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EXPERIMENTAL STUDY OF THE TRANSITION TO TURBULENCE AT A SINGLE STATIONARY DISTURBANCE IN THE BOUNDARY LAYER OF AN OBLIQUE AEROFOIL

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Introduction. Three-dimensional boundary layers are a type of boundary flow which are encountered most often in practice. In contrast to classic transition at a flat plate with a low level of turbulence for the approach flow, which is caused only by development of Tollmien–Schlichting waves propagating along the flow [1], at an oblique aerofoil the mechanism of transition is not so clear and it has only been studied a little.

With small slip angles and approach flow velocities the main instability mechanisms remain as for a two-dimensional aerofoil: intensification of Tollmien–Schlichting waves and lower over the flow in the zone of a positive pressure gradient there are instability waves of flow separation [2]. However, starting with slip angles of the order of 30-40° with quite slow flow velocities (20-30 m/sec) close to the leading edge of an aerofoil as a rule there is formation of a series of stationary rotating vortices [3] whose axes are directed approximately along the current lines of inviscid flow. Appearance of these structures in the flow at an aerofoil and in other converging flows, for example at a rotating disk [4], is connected with presence in the boundary layer of velocity components directed perpendicular to the velocity vector in a free stream. The velocity profile of this transverse flow is inflectional, which according to linear theory promotes development of an inviscid type of instability. In this case disturbances start to strengthen propagating almost along the direction of transverse flow with low frequencies compared with the characteristics for Tollmien–Schlichting waves which develop with much higher Reynolds numbers and have a viscous nature.

The reasons for preferred separation of stationary vortices is connected with the fact that these disturbances appear to be close to the most intensified [5], and second with presence of uncontrolled seeded disturbances from different surface irregularities whose effect is marked close to the leading edge where the thickness of the boundary layer is small [6, 7]. The amplitudes of stationary disturbances may reach considerable values (10-20% of the local external flow velocity U_0) which promotes intense nonlinear activity of them, and in particular it may lead to doubling of the succession frequency of vortices [8] in the transverse direction as detected in experiments [9, 10] and analyzed in [3, 11] from the position of nonlinear interaction of vortices.

The process of further transition to turbulence mainly depends on the characteristics of a specific aerofoil profile. If the pressure gradient changes sign rapidly, then stationary vortices which continue to exist beneath the flow by inertia start to interact with intensified Tollmien–Schlichting waves [8, 12].

At the same time studies [3, 13, 10] show that transition often occurs with subcritical Reynolds numbers and it cannot be connected with intensification of Tollmien–Schlichting waves. In this case in the presence of stationary vortices of considerable amplitude in a region immediately preceding conversion of flow into turbulent new high-frequency disturbances arise and are intensified propagating along the primary vortices. In fact their development leads to the breakdown of laminar flow in individual vortices which gives a 'saw-shaped' picture of transition observed with flow visualization [13]. Subsequently turbulent wedges expand and merge from different vortices embracing the whole boundary layer.

In [3] development of these high-frequency pulsations is connected with secondary flow instability periodically distorted by stationary vortices. According to this concept with quite high vortex amplitudes points of inflection arise in the distributions of longitudinal components of average velocity over the normal coordinate Y and transverse coordinate Z making flow locally inviscidly unstable with high-frequency disturbances. Here primary stationary vortices play the role of a trigger starting intensification of travelling waves whose development naturally leads to terminal stochastization.

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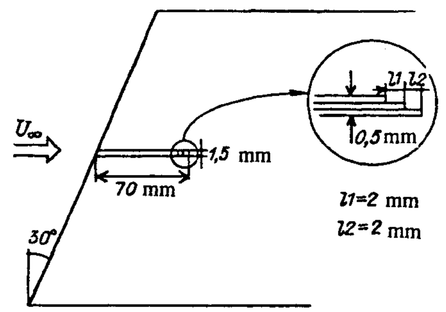

Fig. 1

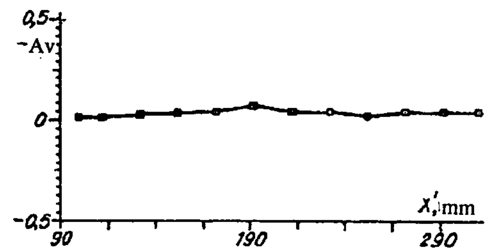

Fig. 2

The validity of the idea of secondary instability is applied to this situation in [3], subsequently it is developed in a theoretical model [14], and it is confirmed by experiment in [10]. Several types of secondary disturbances were observed which may propagate along primary vortices and are connected with inflections in the average velocity profiles. Experiments in [10] were performed on "natural" stationary vortices which did not make it possible for the authors to carry out a detailed study of secondary instability.

With quite a low level of turbulence (less than $\approx 0.1\%$ of U_0) amplitudes of stationary vortices often reach considerable values, and in [6, 7] it was detected that with an increase in the level of disturbances in aerodynamic devices the amplitudes of stationary vortices decrease, but for travelling waves transverse flow is intensified and correspondingly there is a change in their effect on the process of flow stochastization. This behavior demonstrates the competing struggle of different nonlinear mechanisms whose outcome mainly depends on the initial disturbance spectrum in free flow. The broader this disturbance spectrum, the greater is the possible variety of nonlinear interactions between them, which leads to acceleration of turbulization. Nonetheless, experiments in [5, 10, 13, 15] were performed under 'natural' wind tunnel conditions and therefore they only give a qualitative representation of the possible transition processes and they do not make it possible to compare directly experimental and theoretical results. In particular it is probable that presence of uncontrolled processes in experiments in [9] serve as a reason for doubling of the frequency not detected in the experiments of other authors.

The procedure for performing experiments under controlled conditions applied to three-dimensional flows is quite well developed. On a flat plate in [16] a pair of stationary vortices were generated by stickers close to the leading edge and travelling waves were excited by a vibrating strip. At an oblique aerofoil travelling disturbances of instability in the region of flow separation were introduced in [2] in a controlled fashion, stationary vortices for transverse flow were excited by different methods in [6, 12], and in [12] interaction with Tollmien–Schlichting waves was also modelled.

In this work the aim was to model the development of high-frequency waves generated at an individual stationary vortex under controlled conditions. This approach makes it possible to study characteristics of secondary instability irrespective of the possible effect of neighboring stationary vortices and secondary disturbances on each other.

Experimental Procedure. Experiments were performed in a subsonic low-turbulence wind tunnel T-324 at the Institute of Theoretical and Applied Mechanics, Siberian Section of the Russian Academy of Sciences [17]. The T-324 wind tunnel is of the closed circuit type with a sealed working section 1 × 1 square and 4 m long. The level of flow turbulence in the working section with velocities for an experiment of 7-16 m/sec does not exceed 0.04% of the approach flow velocity U_∞.

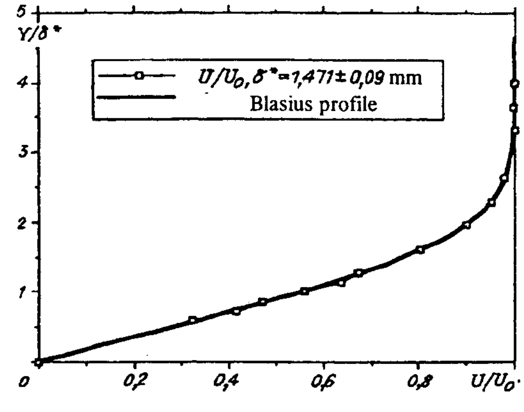

Fig. 3

A diagram of the experiment is given in Fig. 1. A high-support aerofoil profile S-12 [18] with a slip angle of 30° and a chord of 500 mm was selected as the working model. The profile consists of a symmetrical ogival nose with a thickness at the widest part of 16% of the chord and a length of 5.6 mm passing into two identical converging flat surfaces. The profile was arranged vertically and secured rigidly to the horizontal walls of the working section so that the working surface of the profile was a flat plate arranged at a zero attack angle. First the fastening provided the possibility of placing the thermo-anemometer transducers parallel to the surface of the model with high accuracy, and second it simplified analysis of flow round the model since the curvature is only marked close to the nose of the aerofoil and local flow separation [2] in the region of the center of the aerofoil chord, which normally arises with small attack angles, is absent. In addition, it is a natural aerofoil profile for recreational aerobatic aeroplanes which makes the problem more interesting from a practical viewpoint compared with studying a flat plate.

A stationary disturbance was developed behind a projection glued to the surface whose shape, size, and position on the aerofoil are shown in Fig. 1. In order to avoid flow break-away from the end of the projection placed higher in the flow it was continued to the nonworking side of the aerofoil. Its other end placed lower in the flow was smoothed for this purpose [19].

Two coordinate systems are used: XYZ connected with the aerofoil and X'Y'Z' connected with the approach flow. Axis X is directed along the chord of the aerofoil perpendicular to the leading edge and reckoned from it, Z is along the span of the model and is directed into the transverse flow, axes Y and Y' coincide and they are reckoned from the aerofoil surface over the normal to it. Axis X' is directed parallel to the approach flow, Z' is directed perpendicular to plane X'Y'.

Measurements of approach flow velocity were made from the difference of the total and static pressure determined by means of a combined Pitot-Prandtl probe joined to a micromanometer. The main thermo-anemometric measurements were made in the central part of the model in the region $\Delta Z = 80$ mm where secondary flow is almost absent. Only longitudinal components of the average and pulsation velocities U and u' were measured. These values were determined by means of a 55M01 thermo-anemometer from the firm DISA from which they were fed through an analog–digital converter MacADIOS-Adio from the firm GW Instruments (USA) into a Classic II Macintosh personal computer where signals during an experiment were linearized and subjected to further treatment by a specially developed program.

The transducer sensor of the constant temperature thermo-anemometer was a tungsten filament 6 μm in diameter with a working section of ≈ 0.5 mm arranged parallel to the model surface. The coordinating device holding the transducer provided movement of the sensor along the aerofoil surface with an accuracy of 0.5 mm, and over the normal to the aerofoil with 0.01 mm. Coordinate Y (or Y') = 0 was determined visually with an accuracy of 0.1 mm. Measurements in the boundary layer were carried out over coordinates X' (along the free flow), Z (over the leading edge of the aerofoil), and Y. Due to the imperfect construction of the coordinator measurements over z were only performed with a fixed position with respect to X' = 232 mm or with other X', but in a narrow range $\Delta Z = \pm 5$ mm.

The thermo-anemometer transducer was calibrated in a free flow opposite the Pitot–Prandtl probe with flow rates in the range 2-20 m/sec so that the error in determining the average velocity was less than 1%. The calibration function is described by an equation [20]

$$U = k_1(E^2 - E_0^2)^{1/n} + k_2(E - E_0)^{1/2},$$

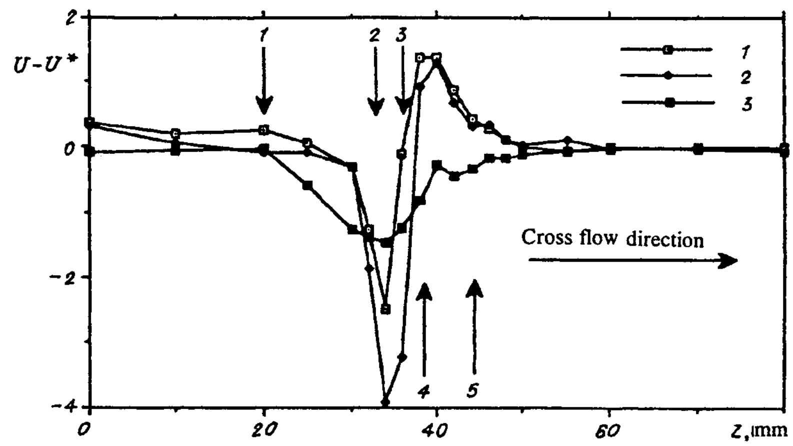

Fig. 4

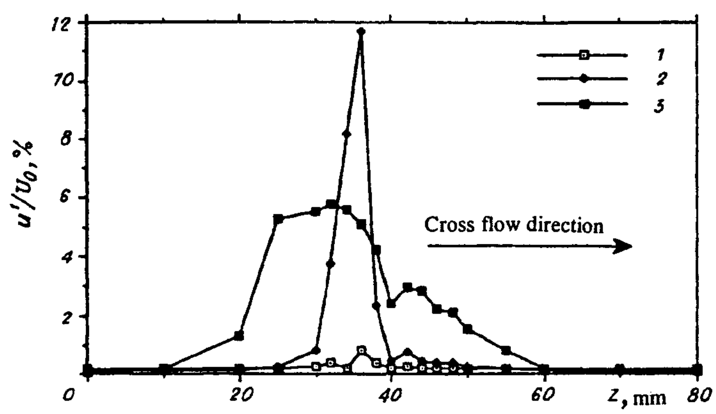

Fig. 5

where E and E_0 are output voltages from the anemometer with flow rate U and at rest respectively; k_1, k_2 and 1/n are constants determined empirically. The first term corresponds to the well-known King expression, and the second is added in order to consider the free convection at slow flow rates.

For controlled excitement of the travelling waves in the boundary flow a procedure was used for transforming sound vibrations into vortex disturbances of the same moving layer frequency with local unevenness of the surface described in [21]. Acoustic vibrations were generated by a dynamic loudspeaker placed behind the model in the diffuse tunnel and emitting sound against the flow direction. Sound frequency and its amplitude were prescribed by means of a sonic signal generator.

It is well known that with excitation of sound in the closed space of wind tunnels there is possibly formation of standing waves which may prevent formation and study of the development of travelling disturbances. However, as special measurements showed, in these experiments the sound amplitude and phase outside the boundary layer close to the region of instability wave generation and development were uniform.

Results of Measurements. Characteristics of the Boundary Layer on an Oblique Aerofoil. Before beginning a study of the transition to turbulence in a stationary vortex some tests were performed for this oblique aerofoil directed at determining the characteristics of an undisturbed boundary layer. Presented in Fig. 2 is the pressure distribution along axis X′ in the region of measurements obtained by calculating the average velocity measured at a distance of 30 mm from the model surface in the absence of a projection with an approach flow velocity of U_∞ = 7 m/sec. It can be seen that with X′ = 100 mm at the aerofoil almost gradient-free flow forms and oscillation of the pressure factor C_p in the measurement section X′ = 100-310 mm does not exceed 0.03.

Profile U(Y) for the average velocity with U_∞ = 7 m/sec for section X′ = 232 mm measured at a distance from the vortex caused by a sticker is shown in Fig. 3. The distance from the wall to the experimental point adjacent to it was determined by linear extrapolation of the average velocity profile close to the wall. Given here for comparison is the Blasius profile for a boundary layer at a flat plate. The comparison is conditional since the velocity profile at an oblique aerofoil differs

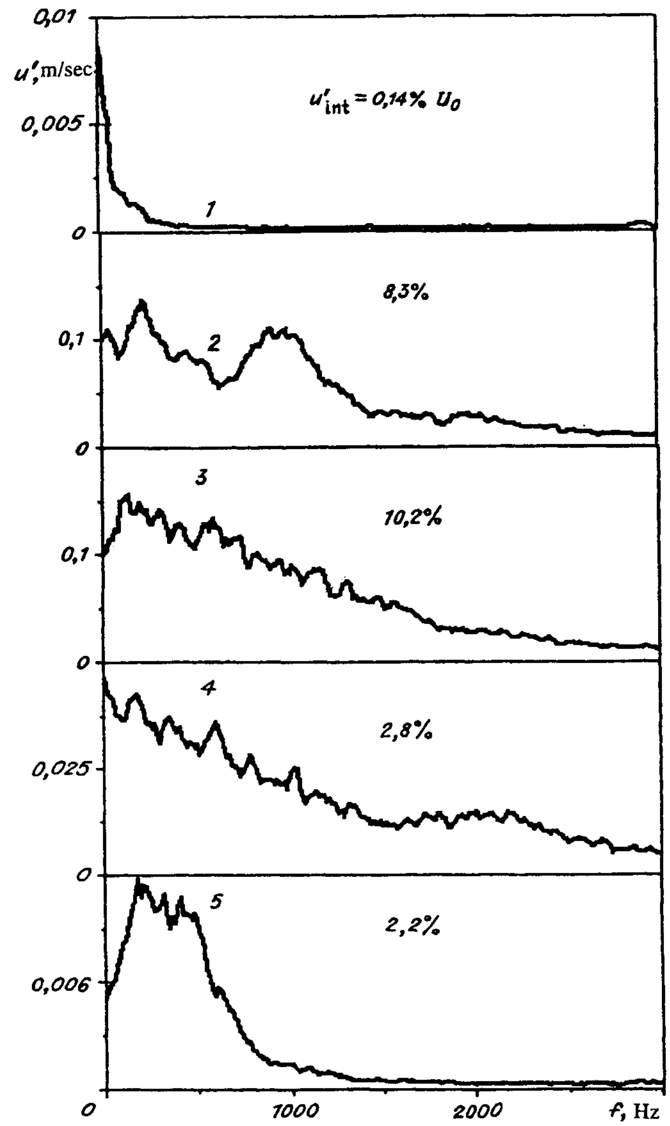

Fig. 6

from that for the flat plate. Nonetheless, due to the fact that a considerable part of the aerofoil in question is a flat surface over which there is no pressure gradient, and consequently cross flow, it is possible to make some estimates. Displacement thickness δ^* and pulse loss thickness ϑ for profile U(Y) were found by numerical integration of experimental data by the trapezoidal method and it was 1.471 and 0.551 mm with errors of 0.09 and 0.011 mm caused mainly by the inaccuracy of determining the distance to the wall which gives a value of shape parameter $H = \delta^*/\vartheta = 2.67 \pm 0.11$, quite close to that for the Blasius profile (2.59).

The majority of measurements with excitation of travelling waves were carried out with flow velocities of 7-8 m/sec in the range X' = 200-315 mm in the gradient-free flow section. Further measurements showed that the boundary layer at the aerofoil remains laminar with a low level of pulsation over the whole measurement range, and any intensification of Tollmien–Schlichting waves noted was marked under natural conditions and with application of an acoustic field on the generation frequency f = 330 Hz which is much higher than the maximum intensifying frequency of Tollmien–Schlichtling waves for a Blasius boundary layer.

Flow Within a Stationary Disturbance. As already noted, an irregularity was set up in the boundary layer of the aerofoil in accordance with Fig. 1. It was shown in [12] that the structure of flow which arises behind these obstacles is close in nature to stationary vortices which arise under natural conditions. Several shapes and sizes of irregularities were tested and it appeared that they lead to excitation of almost the same shape of stationary disturbances. In this work the conservative nature

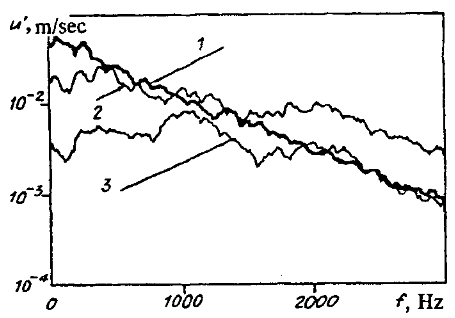

Fig. 7

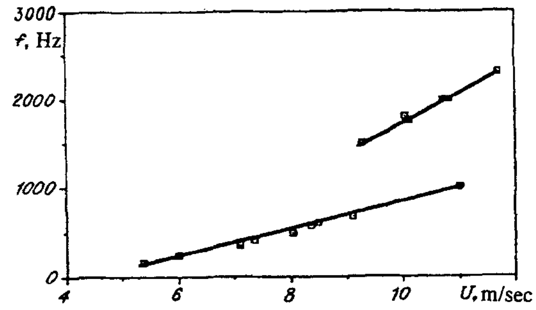

Fig. 8

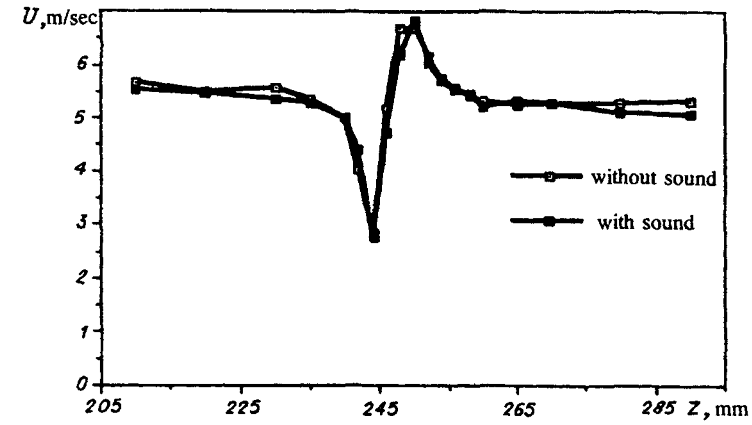

Fig. 9

of the shape of excited disturbances is demonstrated in Fig. 4 by distributions U(Z) measured in section X' = 232 mm at the outer limit of an undisturbed boundary layer with three different flow rates: U_∞ = 7.11 and 16 m/sec (lines 1-3). The velocities were selected so that with X' = 232 mm within the core of a vortex laminar, transitional, and turbulent flow regimes were realized.

The form of the distribution U(Z) with slow approach flow velocities (7 and 11 m/sec) may be explained by excitation of a single stationary vortex rotating clockwise if we look along the external flow (then the cross flow close to the leading edge is directed from left to right). The local reduction in velocity with respect to Z is connected with transfer by the vortex of low-velocity fluid towards the limit of the boundary layer and the increase in velocity down through the cross flow is connected with bringing high-velocity fluid close to the wall.

It can be seen that with velocity U_∞ = 16 m/sec the profile differs from the first two. Whereas with low approach flow velocities the width of the region of average flow distortion by the vortices is ≈25 mm, with U_∞ = 16 m/sec it is greater by almost a factor of two (≈40 mm), and in addition there is a reduction in the disturbance amplitude and its shape. These results and spectral measurements associated with them point to dissociation of the vortex under the action of turbulence and a gradual penetration of turbulence into the laminar boundary layer.

Comparison of the distribution U(Z) of generated disturbances with velocities U_∞ = 7 and 11 m/sec with those obtained in [12] from a single irregularity demonstrates a marked difference from each other. In particular, in [12] this distribution is more complex in nature. Experiments [12] were performed at an oblique plate and quite broad irregularities (≈ 12 mm) placed at a considerable distance from the leading edge. It is possible to suggest that two vortices were excited there with different obstruction sides similar to what occurred in experiments in [16], and the shape of the disturbances obtained in [12] is the superposition of two shapes each of which are like those described here in studies at an oblique aerofoil.

Shown in Fig. 5 is the distribution of pulsations across the vortex axis for regimes 1-3 in Fig. 4. With all of the flow velocities in question the maximum pulsations are reached in the core of the vortex in the region of greatest distortion of average flow in the Z-direction. With U_∞ = 16 m/sec profile u'(Z) is much broader, and as for the average velocity profile (Fig. 4) there is gradual collapse of the vortex.

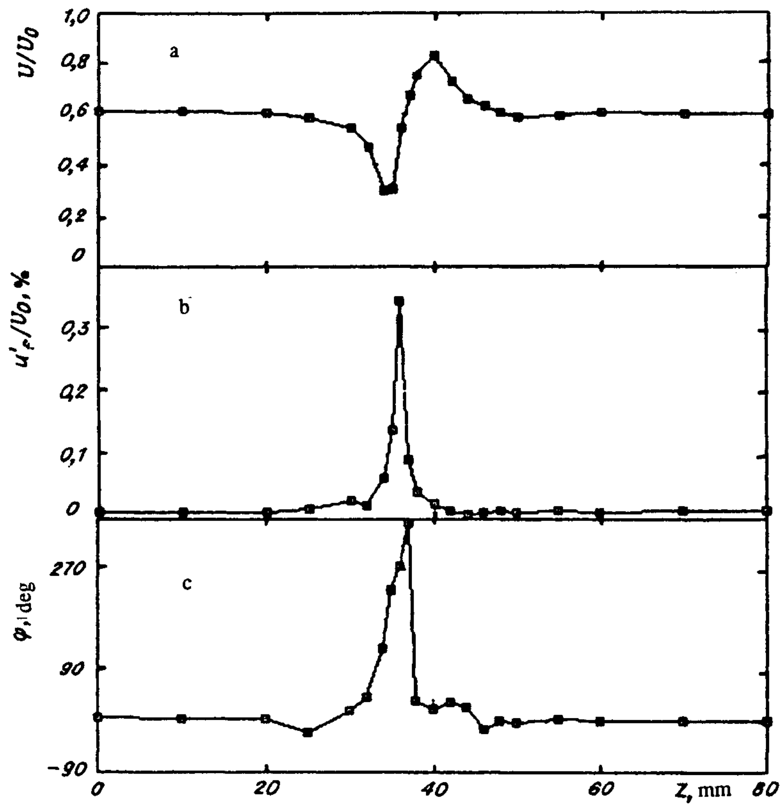

Fig. 10

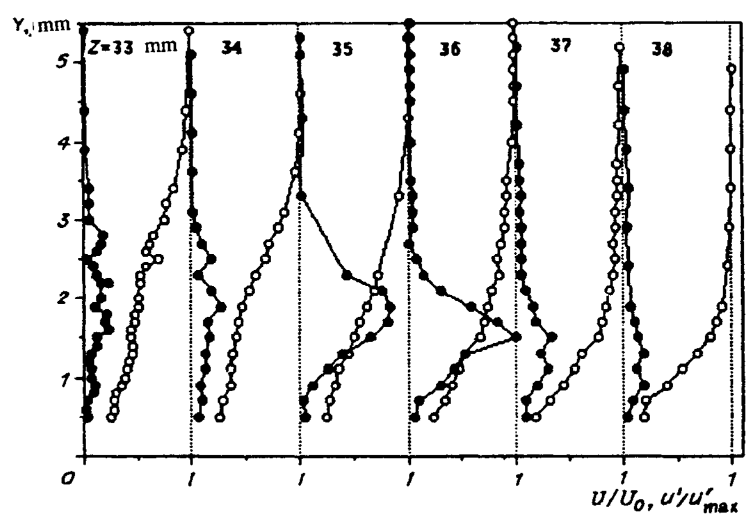

Fig. 11

An idea of the transition which occurs in a vortex is given by spectral pulsations of velocity measured with U_∞ = 11 m/sec at points marked in Fig. 4 with arrows and shown in Fig. 6. Up over the cross flow at a distance from the vortex core in spectrum there is only a low-frequency background of disturbances with integral pulsation intensity less than 0.14% U_0 which points to a laminar boundary layer at the aerofoil outside the vortex in accordance with the preceding paragraph. Close to the vortex core in spectrum 2, two packages of waves are separated with central frequencies close to 250 and 1000 Hz, and over the other direction from the minimum of the average velocity in profile U(Z) 4 there is a package with frequency close to 2000 Hz. The maximum integral pulsations of velocity u_{int}' = 10.2% is reached in spectrum 3 which is close to a sharp drop in velocity in the distribution U(Z). In the next case no separated frequency packages are observed and the spectrum

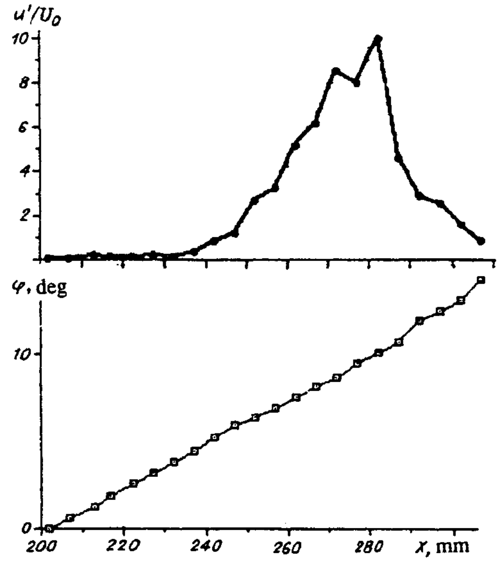

Fig. 12

approaches turbulence. With further distance over Z from the vortex core flow gradually degenerates into laminar. Shown in Fig. 6 is spectrum 5 in which there is still a package with frequencies up to 500 Hz.

Presented in Fig. 7 is a collection of spectra measured at distances from wall 3; 4 mm at the limit of the undisturbed boundary layer δ and 7 mm for spectrum 3 with respect to Z with velocities U = 1.4; 10 and 11 m/sec respectively (lines 1-3). Transition to turbulence occurs first at the aerofoil surface; if close to it the spectra are close to turbulent in form and intensity of pulsations, then at a distance from the wall packages are noted with central frequencies of 1000 and 2000 Hz.

Appearance of a package with frequencies lower than 500 Hz may be attributed to the low-frequency modes of cross flow which should spread along it in the presence of periodically placed stationary vortices and possibly they may exist for quite a long time in the region of relaxation towards a boundary layer undisturbed by a single vortex. Another explanation may be that packages with frequencies of 500 and 2000 Hz are subharmonics and the first higher disturbance harmonics are close to 1000 Hz. In favor of this is the dependence of central high-frequency package frequencies on the velocity of the approach flow measured with X' = 232 mm (Fig. 8).

A package of waves with a frequency of 2000 Hz only arises with comparatively high flow rate which start powerful nonlinear processes in the section selected with respect to X'. It can be seen that frequencies increase linearly with respect to velocity and the difference in central frequencies for package by a factor of two is not a simple coincidence. If it is considered that the region for appearance of high-frequency packages lies in secondary inviscid flow instability in a vortex and it is possible to ignore the effect of Reynolds number on disturbance development, then the main factor with affects the characteristic frequencies of packages is the relative height of the projection h/δ^* and as a consequence the stationary vortex amplitude.

Development of Controlled Travelling Disturbances in a Vortex. We consider some instability characteristics for travelling waves when they were introduced in a controlled fashion and the majority of measurements were carried out in comparison with those without flow excitation. Vibrations were introduced by sound at a frequency f = 330 Hz which is close to the most intensified high-frequency pulsations in a vortex with this velocity at point X' = 232 mm (see Fig. 8)

It is well known that introduction of new, let us say small, disturbances may in some cases affect the average flow in a shear layer [2], changing the object of study itself. The unchangeability of vortex shape with respect to the amplitude of the disturbances generated is demonstrated in Fig. 9 where results are presented for measurements in section X' = 232 mm of distribution U(Z) on introducing disturbances (with an amplitude of about 1% of the maximum pulsation in a vortex) and without them. It can be seen that even this quite high vibration amplitude, which is normally associated with the start of development of nonlinear effects, does not lead to a marked distortion of the vortex. Similar measurements were made at different distances from the wall and they showed similar results. Data in Fig. 9 agree with the results for vortex shape retention with different flow rates described in the previous paragraph since with an increase in velocity the integral amplitude of natural disturbances in a vortex is intensified. This conservative nature of a vortex is important from the point of view of

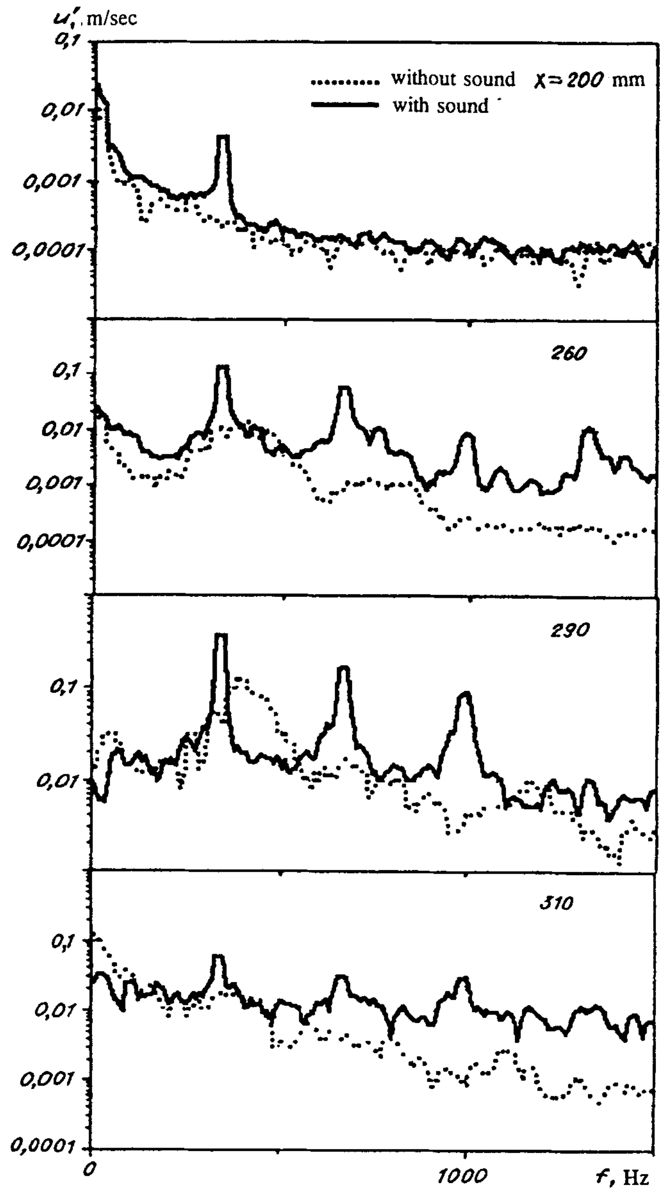

Fig. 13

modelling flow when travelling waves are considered as secondary disturbances on a background of primary flow represented by superposition of undisturbed flow and stationary vortices.

Presented in Fig. 10a-c are the distributions of average velocity U(Z), the mean square pulsations close to f = 330 Hz in a frequency band of 15 Hz $u_f'(Z)$, and their phase $\varphi(Z)$ for a selected sound amplitude. These measurements were made with U_∞ = 8 m/sec and Y = const in the outer part of a vortex close to the maximum of integral velocity pulsations. The maximum vibration is achieved with Z = 36 mm close to the break in distribution U(Z) similar to that described above for a natural package of waves. This distribution of velocity pulsations in the transverse direction was observed in [10] for the lower frequency of two separated modes of secondary instability at an oblique aerofoil. In addition, the similar position of the disturbance maximum with respect to distribution U(Z) is also typical for secondary instability of a sinusoidal type which develops in Hertler vortices [22] whose development is also connected with presence of a strong shear field in the transverse direction.

Confirmation that the secondary instability observed is not connected with the presence of a break in the distribution of average velocity in a normal direction are the profiles U(Y) and $u_f'(Y)$ measured at different coordinate Z in the same section with respect to X′ (Fig. 11). Pulsations are normalized for the maximum $u_{max}' = 2.17\%$ U_0 for section Z = 36 mm in which there is no point of inflection with respect to coordinate Y.

It can be seen from Fig. 10 that the wave phase within a vortex experiences a jump. At the edges it emerges into a constant level, i.e., in these sections the effect of sound on the signal recorded by the thermo-anemometer is considerable. Jumps in phase by 180° or more are often observed in profiles of pulsations $u_f'(Y)$ for instability waves of a different nature [1, 2] and they point to the opposite direction of flow particle vibration at different points of the profile. In this case a similar effect is observed in the transverse direction and probably it is the same in nature.

Presented in Fig. 12 are measurements for the increase in amplitude in the frequency band of 4 Hz and wave phases along the vortex made for $U_\infty = 7$ m/sec with Y = const close to the maximum of velocity pulsation. The propagation velocity for disturbances with frequency f = 330 Hz determined from the curve for the increase in wave phase along the vortex is 0.56 of U_0 over a large section of wave development. On reaching a wave amplitude of ≈2% of U_0 an increase in the phase commences although it is small and it deviates from a linear rule. The maximum in wave amplitude is achieved with X′ = 282 mm. Down over the flow the wave amplitude gradually decreases and the velocity of its propagation increases.

The process of transition to turbulence is demonstrated by a collection of spectra presented in Fig. 13 recorded in the absence and in the presence of sonic action on the flow. It can be seen that a wave of very weak amplitude $u_f'/U_0 = 0.06\%$ (X′ = 210 mm) down over the flow increases and leads to marked intensification of integral pulsations in the transition region, which points to the productivity of nonlinear interaction generated by it.

Thus, it is shown that a single surface irregularity placed close to the nose of an oblique aerofoil may lead to formation in the boundary layer of a single stationary vortex of the same type which arises as a result of instability of cross flow under natural conditions.

A package of high-frequency pulsations forms in this vortex, i.e., secondary disturbances whose development leads down over the flow to a laminar turbulent transition in a narrow region of stationary vortex localization.

The distribution of amplitude and phase of high-frequency vibrations within a vortex has been found. It has been shown that development of these disturbances is connected with presence of a point of inflection on the distribution of average velocity in a vortex in a transverse direction. It is determined that these vibrations under the test conditions spread down through the flow along the vortex axis with a velocity of 0.56 of the external flow velocity.

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REFERENCES

1. B. G. B. Klingmann, A. V. Boiko, K. J. A. Westin, et al., "Experiments on the stability of Tollmien–Schlichting waves," Eur. J. Mech. B/Fluids, **12**, No. 4 (1993).
2. A. V. Boiko, "Development of vortex disturbances in local separation flows," Author's Abstr. Diss. Cand. Phys.-Mat. Sci, ITPM SO RAN, Novosibirsk (1992).
3. Y. Kohama, "Some expectation on the mechanism of cross-flow instability in a swept-wing flow," Acta Mech., **66** (1987).
4. Y. Kohama, "Cross-flow instability in rotating disk boundary layer," Paper/AIAA; No. 87-1340, New York (1987).
5. R. Michel, D. Arnal, E. Coustols, and J. C. Juillen, "Experimental and theoretical studies of boundary layer transition on a swept infinite wing," Laminar-Turbulent Transition: IUTAM Symp., Novosibirsk (1984); Springer-Verlag, Berlin (1985).
6. H. Bippes, "Instability features appearing on swept wing configurations," Laminar-Turbulent Transition: IUTAM Symp., Toulouse (1989); Springer-Verlag, Berlin (1990).
7. H. Bippes, "Experiments on transition in three-dimensional accelerated boundary layer flows," Boundary Layer Transition and Control: Proc. Conf., Cambridge (1991), London (1991).
8. H. L. Reed, "An analysis of wave interactions in swept-wing flows," Laminar-Turbulent Transition: IUTAM Symp., Novosibirsk (1984); Springer-Verlag, Berlin (1985).
9. W. S. Sric and L. G. Yeates, "Generation of cross-flow vortices in a three-dimensional flat plate flow," Laminar-Turbulent Transition: IUTAM Symp., Novosibirsk (1984); Springer-Verlag, Berlin (1985).

10. Y. Kohama, W. S. Seric, and J. A. Hoos, "A high-frequency, secondary instability of cross-flow vortices that leads to transition," Boundary Layer Transition and Control: Proc. Conf., Cambridge (1991), London (1991).
11. H. L. Reed and W. S. Seric, "Stability of three-dimensional boundary layer," Ann. Rev. Fluid Mech., **21**, 235-284 (1989).
12. Yu. S. Kachanov and O. I. Tararykin, "The experimental investigation of stability and receptivity of a swept-wing flow," Laminar-Turbulent Transition: IUTAM Symp., Toulouse (1989); Springer-Verlag, Berlin (1990).
13. J. R. Dagenhart, W. S. Seric, J. A. Hoos, and M. C. Mousseux, "Experiments on swept-sing boundary layers," Laminar-Turbulent Transition: IUTAM Symp., Toulouse (1989); Springer-Verlag, Berlin (1990).
14. T. M. Fisher, S. Hein, and U. Dallman, "A theoretical approach for describing secondary instability features in three-dimensional boundary-layer flows," Paper/AIAA; No. 93-0080, New York (1993).
15. Y. Kohama, F. Ohta, and K. Segawa, "Development and interaction of instabilities in the cross flow field," Laminar-Turbulent Transition: IUTAM Symp., Toulouse (1989); Springer-Verlag, Berlin (1990).
16. A. A. Bakchinov, G. R. Grek, B. G. B. Klingmann, and V. V. Kozlov, "Experimental study of the stability of a three-dimensional boundary layer and transition of it into a turbulent state," Teplofizika i Aeromekahnika, **3** (1994).
17. G. I. Bagaev, V. K. Gorlov, G. V. Medvedev, and N. F. Polyakov, "Low-velocity wind tunnel T-324 with a low level of turbulence," in: Aerophysical Studies [in Russian], ITPM SO AN SSSR, Novosibirsk (1972).
18. B. Yu. Zanin and N. V. Luzhin, "Comparative studies of flow around an aerofoil profile in two wind tunnels," Sib. Fiz.-Tekhn. Zh., No. 2, 99-103 (1991).
19. A. V. Boiko, V. V. Kozlov, A. V. Dovgal', and V. A. Shcherbakov, "Effect of surface roughness on the stability of a boundary layer and its susceptibility to sound vibrations of the flow," All-Union Seminar on Hydrodynamic Stability and Turbulence, IT SO AN SSSR, Novosibirsk (1989).
20. A. V. Johanson and P. H. Alfredsson, "On the structure of turbulent channel flow," J. Fluid. Mech., **122**, 295-314 (1982).
21. L. B. Aizin and N. F. Polyakov, "Generation of Tollmien–Schlichting waves by sound at an individual surface irregularity with flow around it," Preprint No. 17, ITPM, SO AN SSSR, Novosibirsk (1979).
22. J. D. Swearingen and R. F. Blackwelder, "The growth and breakdown of streamwise vortices in the presence of a wall," J. Fluid. Mech., **182**, 255-290 (1987).