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Experimental study of the influence of external disturbances on the position of the laminar-turbulent transition on swept wings at M = 2*

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The influence of external vortex disturbances on the position of the laminar-turbulent transition in boundary layers on swept wings at the Mach number M = 2 is experimentally studied. The experiments are performed with two wing models; the sweep angles of the leading edges are 45° and 72°. The vortex disturbances are generated by a wire placed ahead of the nozzles in the subsonic part of the flow. It is found that such disturbances increase the amplitude and change the spectral composition of oscillations in the boundary layer; moreover, they can induce earlier turbulization of the flow.

Keywords: supersonic boundary layer, swept wing, laminar-turbulent transition, transition Reynolds number, vortex disturbances.

Introduction

The necessity of studying the onset of turbulence in three-dimensional boundary layers is inspired by numerous applications. In particular, such boundary layers are observed in the flow around swept wings of the aircraft. Investigations of this topic are especially important for laminarization of the flow around various structural elements of flying vehicles and for development of methods of predicting the position of the laminar-turbulent transition on aircraft wings.

Though experimental studies aimed at determining the position of the laminar-turbulent transition in supersonic boundary layers on swept wings have been performed since the 1950s and are still continued [1–4], available data are insufficient to obtain a comprehensive idea on this phenomenon. Moreover, the Reynolds numbers of the transition of the supersonic boundary layer on swept wings obtained in different experiments may differ by an order of magnitude [1–4]. Apparently, the noticeable difference in the Reynolds number values may be caused by uncontrolled noise in high-speed wind tunnels.

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It was demonstrated [5] that flow disturbances include vortex, acoustic, and entropy perturbations. Pate [6] analyzed the effect of various modes of unsteady disturbances on the position of the laminar-turbulent transition at supersonic velocities. It was shown that the most influential source of pressure oscillations in supersonic wind tunnels is the turbulent boundary layer on the walls of the nozzle and test section [5–7]. As it follows from publications cited in [5–7], vortex disturbances from the settling chamber produce a weak effect on the transition position. However, it was reported in [8] that a change in the turbulence level in the settling chamber from 0.6 % to 7 % was observed to produce a strong effect on the transition at $M \leq 2.5$, whereas the influence for high Mach number values was insignificant. It should be noted that all experiments described in [5–7] were performed in wind tunnels with a high turbulence level, while the noise in the experiments [8] was somewhat lower. The first experimental studies of the influence of vortex disturbances on the onset of turbulence in supersonic boundary layers were performed in the low-noise wind tunnel T-325 based at the Institute of Theoretical and Applied Mechanics of the Siberian Branch of the Russian Academy of Sciences [9] at the Mach number $M = 2.5$. Kosinov and Semionov [10] measured the levels of oscillations of the mass flow rate and stagnation temperature in the test section of the wind tunnel T-325 at the Mach number $M = 2$. It was demonstrated that oscillations of the stagnation temperature in the flow in the T-325 test section were close to zero, and the free flow mainly contained acoustic disturbances. The mass flow rate oscillations were approximately equal to 0.2 % of the mean flow in a wide range of the unit Reynolds number. Before that, no investigations of the influence of vortex disturbances on the transition location were performed at such a low noise level.

The experiments [9] were performed with a wing model that had a lenticular profile; the sweep angle of the leading and trailing edges was $\chi = 45°$. Vortex disturbances were generated by a wire placed ahead of the nozzles in the subsonic part of the flow. It was shown that vortex disturbances exert a significant effect on the position of the laminar-turbulent transition. In the present study, we consider two wing models with sweep angles of the leading edges equal to 45° and 72°. The receptivity of supersonic boundary layers to vortex disturbances on the wing model with the sweep angle $\chi = 72°$ was not studied in earlier investigations.

Arrangement of experiments

The experiments were performed in the low-noise supersonic wind tunnel T-325 based at the Institute of Theoretical and Applied Mechanics of the Siberian Branch of the Russian Academy of Sciences at the Mach number $M = 2$. The measurements were performed on two models of a swept wing mounted at a zero angle of attack in the central section of the wind tunnel test section. The first model was a wing with a lenticular profile; the sweep angles of the leading and trailing edges were $\chi = 45°$. The model length was 0.38 m, its width was 0.2 m, the maximum thickness was 12 mm, and the relative thickness was 3 %. The drawing of the model can be found in [11]. The second model was a wing with a variable chord length over the wingspan (the chord length was 500 mm near the wing base and 200 mm at near the wing tip). The sweep angle of the leading edge was 72°, and that of the trailing edge was 58°. A detailed description of the model was provided in [12]. According to the classification in terms of the Mach number normal to the leading edge of the model, the wing with the sweep angle $\chi = 45°$ at $M = 2$ corresponds to a situation with a supersonic leading edge, while the wing with $\chi = 72°$ corresponds to a subsonic leading edge.

Vortex disturbances were generated by a wire placed ahead of the nozzles in the subsonic part of the flow. The method of generation of vortex disturbances by a wire is used at subsonic [13–19] and supersonic [9] velocities. Wires with diameters $d = 0.6$, 0.9, 1.9, and 3.3 mm were used in the present experiments. The results on hot-wire measurements of freestream oscillations for different wire diameters were reported in [10]. It was found that freestream disturbances for the wire with the diameter $d = 0.6$ mm could not be identified on the background of natural disturbances. For greater wire diameters, the freestream disturbances were seen to exceed the natural background, and the intensity of vortex disturbances increased with increasing wire diameter. It was also noted that the region of vortex disturbances became greater in the transverse direction with increasing d.

Disturbances in the flow were registered by a constant-temperature hot-wire anemometer. The sensors were made of a tungsten wire 10 μm in diameter and approximately 1.5 mm long. The wire overheating was about 0.8, and the measured disturbance mainly corresponded to mass flow rate oscillations. The mean and fluctuating characteristics of the flow were measured by an automated data acquisition system. The experiment arrangement, data acquisition system, and data processing were described in more detail in [9, 20, 21]. The position of the laminar-turbulent transition was determined by a hot-wire anemometer (the measurement methods were reported in [20]) or by a pneumometric method (with the use of a circular pressure probe mounted on the model surface). The pressure P_0' was determined by a piezo-resistor pressure sensor Siemens KPY-43A, which was connected to the Agilent 34401A voltmeter. The sensor was calibrated before the experiments.

Results and analysis

The influence of external vortex disturbances on the onset of turbulence in a supersonic boundary layer on the wing model with the sweep angle $\chi = 45°$ at the Mach number M = 2 and unit Reynolds number $\mathrm{Re}_1 = 5\cdot10^6\ \mathrm{m}^{-1}$ was studied experimentally. The hot-wire sensor was moved parallel to the leading edge of the model (along the transverse coordinate z') in the cross section $x = 50$ mm (x is the streamwise coordinate) in the supersonic part of the boundary layer in the region with the maximum level of mass flow rate oscillations. The measurement results are presented in Fig. 1, where the coordinate $z' = 0$ mm corresponds to the middle of the model in the transverse direction and is located in the wake behind the wire. The maximum disturbances in the boundary layer were obtained for $d = 3.3$ mm, while the disturbances at $d = 0.6$ mm practically could not be identified on the background of natural disturbances. The maximum amplitude was found to be at $z' = 4$ mm.

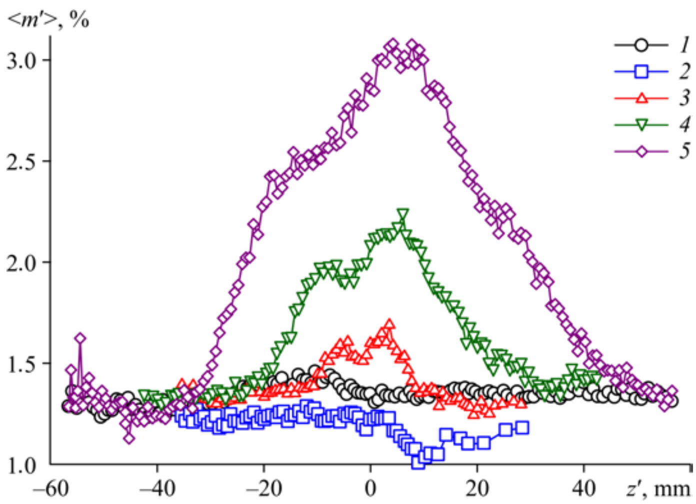

Fig. 1. Distributions of the amplitude of oscillations in the boundary layer on a swept wing versus the transverse coordinate at a distance of 50 mm from the leading edge of the model for different wire diameters: d = 0 (*1*), 0.6 (*2*), 0.9 (*3*), 1.9 (*4*), and 3.3 (*5*) mm.

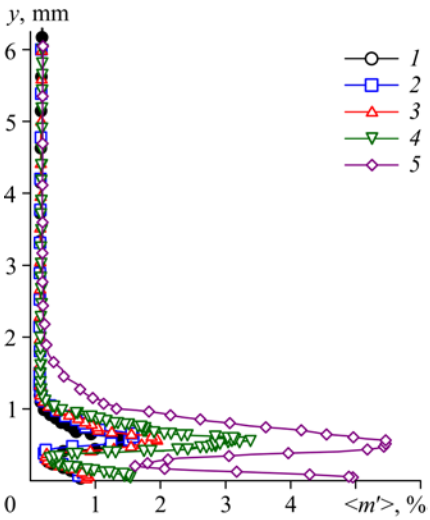

Fig. 2. Profiles of oscillations measured at a distance of 125 from the leading edge of the swept wing for different wire diameters. See the notations in Fig. 1.

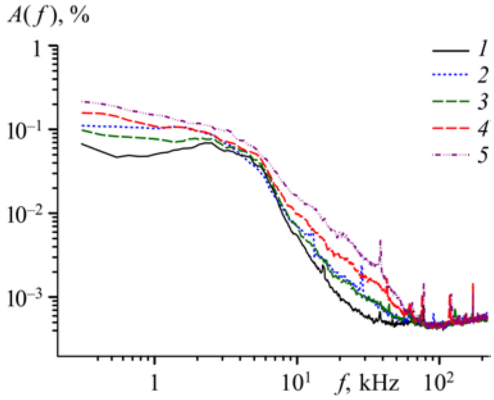

Fig. 3. Amplitude-frequency spectra of oscillations at $x = 50$ mm versus the diameter of the source of disturbances. See the notations in Fig. 1.

The profiles of disturbances for all wire diameters and in the absence of the source of disturbances were measured in the wake behind the wire at $z' = 0$ mm for the streamwise coordinates $x = 50$, 75, 100, and 125 mm. The profiles measured at $x = 125$ mm are presented in Fig. 2 for different sources of vortex disturbances. Here the coordinate $y = 0$ mm corresponds to the model surface determined by means of touching of the hot-wire sensor. The measurements showed that an increase in the wire diameter leads to an increase in the intensity of disturbances generated in the boundary layer.

The amplitude-frequency spectra of mass flow rate oscillations obtained in the region with the maximum disturbances are plotted in Fig. 3 for different diameters of the source of disturbances and streamwise coordinate $x = 50$ mm. The measurements showed that a change in the wire diameter leads to a change in the spectral composition of mass flow rate oscillations in the boundary layer. It is seen that the amplitude grows in both low-frequency and high-frequency ranges with increasing wire diameter.

Figure 4 shows the evolution of the spectra of oscillations in the downstream direction in the absence of the source of disturbances (*a*) and for wire diameters of 1.9 (*b*) and 3.3 (*c*) mm. If the source of disturbances is absent, the most intense growth of oscillations is observed in the frequency range of 10 – 30 kHz (Fig. 4*a*). The linear stability theory predicts that this frequency range corresponds to the most intensely growing oscillations of the transverse flow. For the wire diameters up to 1.9 mm, the most pronounced growth in the boundary layer is also observed in the same frequency range (Fig. 4*b*). However, in the initial cross sections, the amplitude of oscillations here is higher than that in the absence of the source of disturbance, and its growth in the downstream direction is less intense. For the wire diameter of 3.3 mm, enhancement of mass flow rate oscillations is observed in the measurement region in a wide frequency range (Fig. 4*c*), which is typical of the transitional flow regime in the boundary layer.

The experimental investigations of the influence of external vortex disturbances on the position of the laminar-turbulent transition in a supersonic boundary layer on the wing model with the sweep angle $\chi = 45°$ were performed in the section $z' = 0$ mm (in the wake behind the wire). The measured results are presented in Fig. 5 in the form of disturbance growth curves for different wire diameters as functions of the Reynolds number $\mathrm{Re}_x = \mathrm{Re}_1 \cdot x$. The peaks of the distributions correspond to the position of the end of the laminar-turbulent transition. In the present experiments, the measurements for $d = 3.3$ mm and 1.9 mm (curves *5* and *4*) were performed in a situation where the hot-wire sensor was moved along the streamwise coordinate x at a constant unit Reynolds number $\mathrm{Re}_1 = 5 \cdot 10^6$ m^{-1}. For $d = 0.9$ mm and 0.6 mm (curves *3* and *2*), the measurements were performed at a fixed position of the wire sensor $x = 125$ mm and varied

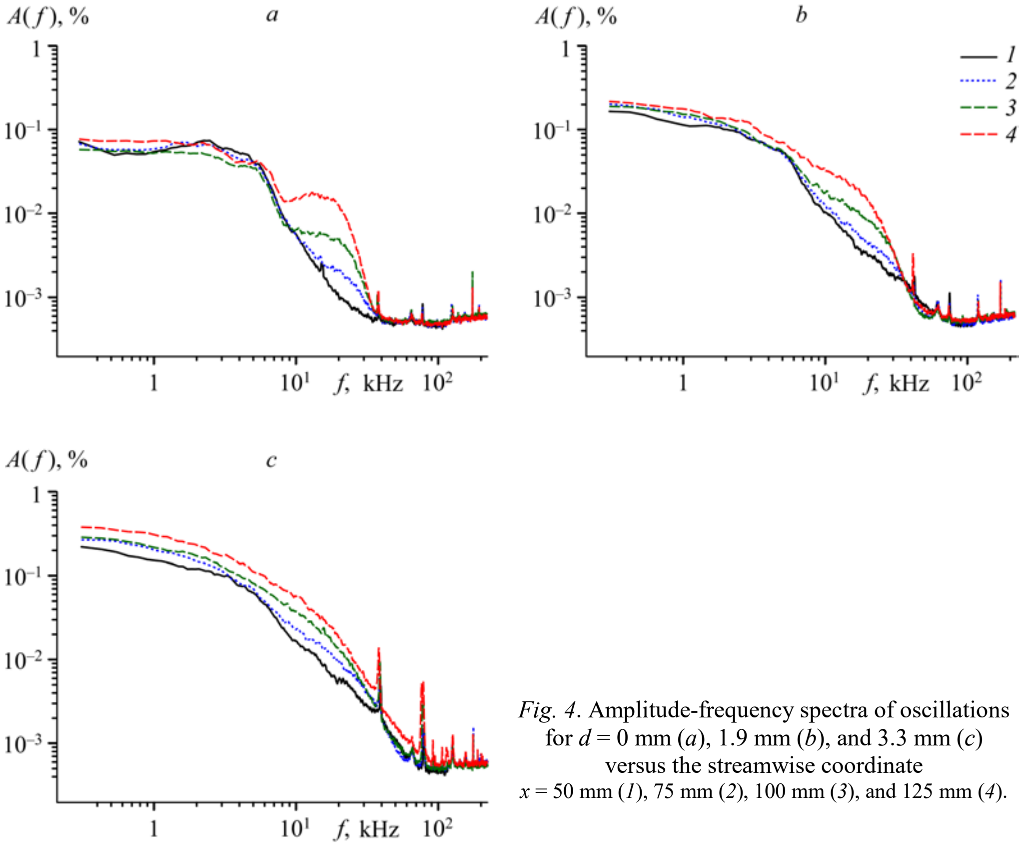

Fig. 4. Amplitude-frequency spectra of oscillations for d = 0 mm (*a*), 1.9 mm (*b*), and 3.3 mm (*c*) versus the streamwise coordinate x = 50 mm (*1*), 75 mm (*2*), 100 mm (*3*), and 125 mm (*4*).

unit Reynolds number of the flow. The measurements without the source of external disturbances (curve *1*) were also performed with a varied unit Reynolds number and a fixed position of the wire sensor at x = 150 mm. The data in Fig. 5 reveal a significant effect of the intensity of vortex disturbances on the position of the laminar-turbulent transition ($\mathrm{Re}_{\mathrm{tr}} \approx 2.1\cdot10^6$

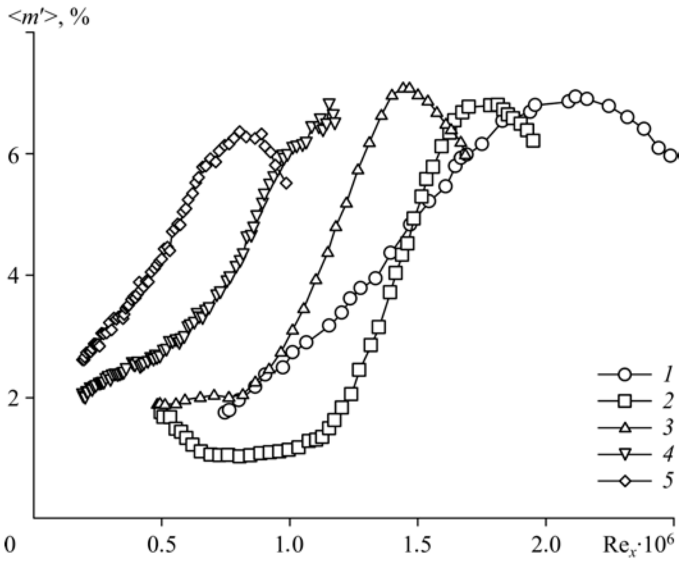

Fig. 5. Distributions of mass flow rate oscillations $\langle m' \rangle$ versus the Reynolds number for different wire diameters. See the notations in Fig. 1.

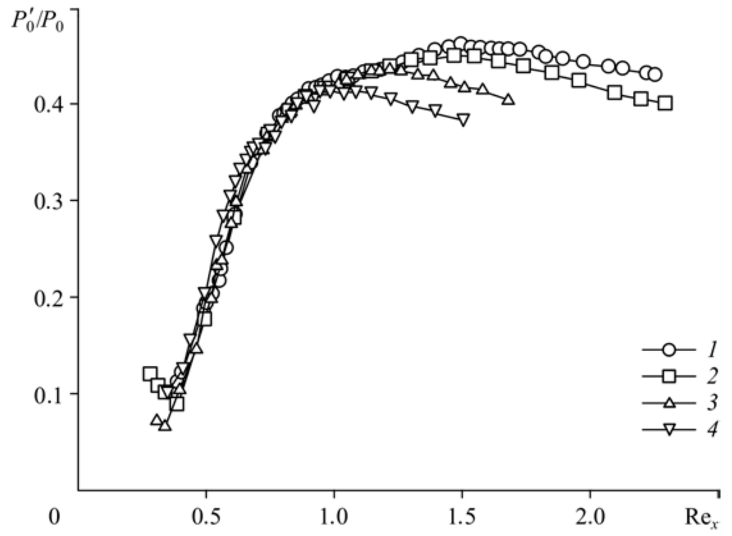

Fig. 6. Curves P'_0/P_0 versus the Reynolds number Re_x on the wing model with the sweep angle $\chi = 72°$ for different wire diameters.
d = 0 mm (*1*), 0.9 mm (*2*), 1.9 mm (*3*), and 3.3 mm (*4*).

in the free stream and $Re_{tr} \approx 0.8\cdot10^6$ in the case with d = 3.3 mm). An increase in the wire diameter leads to a decrease in the transition Reynolds number.

On the wing with the sweep angle of the leading edge $\chi = 72°$ (subsonic leading edge), the position of the laminar-turbulent transition for selected values of the wire diameter was determined by using a total pressure probe, which was mounted in the section $z' = 0$ (in the wake behind the wire) at the distance x = 90 mm from the leading edge of the model. The laminar-turbulent transition was studied at a fixed position of the probe with variation of the unit Reynolds number of the flow Re_1. The measured results are shown in Fig. 6 in the form of the normalized pressure curves P_0'/P_0 as functions of the Reynolds number $Re_x = Re_1 \cdot x$ for different wire diameters. The peaks of the distributions correspond to the position of the end of the laminar-turbulent transition. Similar to the case of a supersonic leading edge, an increase in the wire diameter leads to a decrease in the transition Reynolds number. The maximum influence of vortex disturbances on the transition position is observed for the wire diameter of 3.3 mm ($Re_{tr} \approx 1.5\cdot10^6$ in the free stream and $Re_{tr} \approx 0.9\cdot10^6$ in the case with d = 3.3 mm). At d = 0.9 mm, no noticeable influence of vortex disturbances on the transition position was observed.

Conclusions

The influence of external vortex disturbances on the laminar-turbulent transition in supersonic boundary layers on swept wings with subsonic and supersonic leading edges at the flow Mach number M = 2 was experimentally studied. Vortex disturbances were generated by a wire.

It was experimentally observed that vortex disturbances in the free stream led to an increase in the amplitude and to the changes in the amplitude-frequency composition of mass flow rate oscillations in the boundary layer. It was demonstrated that such disturbances might lead to early turbulization of the flow in a supersonic boundary layer on the wing in the cases of both supersonic and subsonic leading edge. Thus, the transition Reynolds number for the wing with the sweep angle of the leading edge 45° (supersonic leading edge) is $Re_{tr} \approx 2.1\ 10^6$ in the free stream and $Re_{tr} \approx 0.8\cdot10^6$ in the case with the maximum level of external vortex disturbances, For the wing with the sweep angle of 72°, the transition Reynolds number is $Re_{tr} \approx 1.5\cdot10^6$ in the free stream and $Re_{tr} \approx 0.9\cdot10^6$ in the case with the maximum level of external vortex disturbances.

References

1. **S.A. Gaponov and A.A. Maslov,** Development of Disturbances in Compressible Flows, Nauka, Novosibirsk, 1980.
2. **D.M. Bushnell,** Notes on initial disturbances field for transition problem, in: M.Y. Hussaini, R.G. Voigt (Eds.), Instability and Transition, Springer-Verlag, Berlin, 1990, Vol. 1, P. 217−232.
3. **S.P. Schneider,** Effects of high-speed tunnel noise on laminar-turbulent transition, J. Spacecraft and Rockets, 2001, Vol. 38, No. 3, P. 323−333.
4. **N.V. Semionov, Yu.G. Yermolaev, A.D. Kosinov, A.D. Dryasov, A.N. Semenov, and A.A. Yatskikh,** The influence of flow parameters on the transition to turbulence in supersonic boundary layer on swept wing, AIP Conf. Proc., 2016, Vol. 1770, P. 030050-1–030050-6.
5. **M.V. Morkovin,** On supersonic wind tunnels with low free-stream disturbances, ASME, J. Appl. Mech., 1959, Vol. 26, series E, P. 319−324.
6. **S.R. Pate,** Effect of wind tunnel disturbances on boundary layer transition with emphasis on radiated noise: a review, AIAA paper No. 80–431, 1980.
7. **J. Laufer,** Aerodynamic noise in supersonic wind tunnels, Aerospace Sci., 1961, Vol. 28, No. 9, P. 685−692.
8. **J. Laufer and J.E. Merce,** Result and critical discussion of transition-Reynolds numbers measurements on insulated cones and flat plates in supersonic wind tunnels, JPL Report No. 20–90, 1965.
9. **A.D. Dryadov, Yu.G. Yermolaev, A.D. Kosinov, N.V. Semionov, and A.N. Semenov,** Effect of vortex disturbances on the laminar-turbulent transition in a supersonic boundary layer on a swept wing at M = 2.5, Vestn. NGU, Ser. Fizika, 2016, Vol. 11, No. 1, P. 16−22.
10. **A.D. Kosinov and N.V. Semionov,** The laminar-turbulent transition experiments in supersonic boundary layers, AIP Conf. Proc., 2019, Vol. 2125, P. 030105-1–030105-5.
11. **A.D. Kosinov, N.V. Semionov, Y.G. Yermolaev, B.V. Smorodsky, G.L. Kolosov, A.A. Yatskikh, and A.N. Semenov,** The influence of moderate angle-of-attack variation on disturbances evolution and transition to turbulence in supersonic boundary layer on swept wing, Proc. Institution of Mech. Engineers, Part G, J. Aerospace Engng, 2020, Vol. 234, No. 1, P. 96–101.
12. **A.N. Semenov, V.L. Kocharin, and N.V. Semionov,** Numerical simulation of stationary flow around a wing with a subsonic leading edge at M = 2 and 2.5, J. Phys.: Conf. Series, 2019, Vol. 1404, No. 1, P. 012121-1–012121-4.
13. **M.N. Kogan, V.G. Shumilkin, M.V. Ustinov, and S.V. Zhigulev,** Response of boundary layer flow to vortices normal to the leading edge, J. Mech. — B / Fluids, 2001, Vol. 20, No. 6, P. 813–820.
14. **J.F. Watmuff,** Effect of weak freestream uniformity on boundary layer transition, J. Fluid Engng, 2006, Vol. 128, P. 247–257.
15. **A.M. Pavlenko, B.Yu. Zanin, and M.M. Katasonov,** Flow around a small-sized UAV model in a turbulent trace, AIP Conf. Proc., 2018, Vol. 2027, P. 040004-1–040004-7.
16. **A.M. Pavlenko, B.Yu. Zanin, A.V. Bykov, and M.M. Katasonov,** Flow around the wing models with straight and swept leading edge in case of contact with turbulent wake, J. Phys.: Conf. Series, 2019, Vol. 1382, P. 012030-1–012030-6.
17. **A.M. Pavlenko, B.Yu. Zanin, M.M. Katasonov, and A.V. Bykov,** An experimental study of the influence of the type of turbulent wake on the flow around models of wings of various shapes, J. Phys: Conf. Series, 2019, Vol. 1404, P. 012093-1–012093-7.
18. **A.M. Pavlenko, A.V. Bykov, and B.Yu. Zanin,** Influence of external disturbances on the flow of straight and swept wings, J. Phys.: Conf. Series, 2020, Vol. 1666, P. 012039-1–012039-7.
19. **M.M. Katasonov, V.V. Kozlov, N.V. Nikitin, and A.M. Pavlenko,** Emergence and Evolution of Localized Disturbances in a Circular Tube and Boundary Layer, Tutorial, 3rd edition, Novosibirsk State University, Novosibirsk, 2019.
20. **Yu.G. Ermolaev, A.D. Kosinov, A.N. Semenov, N.V. Semionov, and A.A. Yatskikh,** Effect of unit Reynolds number on the laminar-turbulent transition on a swept wing in supersonic flow, Thermophysics and Aeromechanics, 2018, Vol. 25, No. 5, P. 659−665.
21. **N.V. Semionov, Yu.G. Yermolaev, A.D. Kosinov, V.L. Kocharin, A.V. Panina, A.N. Semenov, S.A. Shipul, and A.A. Yatskikh,** Experimental study of the laminar-turbulent transition on models of wings with subsonic and supersonic leading edge at M = 2, J. Phys.: Conf. Series, 2019, Vol. 1404, P. 012097-1–012097-5.