Journal of Applied Mechanics and Technical Physics, Vol. 37, No. 4, 1996

AN EXPERIMENTAL INVESTIGATION OF THE STABILITY OF A WAKE BEHIND A FLAT PLATE FOR VARIOUS PARAMETERS OF THE SUPERSONIC FREE STREAM

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UDC 532.526

The aerodynamic characteristics of an aircraft are determined to a large extent by the wake flow behind it. The aerodynamic drag of a body in the flow can be appreciably different for the laminar and turbulent flow regimes (and the base pressure value, for instance, can differ by a factor of greater than two [1]). However, there are few experiments on wake stability at supersonic speeds, and only one domestic work was performed [2].

The majority of experiments in this work were performed in a T-325 wind tunnel [3] at the Institute of Theoretical and Applied Mechanics of the Siberian Division of the Russian Academy of Sciences for free-stream 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.

A K-109 constant-resistance hot-wire anemometer (in some experiments at $M_\infty = 4$, a TPT-4 hot-wire anemometer) with a sensor with a tungsten wire 6 μm in diameter and 1.2 mm long, a U2-8 selective amplifier, a V7-27A/1 voltmeter, and a spectrum analyzer of the "Brüel and Kjaer" firm (type 2010) with a level plotter (type 2307) were used to measure the stability and transition characteristics.

The test model was a heat-insulated symmetric flat steel plate 61 mm long, 10 mm thick, and 200 mm wide. Its nose was made as a wedge with a bevel half-angle of 14° and a leading-edge bluntness of 0.1 mm. The rear of the plate was blunt and rectangular. The plate was fixed rigidly to the side walls of the test section and positioned at a zero attack angle.

The position of the transition in the wake is readily determined from the position of the maximum of the standard voltage fluctuations $\langle e \rangle$ on the wire of the anemometer sensor as a function of the axial coordinate (see, for instance, [4]). This was similar to determination of the position of the transition in a boundary layer using a hot-wire anemometer (in this work the axial x coordinate was reckoned from the plate end). Figure 1 shows such curves obtained in the symmetry plane of the wake for $M_\infty = 2$ and 4 and $Re_{1\infty} = 9 \cdot 10^6$ m^{-1} (the voltage fluctuations are normalized by their maximum values). It is seen that as the Mach number is reduced from 4 to 2, the transition approaches the model.

Figure 2 shows the growth rates of pertubations in the wake $\alpha_i = (de/e)(b/2dx)$ (b is the wake thickness) versus their frequency f for $M_\infty = 2$ and 4. The measurements were performed in a layer with a maximum values of $\langle e \rangle$ with respect to the normal y coordinate (this layer is nearly critical). It is seen from the figure that the growth rates of pertubations increase appreciably as the Mach number is reduced from 4 to 2.

An increase in the axial x_t coordinate of the transition with an increase in M_∞ from 2 to 4, as observed in this work, agrees completely with the growth in x_t with an increase in M_∞ from 4 to 5 obtained by the author [5] in the wind tunnel "Transit" in the wake behind a model similar to that used in the present work. In addition, the author performed in "Transit" additional experiments at M_∞ =7 in the wake behind the same model. The effect of the Mach number was studied within the range of $Re_{1\infty} = (50\text{–}70) \cdot 10^6$ m^{-1}. For

Institute of Theoretical and Applied Mechanics, Siberian Division, Russian Academy of Sciences, Novosibirsk 630090. Translated from Prikladnaya Mekhanika i Tekhnicheskaya Fizika, Vol. 37, No. 4, pp. 57–61, July–August, 1996. Original article submitted April 11, 1995; revision submitted June 7, 1995.

0021-8944/96/3704-0507 \$15.00

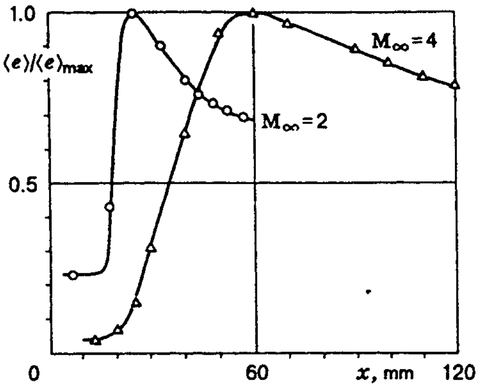


Fig. 1

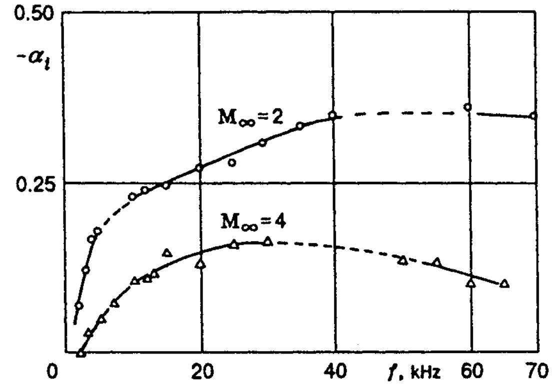
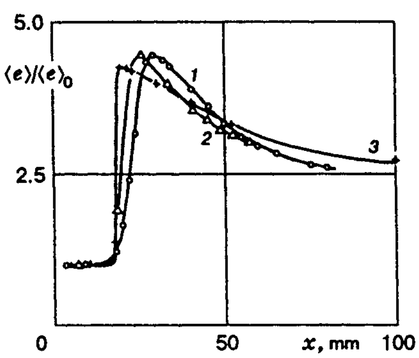


Fig. 2



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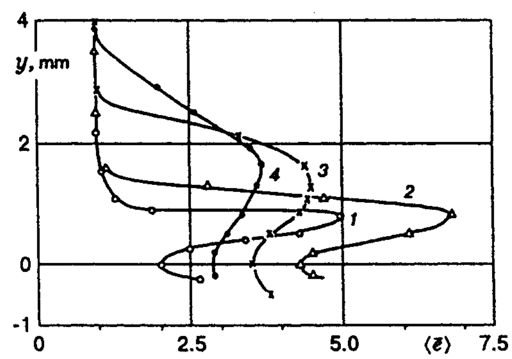

Fig. 4

an increase in M_∞ from 5 to 7, the transition was even farther from the model (as M_∞ changed from 4 to 7 the axial coordinate of transition increased by approximately a factor of two).

Thus, the experiments performed at $M_\infty = 2$, 4, 5, and 7 showed a stabilizing effect of the growth in the Mach number. This fact is in agreement with theoretical papers for both wakes (see, for example, [6]) and mixing layers [7], in which the growth rates of pertubations were found to decrease with increasing Mach number.

The unit effect of the Reynolds number on the location of the transition in the wake was also studied in a T-325 wind tunnel. Experiments were performed in the symmetry plane of the wake at $M_\infty = 2$ and $\mathrm{Re}_{1\infty} = (5.7, 9, \text{and } 15)\cdot 10^6\ \mathrm{m}^{-1}$ (curves 1–3, respectively, in Fig. 3 show the experiment results). All voltage fluctuations in Fig. 3 are made dimensionless to their initial values near the boundary of the recirculation region. The transition delay in the wake is observed with decreasing $\mathrm{Re}_{1\infty}$. This is in line with the results of [8, 9] (at $M_\infty = 4.3$) and [10] (at a hypersonic flow velocity of 6710 m/sec).

The development of pertubations in the wake at $M_\infty = 2$ and $\mathrm{Re}_{1\infty} = 5.7\cdot 10^6\ \mathrm{m}^{-1}$ is illustrated in Fig. 4, which shows dimensionless fluctuation profiles of $\langle \bar{e}\rangle = \langle e\rangle/\langle e\rangle_\infty$ (y is the normal coordinate reckoned from the symmetry plane of the wake) for $x = 20$ and 27 mm (not far ahead of transition) and 44 and 60 mm (curves 1–4). The measurements were performed with fairly high (0.7) overheating of the wire, and the hot-wire anemometer actually recorded mass flow fluctuations. One can see that in the laminar wake the perturbations increase over the entire wake thickness with increasing x, the thickness itself remaining roughly the same. However, after the wake becomes turbulent, the perturbation profile levels out noticeably due to a reduction in the maximum fluctuations in the wake. The thickness of the most perturbed part of the wake

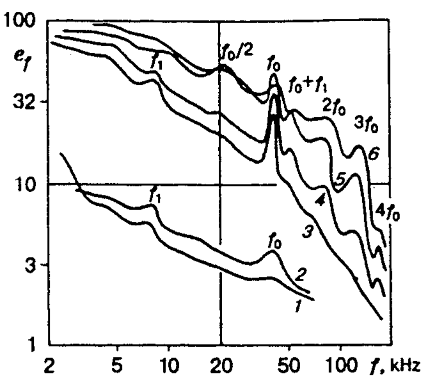

Fig. 5

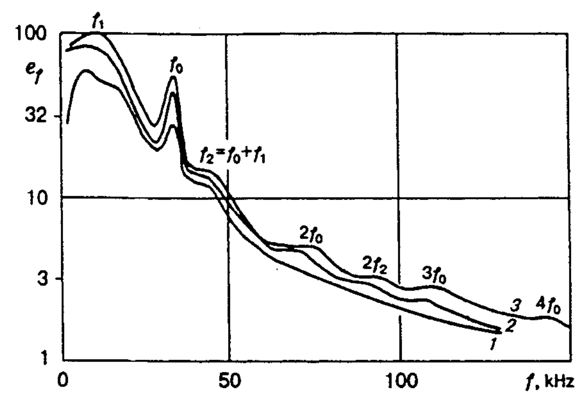

Fig. 6

and the transverse coordinate of the layer with maximum perturbations increase most intensely, which is consistent with the statement of [11, 12] that a noticeable expansion of the wake indicates the transition. The development of perturbations in the wake at $M_\infty = 2$, as is shown in Fig. 4, is completely analogous to the experimental results at $M_\infty = 4$ in [2]. Figures 5 and 6 show the spectra of energy fluctuations on the wire of the anemometer sensor (distributions of the amplitudes of the perturbations e_f for various frequencies f) in a layer with maximum values of $\langle e \rangle$ with respect to y (the layer is close to critical) 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}, respectively, for various values of the axial coordinate. Figure 5 shows spectra 1 and 2 for $x = 12$ and 14 mm (both in a free viscous layer), 3–6 for $x = 22$, 24, 27, and 30 mm (spectrum 6 was obtained in the transition region). Figure 6 presents spectra 1–3 for $x = 40$, 45, and 60 mm (spectrum 3 was obtained in the transition region). Some common features were found for $M_\infty = 2$ and 4. In the final part of the free viscous layer (immediately before its transition to the wake) and in the linear phase of development of the wake itself, a typical maximum appeared in the spectral distribution of fluctuations: perturbations with frequencies $f_0 = 43$ kHz for $M_\infty = 2$ and 35 kHz for $M_\infty = 4$ start to increase rapidly. The Strouhal number calculated from the frequency of this maximum, wake thickness in the throat region, and free-stream velocity was $\mathrm{Sr} = f_0 b_0 / u_\infty = 0.3$. A similar maximum in the fluctuation spectrum was observed in [13] in a wake behind a flat plate at $M_\infty = 6$. In addition, a value of Sr=0.3 was also obtained in [13], and it was shown that this Strouhal number is universal for both subsonic and hypersonic velocities of flow around a plate.

In the nonlinear stage of the development of wake perturbations (roughly at 22 mm $< x <$ 29 mm for $M_\infty = 2$ and 40 mm $< x <$ 56 mm for $M_\infty = 4$), the fundamental tone with frequency f_0 still dominates in the energy spectrum of fluctuations (up to the beginning of transition where perturbations with frequency f_0 are reduced, and the spectrum levels out), but nonlinear interaction of different fluctuations begins. In particular, perturbations with frequency $f_0 + f_1$ (f_1 is the frequency of the second maximum in the energy spectrum of fluctuations in the linear phase) begins to grow rapidly. Most likely, the two maxima resonate, and a wave triplet arises (the third wave with frequency $f_0 + f_1$). In addition, a noticeable growth of harmonics with frequencies $2f_0$, $3f_0$, and $4f_0$ begins. All that occurs with a marked deceleration of the growth of perturbations with f_1 and f_0, which allows the author to assume that energy is pumped from a fundamental tone with f_0 and a perturbation with f_1 to a perturbation with frequency $f_0 + f_1$, and from the fundamental tone it is also pumped to harmonics with frequencies $2f_0$, $3f_0$, and $4f_0$.

Thus, the development of perturbations in the wake behind a flat plate with a symmetric wedge-shaped nose, a sharp leading edge, and a blunt (rectangular) afterbody was experimentally studied at $M_\infty = 2$ and 4. The experiments (and also additional measurements of locations of the transition at $M_\infty = 4$, 5, and 7) showed a stabilizing effect of Mach number increase: the growth rates of perturbations are reduced, and the transition in the wake moves away from the model. The transition in the wake is also delayed as the unit

Reynolds number decreases. The development of wake perturbations at various stages (in particular, in the nonlinear phase) is studied in the paper.

The author is thankful to A. D. Kosinov and N. V. Semenov for assisting in the experiments.

REFERENCES

1. A. N. Mikhalev, " Effect of the Reynolds number on the near-wake parameters for supersonic cones," in: *Physical-Gasdynamics Ballistic Studies* [in Russian], Nauka, Leningrad (1980), pp. 88–98.
2. V. I. Lysenko and N. V. Semionov, "Stability of a wake behind a flat plate at supersonic speeds," *Prikl. Mekh. Tekh. Fiz.*, **36**, No. 6, 55–59 (1995).
3. G. I. Bagaev, V. A. Lebiga, V. G. Pridanov, and V. V. Chernykh, "Supersonic wind tunnel T-325 with reduced turbulence," *Aerophysical investigations* [in Russian], Novosibirsk (1972), pp. 11–13.
4. A. Demetriades, "Experiments on the free shear layer between two supersonic streams," AIAA Paper No. 710, New York (1990).
5. V. I. Lysenko, "Study of transition location in a supersonic boundary layer on a flat plate and in the wake behind it," *Sib. Fiz.-Tekh. Zh.*, No. 4, 44–46 (1993).
6. L. Lees and H. Gold, "Stability of laminar boundary layers and wakes at hypersonic speeds, Part 1, Stability of laminar wakes," *Fund. Phenom. in Hypersonic Flow*, No. 4, Cornell Univ. Press, Buffalo, New York (1964), pp. 310–337.
7. S. A. Ragab and J. L. Wu, "Linear instabilities in two-dimensional compressible mixing layers," *Phys. Fluids, A*, **1**, No. 6, 957–966 (1989).
8. D. K. McLaughlin, J. E. Carter, M. Finston, and J. A. Forney, "Experimental investigation of the mean flow of the laminar supersonic cone wake," *AIAA J.*, **9**, No. 3, 479–485 (1971).
9. D. K. McLaughlin, "Experimental investigation of the stability of the laminar supersonic cone wake," *AIAA J.*, **9**, No. 4, 696–702 (1971).
10. A. J. Pallone, J. I. Erdos, and J. Eckerman, "Hypersonic laminar wakes and transition studies," *AIAA J.*, **2**, No. 5, 855–863 (1964).
11. W. Behrens, "Study of the far part of the wake behind cylinders at hypersonic velocities. Part II. Stability," *AIAA J.*, **6**, No. 2, 225–232 (1968).
12. A. Demetriades, "Hot-wire anemometer measurements in hypersonic wakes behind thin bodies in a hypersonic flow," *AIAA J.*, **2**, No. 2 (1964).
13. W. Behrens and D. R. S. Kau, "Experimental stability studies in wakes of two-dimensional slender bodies at hypersonic speeds," *AIAA J.*, **9**, No. 5, 851–857 (1971).