4. Yu. A. Buevich, S. L. Komarinskii, V. S. Nustrov, and V. A. Ustinov, Inzh.-Fiz. Zh., 49, No. 5, 818-826 (1985).
5. Yu. A. Buevich and V. S. Nustrov, Inzh.-Fiz. Zh., 48, No. 6, 942-950 (1985).
6. N. Sh. Khairedinov, M. G. Alishaev, and A. A. Ben-Yakh'ya, Intensification of Geological Prospecting and Oil Recovery in Western Siberia [in Russian], Tyumen (1984), pp. 47-49.
7. Sh. K. Gimatudinov, Physics of Oil and Gas Beds [in Russian], Moscow (1975).
8. Yu. P. Zheltov, Mechanics of an Oil-and-Gas-Bearing Bed [in Russian], Moscow (1975).
9. Yu. V. Kalinovskii, "Solution of a filtration problem in a cracked-porous medium by the method of integral relations," Submitted to VNIÉgasprom 25.07.1978, Moscow (1978), No. 37.
10. A. Ban, A. F. Bogomolova, V. A. Maksimov, et al., Effect of the Properties of Rocks on the Movement of Fluid inside Them [in Russian], Moscow (1962).

PARAMETERS OF WAVE INSTABILITY IN A BOUNDARY LAYER

B. Yu. Zanin

UDC 532.517.3

The waves developing in a boundary layer during transition from laminar to turbulent flow are investigated experimentally.

The experimental study of flow in a boundary layer of a wing in an aerodynamic wind tunnel and under natural conditions, i.e., in flight (including in clouds and near the earth), has shown [1] that in all these cases the transition from laminar to turbulent flow occurs through the development of an instability wave packet in the region of a positive pressure gradient, despite the different level and frequency composition of the leading flow turbulence. The mean frequency of this wave packet depends on the flow velocity and on the angle of attack.

Quite important and demanding solution is the problem of which factors determine the frequency and wavelength in each specific case. Using this as a starting point, the purpose of the present study has been to explain the general features of the parameters of waves, generated on the same profile for different attack angles of the model and flow velocities in the tube. To solve this problem in an aerodynamic wind tunnel, experimental measurements of wave instability were carried out in a boundary layer on a wing model in a wide range of flow regimes, and then were calculated and analyzed the dimensionless parameters describing this effect, including the known frequency parameter $F = 2\pi f\nu/U_\infty^2$ (see [2]), and the parameters $2\pi f\delta_1/U_\infty$ and $2\pi\delta/\lambda$, used theoretically [3].

The studies were carried out in the aerodynamic wind tunnel T-324 of the Institute of Theoretical and Applied Mechanics, Siberian Branch of the Academy of Sciences of the USSR, having a degree of flow turbulence less than 0.04% [4]. The model of the wing, made of wood and coated varnish, had a NACA 63-2-615 profile. The wingspan of the model was 1 m, and the mean chord, along which measurements were taken, was b = 0.27 m. Ten drainage points were used to measure the static pressure at the upper surface of the model. The model was set up vertically in the operating portion of a tube with a square cross section. The angle of attack was determined relatively to the walls of the operating portion. The experiments were carried out for attack angles of the model of −4, 0, and 4° for a leading flow velocity of 25 m/sec and in the flow velocity region of 10-40 m/sec at an attack angle of the model being 4°.

The thermoanemometric complex DISA 55D was used for measurements in the boundary layer. The detector of the thermoanemometer with a filament of diameter of 6 μm and length of 2 mm was attached to the support, coated inside the tube by a fairing so as to reduce vibrations. The support was fixed in a coordinate grid, established in the window of the operating portion, and allowing to displace the detector with an accuracy of ±0.5 mm in the longitudinal x direction and with an accuracy of ±0.01 mm in the transverse y direction. To guarantee reliable determination of the moment the detector touches the surface of the model, which is necessary for correct determination of the boundary layer thickness, the model was rubbed with

Institute of Theoretical and Applied Mechanics, Siberian Branch, Academy of Sciences of the USSR, Novosibirsk. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 53, No. 4, pp. 624-629, October, 1987. Original article submitted July 28, 1986.

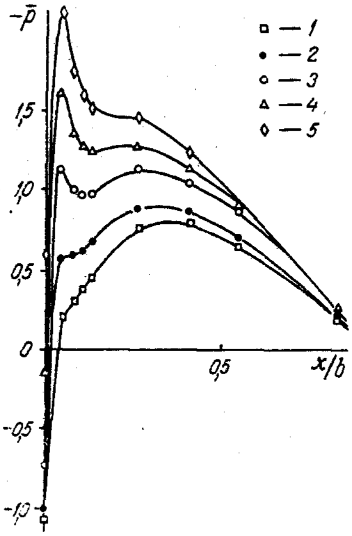

Fig. 1. Pressure distribution at the model at tube flow velocity 25 m/sec for different angles of attack: 1) α = 0°; 2) 2; 3) 4; 4) 6; 5) α = 8°.

graphite in the measurement region, and was electrically joined to the wall of the operating portion. The contact moment was determined from the electric contact. The thickness of the boundary layer was measured with an accuracy of ±0.1 mm. The detector was attached to the DISA thermoanemometer by a 55D01 series. By means of the thermoanemometer the signal was reduced at a DISA 55D10 linearizer, and further at a V7-16 voltmeter so as to measure the mean velocity and on a DISA 55D35 rms voltmeter to measure the spectral integral of the fluctuation intensity. The frequency analysis of the fluctuations was carried out by CK-4-56 analyzers with a transmission band of 3 Hz and a Rhode und Schwarz FAT-1 with a transmission band of 4 Hz, by means of which was determined the intensity of each separate harmonic.

The mean frequency of the wave packet was measured by means of the CK-4-56 analyzer from the maximum fluctuation amplitude by manual control of the analyzer scan. The spread in determining this frequency from data of multiple measurements was ±10 Hz. The instability wavelength was determined by the method discussed in [5]. To stabilize the wave phase, oscillations were dynamically created in the aerodynamic wind tunnel with a frequency corresponding to the mean frequency of the wave packet, using a G3-33 generator. The sound level created dynamically exceeded the noise level in the tube by 3-4 dB. The signal at the generator was also reduced by the two-ray C1-55 oscillator as basis. The thermoanemometer detector was displaced along the line of equal mean velocity $U = 0.5U_\infty$. A signal of the same frequency was extracted from the thermoanemometer signal by means of the FAT-1 analyzer, and was also reduced at the oscillograph. The phase and the wavelength were determined by displacing the thermoanemometer signal with respect to the basic signal.

As shown by static pressure measurements at the surface of the model (Fig. 1), carried out for different attack angles, for positive attack angle at the upper surface of the model there occurs a clearly expressed peak of the pressure minimum at the forward portion of the channel, while for decreasing angle of attack this peak is also enhanced. Thus, in this case there exist two local minima on the profile in the pressure distribution, and, correspondingly, two regions with a positive pressure gradient. (For a varying flow velocity the pressure coefficient remains constant.) A wave instability packet is generated and evolves in each of these regions. This is indicated by the measurement results of the frequency composition of fluctuations in the boundary layer along the model chord on the velocity line $U = 0.5U_\infty$ (Fig. 2). There exist two wave packets in the spectra with different mean frequencies. The occurrence of the first packet at x > 40 mm is, obviously, caused by the presence of a region of a positive pressure gradient in the forward portion of the profile. The wave formed here is gradually damped, with the damping also extended following the appearance and initial amplification of the second instability wave, x = 140 and 150 mm. The mean frequency of the first packet at U_∞ = 25 m/sec is 790 Hz at x = 40 mm, and decreases somewhat down the flow. The mean frequency of the secondary flow is 1940 Hz. It is precisely these latter oscillations which lead to the transition. The dimensionless parameters were, indeed, determined for them.

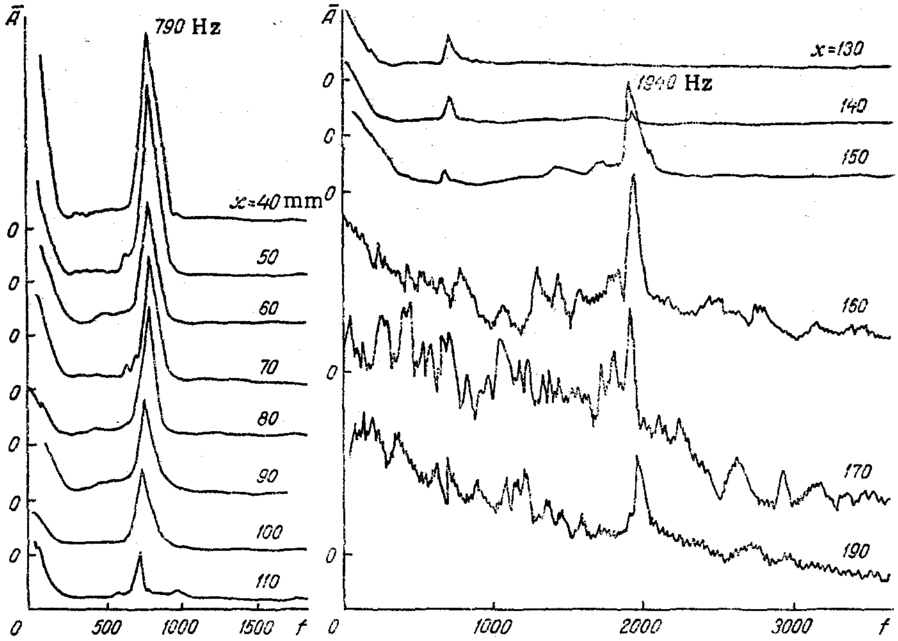

Fig. 2. Fluctuation frequency spectra in the boundary layer with U_∞ = 25 m/sec and α = 4°. f, Hz; x, mm.

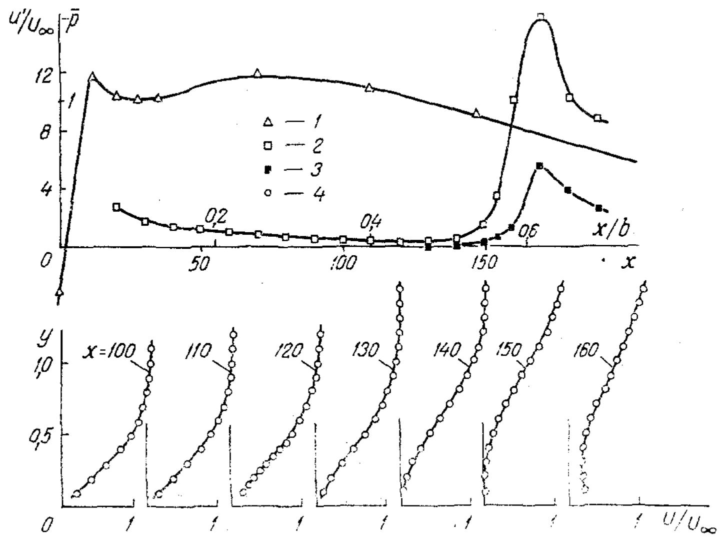

Fig. 3. Boundary layer characteristics in the transition region for U_∞ = 25 m/sec and α = 4°: 1) pressure coefficients; 2) spectral integral intensity of fluctuations; 3) fluctuation intensity with frequency 1940 Hz; 4) mean velocity profile. u'/U_∞ in %, y in mm.

The variation of the fluctuation amplitude in the boundary layer can be traced from the growth curve of fluctuations, constructed along the line of equal mean velocities $U = 0.5U_\infty$, i.e., near the fluctuation maximum. Also given here, in relative coordinates, is the pressure distribution at the model. Starting with the point x = 20 mm (there are no measurements closer to the leading edge), the fluctuation level decreases, with this fluctuation damping continued in the region of positive pressure gradient (x > 70 mm) up to coordinates x = 120-130 mm. Further starts a sharp increase in perturbation in the boundary layer. As seen from Fig. 3, the mean velocity profile in this region (x = 120-130 mm) acquires a shape with an inflection point, with a break in flow occurring then. Thus, the sharp perturbation increase in the boundary layer starts in the given case in the region of occurrence of an inflection point in the mean velocity profile and flow breakdown. The amplitude of wave fluctuations with frequency 1940 Hz increases simultaneously with the increasing total fluctuation level. In calculating the parameter $2\pi f\delta/U_\infty$ the problem arises, for which boundary layer thickness, i.e.,

TABLE 1. Measurement Results of Boundary Layer Parameters

U_∞, m/sec	10	15	25	25	25	30	40
α, deg	4	4	—4	0	4	4	4
x, mm	110	130	150	140	120	130	140
δ, mm	1,7	1,7	1,2	1,2	1,15	1,15	1,12
δ_1, mm	0,6	0,69	0,43	0,425	0,435	0,44	0,44
f, Hz	510	735	1530	1850	1940	2280	3200
$\mathrm{Re}\,\delta_1$	403	695	721	713	730	886	1181
$\frac{2\pi f \nu}{U_\infty^2} \cdot 10^6$	477	306	229	277	290	237	187
$\frac{2\pi f \delta_1}{U_\infty}$	0,192	0,212	0,165	0,198	0,212	0,21	0,221
$\frac{2\pi f \delta}{U_\infty}$	0,544	0,523	0,461	0,558	0,56	0,549	0,563
λ, mm	12	12	8	7,5	7	7,5	—
$\bar{c}_r$	0,612	0,588	0,49	0,555	0,543	0,57	—
$\frac{2\pi\delta}{\lambda}$	0,89	0,89	0,942	1,00	1,03	0,963	—

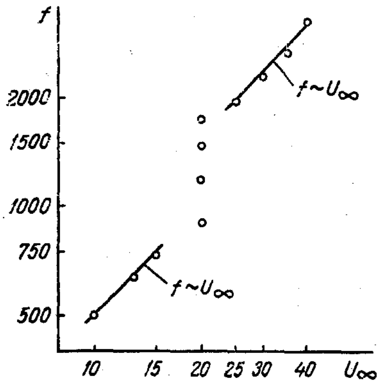

Fig. 4. Mean frequency of the wave packet and the wavelength as a function of flow velocity U_∞, m/sec.

for which characteristic point on the profile it ought to be determined. It is assumed that on the growth curve of fluctuations (see Fig. 3) occurs the most important point of minimum fluctuation amplitude, since the sharp increase in perturbation occurs precisely at it. As noted above, it is precisely in this region that the inflection point occurs in the mean velocity profile, as well as the flow breakdown. Therefore, the parameters $2\pi f\delta/U_\infty$ and $2\pi f\delta_1/U_\infty$ were calculated precisely for this point, i.e., for each regime was constructed a growth curve, its minimum was determined, and in the minimum region were measured the velocity profile in the boundary layer and the layer thickness.

The results of the parametric measurements are shown in Table 1. It appears that with the velocity increasing by 4 times the frequency parameter decreases by 2.6 times. At the same time the parameters $2\pi f\delta/U_\infty$ and $2\pi f\delta_1/U_\infty$, calculated for an attack angle of 4°, are approximately constant. The maximum spread in values is less than 8% for the parameter $2\pi f\delta/U_\infty$.

Then was determined the wavelength for oscillations with the mean frequency of the wave packet, and calculated were the wave propagation velocity c_r and the dimensionless parameter

$2\pi\delta/\lambda$. For a flow velocity of 40 m/sec it was not possible to measure the wavelength, since the noise level in the tube exceeded the sound amplitude created dynamically, and the phase was not stabilized. The wave propagation velocity decreases for an attack angle decreasing to $\alpha = -4°$. In all regimes considered, including different attack angles, the parameter $2\pi\delta/\lambda$ is quite close to unity. Therefore, the instability wavelength for the given case can be determined from the simple relationship $\lambda = 2\pi\delta$, where δ is the boundary layer thickness in the formation region of the mean velocity profile with the inflection point and the flow breakdown.

The mean frequency of the instability wave packet and the wavelength depend on the flow velocity (Fig. 4). In the velocity ranges 10-15 and 25-40 m/sec, the frequency is directly proportional to the velocity, but with different proportionality coefficients. This is explained by the fact that, as seen from Table 1, the instability wavelength is constant for flow velocities 10-15 m/sec, and is approximately 12 mm, while with further velocity increase it changes sharply, and for velocities 25-35 m/sec it has a different, but also approximately constant value of 7-7.5 mm. The thickness δ also varies sharply from 1.7 mm at 10-15 m/sec to 1.12-1.15 mm for 25-40 m/sec. The velocity 20 m/sec is intermediate between these two ranges. For this flow velocity there are some discrete frequencies in the frequency spectrum. The coordinate x of the point, at which the value of the fluctuation amplitude is minimal, is gradually displaced with increasing velocity to below the flow, but then, during transition from one velocity range to the other, this coordinate is also shifted discontinuously to above the flow, and the process is repeated (see Table 1).

Thus, the study performed has shown that for intability waves, evolving during the break of a laminar boundary layer, there exist dimensionless parameters, uniquely determining the frequency and length of this wave.

NOTATION

U_∞, incoming flow velocity; U, local mean velocity; u', root-mean-square value of longitudinal velocity fluctuations; b, profile chord; x, distance along the chord; y, distance from the surface of the profile; α, angle of attack; δ, boundary layer thickness for 0.99 of the local velocity; δ_1, displacement thickness; f, frequency; λ, wavelength; γ, kinematic viscosity coefficient; $Re_{\delta_1} = U_\infty\delta_1/\nu$, Reynolds number in the displacement thickness; $\bar{p}$, pressure coefficient; and $\bar{A}$, relative fluctuation amplitude.

LITERATURE CITED

1. B. Yu. Zanin, Proc. II IUTAM Symp. Laminar-Turbulent Transition, Novosibirsk, 1984; Berlin (1985), pp. 541-546.
2. Yu. S. Kachanov, V. V. Kozlov, and V. Ya. Levchenko, Generation of Turbulence in a Boundary Layer [in Russian], Novosibirsk (1978).
3. W. Tollmien, Development of turbulence, I., Mitteilung Nachr. Ges. Wiss., Gottingen (1929), pp. 447-450 (Quoted in: H. Schlichting, Boundary Layer Theory).
4. G. I. Bagaev, V. K. Golov, G. V. Medvedev, and N. F. Polyakov, Aerophysical Studies [in Russian], Novosibirsk (1972), pp. 5-8.
5. A. V. Dovgal' and V. V. Kozlov, Izv. Akad. Nauk SSSR, Mekh. Zhidk. Gaza, No. 2, 48-52 (1983).