CONTROL OF FLOW SEPARATION ON A SWEPT WING AT LOW REYNOLDS NUMBERS

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Summary The present work is devoted to investigation of flow separation on swept and unswept wings at chord Reynolds numbers of the order of 10^5. With the help of oil-film visualization the limiting streamlines of the 3D separated flow structure at near-stall conditions were determined. The flow separation is dominated by vortex pairs with their focuses located near the wing tips. It is demonstrated how the vortex structure is deformed with sweep angle. Two methods of the wing surface modification (using a 3D hump mounted close to the leading edge and surface waviness) are suggested to prevent the leading-edge stall on swept and unswept wings. The results of the present study can be used to design blades of wind turbines and wings of small-sized air vehicles.

INTRODUCTION

Nowadays the interest of researchers turned again to the wing aerodynamics at low Reynolds numbers. Here the term “low Reynolds numbers” means $Re<0.5*10^5$ based on the wing chord [1]. Such an interest is closely related to rapid development of unmanned air vehicles and wind turbines. A wide range of unmanned aircraft (UA) with the take-off weight less than 10 kg has a small wing chord and speeds of their flight which are comparable with atmospheric wind speeds. Such conditions mean that UA wings are exploited at the Reynolds numbers of the order of 10^5, moreover, due to aircraft construction peculiarities [2] or side gusts, UAs can be used at a significant sweep angle. Similar conditions are also observed on blades of wind turbines with power up to 100 kilowatt. A significant change in Reynolds number from the blade root to its tip can be referred to as a peculiarity of the wind turbine blade. Consequently, the situation when a part of the blade operates at $Re<10^5$ and another one operates at $Re>10^5$ is very frequent. Also, we note that the structure of the boundary layer in the range $Re=10^5$ – 10^6 changes significantly. At $Re=10^5$ the laminar-turbulent transition takes place through formation of a separation bubble, while at $Re=10^6$ the separation bubble can be completely eliminated. Such difference in the boundary layer structure determines different approaches to control of the leading-edge stall. In this paper the research results on aerodynamics of a wing with aspect ratio $\lambda=3.5$ are reported.

EXPERIMENTAL RESULTS

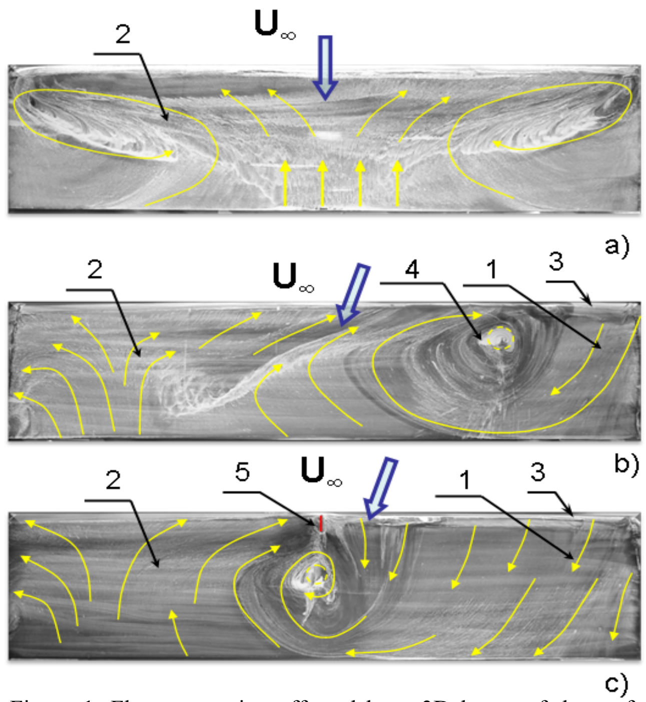

Figure 1. Flow separation affected by a 3D hump of the surface at $Re=2.8*10^5$: $\alpha=16^o$, $\beta=0^o$ (a); $\alpha=16^o$, $\beta=15^o$(b, c). 1 – reattached flow; 2 – reverse flow; 3 – separation bubble; 4 – vortex core; 5 – hump.

A wing profile Z-15-25 [3] was tested at the Reynolds number varying from $1.4*10^5$ to $2.8*10^5$. The wing tips were rounded off on the radius equal to the half of the current airfoil height. The wing angle of attack α was chosen close to the critical one and later on with the use of oil-film visualization it was checked how the separation structure changed with sweep angle which was taken as $\beta=15^o$.

Oil-film visualization performed on the leeward side of the wing in the absence of the sweep angle and the Reynolds number equal to $2.8*10^5$ is shown in figure 1a. A typical 3D structure of flow separation is found. It is distinguished by a vortex pair with the focuses located close to the wing tips. At the sweep angle $\beta=15^o$, a limited area of reattached flow with a narrow (5% chord) separation bubble emerges at the right side of fig. 1b. The core of the right vortex becomes more pronounced while the core of the left vortex is not clearly traced. When installing a 3D hump in the form of a 4mm-high rib as is shown in figure 1c, the amount of the reattached flow is increased covering a half of the wing span.

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When decreasing the Reynolds number to $1.4*10^5$, a 3D flow structure is observed as well as under the stall conditions but the vortex cores are not so pronounced (figure 2a). At the non-zero sweep angle (figure 2b), a limited area of reattached flow is found in the right corner of the wing, however, in this case the separation bubble covers about 15% of the chord. It can be supposed that the core of the right vortex correlates with the size of the separation bubble and cannot be clearly traced. The structure of the left hand part of the separation region does not indicate a pronounced vortex core. Then, a wing model with the same profile and a wavy surface [4] was tested. The wave height was equal to 2 mm and its transverse period was taken as 25 mm. Oil-film visualization showed that in this case the flow is reattached on the entire span of the wing (figure 2c).

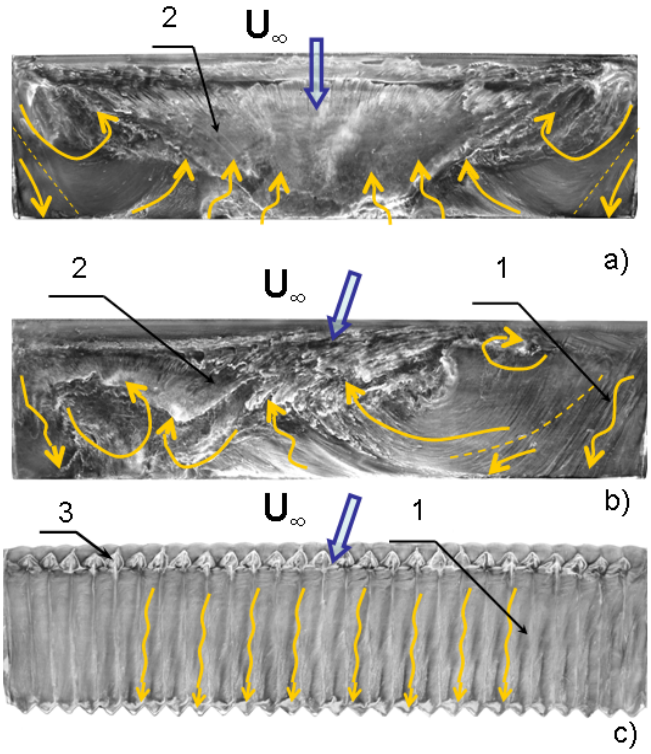

Figure 1. Flow separation affected by the surface waves at $Re=1.4*10^5$: $\alpha=16^o$, $\beta=0^o$ (a); $\alpha=16^o$, $\beta=16^o$(b, c). 1– reattached flow; 2 – reverse flow; 3 – separation bubbles.

CONCLUSIONS

The experimental results showed significant deformation of the separated flow region on the wing with the sweep angle. Two methods were implemented to eliminate the leading edge stall on the swept wing. At the Reynolds number of $2.8*10^5$ the flow reattachment was forced by a 3D hump mounted on the wing surface. At the Reynolds number of $1.4*10^5$ this was achieved using the surface waviness. Both methods can be applied on blades of wind turbines and wings of small-sized air vehicles. The focus of the future work on the present topic is testing of the above methods in a wider range of Reynolds numbers with optimization of the control parameters.

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