Investigation of the influence of the three-dimensional roughness element on the flow over trapezoidal flying wing

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Abstract. The paper is devoted to the investigation of the flow and effects taken place when three-dimensional roughness element is placed on the leading edge of the trapezoidal flying wing. The experimental study was carried out in the working park of the subsonic wind tunnel. Low Reynolds numbers allowed running experiments at in-flight-like conditions. Pictures of the flow structure were obtained by liquid crystal thermography. It was found that longitudinal disturbances on the leading edge and behind three-dimensional roughness element form differently. Inner configuration of the longitudinal structure was shown by hot-wire measurements.

1. Introduction

Nowadays unmanned aerial vehicles or drones are widespread not only in military applications but are also used for civil tasks, such as aerial photography, surveillance, and deliveries. The most optimal concept of the drone aircraft is a trapezoidal flying wing. Since such type of wings has a sweep shape, it leads to the appearance of cross-flow instability which for its part can cause rapid laminar turbulent transition. Level of stream turbulence can affect cross-flow instability [1]. For turbulence level less than 0.1%, the cause of laminar-turbulent transition appearance lies in the development of stationary disturbances excited by surface roughness. For high turbulence level traveling disturbances of cross-flow instability facilitate the transition to turbulence. Free-stream vortices are the source of these traveling disturbances, they add inflection points and thus change the boundary layer structure. Further appearance of secondary disturbances leads to the laminar-turbulent transition [2, 3].

Typical in-flight level of stream turbulence is about 0.05% [4]. This regime can be easily realized in subsonic wind tunnels. Trapezoidal flying wing is the model of many actual aerial vehicles. Thus investigation on the surface of such of wing allows observing the effects appearing for in-flight Reynolds numbers. This work represents the study of the physical mechanisms of laminar-turbulent transition on flying wing model in the favourable pressure gradient area in the presence of three-dimensional roughness element. This experimental investigation is included into a set of works devoted to the investigation of the flow over the trapezoidal flying wing model. First results were published in [5].

2. Experimental setup

The experiment was carried out in the working part of the subsonic wind tunnel AT-324 ITAM SB RAS. Stream turbulence level of this wind tunnel is less than 0.04%. Pitot-Prandtl nozzle connected to
A micro manometer was used to control the free-stream velocity. A minimum value of the velocity was 7.2 m/s and a maximum value was 20 m/s. Reynolds numbers varied in range from $1.8 \times 10^5$ to $5 \times 10^5$.

Investigations were carried out on the windward side of the flying wing model. It was placed in the wind tunnel at angle of attack $\alpha = -5^\circ$ for creating favourable pressure gradient over surface being studied. This parameter was constant during the experiment. Such angle allowed efficiently suppressing the Tollmien-Schlichting waves and realizing appropriate conditions for the appearance of cross-flow instability disturbances.

![Figure 1. Trapezoidal flying wing (a) and dimensions (b).](image)

The axes Ox and Oz of orthogonal coordinate system were in one plane on the wing surface (see figure 1). Zero point in the coordinate system was at the distance of 176 mm from the head of the wing in Oz coordinate direction. Visualization of the flow was made by liquid crystal thermography. This method allows seeing structures forming on the wing surface and obtaining panoramic pictures of the flow. Quantitative data were collected by hot-wire anemometry. The excitation of the stationary disturbances was realized by cylindrical three-dimensional roughness element placed on the leading edge of the wing. The height of the roughness element was 0.98 mm and diameter was 1.6 mm.

3. Results
Mean velocity distribution was measured over the wing at a distance of 20 mm away from the surface (see figure 2). Free-stream velocity $U_0 = 10$ m/s. It can be seen that flow accelerates from the leading edge and further downstream. It means that favourable pressure gradient forms over the wing and area being investigated.
Measurements of mean velocity profiles $U(y)$ for $z = 0$ mm show that boundary layer grows streamwise but still remains attached to the surface of the wing (see figure 3).

During the experiment, pictures of the flow downstream of the three-dimensional roughness element were obtained (see figure 4). Visualization was realized by liquid crystal film placed on the leading edge. The three-dimensional roughness element was located at a distance of 6 mm for $x$ coordinate away for the leading edge. The choice of this location is conditioned by the area of maximum receptivity being near the leading edge, so the roughness element can excite the most intensive longitudinal structures. Visualization shows that longitudinal structures form not only behind three-dimensional roughness element but also on the leading edge. These structures have straight
trajectory while longitudinal disturbance downstream of the roughness element has slightly bent trajectory.

![Figure 4. Three-dimensional roughness element on the leading edge.](image)

\( a \) — \( U_0 = 7.2 \) m/s; \( b \) — \( U_0 = 15.1 \) m/s

The inner structure of the longitudinal disturbance downstream of the three-dimensional roughness element for different transverse sections was obtained by hot-wire anemometry (see figure 5). It can be seen that two disturbances form behind the roughness element, one of them being maintained bigger by cross-flow. Downstream the disturbance generally grows in size. Spectra of velocity pulsation (see figure 6) show presence of wave package with main frequency at high frequency area. Downstream this package moves toward the low frequency range.
Figure 5. Development of the formation of the longitudinal disturbance behind the roughness element. a – x = 91 mm; b – x = 121 mm; c – x = 131 mm; d – x = 141 mm; e – x = 171 mm; f – x = 191 mm.
Figure 6. Spectra of velocity pulsation. a – x = 91 mm; b – x = 121 mm; c – x = 131 mm; d – x = 141 mm; e – x = 171 mm; f – x = 191 mm.

Conclusions
The experimental investigation of the flow over the windward side of the trapezoidal flying wing has been carried out. Liquid crystal thermography has shown that longitudinal structures are formed whether there is a localized three-dimensional roughness element or not. The difference between these two cases is in the trajectory of the longitudinal disturbance. Quantitative data have been obtained by hot-wire anemometry and shown the inner structure and the process of development of longitudinal disturbance.
Acknowledges
The study of the flow structure behind the three-dimensional roughness element on the trapezoidal wing model using the hot-wire method was carried out with the support of the Russian Science Foundation (project No. 16-19-10330). Part of the study of the flow behind the roughness element using the liquid crystal thermography was carried out with the financial support of the Russian Foundation for Basic Research (RFBR) in the framework of the implementation of scientific project No. 19-31-90018.

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