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NASA TECHNICAL MEMORANDUM NASA TM-88533

STABILITY CHARACTERISTICS OF A SUPERSONIC BOUNDARY LAYER AND THEIR RELATION TO THE POSITION OF THE LAMINAR-TURBULENT TRANSITION POINT

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Translation of "Kharakteristiki ustoychivosti sverkhzvukovogo pogranichnogo sloya i ikh svyaz' s polozheniyem perekhoda laminarnogo sloya v turbulentnyy," Izvestiya Sibirskogo otdeleniya Akademii Nauk SSSR, Seriya tekhnicheskikh nauk, issue 1, no. 4, 1985, pp. 79-86.

(NASA-TM-88533) STABILITY CHARACTERISTICS OF A SUPERSONIC BOUNDARY LAYER AND THEIR RELATION TO THE POSITION OF THE LAMINAR-TURBULENT TRANSITION POINT (National Aeronautics and Space Administration) 15 p G3/02 N87-16797 Unclas 43861

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D.C. 20546 JANUARY 1987

STABILITY CHARACTERISTICS OF A SUPERSONIC BOUNDARY LAYER AND THEIR RELATION TO THE POSITION OF THE LAMINAR-TURBULENT TRANSITION POINT

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There is, as yet, no complete theory allowing prediction of the position of the transition of a laminar compressible boundary layer into a turbulent one. Approximated approaches are employed for practical purposes. They are generally based on use of the linear theory of stability, which has been fairly well developed (see [1], for example). Use of the linear stability theory in combination with information about the field of disturbances provided encouraging results for predicting boundary-layer transition on models in wind-tunnel tests [2]. In flight tests, however, and in tests in many aerodynamics installations, the initial disturbance spectrum in the boundary layer is unknown. In this case it is possible to use the (rougher, of course) e^n method of predicting the transition point, which recommends itself well at subsonic speeds in both wind-tunnel and flight experiments, including for three-dimensional boundary layers (see [3], for instance). In this method the position of the transition is established upon achievement of disturbance-amplitude ratio $A = Q/Q_0 = e^n$ (Q_0 is the disturbance amplitude on the lower branch of the neutral stability curve, Q is the present value of the amplitude), which is the amplification coefficient of disturbances in the unstable region. Since for M > 1 there are no generalizing detailed calculations for predicting the transition point, although there is a great need for carrying them out, these calculations were made. /79*

Taken as the basis was a program for calculating the coefficients for increase in disturbances, α_i, in a boundary layer with a heat-transfer pressure gradient [4]. The procedure for calculating the

*Numbers in the margin indicate pagination in the foreign text.

stability characteristics is laid out fairly well in [1, 5] as well.

The flow of a compressible heat-conducting gas in the boundary layer is described by system of equations

$$\frac{\partial\left(r_w^k\rho u\right)}{\partial s}+\frac{\partial\left(r_w^k\rho v\right)}{\partial y}=0;$$
$$\rho u\frac{\partial u}{\partial s}+\rho v\frac{\partial u}{\partial y}=u_e\rho_e\frac{du_e}{ds}+\frac{\partial}{\partial y}\left(\mu\frac{\partial u}{\partial y}\right);\qquad(1)$$
$$\rho u\frac{\partial I}{\partial s}+\rho v\frac{\partial I}{\partial y}=\frac{\partial}{\partial y}\left(\frac{\lambda}{c_p}\frac{\partial I}{\partial y}\right)+\frac{\partial}{\partial y}\left[\left(\mu-\frac{\lambda}{c_p}\right)\frac{\partial\left(u^2/2\right)}{\partial y}\right].$$

Here I is the total enthalpy, c_p is the specific heat, $r_w(s)$ is the body surface equation, μ and λ are viscosity and heat conductivity, e is a subscript denoting that the parameters are taken at the external border of the boundary layer, $k = 1$ for the axisymmetric case, and $k = 0$ for two-dimensional flow. From equations (1), the last is valid at $dI_e/ds = 0$.

The flow of air around an impermeable surface with a given wall temperature was examined. In this case the boundary conditions are /80

$$u(0)=v(0)=0;\ I(0)=I_w;\ I(\infty)=u(\infty)=1.\qquad(2)$$

Assuming limited similitude [6] (as shown by research specially conducted by the author, this assumption is quite possible), system (1) was converted into a system of ordinary differential equations and numerically integrated (see [1] for more detail). As a result of the integration, the distribution of longitudinal velocity and temperature, their derivatives, and the viscosity across the boundary layer were determined, as required when solving stability equations.

To determine the coefficients of increase in disturbances, the system of stability equations in the Dunn-Lin approximation [7] was used:

$$\rho\left[i\left(\tilde{\alpha}u-\tilde{\omega}\right)\tilde{f}+u'\tilde{\alpha}\varphi\right]=-\frac{i\tilde{\alpha}\pi}{\gamma\tilde{M}^2}+\frac{\mu}{\tilde{\mathrm{Re}}}\tilde{f}'',$$
$$\rho\left[i\tilde{\alpha}\left(\tilde{\alpha}u-\tilde{\omega}\right)\varphi\right]=-\frac{\pi'}{\gamma\tilde{M}^2},$$
$$i\left(\tilde{\alpha}u-\tilde{\omega}\right)r+\rho'\tilde{\alpha}\varphi+\rho\tilde{\alpha}\left(i\tilde{f}+\varphi'\right)=0,\qquad(3)$$
$$\rho\left[i\left(\tilde{\alpha}u-\tilde{\omega}\right)\theta+\tilde{\alpha}T'\varphi\right]=-\tilde{\alpha}\left(\gamma-1\right)\left(i\tilde{f}+\varphi'\right)+\frac{\gamma\mu}{\sigma\tilde{\mathrm{Re}}}\theta'',$$

$$\frac{\pi}{p} = \frac{r}{\rho} + \frac{\theta}{T}$$

with boundary conditions

$$\tilde{f}(0) = \varphi(0) = \theta(0) = 0;$$
$$\tilde{f},\ \varphi,\ \theta \to 0 \text{ at } y \to \infty. \tag{4}$$

Here u, ρ, p, and T are the time-averaged velocity, density, pressure, and temperature; f, ϕ, r, θ, and π are the disturbance amplitudes of longitudinal and normal velocities, density, temperature, and pressure; $\tilde{\alpha} = \tilde{\alpha}_r + i\tilde{\alpha}_i$ is the wave number of the disturbance in the direction of wave propagation; $\tilde{\omega}$ is the transformed angular velocity of the disturbance; $\tilde{\mathrm{Re}} = \mathrm{Re}\cdot\cos\chi$, $\mathrm{M} = \mathrm{Me}\cdot\cos\chi$, $\tilde{\alpha} = \alpha/\cos\chi$, $\tilde{\omega} = \omega/\cos\chi$, $\tilde{f} = f/\cos\chi$, where Re is the Reynolds number, M is the Mach number, χ is the slope of the wave relative to the main flow. The stroke designates differentiation with respect to the coordinate normal to the surface.

The Reynolds number, determined from the transverse (normal) scale δ,

$$\mathrm{Re} = \frac{u_e\delta}{\nu_e} = \frac{\left(\int_0^s u_e\nu_e\rho_e^2 r_w^{2k}\,ds\right)^{1/2}}{\nu_e\rho_e r_w^k}, \tag{5}$$

where u is the longitudinal velocity; ρ is the density; ν is the kinematic viscosity ($\nu = \mu/\rho$) and s is the coordinate along the surface of the body; $r_w(s)$ is the body surface equation; e is a subscript denoting that the parameters are taken at the external border of the boundary layer; $k = 1$ for the axisymmetric case; $k = 0$ for two-dimensional flow. With gradient-free flow (i.e., at $\beta = (2\bar{s}/u_e)(du_e/d\bar{s}) = 0$, where $\bar{s} = \int_0^s u_e\nu_e\rho_e^2 r_w^{2k}\,ds$) for the axisymmetric case $\mathrm{Re} = \sqrt{\frac{u_e}{\nu_e}}\left(\int_0^s r_w^2\,ds\right)^{1/2} \Big/ r_w$, and for two-dimensional flow, $\mathrm{Re} = \sqrt{\frac{u_e s}{\nu_e}}$.

The method of solving system of equations (3) with boundary conditions (4) is described in detail in [1]. New variables were introduced, and system (3) was formed into a system of six ordinary first- /81
order differential equations. It was integrated numerically using the orthogonalization method. The calculations assumed Prandtl number

$\sigma = 0.72$, adiabatic constant $\gamma = 1.41$, and Sutherland's law for change of viscosity with temperature.

As written, problem (3)-(4) corresponds to a two-dimensional problem. In fact, however, it allows obtaining information about three-dimensional disturbances [7]. The results of integration permitted obtaining relation $\alpha_i = \Phi(\mathrm{Re}, \chi, F)$, where $F = \tilde{\omega}\cdot\cos^2 \chi/\mathrm{Re}$; $\mathrm{Re} = \tilde{\mathrm{Re}}/\cos \chi$; $\alpha_i = \tilde{\alpha}_i \cos \chi$ (χ is the angle of disturbance propagation). When solving the problem it was assumed that $\tilde{\omega}$ is real, and $\beta_i/\alpha_i = \beta_r/\alpha_r$ [2], where $\beta = \beta_r + i\beta_i$ is the wave number in the lateral direction. Then $\chi = \tan^{-1} (\beta_r/\alpha_r)$.

The degree of spatial intensification of disturbance α_i is associated with the disturbance amplitude Q by relation

$$\mathrm{Real}\left(\frac{d(\ln Q)}{ds}\right) = -\alpha_i. \tag{6}$$

From (6) and (5) it follows that

$$\ln|Q/Q_0| = -2\int_{\mathrm{Re}_0}^{\mathrm{Re}} \frac{\alpha_i d\mathrm{Re}}{I}, \tag{7}$$

where $I = 1 - \frac{2\bar{s}}{\mu_e r_w^k}\cdot\frac{d\left(\mu_e r_w^k\right)}{d\bar{s}}$. For a plate and a wedge, $I = 1$, for a cone $I = 1/3$.

Expression (7) defines the ratio of disturbance amplitudes at points with coordinates Re and Re_0, which is the coefficient of disturbance intensification in the area under consideration. If point Re_0 corresponds to the lower branch of the neutral stability curve and the initial spectrum of boundary-layer natural oscillations is known, expression (7) can be used to predict the transition, considering (by analogy with $M < 1$), for example, that the transition occurs if the amount of pulsation at the frequency under examination is on the order of 1% of u_∞.

If, however, the spectrum of boundary-layer natural oscillations is unknown, to predict the position of the transition we can try to use the approach to this problem suggested by Smith [8] and developed by a number of authors for the case of subsonic flow. This approach is based on the results of work by Schubauer and Skramstad [9] and many other works showing that the boundary layer selectively intensifies the disturbances so that the transition is produced by disturbances whose frequencies lie in a limited area. For an established local Reynolds number, we distinguish from the entire spectrum of disturbances observed in the boundary layer the one most magnified in amplitude, whose frequency corresponds to the upper branch of the neutral curve. Also lying near the upper branch is the frequency of the main wave, observed directly in front of the transition.

Smith's approach is as follows. For an established frequency, the maximum of the disturbance-amplitude ratio Q/Q_0 corresponds to the upper branch of the neutral curve. Smith, Jaffe, and Okamura [10] suggested associating the position of a transition point found experimentally (on various models in low-turbulence wind tunnels) with the value of $Q/Q_0 = e^{10}$ corresponding to the transition. A number of authors have suggested determining the transition from a point where the disturbance is magnified e^9 times. At supersonic speeds the e^n method obviously is also suitable for rough estimation of the transition location. Unfortunately, at present it is virtually impossible to check the validity of the choice of specific value for n ($n = 9$, for example) by comparison with experimental data for $M > 1$, because of the absence of full-scale flight test data (except [10] at $M \leq 2$). The value $n \simeq 3$ [2] is best suited for usual supersonic /82 wind tunnels (with a fairly high initial level of disturbances in the boundary layer). It must be emphasized once again, however, that a more accurate method of determining the transition location should include knowledge of the spectrum of external disturbances and laws of boundary layer sensitivity (after which the initial spectrum of natural oscillations in the boundary layer becomes known), the ability to calculate the nonlinear stage of disturbance development, use of a more complete system of stability equations (with all dissipative terms, considering non-parallelism of flow), more accurate determination of the criterion of transition beginning (the amplitude "one-percent" method of determining the transition is also not entirely accurate), and consideration of some other less-significant factors.

But for a rough, approximate prediction of the transition point there is some sense in using the method employed in this work.

As opposed to subsonic speeds (where two-dimensional disturbances are the most unstable), at $M > 1$ we have to examine $\alpha_i = \alpha_i(\mathrm{Re}, F, \chi)$, where $F = \omega/\mathrm{Re}$ is a dimensionless frequency. The maximum α_i for $M = 1.5$-4 are reached in the $\chi \approx 50$-$85°$ range. In our work the calculations were performed for critical angle χ^*, defined as the angle at which integral $-2\int_{\mathrm{Re}_{eo}}^{\mathrm{Re}} \frac{\alpha_i d\,\mathrm{Re}}{I}$ from (7) most rapidly reached the required value of n (in particular, $n = 9$), i.e., at $\chi = \chi^*$ the Reynolds number determined at $A = e^n$ is minimal; it was conditionally adopted as the transition Reynolds number Re_t.

The stability characteristics and the conditional location of the transition were calculated for the first stable mode of disturbances at different Mach numbers ($M = 1.5$-4) and different values of the velocity (pressure) gradient ($\beta = 0 \div 0.4$) on heat-insulated (temperature factor $T_w = 1$) and cooled ($T_w < 1$) surfaces. The value of Re_t was calculated chiefly for flat bodies. It should be noted, however, that at $\beta > 0$ calculations were carried out for several arbitrary bodies with minor change of β and M_e along the surface of the body at certain places on it. For a real body with a known distribution of $\beta(s)$ and $M_e(s)$ we have to define a conditional location of the transition using integral $-2\int \frac{\alpha_i [\beta(s), M_e(s)]\, d\,\mathrm{Re}}{I}$. As the corresponding calculations showed, the difference between the location of the transition on an airfoil profile calculated in this manner (from $Q/Q_0 = e^{2.8}$, which is characteristic for wind tunnels) and that obtained in tests in a T-313 wind tunnel [13] did not exceed 10%.

The static temperature for all Mach numbers was taken as the same -- $T_e = -50°\mathrm{C}$ (save only for calculations intended for comparison of theoretical results and experimental data obtained in a wind tunnel).

Results of Calculations

Figure 1 shows the effect of pressure gradient β on the position of the neutral curve ($\alpha_i = 0$) and lines of equal value of $\alpha_i (-\alpha_i > 0)$ characteristic for a heat-insulated surface. The curves of neutral stability are limited below the frequency at which the coefficient of amplification A reaches the value of e^9 (this also refers to other graphs with coordinates F and Re). The strong stabilizing effect of a negative pressure gradient ($\beta > 0$) can be seen on both the position of the neutral curve (and correspondingly of the critical Reynolds number Re_{cr} -- the minimum Reynolds number at which disturbances begin to increase at any frequency) and the coefficient of disturbance increase. Figure 1 also shows the reduction of the frequency determining the transition with increase in β. /83

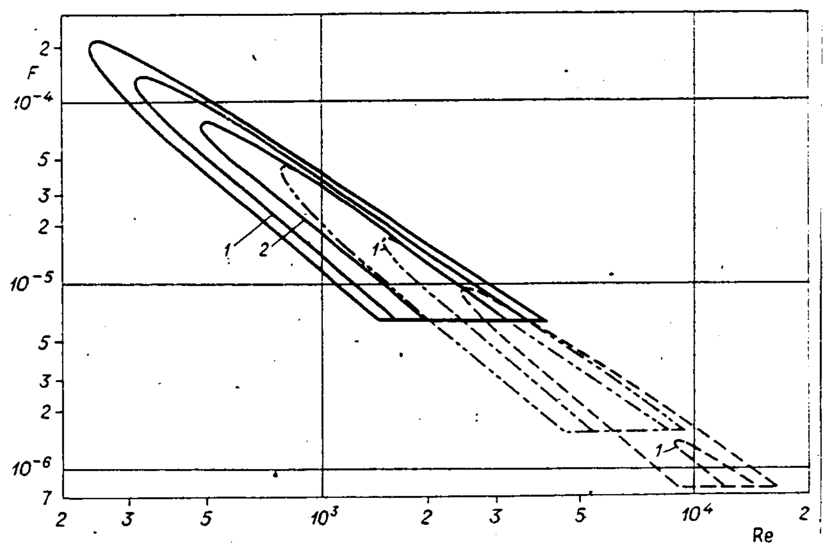

Fig. 1.

$M = 1{,}5$, $T_w = 1$; $-\beta = 0$, $-\cdot-$ 0,1, $---$ 0,2; $-\alpha_i$: 1 — 0,001, 2 — 0,002.

Calculations at $T_w = 1$ and various M and β revealed that the critical Reynolds number decreases with increasing Mach number in the M = 1.5-4.0 range. A negative pressure gradient ($\beta > 0$) (as can be seen in Fig. 1) has a strong stabilizing effect on the stability characteristics. While for a gradient-free flow the least transition-determining frequency corresponds to M = 1.5, at β = 0.2-0.4 it is at M = 2.5-4.

Based on Fig. 1 and similar graphs for M = 2-4, relations were constructed between the conditional transition Reynolds number Re_t and Mach number at $T_w = 1$, and they are shown in Figs. 2 ($\beta = 0$) and 3 ($\beta = 0.1$ and 0.2). Also shown in Fig. 2 are the relations between Mach number and critical Reynolds number Re_{cr} and maximum coefficients of increase in disturbances. A distinct correlation can be seen between these two relations and the relation between Re_t and M. The maximum of ratio $Re_{cr}/(-\alpha_i)_{max}$ corresponds approximately to the maximum of the relation between Re_t and M. This is explained by the fact that for this case ($T_w = 1$, $\beta = 0$), the lower Re_{cr}, the lower the Re_0 in relation $-2\int_{Re_0}^{Re_1} \alpha_i d\,Re = 9$ (Re_0 corresponds to the lower branch of the neutral curve, and Re_1 to the upper), and the higher $-\alpha_i$ in this relation, the faster the required value of the integral accumulates, i.e., $Re_t = Re_0 + (Re_1 - Re_0)$, where $Re_0 \sim Re_{cr}$ and $(Re_1 - Re_0) \sim 1/(-\alpha_i)_{max}$. Thus, the lower Re_{cr} and the greater $(-\alpha_i)_{max}$, the lower Re_t. And with increase in β at significant rise in Re_t, difference $(Re_1 - Re_0) - Re_0$ also rises significantly, and at $\beta \geq 0.1$ the position of the transition is determined chiefly by $(Re_1 - Re_0) \sim 1/(-\alpha_i)_{max}$, which is shown by Fig. 3 (Fig. 3a shows the maximum values of the coefficients of increase in disturbances at the frequency determining the transition).

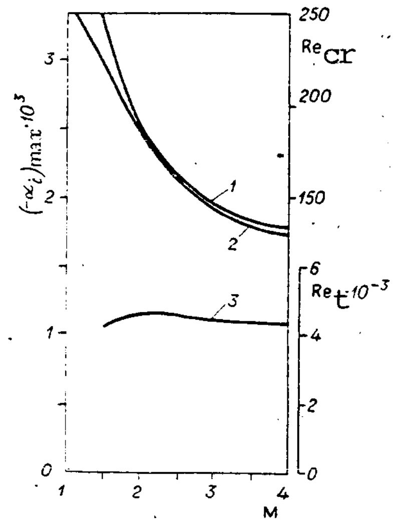

Fig. 2.
$T_w = 1$, $\beta = 0$; 1 -- $(-\alpha_i)_{max}$; 2 -- Re_{cr}; 3 -- Re_t.

Figure 4 shows a comparison of the values of Re_t obtained in this work (at $T_w = 1$ and $\beta = 0$) and experimental data -- the results of *F*-15 (cone) flight tests [12] and experiments in a T-325 wind tunnel (flat plate) [13] (no full-scale flight tests were conducted at M > 2). Calculation of Re_t for a cone ($I = 1/3$) (curve 1) were conducted using the e^n method at $n = 9$. The relation of Reynolds number determined from $A = e^{2.7}$ (curve 2) is close for the results of tests in common supersonic /84 wind tunnels (where the initial level of disturbances in the boundary layer is fairly high)

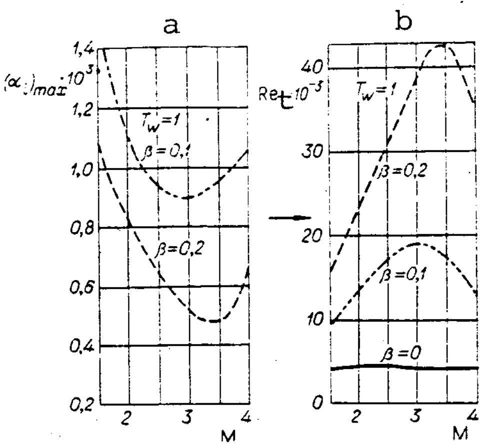

Fig. 3.

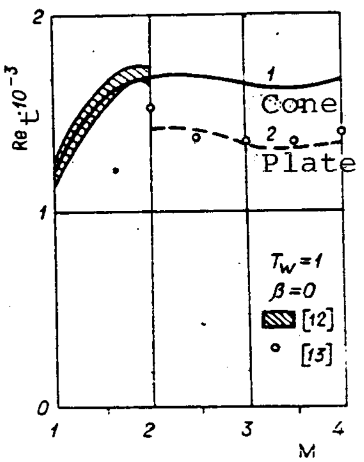

Fig. 4.

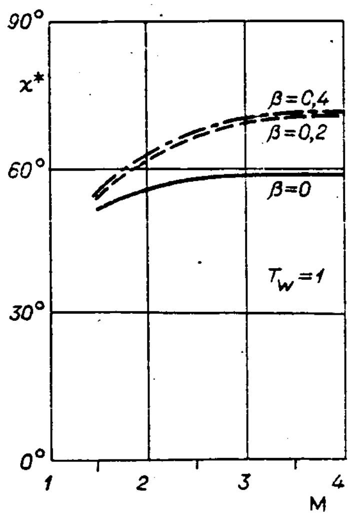

Fig. 5.

(the data in [13] were obtained at a stagnation temperature T_0 = 300 K and single Reynolds number $Re_1 = (u/\nu)_\infty = 25 \times 10^6$ 1/M). The agreement of experimental and calculated values of Re_t is quite satisfactory, on the whole. It should be noted here that exponent n = 2.7 describes the experimental data well at $Re_1 = (25\text{-}35) \times 10^6$ 1/M. For $Re_1 \times 10^{-6}$ = 10 and 60 [1/M] the difference between the transition Reynolds numbers obtained in the wind tunnel and calculated from $e^{2.7}$ reaches 18% at M = 4, but in this case the calculated and experimental data correlate better at another exponent n (2.2 and 3, respectively). Both experiments and calculations demonstrate that there is a local maximum (at M $\simeq$ 2) and minimum (at M $\simeq$ 3.5-4) in relation $Re_t = Re_t(M)$ at T_w = 1 and β = 0.

Figure 5 displays the rise in critical angle χ^* with increasing Mach number and with increase in β from 0 to 0.2. Further increase in β has virtually no effect on the value of χ^*.

The next series of calculations was /85
performed for a maximally cooled surface at $T_w = T_e$ = -50°C (T_e is the static temperature, i.e.,

This situation corresponds to some extent to a hypothetically possible initial stage of aircraft flights in the atmosphere (when the aircraft has not

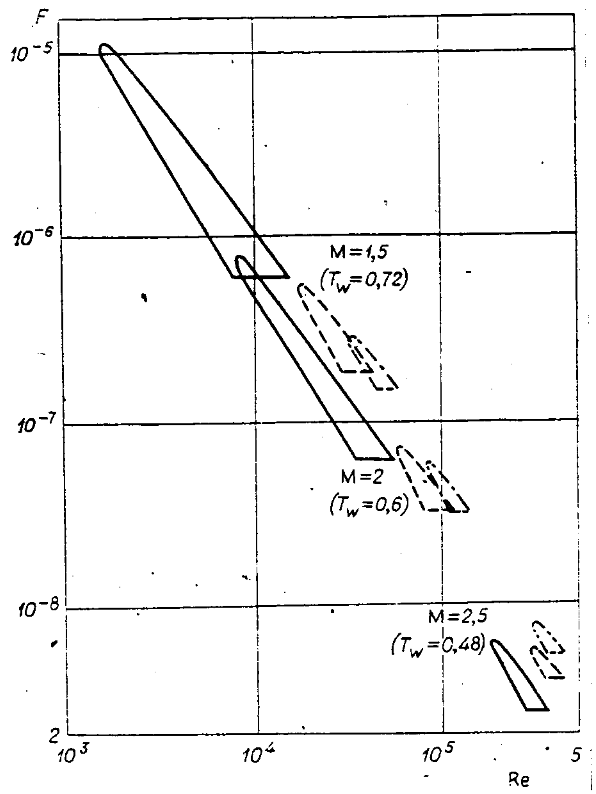

Fig. 6.

$T(w) = T_e = -50°C$; T_w = - β = 0; -- 0.2; --- 0.4.

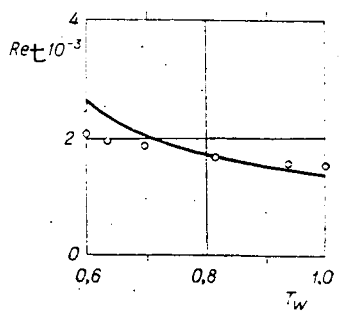

Fig. 7.

M = 4, β = 0, T_0 = 300K; - $e^{2.7}$, o [13].

had time to heat up). The results of the calculations are shown in Fig. 6. The sharp increase in the conditional transition Reynolds number can be seen with increasing Mach number (for $Re_t > 10^6$ for $M \geq 3$). Here the effect of β on Re_t and the position of the neutral curve weakens. For $M \gtrsim 2.3$ the frequency determining the transition rises with increasing β. As research showed, beginning at M = 1.5 the pressure gradient in the β = 0-0.4 range has no effect on the value of the critical angle χ*.

Additional calculations at M = 4 and different β and T_w established a moderate increase in Re_t with decrease in T_w to a certain value, but with stronger cooling there is an abrupt increase in the transition Reynolds number.

Figure 7 shows a comparison between the transition location calculated from $e^{2.7}$ and "wind tunnel" data [13] with change in the temperature factor.

Thus, the possibility of estimating the position of the transition using the e^n method ($n \simeq 9$ for flight tests on a cone) has been shown by comparison with experimental data (Figs. 4 and 7). It has been shown that while for β = 0 and T_w = 1 the relation between Re_t and M is determined by the dependence of both maximum coefficients of increase and critical

Reynolds number on Mach number, for $\beta > 0.1$ the location of the transition is determined chiefly by the coefficients of increase.

It has been found that whereas for a heat-insulated surface the pressure gradient exerts a substantial effect on the flow stability characteristics and the location of the transition, with strong surface cooling the effect of pressure gradient diminishes. The significant stabilizing effect of the temperature factor on the transition location has been confirmed. The value of critical angle χ^* in the $\beta = 0.2$-0.4 range is virtually unchanged.

The author is grateful to A. A. Maslov for his assistance in this work.

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STANDARD TITLE PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TM-88533	A85-42123	

4. Title and Subtitle	5. Report Date
STABILITY CHARACTERISTICS OF A SUPERSONIC BOUNDARY LAYER AND THEIR RELATION TO THE POSITION OF THE LAMINAR-TURBULENT TRANSITION POINT	January 1987
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
V. I. Lysenko, Institute of Theoretical and Applied Mechanics, USSR Academy of Sciences Siberian Branch	
	10. Work Unit No.
9. Performing Organization Name and Address	11. Contract or Grant No.
Leo Kanner Associates Redwood City, California 94063	NASW - 4005
	13. Type of Report and Period Covered
	Translation
12. Sponsoring Agency Name and Address	
National Aeronautics and Space Administration Washington, D.C. 20546	14. Sponsoring Agency Code

15. Supplementary Notes

Translation of "Kharakteristiki ustoychivosti sverkhzvukovogo pogranichnogo sloya i ikh svyaz' s polozheniyem perekhoda laminarnogo sloya v turbulentnyy," Izvestiya Sibirskogo otdeleniya Akademii nauk SSSR, Seriya tekhnicheskikh nauk, issue 1, no. 4, 1985, pp. 79-86.

16. Abstract

By comparing the calculated results with experimental data, it is demonstrated that the position of the laminar-boundary transition point of a boundary layer can be estimated by using the e^n method. The effect of the Mach number, pressure gradient, and heat transfer on the laminar-turbulent transition is discussed. It is found that under conditions of strong cooling, the effect of the pressure gradient on the position of the transition point is less pronounced than in the absence of heat transfer.

17. Key Words [Selected by Author(s)]	18. Distribution Statement
	Unclassified-Unlimited

19. Security Classif.(of this report)	20. Security Classif. (of this page)	21. No. of pages	22.
Unclassified	Unclassified	15	