations, thus leading to the critical condition of breakdown. Consequently, a condition of breakdown of the axisymmetric swirling flows that the critical angular velocity ω_c is nearly 1.0 was obtained. When comparing this value with the already obtained experimental data, a great difference between them was not found.[4] In this Note more complicated and extended axial velocity profiles are used, for which expressions for calculating the critical angular velocity are derived, and the critical angular velocity is calculated for some axial velocity profiles characteristic of the swirling flows.

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Formulation of the Problem

Several experiments on breakdown of swirling flows have been performed so far[5-7] and referring to those data, in a previous paper[4] a simple function for the axial velocity profile was used; specifically where r and z are the radius and axial length, respectively, in cylindrical coordinates.

$$w = 1 - A(1-\tilde{a}r^2)z(z-2\tilde{b}) \tag{1}$$

where $A = 1/\{L(L-2\tilde{b})\}$, and $\tilde{a}$, $\tilde{b}$, and L are parameters. Each variable is made nondimensional with reference to the core radius and the velocity on the axis at the upstream boundary. In this Note this simple profile is extended to a rather complicated one as follows:

$$w = 1 + az + bz^2 + (c + dz + ez^2 + fz^3)(g + hr)r^2 \tag{2}$$

where $a,b,c,d,e,f,g,$ and h are parameters.

Using this axial velocity profile, the radial velocity component u can be calculated directly from the continuity equation.

$$u = -r(a+2bz)/2 - (d+2ez+3fz^2)(g/4+hr/5)r^3 \tag{3}$$

In Eqs. (2) and (3), p_1 and p_2, which are the pressures obtained from the radial and axial equations of motion, respectively, are represented by the following expressions:

$$\begin{aligned}
p_1 = {} & -\{r(a+2bz)/2 + (d+2ez+3fz^2)(g/4+hr/5)r^3\}^2/2 \\
& + (1+az+bz^2)\{b/2 + 2(e+3fz)(g/16+hr/25)r^2\}r^2 \\
& + (c+dz+ez^2+fz^3)\{b(g/4+hr/5)r^4 + 2(e+3fz) \\
& \times (g^2/24 + 9ghr/140 + h^2r^2/40)r^6\} + \int_0^r \frac{v^2}{r}\,\mathrm{d}r \\
& - \epsilon(d+2ez+3fz^2)(g+hr)r^2 - \epsilon 6f(g/16+hr/25)r^4 \\
& + \{1-(1+az+bz^2)^2\}/2 + \epsilon 4g(c+dz/2 \\
& + ez^2/3 + fz^3/4)z + \epsilon 2bz
\end{aligned} \tag{4}$$

and

$$\begin{aligned}
p_2 = {} & r^2 z(2g+3hr)\{ac + (ad+2bc)z/2 + (ae+2bd)z^2/3 \\
& + (af+2be)z^3/4 + 2bfz^4/5\}/2 \\
& + (g/4+hr/5)r^4 z(2g+3hr)\{cd + (2ec+d^2)z/2 \\
& + (fc+de)z^2 + (2df+e^2)z^3/2 + efz^4 + f^2z^5/2\} \\
& - [\{1+az+bz^2 + (c+dz+ez^2+fz^3)(g+hr)r^2\}^2 \\
& - \{1+c(g+hr)r^2\}^2]/2 \\
& + \epsilon(4g+9hr)z(c+dz/2+ez^2/3+fz^3/4) \\
& - \epsilon 6fz(g/4+hr/5)r^3 - \{ar/2 + d(g/4+hr/5)r^3\}^2/2 \\
& + \{b/2 + 2e(g/16+hr/25)r^2\}r^2 + c\{b(g/4+hr/5) \\
& + 2e(g^2/24 + 9ghr/140 + h^2r^2/40)r^2\}r^4 \\
& + \omega^2r^2/2 - \epsilon d(g+hr)r^2 - \epsilon 6f(g/16+hr/25)r^4
\end{aligned} \tag{5}$$

where $\epsilon \equiv Re^{-1}$.