Flow around the wing models with straight and swept leading edge in case of contact with turbulent wake

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Abstract. The paper presents the results of experimental studies of the flow around wing models with a straight and swept leading edge in contact with a turbulent wake. The experiments were carried out in subsonic wind tunnels at low Reynolds numbers. A fluffy thread was used to simulate a turbulent wake in the flow. The flow patterns on the surface of the wings were obtained before and after the impact of the turbulent wake at various angles of attack, wing sweep angles and free-stream velocity values. It was found that the wake has a significant effect on flow separation and on vortex structures arising above the wings. The evolution of the vortex flow patterns in the areas of separation of the boundary layer and with a change in the flow regime is shown.

1. Introduction

Successes in the field of microelectronics and artificial intelligence systems led to the rapid development of aviation technology. This is, first of all, unmanned aerial vehicles (UAVs) with a take-off weight of 10 g to 10 kg. Their variety and fields of application have grown so quickly lately that not even a single scheme has been developed for their classification. This type of aircraft is used in solving various tasks of a civil and military nature.

An important task is to study the effect of a turbulent wake on the flow around such devices that are operated at low altitudes in the surface boundary layer, where the atmosphere is strongly disturbed. In addition, the UAV during the flight can get into the zones of turbulent vortex wakes behind ground structures, behind other aircraft or behind the relief of the surface of the earth. Therefore, the study of the influence of these factors on the flow around of UAVs has great practical importance for a new direction in aviation – the use of small aircraft for various purposes, which are now becoming increasingly widespread.

This work is devoted to the study of the flow around wing models with a straight and swept leading edge under turbulent wake conditions. The results of the study demonstrated that such a turbulent wake can lead to a significant change in the flow around the UAV under certain flight conditions. The presented work is a continuation of a complex of works on the study of the flow around models of straight and swept wings, the first results of which are published in [1-5].

2. Measurement technique

Experimental studies were conducted in two subsonic wind tunnels mT-324 and T-324 of the Khristianovich Institute of Theoretical and Applied Mechanics. Installation mT-324 refers to a closed
type of wind tunnels with an open working part of square section with dimensions of 200 × 200 × 700 mm. The degree of flow turbulence in the test section is 0.4%. The installation is intended to conduct experiments at low subsonic speeds up to 20 m/s. The wind tunnel T-324 also refers to a closed type of pipe. The dimensions of the closed test section are 1x1x4 meters (width x height x length). The degree of free flow turbulence in the wind tunnel does not exceed 0.04%. The maximum allowable flow velocity in the wind tunnel was 50 m/s.

In the experiments, models of wings with a straight and swept leading edge were used. The models were made of wood and covered with several layers of paint. The surface of the wing was carefully polished to ensure smoothness. The straight wing chord was 100 mm, the span was 200 mm. The central chord of the swept model was equal to 130 mm, the terminal chord was 65 mm, and the span was 200 mm. The sweep angle was 34°. To generate a turbulent wake, a fleecy thread with a diameter of about 1 mm was used. The thread stretched upstream in front of the model. The distance between the thread and the model was varied to obtain the maximum effect on the flow around the wing.

Several flow regimes were implemented in experiments. The parameters were varied: angle of attack in the range from 0° to 14°; sliding angle from 0° to 30°; flow velocity from 9.8 to 13 m/s.

To visualize the near-wall flow, the oil coating method was used. A mixture of titanium dioxide and kerosene was applied on the surface of the wing. During the flow around the model, the kerosene evaporated, and the limiting streamlines appeared on the surface. The method of hot-wire anemometry was used to obtain quantitative data on the structure of the flow behind the thread.

3. Results

The first series of experiments was devoted to the study of the influence of the slip angle on the flow around the model of a straight wing in case of contact with turbulent wake (see figure 1). The model was installed at a sliding angle of 30° and at zero angle of attack. The flow velocity was $U_\infty = 9.8$ m/s. During a free flow around the wing without a turbulent wake, an attached flow is observed on the surface with the formation of a local tear-off bubble near the trailing edge. The turbulent wake leads to a change in the flow structure and a significant decrease in geometrical sizes of the bubble.

The second series of experiments aimed to study the flow around a model at a critical angle of attack depending on the slip angle in case of contact with turbulent wake (see figure 2). The angle of attack was $\alpha = 14°$. The slip angle varied from 0° to 30°. The flow velocity was $U_\infty = 13$ m/s. Figure 2a shows flow around the wing in the free flow. Two large-scale vortices, a backflow region and a stagnant region are formed on the surface. The turbulent wake completely changed the structure of the flow near the surface. The turbulent wake leads to a change in the flow structure and a significant decrease in geometrical sizes of the bubble.

Increasing the slip angle to 15° and 30° leads to the disappearance of large-scale vortices and the formation of a stagnant region that is shifted closer to the side of the model (see figures 2c and 2e). The turbulent wake leads to a decrease

![Figure 1. Visualization of free flow around the wing (a) and when it enters the turbulent wake (b).](image-url)
in geometrical dimensions of the stagnant region at a slip angle of 15° (see figure 2d) and to a full flow attachment at a slip angle of 30° (see figure 2f).

The third series of experiments was aimed at studying the effect of a turbulent wake on the flow around a model with an arrow-shaped leading edge depending on the angle of attack (see figure 3). The flow velocity was \(U_{\infty} = 10\, \text{m/s}\). The slip angle was 0°. The visualization at zero angle of attack showed that two large local bubbles form on the model's surface, which spread throughout the entire wing span (see figure 3a). The turbulent wake significantly reduced the size of the bubbles (see figure 3b). Increasing the angle of attack to \(\alpha = 8°\) led to the displacement of bubbles towards the leading edge (see figure 3c). A flow separation with two vortices formed near the trailing edge of the model. Separation region disappeared in case of contact with turbulent wake, bubbles also decreased in size, the area of attached flow has increased (see figure 3d). At a critical angle of attack \(\alpha = 14°\), a stall regime is realized on the wing (see figure 3e). Two regions of the reverse flow and two pairs of large-

![Figure 2](image)

**Figure 2.** Visualization of flow around the wing depending on the slip angle: a – free flow, slip angle \(\beta = 0°\); b – turbulent wake, slip angle \(\beta = 0°\); c – free flow, slip angle \(\beta = 15°\); d – turbulent wake, slip angle \(\beta = 15°\); e – free flow, slip angle \(\beta = 30°\); f – turbulent wake, slip angle \(\beta = 30°\).
scale vortices are formed. The influence of the turbulent wake leads to a complete change in the flow structure (see figure 3f). For most of the wing, an attached flow is realized with the formation of two stagnant zones near the leading edge.

Figure 3. Visualization of the flow around the flying wing model in different regimes: a- free flow, angle of attack $\alpha = 0^\circ$; b – turbulent wake, angle of attack $\alpha = 0^\circ$; c – free flow, angle of attack $\alpha = 8^\circ$; d – turbulent wake, angle of attack $\alpha = 8^\circ$; e – free flow, angle of attack $\alpha = 14^\circ$; f – turbulent wake, angle of attack $\alpha = 14^\circ$. 
Quantitative data were obtained on the structure of the flow in the wake of the thread using the method of hot-wire anemometry (see figure 4 and figure 5).

**Figure 4.** Hot-wire measurements of flow behind the thread: a – average velocity profiles along the Y coordinate (across the thread); b – velocity pulsations amplitude along the Y coordinate (across the thread).

**Figure 5.** Hot-wire measurements of flow behind the thread: a – average velocity profiles along the Z coordinate (along the thread); b – the velocity pulsations amplitude along the Z coordinate (along the thread).
Conclusions
Experimental studies were performed on the flow around wing models with a straight and swept leading edge in contact with a turbulent wake. It was found that the turbulent wake leads to a significant change in the flow structure near the model, up to the complete elimination of the flow global stall. Pictures of visualization of the flow around the wings are obtained depending on the speed of the oncoming flow, the slip and the attack angles. Quantitative data on the structure of the turbulent wake in space were obtained.

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