ENGINEERING TRANSACTIONS • *Engng. Trans.* • **46**, 3–4, 251–260, 1998
Polish Academy of Sciences • Institute of Fundamental Technological Research
10.24423/engtrans.642.1998

EXPERIMENTAL RESEARCH ON STABILITY AND TRANSITION IN HIGH-SPEED WAKES.

PART 2. INFLUENCE OF PARAMETERS OF SUPERSONIC FREE FLOW ON DEVELOPMENT OF DISTURBANCES IN A WAKE

V. I. LYSENKO (NOVOSIBIRSK)

1. EQUIPMENT AND EXPERIMENTAL TECHNIQUE

The present experiments were performed in the wind tunnel T-325 (BAGAEV *et al.* [1]) at free-flow Mach numbers $M_\infty = 2$ and 4 and unit Reynolds numbers $Re_{1\infty} = (5.7; 9 \text{ and } 15) \cdot 10^6\ m^{-1}$. The flow stagnation temperature was about 290 K.

To measure the characteristics of stability and transition, the constant-temperature hot-wire anemometer K-109 (in several experiments at $M_\infty = 4$ – the hot-wire anemometer TPT-4) with tungsten probe was used, with the wire of 6 microns in diameter and 1.2 mm length, selective amplifier U2-8, 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).

Insulated symmetric flat steel plate of 61 mm length, 10 mm thickness and 200 mm width was used as a test model, having the nose in the form of a wedge, with the bevel half-angle of 14° and the leading-edge bluntness of 0.1 mm. The stern of the plate was blunt, of rectangular form. The model was fixed rigidly to the lateral walls of the test section of the wind tunnel and was placed at zero angle of attack.

2. RESULTS

In Fig. 1 are shown the dependences of root-mean-square fluctuations of voltage in the wire of the hot-wire-anemometer probe on the longitudinal coordinate in the plane of symmetry of the wake for $M_\infty = 2$ and 4 at $Re_{1\infty} = 9 \cdot 10^6\ m^{-1}$ (the voltage fluctuations were normalized by their maximum values). It is seen that, with decreasing Mach number from 4 to 2, the transition considerably approaches the model.

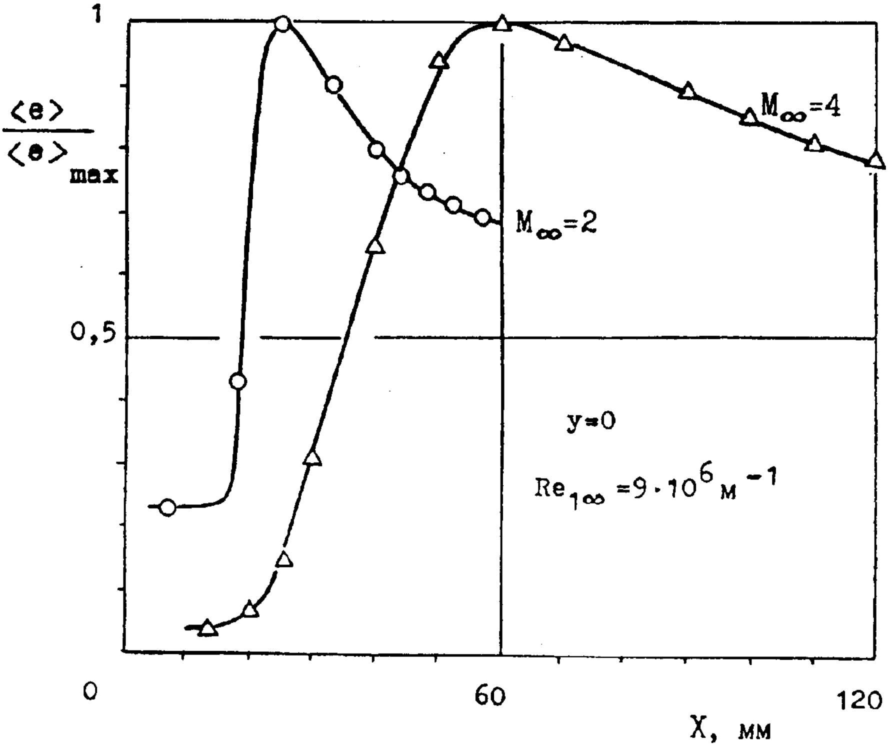

FIG. 1. Distribution of the hot-wire fluctuations along longitudinal coordinate at $y = 0$ for $M_\infty = 2$ and 4.

In Fig. 2 the disturbance amplification rates in the wake $-\hat{\alpha}_i = (de_f/e_f) \cdot b/2dx$ (b is the wake thickness) depending on frequency f for $M_\infty = 2$ and 4 are shown. The measurements were carried out in the layer with maximum (across the wake) values of $< e >$ (this layer is close to the critical one). In Fig. 2 it is seen that, with decreasing Mach number from 4 to 2, the disturbance amplification rates increased considerably.

The growth of longitudinal coordinate of transition x_t with M_∞ increasing from 2 up to 4 in that part of the work corresponds to the growth of x_t with M_∞ increasing from 4 up to 5 and from 5 up to 7, obtained by the author in the hotshot tunnel "Transit" (see Part 1) in the wake behind the model, similar to that used in the first part of the work (in "Transit" with M_∞ changing from 4 up to 7 for $\mathrm{Re}_{1\infty} \approx 60 \cdot 10^6$ m^{-1}, the longitudinal coordinate of transition increased by 100%, approximately).

Thus, the experiments set up at $M_\infty = 2, 4, 5$ and 7, have shown the stabilizing influence of the growth of the Mach number on the development of disturbances in a wake. With increasing Mach number (from 2 up to 4), the disturbance amplification rates decrease essentially. This conclusion does not contradict the results of a number of theoretical researches of stability of mixing layers (JACKSON and GROSCH [2 – 6]; KUDRYAVTSEV and SOLOVYOV [7, 8]; RAGAB and WU [9]; ZHUANG *et al.* [10]; KIM [11]; MACARAEG and STREETT [12]), in which it was shown that at fixed $\overline{T}_w$, the increase of M increases the stability of flow in a shear layer with respect to subsonic disturbances. This conclusion corresponds to the theoretical works on the stability of wakes (LEES [13]; LEES and GOLD [14]; GERTSENSTEIN and KOSHKO [15]; CHEN *et al.* [16]), in which it was found that, with the growth of the Mach number, the disturbance amplification rates decrease.

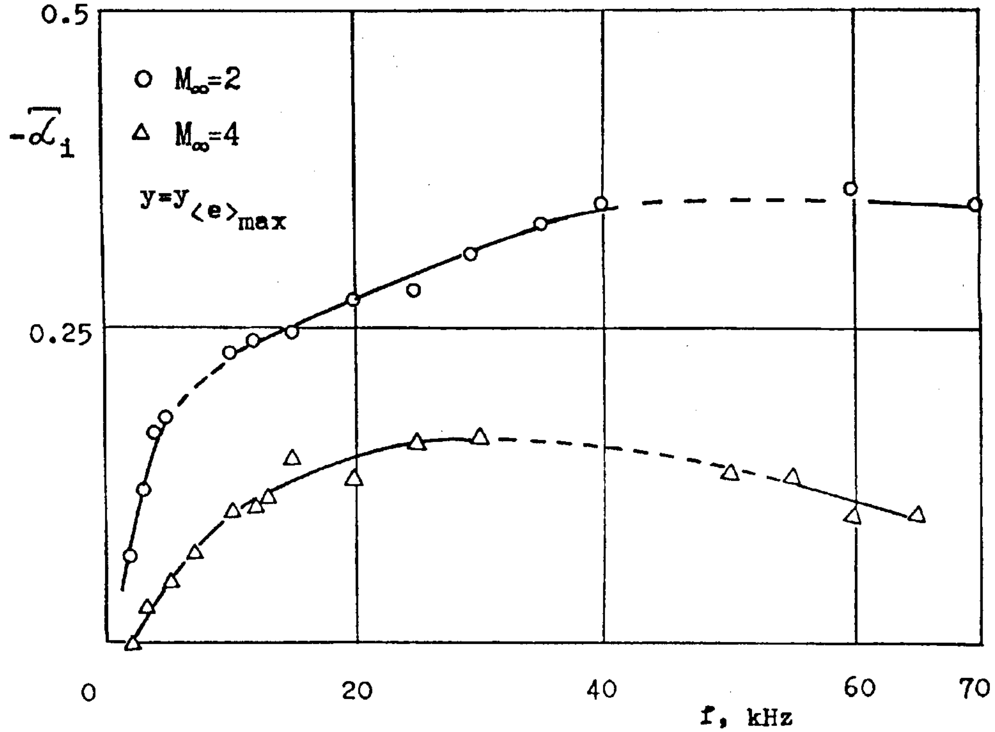

FIG. 2. The disturbance amplification rates as a function of frequency at $y = y_{<e>\max}$ for $M_\infty = 2$ (○) and 4 (△).

The influence of the unit Reynolds number on the development of disturbances in a wake was also investigated. The experiments were performed in the plane of symmetry of the wake at $M_\infty = 2$ and $Re_{1\infty} = (5, 7; 9 \text{ and } 15) \cdot 10^6 \text{ m}^{-1}$ curves 1–3 in Fig. 3, where the results of researches are presented. In Fig. 3 all voltage fluctuations are nondimensionalized by their initial values near the border of a recirculation zone. Stabilization of disturbances (reduction of amplification rates) and the withdrawal of transition in the wake at decreasing $Re_{1\infty}$ are shown. It corresponds to the results of the paper by McLughlin [17], in which with the help of a hot-wire anemometer, a significant reduction of the level of disturbances was found in a wake at decreasing $\mathrm{Re}_{1\infty}$.

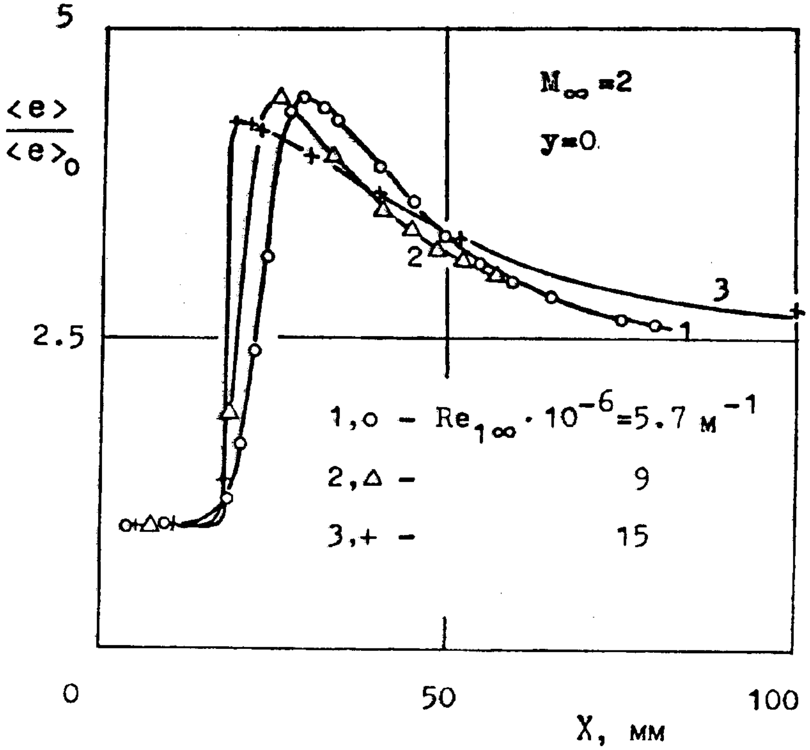

FIG. 3. Distribution of the hot-wire fluctuations along streamwise coordinate at $M_\infty = 2$ and $y = 0$ for different unit Reynolds numbers ($1, \bigcirc - 5.7 \cdot 10^6$ m^{-1}; $2, \Delta - 9 \cdot 10^6$ m^{-1}; $3, +, -15 \cdot 10^6$ m^{-1}).

The development of disturbances in the wake at $M_\infty = 2$ and $\mathrm{Re}_{1\infty} = 5.7 \cdot 10^6$ m^{-1} is illustrated by Fig. 4, where the nondimensional profiles of fluctuations $< \bar{e} > = < e > / < e >_\infty$ (normal coordinate y is measured from the plane of symmetry of the wake) for $x = 20, 27$ (shortly before transition), 44 and 60 mm (lines 1-4) are shown. The measurements were performed at the rather large wire overheating of 0.7, when the hot-wire anemometer registered actually the fluctuations of the mass flow. It is seen that in the laminar wake with increasing x the growth of disturbances takes place; in addition, the wake thickness remains almost the same. However, after the wake turbulization the appreciable flattering of the profile of disturbances occurs at the expense of reduction of maximum in-the-wake fluctuations. In addition, the thickness of the most disturbed part of the wake and the normal coordinate of the layer with the maximum disturbances increase more intensively, what corresponds to the statement of BEHRENS [18] and DEMETRIADES [19] that the appreciable expansion of a wake is the attribute of the transition. The development of the wake disturbances at $M_\infty = 2$, shown in Fig. 4, is completely similar to the obtained results of the earlier research made at $M_\infty = 4$.

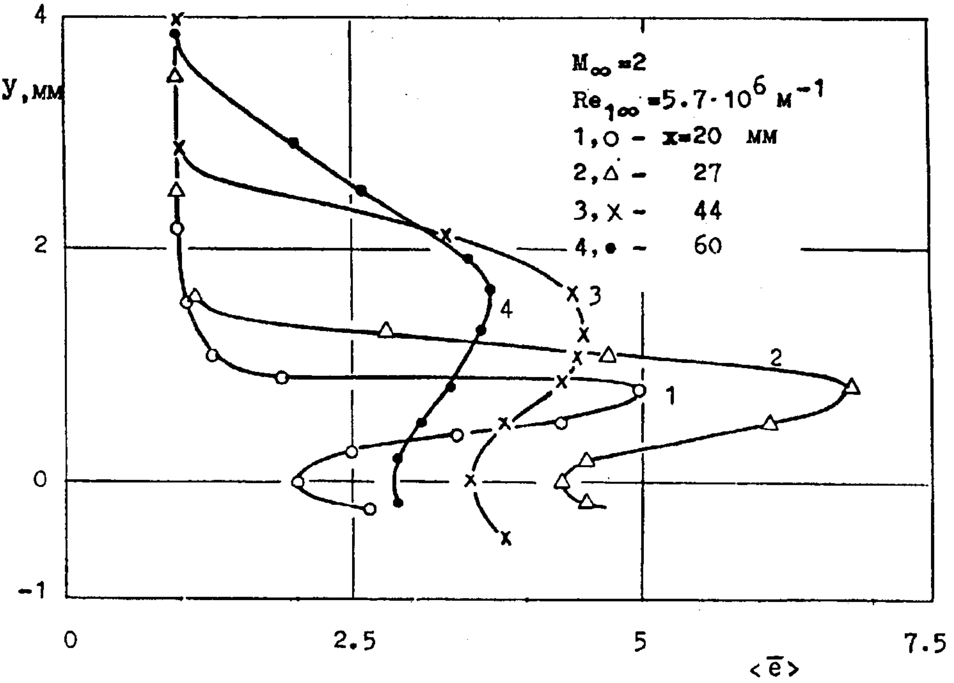

FIG. 4. Nondimensional profiles of fluctuations for $M_\infty = 2$ at different longitudinal coordinates (1, ○ – $x = 20$ mm; 2, Δ – 27 mm; 3, × – 44 mm; 4, • – 60 mm).

In Figs. 5 and 6, the spectra of energy of pulsations in the wire of probe of the hot-wire anemometer (the distribution of amplitude of disturbances e_f for different frequencies f) in the layer with maximum (across the wake) values of $< e >$ (layer close to the critical one), respectively at $M_\infty = 2$, $\mathrm{Re}_{1\infty} = 5.7 \cdot 10^6$ m^{-1} and $M_\infty = 4$, $\mathrm{Re}_{1\infty} = 9 \cdot 10^6$ m^{-1} for different values of longitudinal coordinate are shown. In Fig. 5 the spectra 1 and 2 for $x = 12$ and 14 mm (both in the free viscous layer) are plotted; 3 – 6 – for $x = 22$, 24, 27 and 30 mm (the spectrum 6 was obtained in the transitional zone); and in Fig. 6, the spectra 1 – 3 – for $x = 40$, 45 and 60 mm (spectrum 3 was obtained in the zone of transition).

Similar spectra of energy of fluctuations, but for $y = 0$ (in the plane of symmetry of the wake), are presented in Fig. 7 ($M_\infty = 2$, here the curves 1 – 4 correspond to $x = 22$, 24, 27 and 30 mm) and in Fig. 8 ($M_\infty = 4$, the curves 1 – 4 correspond to $x = 40$, 45, 50 and 60 mm).

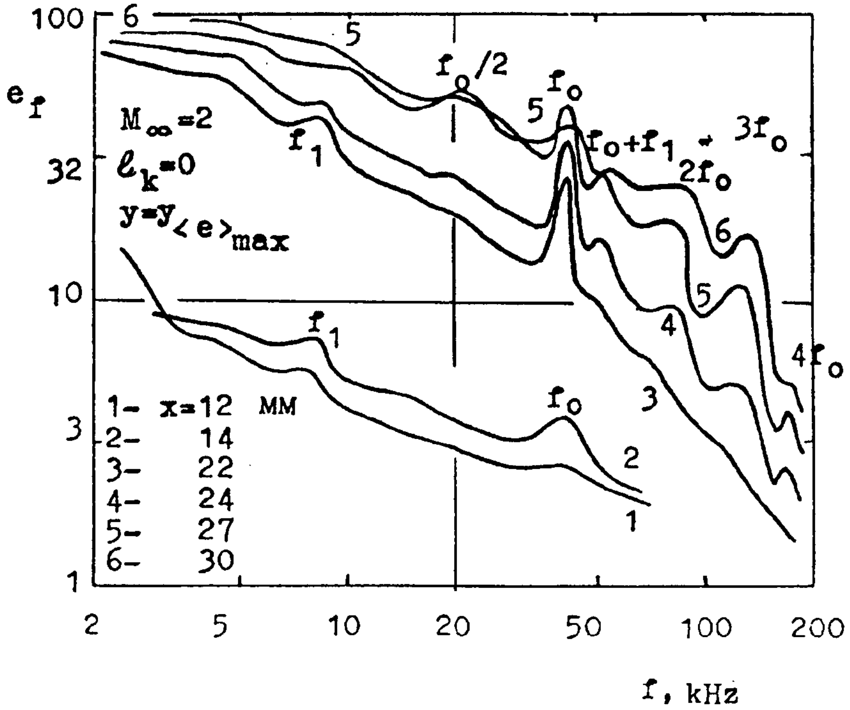

FIG. 5. The energy spectra at $M_\infty = 2$, $l_k = 0$ and $y = y_{<e>\max}$($1 - x = 12$ mm, 2 – 14, 3 – 22, 4 – 24, 5 – 27, 6 – 30).

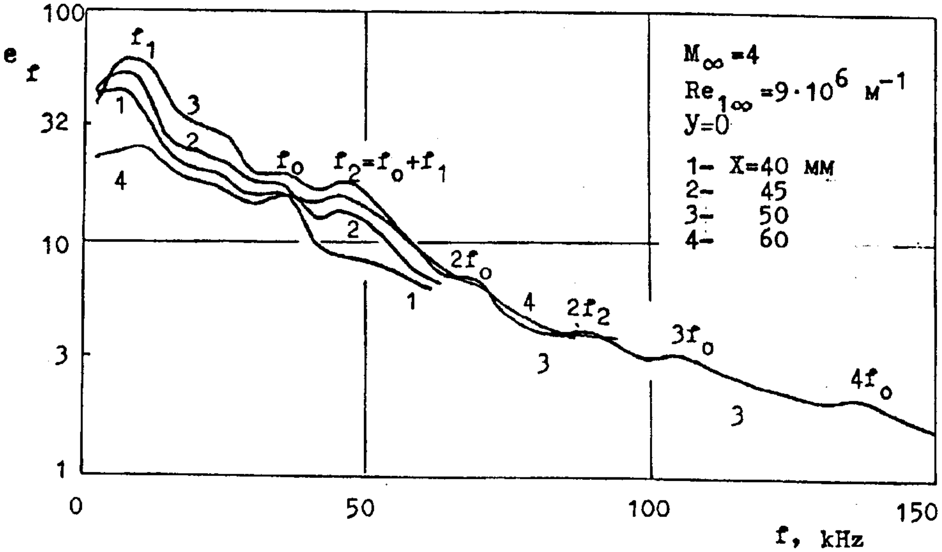

FIG. 6. The energy spectra at $M_\infty = 4$ and $y = 0$ ($1 - x = 40$ mm, 2 – 45, 3 – 50, 4 – 60).

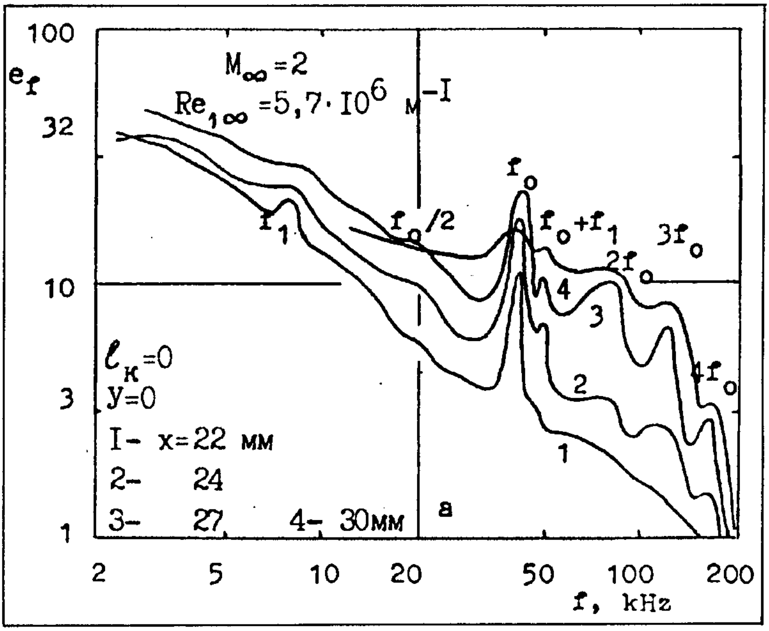

FIG. 7. The energy spectra at $M_\infty = 2$, $Re_{1\infty} = 5.7\cdot 10^6$ m^{-1}, $l_k = 0$ and $y = 0$ ($1 - x = 22$ mm, $2 - 24$, $3 - 27$, $4 - 30$).

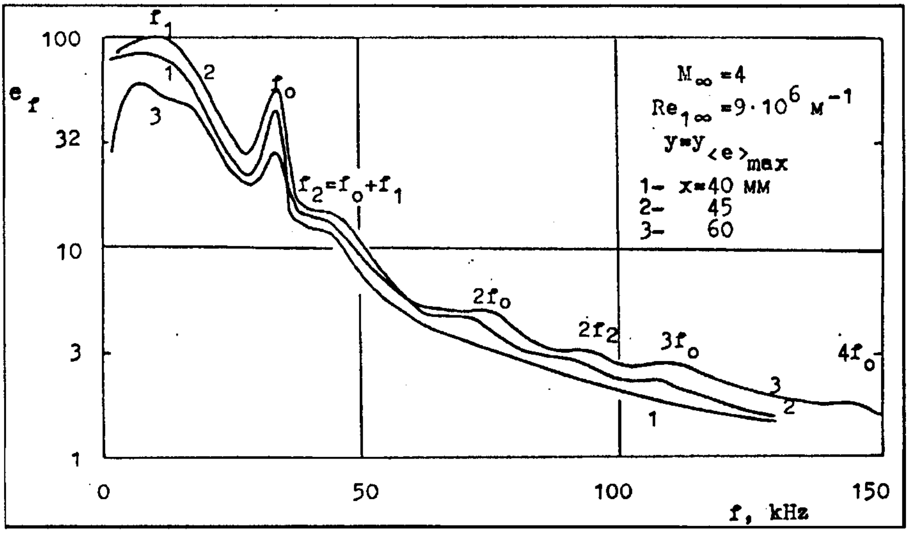

FIG. 8. The energy spectra at $M_\infty = 4$, $Re_{1\infty} = 9\cdot 10^6$ m^{-1} and $y = y_{<e>\max}$ ($1 - x = 40$ mm, $2 - 45$, $3 - 60$).

For $M_\infty = 2$ and 4, the common objective laws were found. In the final part of a free viscous layer (directly before its transition into a wake) and in the linear stage of development of a wake (regular wake), appears a distinct maximum in the spectral distribution of fluctuations – the disturbances with frequency $f_0 = 43$ kHz for $M_\infty = 2$ and 35 kHz for $M_\infty = 4$ begin to grow essentially. The Strouhal number, based on frequency of this maximum, thickness of the wake near the throat and speed of the undisturbed flow, are equal to $S = f_0 b_0 / u_\infty = 0.3$, respectively.

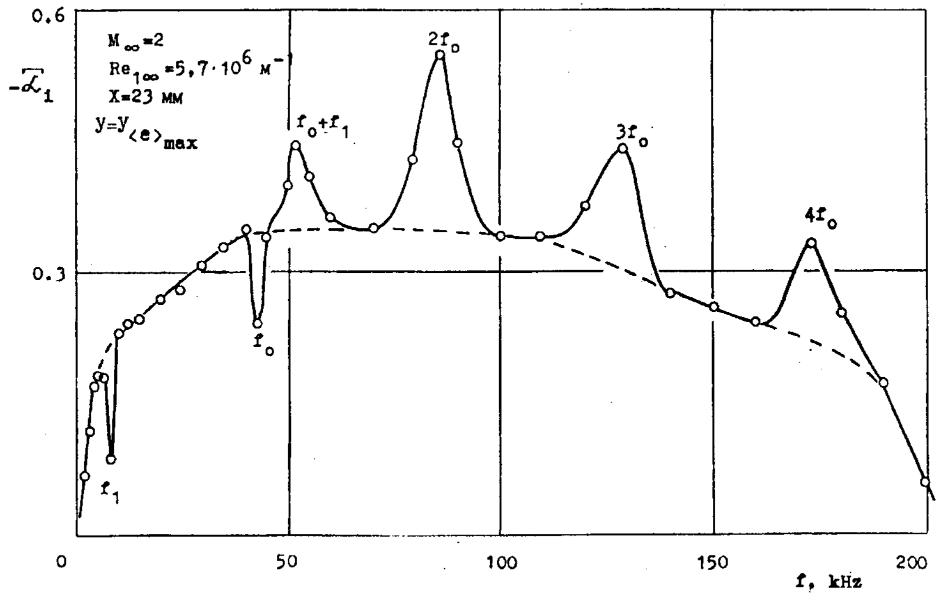

FIG. 9. The wake disturbance amplification rates as a function of frequency at $M_\infty = 2$, $Re_{1\infty} = 5.7 \cdot 10^6$ m^{-1}, $x = 23$ mm and $y = y_{<e>\max}$.

In the nonlinear stage of development of disturbances in the wake (at 22 mm $< x <$ 29 mm for $M_\infty = 2$ and at 40 mm $< x <$ 56 mm for $M_\infty = 4$), the basic tone with frequency f_0 still dominates in the spectrum of energy of fluctuations (down to the beginning of the transition, when the disturbances with frequency f_0 decrease, and the spectrum becomes more flat); however, the nonlinear interaction of different fluctuations begins. In particular, the disturbances with frequency $f_0 + f_1$ (f_1 – frequency of the second maximum in the spectrum of energy of fluctuations in the linear stage) begin to grow essentially. Most likely, these two maxima are in mutual resonance, and the triplet of waves (the third wave with frequency $f_0 + f_1$) arises. Besides, the appreciable growth of harmonics with frequencies $2f_0$, $3f_0$, $4f_0$ begins. All this occurs against a background of appreciable moderation of growth of the disturbances with f_0 and f_1, that allows the author to make the assumption that there is the transfer of energy from the basic tone with f_0 and disturbance with f_1 (or only from the basic tone) to the disturbance with frequency $f_0 + f_1$, and from the basic tone – yet to the harmonics with frequencies $2f_0$, $3f_0$, $4f_0$. Figs. 9 – 10 (the dependences of the disturbance amplification rates on the frequency accordingly for: $\mathrm{M}_\infty = 2$, $y = y_{<e>\max}$; $\mathrm{M}_\infty = 4$, $y = y_{<e>\max}$) confirm this assumption.

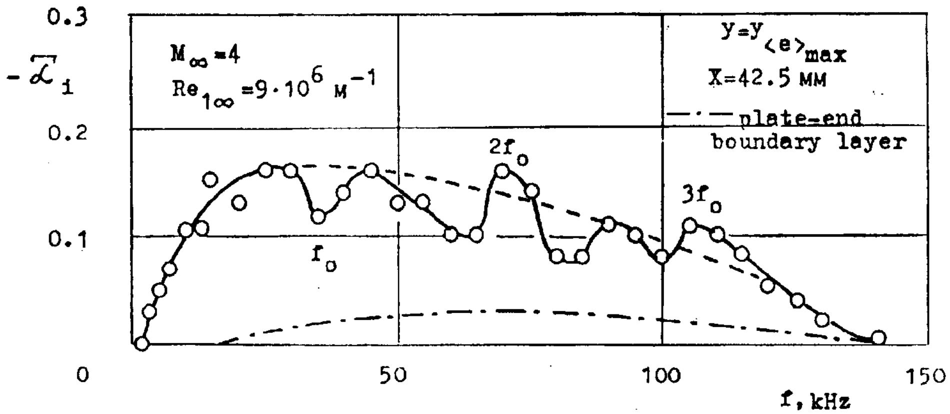

FIG. 10. The disturbance amplification rates as a function of frequency in the wake and in the plate-end boundary layer (— · —) at $\mathrm{M}_\infty = 4$, $\mathrm{Re}_{1\infty} = 9 \cdot 10^6$ m^{-1} and $y = y_{<e>\max}$.

3. CONCLUSIONS

Thus, at $\mathrm{M}_\infty = 2$ and 4, the experimental research of development of disturbances in the wake behind the flat plate with symmetric wedge-shaped nose with sharp leading edge and blunt (beveled at the right angle) stern were carried out. These experiments (and also the research on determination of the transition position at $\mathrm{M}_\infty = 4$, 5 and 7 in Part I) have shown the stabilizing influence of the growth of Mach number – the disturbance amplification rates decrease, and the transition in a wake moves away from the model. A wake is also stabilized with decreasing unit Reynolds number. In the nonlinear stage of development of disturbances in a wake, the growth of harmonics was established.

REFERENCES

1. G.I. BAGAEV, V.A. LEBIGA, V.G. PRIDANOV, V.V. CHERNYH, *A supersonic wind tunnel T-325 with low-degree turbulence* [in Russian], [in:] Aerodynamic Researches, 11–13, Novosibirsk 1972.

2. T.L. Jackson, C.E. Grosch, *Inviscid spatial stability of a compressible mixing layer*, NASA-CR-181671, ICASE Rep. no.2, 1988.
3. T.L. Jackson, C.E. Grosch, *Inviscid spatial stability of a compressible mixing layer*, J. Fluid Mech., **208**, 609–637, 1989.
4. T.L. Jackson, C.E. Grosch, *Absolute/convective instabilities and the convective Mach number in a compressible mixing layer*, Phys.Fluids A, **2**, 6, 949–954, 1990.
5. T.L. Jackson, C.E. Grosch, *Inviscid spatial stability of a compressible mixing layer. Part 2. The flame sheet model*, J. Fluid Mech., **217**, 391–420, 1990.
6. T.L. Jackson, C.E. Grosch, *Inviscid spatial stability of a compressible mixing layer. Part 3. Effect of thermodynamics*, J. Fluid Mech., **224**, 159–175, 1991.
7. A.N. Kudryavtsev, A.S. Solovyov, *Stability of a shear layer of compressible gas* [in Russian], Zh. Prikl. Mekh. Tekh. Fiz., 6, 119–127, 1989.
8. A.N. Kudryavtsev, A.S. Solovyov, *Stability of a viscous compressible shear layer with temperature leap* [in Russian], Zh. Prikl.Mekh. Tekh. Fiz., 4, 88–95, 1991.
9. S.A. Ragab, J.L. Wu, *Linear instabilities in two-dimensional compressible mixing layers*, Phys. Fluids A, 1, 957–966, 1989.
10. M. Zhuang, T. Kubota, P.E. Dimotakis, *Instability of inviscid, compessible free shear layers*, AIAA J., **28**, 10, 1728–1733, 1990.
11. S. Kim, *A new mixing length model for supersonic shear layers*, AIAA Pap., 18, 6p., 1990.
12. M.G. Macaraeg, C.L. Streett, *New instability modes for bounded, free shear flows*, Phys. Fluids A, **1**, 8, 1305–1307, 1989.
13. L. Lees, *Hypersonic wakes and trails*, AIAA J., **2**, 3, 417–428, 1964.
14. L. Lees, H. Gold, *Stability of laminar boundary layers and wakes at hypersonic speeds. Part 1. Stability of laminar wakes*, [in:] Fund. Phenom. in Hypersonic Flow, 4, 310–337, Cornell Univ. Press, Buffalo, N.Y. 1964.
15. S. Ya, Gertsenstein, A.V. Koshko, *Stability of axis-symmetrical compressible inviscid wake* [in Russian], [in:] Aerodynamics of large speeds, 142–150, Institute of the Mechanics of Moscow Univ., Moscow 1972.
16. J.H. Chen, B.J. Cantwell, N.N. Mansour, *The effect of Mach number on the stability of a plane supersonic wake*, Phys. Fluids A, **2**, 6, 984–1004, 1990.
17. D.K. McLaughlin, *Experimental investigation of the stability of the laminar supersonic cone wake*, AIAA J., **9**, 4, 696–702, 1971.
18. W. Behrens, *Far wake behind cylinders at hypersonic speeds: II. Stability*, AIAA J., **6**, 2, 225–232, 1968.
19. A. Demetriades, *Hot-wire measurements in the hypersonic wakes of slender bodies*, AIAA J., **2**, 2, 245–250, 1964.

RUSSIAN ACADEMY OF SCIENCES
INSTITUTE OF THEORETICAL AND APPLIED MECHANICS
Novosibirsk 630090, Russia;

e-mail: gaponov@itam.nsc.ru

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