Influence of propeller diameter mounted at wingtip of high aspect ratio wing on aerodynamic performance

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Abstract. In this paper, the propeller diameter effect on cruising characteristics of a solar-powered aircraft with a high aspect ratio wing is considered. Numerical studies were performed using a program based on the Reynolds-averaged Navier-Stokes equations for Mach numbers $M=0.145$ and Reynolds numbers $Re = 0.3 \times 10^6$. Three aircraft configurations were considered: without propellers, with running two-bladed propellers with diameters of 0.22 m and 0.33 m. Numerical studies showed that the installed propeller introduces significant non-linearity into the lift curves and propeller thrust coefficient versus angle of attack curves. The propeller slipstream velocity field changes depending on the propeller advance ratio and the flow velocity, thus influencing the pressure distribution on the wing and the aircraft aerodynamic performance.

1. Introduction
The introduction of green energy in aviation poses new scientific and technical challenges for researchers. Experimental aircraft with electric motors and hybrid power sources, combining electrical and solar batteries, are being studied [1-4] in the world. The solar-powered aircraft have ultra-high aspect ratio wings. The upper surface of the wing is covered with solar panels, which allows for a long-duration flight. The power plant with a wingtip-mounted propeller unloads the wing and increases the system efficiency by reducing the induced drag [5-8]. This paper presents the numerical study of a slipstream effect of the high-aspect-ratio-wing-tip-mounted propeller with various diameters on the aerodynamic performance of a solar-powered aircraft in cruise mode. The aerodynamic performance was investigated by CFD calculation.

2. CFD analysis
Aerodynamic design of the solar-powered aircraft is based on conventional high-wing configuration with wing aspect ratio of 23.4, a circular fuselage, a conventional empennage with a single vertical stabilizer and a fuselage-placed horizontal tail, Fig. 1. Engine nacelles are mounted at the wingtips of the rectangular wing. Three aircraft configurations are considered: without propellers, Fig. 2, a, with running two-bladed propellers with diameters ($D$) of 0.22 m and 0.33 m, Fig. 2, b, c.
Figure 1. General view of the solar-powered aircraft.

Figure 2. Investigated wing tip configurations: a) - no propellers, b) - 0.22 m propeller diameter, c) - 0.33 m propeller diameter.

The studies were carried out using the ANSYS FLUENT program, based on the solution of the Reynolds-averaged Navier-Stokes equations, on a structured computational grid (about 20 million cells). The $k-\varepsilon$-realizable turbulence model was performed. In the near-wall region, a one-parameter turbulence model adapted to low-Reynolds-number flows was used.

In order to simultaneously calculate the forward movement of the fuselage and the rotation of the propeller, two calculation zones were set: one, where the airflow runs into the model under study, and the other, where the rotational air motion simulates the propeller rotation [9, 10].

The cruise condition was defined as 25 and 50 m/s flow velocity ($V_\infty$). The angles of attack (AoA, $\alpha$) ranged from 1° to 7° at the zero side slip angle ($\beta$). The propeller speed was fixed for both variants and it was $n = 15000$ rpm.
3. Results and Discussion

The effect of the AoA on lift coefficient ($C_L$) of the aircraft for different values of propeller advance ratio $J=V_\infty/nD$ is shown in Fig. 3. As it can be seen at the inflow velocity of $V_\infty=25$ m/s, the rotation of the tractor propeller introduces significant non-linearity into the lift curve. An increase in the inflow velocity to $V_\infty=50$ m/s enhances the aircraft lift and makes the curves of $C_L$ (AoA) linear in the investigated angle-of-attack range.

![Figure 3](image)

**Figure 3.** The effect of the AoA on lift coefficient: a) $V_\infty=25$ m/s, b) $V_\infty=50$ m/s.

The dependences of the propeller thrust coefficient on the AoA at different values of the propeller advance ratio are shown in Fig. 4. The propeller thrust coefficient was defined by an equation:

$$C_t = T / \rho \omega n^2 D^3,$$

where $T$ – propeller thrust (N), $\rho$ – air density (kg/m$^3$). Increasing the flow velocity leads to an increase in the propeller thrust. It is shown that although the thrust of the propeller with the diameter of $D=0.22$ m is less than the one of the propeller with the diameter of $D=0.33$ m, it is practically independent of the AoA. However, the propeller thrust with the diameter of $D=0.33$ m does not depend on the AoA only when the flow velocity equals $V_\infty=25$ m/s (Fig. 4, a) and at the flow velocity of $V_\infty=50$ m/s the propeller thrust decreases with increasing of the AoA.
Figure 4. Dependences of the propeller thrust coefficient on the AoA at different values of the propeller advance ratio: a) \( V_\infty = 25 \) m/s, b) \( V_\infty = 50 \) m/s.

Figure 5. Measurement line position behind the propeller
The tractor propeller significantly influences the flow around the wing and its aerodynamic characteristics. The parameters of the flow velocity and the propeller diameter are particularly important. The flow velocity was measured on the line behind the propeller in front of the port wing. (Fig. 5). The spanwise velocity distribution behind the propeller is shown in Fig. 6. It is seen that the propeller diameter has the greatest effect on the flow incoming onto the wing leading edge at velocity of $V_{\infty} = 25$ m/s (Fig. 6, a). Increasing the flow velocity to $V_{\infty} = 50$ m/s aligns the propeller slipstream velocity field (Fig. 6, b).

**Figure 6.** Spanwise velocity distribution behind the propeller: a) - $V_{\infty} = 25$ m/s, b) - $V_{\infty} = 50$ m/s.

The inflow velocity and the two-bladed propeller rotation perturbations effect the pressure distribution on the wing surface and change its lift coefficient depending on the propeller diameter (Fig. 7). At the velocity of the incoming flow of $V_{\infty} = 25$ m/s, the rotation of the propeller leads to both an increase in pressure and decrease in pressure at the nose of an airfoil. Increasing the flow velocity to $V_{\infty} = 50$ m/s aligns the pressure distribution behind the tractor propeller.
Figure 7. Pressure coefficient distribution in the wing section $z = 0.9$, $\alpha = 1^\circ$: a) - $V_\infty=25$ m/s, b) - $V_\infty=50$ m/s.

4. Conclusions
Numerical studies showed that the installation of the propeller introduces significant non-linearity into the lift curves and propeller thrust - angle of attack curves.

The propeller slipstream velocity field changes depending on the propeller advance ratio and the flow velocity, thus influencing the pressure distribution on the wing and the aircraft aerodynamic performance.
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