INFLUENCE OF THE SWEEPBACK ANGLE AND THE UNIT REYNOLDS NUMBER ON BOUNDARY-LAYER TRANSITION AT SUPERSONIC VELOCITIES

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The study of the flow around swept wings is associated with the investigation of three-dimensional boundary-layer transition from the laminar into the turbulent state at supersonic flight velocities. It has been detected earlier [1] that the transition region on a swept wing is considerably closer to the leading edge than on a straight wing. Investigations [2] have shown that the diminution in length of the laminar section as the sweep angle χ increases is related mainly to the intensity of the transverse currents due to leading-edge bluntness, as well as to the presence of a pressure gradient in the chord direction.

However, the test data available on this question at supersonic speeds refer to swept wings with flat surfaces, i.e., to flat sweptback plates [3].

The increase in the transition Reynolds number Re* as the unit Reynolds number $(U/\nu)_\infty$ grows is characteristic [4, 5]; nevertheless the nature of this phenomenon has not as yet been fully clarified.

The combined influence of the sweep angle and the unit Reynolds number on the length of the laminar section is of interest in a study of the problem of transition on swept wings.

In this connection, the joint influence of the quantities χ and $(U/\nu)_\infty$ on the location of transition from the laminar to the turbulent flow mode was investigated in the Institute of Theoretical Problems of Mechanics of the Siberian Branch of the USSR Academy of Science.

The experiments were conducted at the Mach numbers M = 3 and 4 in the $(U/\nu)_\infty = (20\text{-}58) \cdot 10^6\ \mathrm{m}^{-1}$ Reynolds-number range at zero angle of attack in a supersonic wind tunnel with $0.6 \times 0.6\ \mathrm{m}^2$ working section.

The model under investigation is a wing of straight planform with a 250-mm chord, 400-mm span, and c* = 0.03 relative profile thickness. The diagram of fastening the model 1 to the sting 2 is presented in Fig. 1.

The upper (working) surface of the model is executed in parabolic arcs, while the lower was not profiled out of structural considerations. The leading-edge thickness was checked by a UIM-21 type microscope and was 0.11 mm. The height of the microroughness of the working surface did not exceed 1.6 μ. The units 3 fastening the model to the sting were executed so that the sweep angle of the leading edge could be varied between 0 and 90° limits.

TABLE 1

χ	M_∞	$(U/\nu)_\infty \cdot 10^{-6}$, м$^{-1}$	$T_{0\infty}$, °K
—1	3.03	20.5,41.0,51.1	270
19	3.04	21.5,41.2,51.3	265
39	3.03	20.4,42.6,53.7	265
49	3.04	21.1,41.4,52.4	264
—1	4.06	23.7,36.5,54.0	274
19	4.07	23.6,36.6,54.7	270
39	4.06	23.9,36.0,54.6	271
49	4.08	23.6,36.6,58.1	266

The location of transition was determined by the change in total pressure p_0* in the boundary layer along the free-stream direction at a fixed distance from the wall. Points at which the measured pressure p_0* reached the minimum and maximum value, respectively, were taken as the beginning and ending of transition. The pressure detector, mounted on the vertical support of the traversing gear which had a servo drive, could be displaced along the model surface in the free-stream direction. Two plane pressure detectors with the effective height 0.35 and 0.2 mm were used. The error in determining the location of the detector on the profile generator (x) and its perpendicular (y) is ±1 and ±0.1 mm, respectively.

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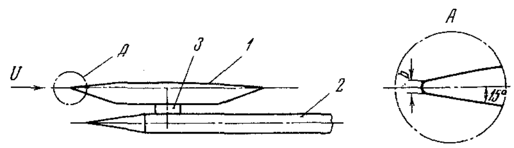

Fig. 1

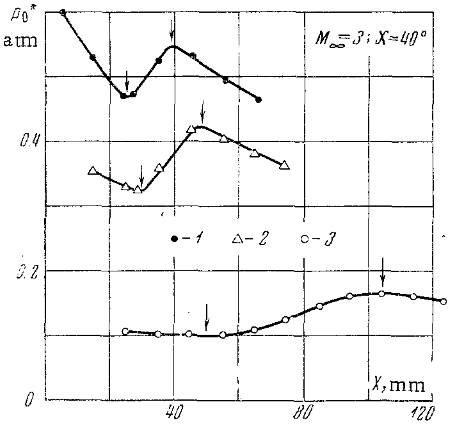

Fig. 2

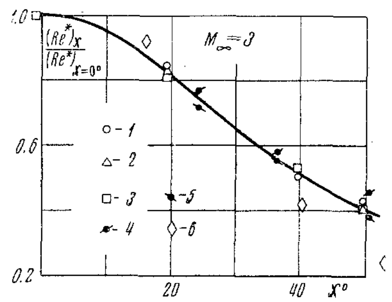

Fig. 3

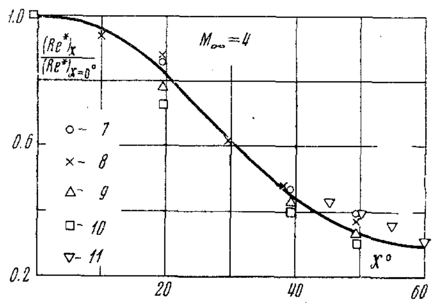

Fig. 4

The total pressures were measured at discrete locations of the detector at $\Delta x \approx 10$ mm intervals. A group recording manometer of class 0.5 with a 0.2 gauge atm. range of measurement was used to measure the pressure.

It should be noted that when $(U/\nu)_\infty \gtrsim 50 \cdot 10^6$ and $\chi \geq 40°$ the boundary-layer thickness at the end of the laminar section turned out to be commensurate with the height of the total pressure detector. Available data on this question show that an increase in the detector height up to the dimension of the boundary-layer thickness does not affect the Re number of the end of transition and increases the Re number of the beginning of transition somewhat. Hence, there is a foundation to assume that the results herein have been obtained with a sufficient degree of accuracy.

The information about the test modes are presented in the table.

Presented in Fig. 2 are typical experimental curves of the total pressure distribution in the boundary layer along the free-stream direction for $M_\infty = 3$, $\chi = 40°$ as a function of $p^*(x)$, where the points 1, 2, 3 refer to $(U/\nu)_\infty = 53.7 \cdot 10^6$, $42.6 \cdot 10^6$, and $20.4 \cdot 10^6$ m^{-1}, respectively. It is seen that the nature of the pressure distribution depends essentially on the unit number $(U/\nu)_\infty$, where the smooth form of the dependence p_0^* changes to a curve with a clearly expressed minimum or maximum as the unit number increases.

Shown in Figs. 3 and 4 is the influence of the sweep angle χ and the unit number $(U/\nu)_\infty$ on the normalized Reynolds number $(Re^*)_\chi/(Re^*)_{\chi=0}$ at $M_\infty = 3$ and 4, where the points 1, 2, 3 refer, respectively, to $(U/\nu)_\infty = 20.0 \cdot 10^6$, $40.0 \cdot 10^6$, $55.0 \cdot 10^6$ m^{-1}; 4 and 5 are borrowed from [6] for $(U/\nu)_\infty = 14.0 \cdot 10^6$ and $23.6 \cdot 10^6$ m^{-1}, respectively, and data of M. A. Alekseev were used for 6. Analogously, the points 7, 8, 9, 10 are the results of the present research for $(U/\nu)_\infty = 20.0 \cdot 10^6$, $30.0 \cdot 10^6$, $40.0 \cdot 10^6$, and $55.0 \cdot 10^6$ m^{-1}, respectively, while 11 was taken from data in [3] for $(U/\nu)_\infty = 63.6 \cdot 10^6$ m^{-1}.

The results of the present research are compared with data obtained in other wind tunnels. It is seen that the experimental values of $(Re^*)_\chi/(Re^*)_{\chi=0}$ are in satisfactory agreement and are described by a certain average curve, whose shape depends on the number M_∞. This affords a foundation for assuming that the change in the normalized Reynolds number as a function of the sweep angle is apparently independent of the unit Re number.

Dependences for the value $(U/\nu)_\infty = 20.0 \cdot 10^6$ m^{-1}, which characterizes the number Re* evaluated at the beginning 1 and ending 2 of the transition are represented in Fig. 5 and show that the point of transition shifts quite rapidly toward the wing leading edge as the sweep angle increases. The most intensive diminution in the length of the laminar section is observed in the χ = 20-40° range of angles. The transition region broadens as the number M_∞ increases from 3 to 4.

Presented in Fig. 6 are values of Re* calculated at the end of the transition, as a function of the tunnel unit number $(U/\nu)_\infty$ for different values of the sweep angle χ, where the points 1, 2, 3 are represented at the number $M_\infty = 3$ and correspond to the values χ = 0, 20, 40, 50° of the angle, and the points 5, 6, 7, 8

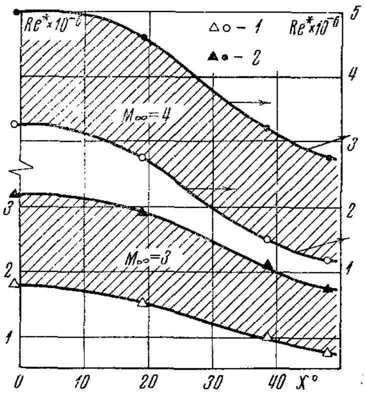

Fig. 5

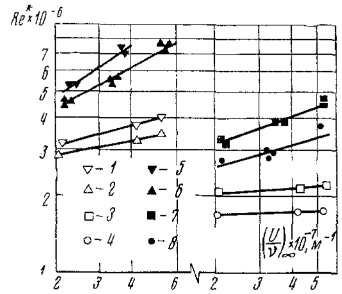

Fig. 6

refer to the same values of the angle χ, for the number $M_\infty = 4$. The systematic increase in the transition number Re* as the unit Reynolds number grows is seen. As the angle χ increases, the tendency for the number Re* to grow is reduced substantially, and in individual cases ($M_\infty = 3$, $\chi \geq 40°$) practically no influence of $(U/\nu)_\infty$ on the location of transition is detected. An increase in the number M_∞ from 3 to 4 causes a rapid growth in the number Re, as has been remarked earlier by Michel, Potter, and others.

Therefore, experimental investigations of the combined influence of the sweep angle and the unit Reynolds number on the location of boundary-layer transition on a swept wing in a broad range of numbers $(U/\nu)_\infty$ for $M_\infty = 3$ and 4 have shown that as the sweep angle increases the location of transition shifts rapidly toward the wing leading edge. The results obtained are in satisfactory agreement with the results of other authors. A continuous increase in the number Re* holds on straight wings as the unit number $(U/\nu)_\infty$ grows, just as on a flat plate. The tendency for the number Re* to grow is reduced substantially at large sweep angles $\chi \geq 40°$.

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