Results of numerical simulation on a thick teardrop airfoil at low Reynolds numbers

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Abstract. A symmetrical thick teardrop airfoil was investigated in this work. A numerical simulation was performed with a laminar flow, using the Implicit Large Eddy Simulation method. The fields of flow parameters in the vicinity of the airfoil were obtained for Reynolds numbers 3.5e+4 and 6.9 e+4.

1. Introduction

Currently, unmanned aerial vehicles (UAV) are actively developing. Small UAVs intended for research, civil and military tasks [1, 2]. They are becoming more popular and needed. This makes the research at low Reynolds numbers relevant.

In this paper, a symmetrical thick teardrop airfoil is considered. The airfoil can be used for elements of frame for multicopters, wing strut for aircraft and fuselage for any small UAVs. The airfoil is found in sailing, cycling and industrial construction.

Phenomena of drag crisis, hysteresis and change of direction (revers) of lift coefficient (CL) was founded in experiments [3, 4]. The drag crisis is observed on the teardrop airfoil at zero angle of attack. The critical Reynolds number at which the flow is attached is found in articles [3, 4], \( Re^* \approx 6.3 \times 10^4 \). At a subcritical flow \( (Re < Re^*) \) the laminar flow separation is observed. At supercritical flow \( (Re > Re^*) \) a laminar separation bubble is formed. Velocities are chosen by corresponding to the sub- and supercritical flow regimes for research. Dramatically change CL at a small deviation from zero for angle of attack was founded [4]. Task of numerical simulation of these phenomena was became an actual.

Steady and transient models for Reynolds-averaged Navier-Stokes (RANS) equations was got incorrect result for laminar separation and laminar-turbulent transition for the thick airfoil at low Reynolds numbers. The numerical study of the flow field around the airfoil was performed using an implicit large eddy simulation (ILES). This approach has laminar viscosity only and turbulent eddies solve on mesh without turbulent models. This approach can be used to study the flow with a laminar-turbulent transition [5].

2. Methodology

A three-dimensional problem of the wing section streamlining is investigated. The section of a rectangular wing with the airfoil under study has a chord of 0.1 m and a span of 0.03 m. It is considered at flow velocities of 5 m/s and 10 m/s. This corresponds to Reynolds numbers 3.5 \times 10^4 and 7.0 \times 10^4. The angle of attack does not change and is equal to zero.
The size of the computational area and the number of cells is limited by the PC computing power. The computational domain has the shape of a cylinder circumscribed around the wing section with a base radius of 4 chords and a depth of 0.3 chords. The axis of the cylinder passes through the midpoint of the chord. At the front and rear boundaries, the periodicity conditions are set.

The mesh thickens towards the airfoil. The total number of cells on the meshes was about 0.9, 3.3 and 12.0 million. The results are differed slightly. A mesh of 3.3 million cells was chosen as the general. The time step is chosen for the Courant number to be much less than 1. For the calculated cases of 5 m/s and 10 m/s, it is $2.5 \times 10^{-8}$ s and $1.25 \times 10^{-6}$ s, respectively. It was not possible to simulate free-flow disturbances corresponding to natural ones. Therefore, there were no initial disturbances in the flow. The aim is to get the correct pattern of the flow at least, because RANS and URAN models showed no correct result.

3. Result and Discussion

The flow velocity of 5 m/s ($Re \approx 3.5 \times 10^{4}$) corresponds to the subcritical flow regime. Here, a laminar flow separation is observed at about 20% of the airfoil (Figure 1, a). Behind the separation point along the airfoil surface there is a stagnant zone and a reverse flow near the wall. According to the picture of the root-mean-square deviations of the horizontal velocity, one can observe how pulsations grow in the detached shear layer. All this testifies to the fact that the flow separation is more laminar, and laminar-turbulent transition occurs only after its separation.

A flow velocity of 10 m/s ($Re \approx 6.9 \times 10^{4}$) corresponds to the supercritical flow regime. A laminar separation bubble is observed between 20% and 65% of the airfoil chord (Figure 1, b). At the point of separation velocity pulsations are absent, but along the laminar separation the bubble is gradually increasing. An attached flow occurs approximately in the area of maximum velocity pulsations. The boundary layer becomes fully turbulent. As a result, in the remaining section, the airfoil is continuously streamlined, even on the rounded trailing edge.

The drag coefficients (CD) of the profile in the considered sub- and supercritical cases differ about 4 times: 0.31 at 5 m/s and 0.07 at 10 m/s, while the standard deviations of CD are 0.028 and 0.006, respectively, i.e. the amplitudes of the pulsations differ almost 5 times. The amplitudes of pulsations in the CL at the subcritical mode are almost 2.5 times higher than at the supercritical one: RMS 0.047 versus 0.019. These results correlate with the data obtained in [3].

Slipstream formed at 10 m/s. Karman vortex street is clearly observed at 5 m/s. The RMS of the vertical velocity clearly shows the mixing area of the flow in the wake behind the body. The amplitude of the pulsations of the vertical velocity component in the wake of the airfoil increases in the presence of the Karman vortex street (Figure 2, a), while it decreases in the slipstream (Figure 2, b).

The oscillation frequency of the Karman vortex street is in the frequency range of up to 100 Hz (Strouhal number $Sh < 2$). Using the fast Fourier transform, we separate the low frequencies from the high frequencies. From the RMS fields of the horizontal and vertical velocity components taken for the corresponding frequency range, it may be seen that frequencies above 100 Hz are localized only in the detached shear layer (Figure 3, c and d). Pulsations with frequencies of up to 100 Hz on the vertical velocity component localize in the wake behind the body (Figure 3, b.) and on the horizontal component - in the wake behind the body separated along the shear layer (Figure 3, a.). The latter observation can also indicate that the position of the points of separation and laminar-turbulent transition along the surface of the airfoil can also be influenced by the vortex wake. Frequencies corresponding thereto (Figure 4).

Conclusions

The use of the ILES approach allows qualitatively and quantitatively reproducing the processes of both separation and laminar-turbulent transition close to the experimental data.

Separation fluctuations in frequencies allow separating the low-frequency fluctuations caused by the Karman vortex street and high ripple caused by the turbulent eddies.
Figure 1. Average and pulsations components of the horizontal component of velocity at subcritical (a) and supercritical (b) flow around the airfoil.

Figure 2. Pulsations of the vertical component of velocity at subcritical (a) and supercritical (b) flow around the airfoil.

Figure 3. Pulsations of the horizontal (a, c) and vertical (b, d) components of velocity at subcritical flow in the low-frequency (a, b) and high-frequency (c, d) spectrum.
Figure 4. The amplitude-frequency spectrum for (a) 5 and (b) 10 m/s in zones of maximum pulsation.

It is important to note that there were no initial disturbances in the incoming flow, and the flow was completely laminar. However, external disturbances can significantly affect the separation and reattachment of the boundary layer. Therefore, the problem of using the ILES model for the flow of disturbances that reproduce the turbulence of the flow in an aerophysical experiment or in natural conditions remains unresolved.

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