ENGINEERING TRANSACTIONS • Engng. Trans. • 46, 261–269, 1998
Polish Academy of Sciences • Institute of Fundamental Technological Research
10.24423/engtrans.643.1998

EXPERIMENTAL RESEARCH ON STABILITY AND TRANSITION IN HIGH-SPEED WAKES. PART 3. INFLUENCE OF THICKNESS OF A FLAT PLATE AND LENGTH OF ITS STERN ON STABILITY OF A SUPERSONIC WAKE

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1. Equipment and experimental technique

The experiments were carried out in the wind tunnel T-325 (Bagaev *et al.* [1]) at Mach number of free flow $M_\infty = 2$, unit Reynolds number $Re_{1\infty} = 5.7 \cdot 10^6$ m^{-1} and the flow stagnation temperature of about 290 K.

To measure the characteristics of stability and transition, we have used the constant-temperature hot-wire anemometer K-109 (in several experiments at $M_\infty = 4$ – hot-wire anemometer TPT-4) with tungsten probe and the wire of 6 microns in diameter and 1.2 mm length, a selective amplifier U2-8, a voltmeter V7-27A/1 and the analyzer of a spectrum of the company "Bruel and Kjaer" (type 2010) with recorder of the level (type 2307).

As the test models were used the insulated symmetric steel flat plates of length (from the leading edge to the beginning of a stern part) $l = 61$ mm, thickness of 10 and 3 mm and width of 200 mm, having the nose as a wedge with the bevel half-angle of 14° and 0.1 mm bluntness. The stern of plates had the shape of a reversed wedge, moreover if for the thin model (of thickness of 3 mm) the bevel half-angle was 14° (i.e. the same as for the nose), for the changeable stern part of the thicker plate (of thickness of 10 mm) the bevel half-angle was different – 7°, 14° and 90° (in the latter case the back surface of the model was flat, the plate was beveled at the right angle). The length of the stern part l_k (see the scheme in Fig. 1) had three different values – 40, 20 and 0 mm, and accordingly, the relation of the stern length to the plate thickness was $l_k/\Delta = 4$, 2 and 0. Both plates were fixed rigidly to the lateral walls of the test section of the wind tunnel and were placed at zero angle of attack.

2. Results

In Fig. 1 the dependences of root-mean-square fluctuations of voltage on the longitudinal coordinate are shown; they were obtained in the present experiments in the plane of symmetry of a wake, for two plates of different thickness (of 3 and 10 mm) at $l_k/\Delta = 2$. The voltage fluctuations were nondimensionalized by their maximum value, and longitudinal coordinate x was measured off from the beginning of the stern part. The curve 1 corresponds to $\Delta = 3$ mm ($l_k = 6$ mm), and the curve 2 – to $\Delta = 10$ mm ($l_k = 20$ mm). The vertical lines 3 and 4 mark the positions of the back edges of both models (of thickness of 3 and 10 mm respectively).

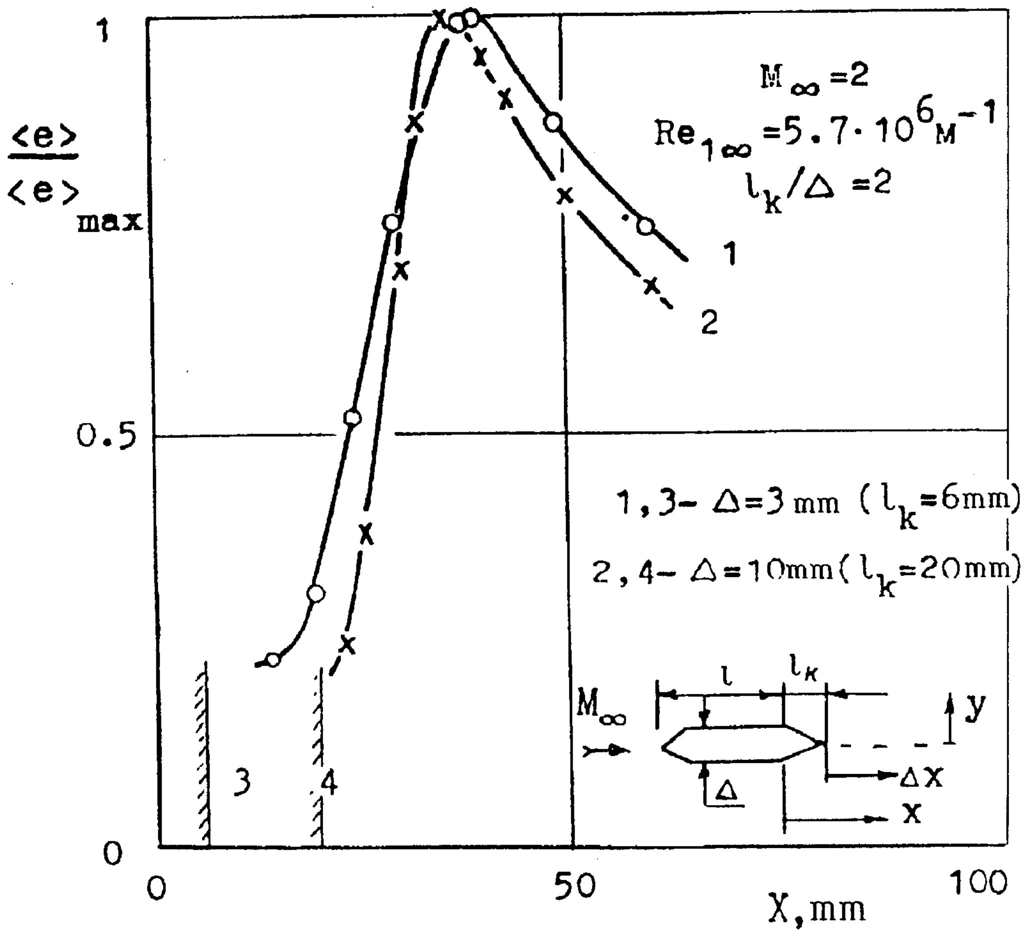

FIG. 1. Distribution of the fluctuations along the longitudinal coordinate at $M_\infty = 2$ and $l_k/\Delta = 2$ (1, 3 – $\Delta = 3$ mm, $l_k = 6$ mm; 2, 4 – $\Delta = 10$ mm, $l_k = 20$ mm).

Figure 1 shows that, with the growth of thickness of a plate, the disturbance amplification rates in a wake increase, what results in earlier transition. And if at using (in Fig. 1) the longitudinal coordinate x, this change in position of the transition is not significant, at using the longitudinal coordinate $\Delta x = x - l_k$ (measured from the model back edge), the destabilizing influence of the growth of the plate thickness becomes more clear.

In Fig. 2 are shown the nondimensional profiles of the voltage fluctuations $<\bar{e}>=<e>/<e>_\infty$ (normal coordinate y was measured from the symmetry plane of the wake) for both plates at $x = 24$ mm (curve 1 applies to $\Delta = 10$ mm and $\Delta x = 4$ mm, curve 2 – to $\Delta = 3$ mm and $\Delta x = 18$ mm). They correspond to the initial zone of development of disturbances, when the pulsations in the wake behind the thicker plate have not yet "overtaken" (with respect to intensity) the similar disturbances behind the thin model. In the figure the profile of fluctuations for $\Delta = 3$ mm and $x = 36$ mm (curve 3) is also presented.

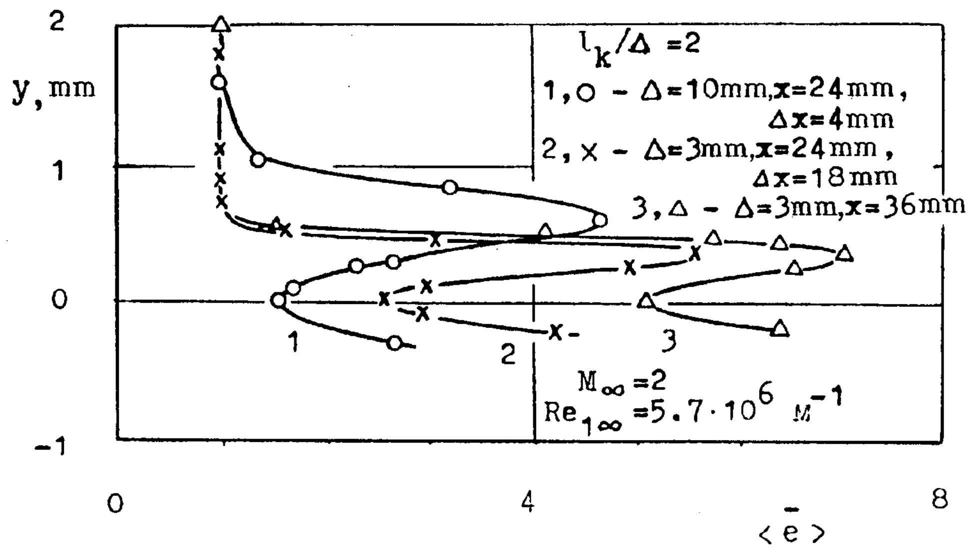

FIG. 2. Profiles of fluctuations at $M_\infty = 2$ and $l_k/\Delta = 2$ and $l_k/\Delta = 2$ (1, ○ – $\Delta = 10$ mm, $x = 24$ mm, $\Delta x = 4$ mm; 2,× – $\Delta = 3$ mm, $x = 24$ mm, $\Delta x = 18$ mm; 3, Δ – $\Delta = 3$ mm, $x = 36$ mm).

In Fig. 3 the spectra of energy of fluctuations are shown in the wire of hot-wire-anemometer probe (the distributions of amplitude of disturbances e_f on frequency f) in both wakes at $\Delta x = 7$ mm (there the curve 1 corresponds to $\Delta = 3$ mm and $x = 13$ mm, the dependence 2 – to $\Delta = 10$ mm and $x = 27$ mm), i.e. at equal distances from the back edges of models. The measurements were performed in a layer with maximum (across the wake) values of $<e>$. One can see, that the disturbances behind the thicker plate develop more intensively than the oscillations behind the thin one. But besides, Fig. 3 shows that in both spectral distributions of fluctuations in the wakes, the distinct peak (at frequencies of 48 and 133 kHz according to the plates of thickness of 10 and 3 mm) is available. Strouhal number, based on the frequency of such maximum f_0, the wake thickness near the wake throat (determined from the speed profile) and the speed of undisturbed flow, is equal to 0.3.

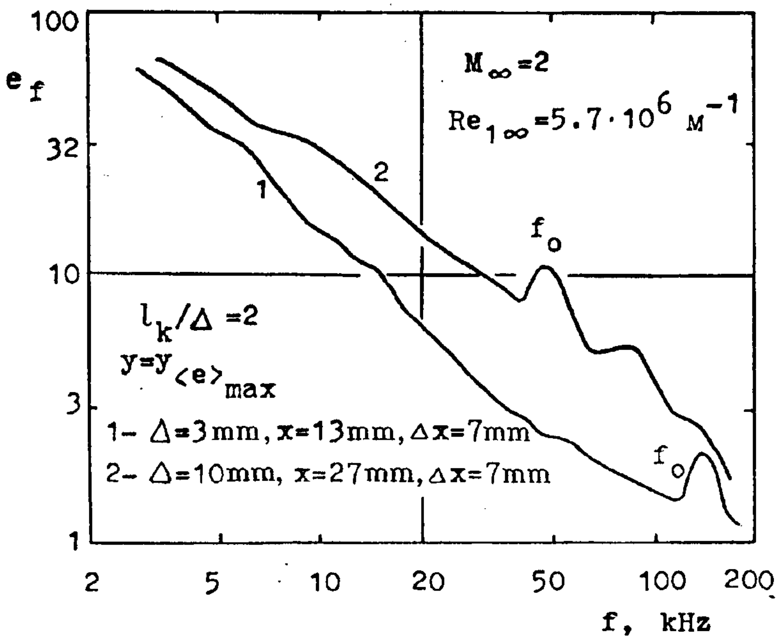

FIG. 3. The energy spectra at $M_\infty = 2$, $l_k/\Delta = 2$ and $y = y_{<e>max}$ (1 – $\Delta = 3$ mm, $x = 13$ mm, $\Delta x = 7$ mm; 2 – $\Delta = 10$ mm, $x = 27$ mm, $\Delta x = 7$ mm).

The conclusions drawn on the grounds of Figs. 1 and 3 concerning the increase of disturbance amplification rates in a wake following the growth of the thickness of a plate, corresponds to the results of the research by BEHRENS [2] in the wakes of cylinders at $M_\infty = 6$. And in the paper by BEHRENS *et al.* [3] dealing with the study of the wakes of wedges at $M_\infty = 4.5$, increasing the model thickness resulted in earlier transition, similarly to the present experiments.

Then the series of experiments were made, devoted to the research on influence of the length of the stern part (as a opposite wedge) of a plate on the stability and transition in a wake. The model of 10 mm thickness with changeable stern part was used. The length of the stern l_k had three values – 40, 20 and 0 mm (accordingly $l_k/\Delta = 4$, 2 and 0).

In Fig. 4 are shown the dependences of voltage root-mean-square pulsations in the plane of symmetry of the wake, nondimensionalized by their maximum values, on the longitudinal coordinate x. Curve 1 corresponds to $l_k = 0$ (in this case there is a large recirculation zone behind the model), curve 2 – to $l_k/\Delta = 2$, the dependence 3 – to $l_k/\Delta = 4$. Vertical lines 4 and 5 mark the positions of the back edges of the models with $l_k = 20$ and 40 mm respectively.

The curve $< e > / < e >_{\max} = f(x)$ for $l_k = 0$ (at the large recirculation zone of length of about 15 mm), corresponds approximately to a similar curve for the model with the stern in the form of a reversed wedge and $l_k \approx 15$ mm (the dotted vertical line 6 on the diagram corresponds to $l_k = 15$ mm). Therefore for comparison of the dependences 1–3 (on the left-hand part of the figure) in other coordinates ($< e > / < e >_{\max}$ and Δx; such dependences are located on the right) we have assumed $\Delta x = x - 15$ mm for the curve 1.

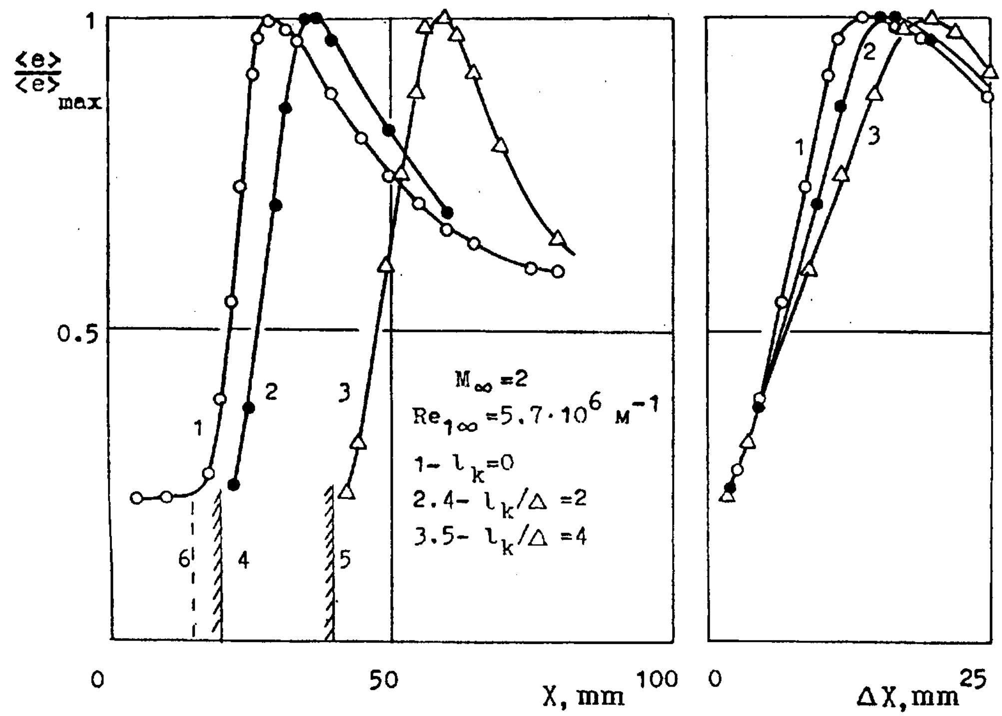

FIG. 4. Distribution of the fluctuations along the longitudinal coordinates x and Δx at $M_\infty = 2$ ($1 - l_k = 0$; $2, 4 - l_k/\Delta = 2$; $3, 5 - l_k/\Delta = 4$).

Figure 4 shows, that the wake-transition position moves back with the increase of the stern-part length. In general, it is connected with removing of the wake throat and accordingly, the coordinate of the beginning of the intensive increase of disturbances. But comparison of intensities of growth of fluctuations depending on coordinate Δx for all three cases shows, that the wake stability slightly increases (the disturbance amplification rates decrease only a little). As the length of the plate stern increases, the "gradient" of flow in the model wake decreases, and the flow (above the model stern part and directly in the wake) slowly becomes similar to the flow above the flat plate. To the point, the transition in the boundary layer on the long flat plate at the present parameters of free flow begins at the value of longitudinal coordinate, measured from the leading edge, not less than 160 mm.

In Fig. 5 the nondimensional profiles of fluctuations are given for three cases: 1 – $l_k = 0$, $x = 24$ mm; 2 – $l_k/\Delta = 2$, $x = 24$ mm, $\Delta x = 4$ mm; 3 – $l_k/\Delta = 4$, $x = 44$ mm, $\Delta x = 4$ mm. That is, it is possible to compare in pairs the curves 1–2 ($x = 24$ mm) and 2–3 ($\Delta x = 4$ mm). The comparison of curves 2 and 3 shows some delay in development of disturbances in a wake with increasing length of the stern part.

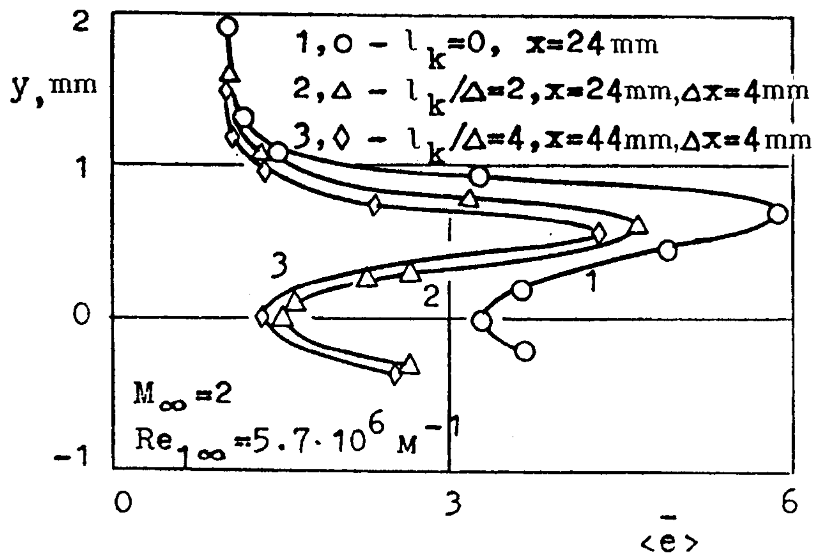

FIG. 5. Profiles of fluctuations at $M_\infty = 2$ (1, ○ – $l_k = 0$, $x = 24$ mm; 2, Δ – $l_k/\Delta = 2$, $x = 24$ mm, $\Delta x = 4$ mm; 3, ◇ – $l_k/\Delta = 4$, $x = 44$ mm, $\Delta x = 4$ mm).

And in Fig. 6 the spectra of energy of fluctuations in the plane of symmetry of the wake ($y = 0$, Fig. 6a) and in the layer, close to the critical layer with maximum (across the wake) values of $< e >$ (Fig. 6b), are given. In Fig. 6a the curve 1 corresponds to $l_k = 0$, $x = 27$ mm, and the curve 2 – to $l_k/\Delta = 2$, $x = 27$ mm, $\Delta x = 7$ mm. In Fig. 6b the curve 1 corresponds to $l_k = 0$, $x = 24$ mm; 2 – $l_k/\Delta = 2$, $x = 24$ mm, $\Delta x = 4$ mm; 3 – $l_k/\Delta = 4$, $x = 44$ mm, $\Delta x = 4$ mm; 4 – $l_k = 0$, $x = 27$ mm; 5 – $l_k/\Delta = 2$, $x = 27$ mm, $\Delta x = 7$ mm. The comparison of the curves 2 and 3 ($\Delta x = 4$ mm) in Fig. 6b shows the increase of disturbances in a wake with decreasing stern length.

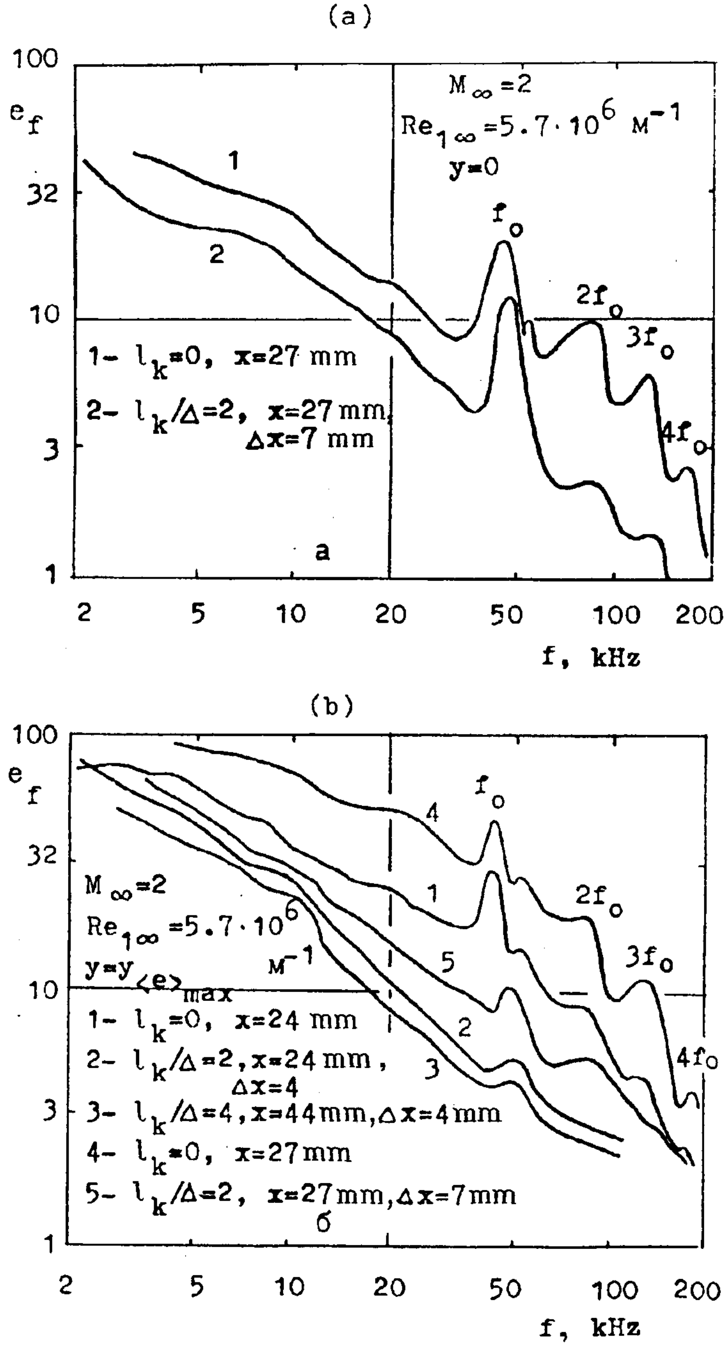

FIG. 6. The energy spectra at $M_\infty = 2$: (a) for $y = 0$ ($1 - l_k = 0$, $x = 27$ mm; $2 - l_k/\Delta = 2$, $x = 27$ mm, $\Delta x = 7$ mm); (b) for $y = y_{<e>\max}$ ($1 - l_k = 0$, $x = 24$ mm; $2 - l_k/\Delta = 2$, $x = 24$ mm, $\Delta x = 4$ mm; $3 - l_k/\Delta = 4$, $x = 44$ mm, $\Delta x = 4$ mm; $4 - l_k = 0$, $x = 27$ mm; $5 - l_k/\Delta = 2$, $x = 27$ mm, $\Delta x = 7$ mm).

However Fig. 6 is also interesting for another reason. In the nonlinear stage of the wake-fluctuations development, we can observe the growth of disturbances with frequencies $2f_0$, $3f_0$, $4f_0$, being multiples of the basic tone frequency f_0.

3. Conclusions

Thus, at the Mach number $M_\infty = 2$ we have experimentally investigated the development of disturbances in the wakes behind the flat plates (with the symmetric wedge-shaped nose and stern) of different thickness and with different lengths of the stern part.

It has been found that with growing model thickness, the disturbance amplification rates in a wake increase, what results in earlier transition from laminar wake to the turbulent one. It was also found that, as the length of the stern part of a plate increases, the position of the wake transition moves back and, in addition, the wake stability slightly increases (though not significantly). A distinct maximum (basic tone) was detected in the spectral distribution of fluctuations in the laminar part of a wake, and the value of the Strouhal number (based on the frequency of this maximum) of 0.3 is universal for plates of different thickness.

General Conclusions

1. The condition (laminar, transitional or turbulent) of the boundary layer at the end of a model exerts the influence (by means of the change of profiles of speed and other parameters, and also at the expense of change of the level of disturbances) on the position of the transition in a wake, though the processes of turbulence can occur simultaneously both in the boundary layer, and in the wake (due to the corresponding instabilities).

2. Compressibillity of flow (increasing Mach number) stabilizes the wake disturbances – their amplification rates decrease, and the transition moves away from the model.

3. Cooling of a model surface at $M_\infty \sim 7$ produces a destabilizing influence on the development of disturbances in a wake.

4. With increasing unit Reynolds number, the beginning of transition in a wake moves forward to a critical back point.

5. At Mach numbers $M_\infty = 2$ and 4, the development of disturbances in the free viscous layer and in the wake behind the flat plate with symmetric wedge-shaped nose (with the sharp leading edge) and blunt (beveled at the right angle) stern was investigated. The development of wake disturbances was traced both

in the linear and nonlinear stages of development. The characteristics of stability of flow in the free viscous layer and wake have been obtained.

6. It was confirmed that in the spectral distribution of fluctuations, there appears a distinct maximum, corresponding to the Strouhal number of 0.3 (based on the frequency of this maximum).

7. With the growth of a model thickness, the disturbance amplification rates in a wake increase, what results in earlier transition from a laminar wake into the turbulent one.

8. With the growth of length of the plate stern, the position of the wake transition moves back accordingly, while the wake stability increases a little (though very unsignificantly).

9. In the nonlinear stage of development of disturbances, the occurrence of the triad of waves, satisfying to the resonant correlation of frequencies, and the growth of harmonics are observed.

Acknowledgement

The author thanks A.D. Kosinov and N.V. Semionov for their assistance.

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Reveived June 2, 1997; new version May 18, 1998.