An experimental study of the influence of the type of turbulent wake on the flow around models of wings of various shapes

A M Pavlenko, B Yu Zanin, M M Katasonov and A V Bykov
Khristianovich Institute of Theoretical and Applied Mechanics SB RAS,
4/1, Institutskaya str., Novosibirsk, 630090, Russia
pavlyenko@gmail.com

Abstract. This paper presents the results of experimental studies aimed at studying the influence of the type of turbulent wake on the flow around models of various shapes. The patterns of visualization of flow structure for each flow regime were obtained on all models. The structure of the turbulent wake in space for two sources of disturbances is investigated. A comparison was made between the results. It was found that, depending on the type of turbulent wake, the separation region can significantly decrease in size.

1. Introduction
It is well known that during the cruise flight mode, local separation zones at subsonic speeds may form on the surface of the wings of aircraft [1-2]. With an increase in the angle of attack, the local separation region shifts toward the leading edge until it disappears completely. Moreover, near the trailing edge of the wing, a separation of the turbulent boundary layer begins to form. A further increase in the angle of attack to critical values leads to a separation of the flow from the leading edge, the formation of large-scale vortices and a return flow. The presence of stationary disturbance sources on the surface of the wings can lead to a change in the structure of the separated flow, up to its complete elimination, depending on the flow regime [3-6]. A new area of research is the study of the influence of external disturbances on the structure of separated flows [7]. The results of experimental studies presented below are the result of the continuation of a whole range of work on the study of the flow around an aircraft when it enters a turbulent wake. Due to the rapid development of small unmanned aircraft, the relevance of these studies is not in doubt.

2. Experimental setup
The experiments were carried out in two closed-type subsonic wind tunnels MT-324 and T-324 ITAM SB RAS Novosibirsk (Russia). The degree of free-stream turbulence of the MT-324 wind tunnel was 0.4% and T-324 was 0.04%. The study was carried out on models of wings with a straight and arrow-shaped leading edge, the dimensions of which are shown in figure 1. The span of the straight wing was 200 mm and the chord was 100 mm. Three types of hairy thread with a diameter of 0.5, 1.5 and 3 mm and three smooth fishing lines with a diameter of 0.8, 2 and 3 mm were used as a source of external disturbances. One specific thread (fishing line) was pulled upstream in front of the model and created a turbulent wake behind itself, which ran onto the wing model. The distance between the thread (fishing line) and the model was 760 mm and did not change in all experiments.
Soot-oil visualization was used as the main research method. A mixture of titanium dioxide and kerosene was applied to the surface of the model. After drying of kerosene, limiting streamlines appeared on the wing. To obtain quantitative data on the structure of the flow behind the thread and fishing line, the method of hot-wire anemometry was used.

3. Results

3.1. Investigation of the effect of a turbulent wake on the flow around a model with an arrow-shaped leading edge

The first series of experiments was aimed at studying the flow around a flying wing model when it enters a turbulent wake at a supercritical angle of attack. These studies have focused on the stall flow regime. The angle of attack was set at $\alpha = 18^\circ$. The free-stream velocity was $U_\infty = 22.5$ m/s. For given parameters, a stall flow regime is realized on the wing over the entire surface of the wing (see figure 2a). The direction of flow in photos is from top to bottom. The flow breaks from the leading edge, and two large-scale against the rotating vortices are formed. Then a thread (fishing line) was pulled to generate a turbulent wake 20 mm below the level of the leading edge at a zero angle of attack. When a wing enters a turbulent wake generated by a fishing line with a diameter of 0.8 mm, a stall flow regime is preserved on the model surface (see figure 2b). An increase in fishing line diameter to 2 mm led to a change in flow around. One large-scale vortex has substantially decreased in size and its focus has shifted in the left lateral edge (see figure 2c). The area of the attached flow in the left part of the wing increased. An increase in the diameter of the fishing line to 3 mm led to similar results in the case of 2 mm fishing line. It is worth noting that the right large-scale vortex has slightly decreased in size (see figure 2d). The wake of the hairy with a diameter of 0.5 mm affected the flow around the model in the same way as a fishing line with a diameter of 3 mm (see figure 2e).

The most interesting result was obtained under the influence of a hairy thread 1.5 mm in diameter (see figures 2f and 2g). This experiment was repeated several times and it was found that under the same conditions on the wing two types of flow are possible. The first type of flow is a significant increase in the region of the attached flow with a shift of the focal points of the vortices to the lateral edges of the model (see figure 2f). The second type of flow is a similar result in the case of hairy thread with a diameter of 0.5 mm (see figure 2g). A turbulent wake behind a hairy filament with a diameter of 3 mm led to a stable flow regime with the formation of small-sized vortices at the lateral edges (see figure 2h).

Then the thread (fishing line) was lowered 40 mm below the level of the leading edge at a zero angle of attack. Again experiments were conducted with three types of fishing line and three types of hairy thread. As an example, figure 3a shows the effect of the trace of a hairy thread 1.5 mm in diameter.
On the wing, the region of the attached flow significantly increased, and small-sized eddies formed near the lateral edges. This result was obtained for all 6 types of turbulent wake sources.

Figure 2. Visualization of the flow around the model with arrow-shaped leading edge in different regimes: a- free flow; b- turbulent wake of fishing line with Ø0.8 mm; c- turbulent wake of fishing line with Ø2 mm; d- turbulent wake of fishing line with Ø3 mm; e- turbulent wake of hairy thread with Ø0.5 mm; f and g- turbulent wake of hairy thread with Ø1.5 mm; h- turbulent wake of hairy thread with Ø3 mm.
The installation of turbulators in the form of cones on the surface of the model led to a change in the flow structure (see figure 3b). The height of the cone was 12 mm, the diameter of the base was 8 mm. The cones were installed 100 mm from the side edges. Near the surface, there are two regions of return flow and two large-scale vortices. This flow pattern was observed both during free-flow flow and when a wing enters a turbulent wake.

The effect of a turbulent wake behind a hairy thread 1.5 mm in diameter, set at an angle to the horizontal plane of the wing at 27 degrees, did not lead to a change in the flow structure (see figure 3c). As in the case of a free flow around a wing, there is a global stall with a pair of large-scale vortices on the wing.

Then the same thread was installed on ¼ of the span of the model at an angle of 90 degrees to the horizontal plane of the wing. This led to the full attachment of the flow on the right side of the model (see figure 3d).

Figure 3. Visualization of the flow around the model with arrow-shaped leading edge in different regimes: a- turbulent wake of hairy thread with Ø1.5 mm; b- turbulent wake of hairy thread with Ø1.5 mm and two cones; c- turbulent wake of hairy thread with Ø1.5 mm at an angle of 27 degrees; d- turbulent wake of hairy thread with Ø1.5 mm at an angle of 90 degrees.

3.2. Investigation of the effect of a turbulent wake on the flow around a model with an straight leading edge

The second series of experiments was devoted to the study of the influence of the type of turbulent wake on the flow around the straight wing model at different yaw angles (see figure 4). The model was installed at an angle of attack of $\alpha = 12^\circ$. The yaw angle varied from 0 to 30 degrees. The free-stream velocity was $U_c = 13$ m/s.

The classical separation of the flow from the leading edge with the formation of a return flow and a pair of large-scale vortices is observed in a free flow (see figure 4a). An increase in the yaw angle to 15 degrees led to a shift of the local separation zone towards the left side edge (see figure 4b). It should
be noted that large-scale vortices disappeared. The local separation region decreases significantly when the yaw angle reaches 30 degrees (see figure 4c).

![Figure 4](image)

**Figure 4.** Visualization of the flow around the model with straight leading edge in different regimes: a- free flow, yaw angle $\chi=0^\circ$; b- free flow, yaw angle $\chi=15^\circ$; c- free flow, yaw angle $\chi=30^\circ$; d- turbulent wake of fishing line, yaw angle $\chi=0^\circ$; e- turbulent wake of fishing line, yaw angle $\chi=15^\circ$; f- turbulent wake of fishing line, yaw angle $\chi=30^\circ$; g- turbulent wake of hairy thread, yaw angle $\chi=0^\circ$; h- turbulent wake of hairy thread, yaw angle $\chi=15^\circ$; i- turbulent wake of hairy thread, yaw angle $\chi=30^\circ$.

Then a fishing line with a diameter of 0.8 mm was installed in front of the model. Experiments were conducted at yaw angles of 0, 15, and 30 degrees, which gave results on the influence of the turbulent wake around the model. In all three cases, the attached flow prevails on the wing with a significant decrease in the local separation region (see figures 4d, 4e, and 4f).

The maximum effect from the influence of the turbulent wake was observed from a hairy thread 1.5 mm in diameter, which was installed instead of the fishing line (see figures 4g, 4h and 4i). At zero yaw angle, we managed to maximally attach the flow (see figure 4g). The local separation regions disappeared.

3.3. *Investigation of the structure of the flow behind hairy thread and smooth fishing line*

The third series of experiments was devoted to obtaining quantitative data on the flow structure behind a hairy thread 1.5 mm in diameter and a smooth fishing line with a diameter of 0.8 mm. The method of hot-wire measurements was used. The free-stream velocity was $U_\infty = 13$ m/s. The measurements were carried out across the thread (fishing line) in the Y coordinate, along the thread (fishing line) in the Z coordinate, and depending on the distance between the sensor and the thread (fishing line) at $x = 95, 350$ and 540 mm (see figures 5 and 6).
Figure 5. Hot-wire measurements of turbulent wake depending on the longitudinal coordinate x. a- profiles of average velocity along the Y axis behind the thread (top) and fishing line (bottom). The absolute value. b- the amplitude of the velocity pulsations along the Y axis behind the thread (top) and fishing line (bottom).

Figure 6. Hot-wire measurements of turbulent wake depending on the longitudinal coordinate x. a- profiles of average velocity along the Z axis behind the thread (top) and fishing line (bottom). The absolute value. b- the amplitude of the velocity pulsations along the Z axis behind the thread (top) and fishing line (bottom).

It was found that the width of the trace of the thread is about 25 mm at a distance of 540 mm, which is 5 mm more than the trace of the fishing line under the same conditions. The average amplitude of the velocity pulsations at x = 95 mm is 1% higher in the wake of the thread compared to the trace of the fishing line, but moving downstream the amplitude of the velocity pulsations is leveled. A distinctive feature is the presence of longitudinal structures in the wake of the thread. In the trace of the fishing line, longitudinal structures are not observed.
4. Conclusions
Research of the influence of the type of turbulent wake on the structure of the flow around wing models in the detached mode at supercritical angles of attack were conducted. Photos of visualization of the limiting streamlines near the surface of the models for each case are obtained. Quantitative data were obtained on the structure of the trace of hairy thread and fishing line. A comparative analysis of the results are obtained. It was found that under certain conditions on the flying wing, two types of flow are possible when it enters into a turbulent wake. The influence of a turbulent wake can lead to either a complete flow attachment or a partial one. Partial flow attachment implies the presence of one large-scale vortex on half of the wing and attached flow around the other half of the wing. Such a flow regime can lead to dramatic consequences during the flight of an aircraft, due to the difference in the lifting force at different halves of the model in the presence of a stall and an attached flow. It was found that there is a certain region in space relative to the wing model, by installing a turbulent wake source in it, it is possible to achieve a stable and detached flow near the surface of the wing model.

Acknowledgments
This work was supported by the project of Russian Science Foundation No 18-79-00189. The authors are grateful to the Joint Access Center “Mechanics” of ITAM SB RAS for the provided equipment.

References
[1] Boiko A V, Dovgal A V, Zanin B Yu and Kozlov V V 1996 Thermophysics and Aeromechanics 3 1-13
[2] Traub L W and Cooper E 2008 Journal of aircraft 45 1322-33
[3] Pavlenko A M, Zanin B Y, Katasonov M M and Zverkov I D 2010 Thermophysics and Aeromechanics 17 15-20
[4] Zanin B Yu, Kozlov V V and Pavlenko A M 2012 Fluid dynamics 47 133-40
[5] Pavlenko A M, Zanin B Y and Katasonov M M 2015 Vestnik of NSU 10 19-25 In Russian
[6] Boiko A V, Dovgal A V, Zanin B Yu, Kozlov V V, Lushin V N and Syzrantsev V V 1995 Thermophysics and Aeromechanics 2 37-45 In Russian
[7] Pavlenko A M, Zanin B Y and Katasonov M M 2018 AIP Conference Proceedings vol 2027 edited by V.M. Fomin NY American Institute of Physics Melville 030060 DOI: 10.1063/1.5065278