Influence of interference between the fuselage and the propeller ring on the maximum thrust of the air pusher propeller

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Abstract. The geometrical parameters of ring profiles were presented and the estimation of its influence on the peak values of propeller thrust was described. The results of computational studies using software based on Reynolds-Averaged Navier-Stokes (RANS) equations to investigate the influence of the rear fuselage and the shape of the ring profile on the thrust of pusher propeller were presented. The pressure distribution and the velocity field changed depending on the shape of the rear fuselage and the ring profile, and their influence on the maximum thrust was shown.

1. Introduction

The propeller ring configuration is widely used in flying vehicles in order to increase thrust, to protect the propeller against damages, to increase maintenance safety and to reduce noise [1, 2]. The advantages of the propeller ring (PR) make it possible to use it for hovercraft, light aircraft, VTOL aircraft, small-sized long-range aircraft, and for solving various problems as well. The propeller ring can also serve as a fenestron tail [3] for single-rotor helicopters, low-speed aircraft and airships [4 - 6].

Nowadays the propeller ring design is used in many vehicles, and investigations of propeller ring engine (PRE) provokes significant interest [1-9]. Previous studies in this area have focused on flow features and influence of structural elements on the PRE thrust. For example, according to experimental data, which were obtained when investigating aerodynamic characteristics of disk-shaped drones with the ring propeller configuration in the T-1 MAI wind tunnel (Russia), at constant rotor speeds and increasing angle of attack, the lifting efficiency also increased [7]. It was shown that the propeller ring reduced the rotation speed of the flow in the wake of the propeller [8], and also the experiments proved that the ring profile influenced PRE performance [9].

To study the operating conditions of the propeller in the aerodynamic wake of the body of rotation, to evaluate the thrust of the propeller and the aerodynamic characteristics of the combination “body of rotation/air pusher propeller”, the experimental studies of the fuselage model with a pusher six-bladed propeller were carried out in the T-102 TsAGI wind tunnel [10]. The wind tunnel tests were conducted with a fixed number of rotor speed $N = 6000$ rpm, in the range of free-stream velocities $V = 0 \ldots 50$ m/s. The maximum Reynolds number calculated from the length of the axisymmetrical body at velocity $V = 50$ m/s was $Re = 8.3 \cdot 10^6$. The diameter $D = 0.24$ m six-bladed propeller with blades made of P-107 profile, was used as a propeller.
Previous numerical studies [11, 12] on increasing the thrust of an air pusher propeller by changing the rear fuselage and installing the propeller in the ring (Fig. 1) showed that:

- the use of propeller ring led to a significant increase in the thrust of the propeller (where the total thrust was determined as $T_{\text{total}} = T_{\text{propeller}} + T_{\text{ring}}$ (kg)) in the entire calculated range of flight speeds;
- the only change in the shape of the initial rear fuselage (without using a ring) of R.H. Liebeck profile [23, 14] reduced the base drag without creating a separation, and led to a slight increase in propeller thrust in the entire calculated range of flight speeds;
- the use of the ring and the change in the shape of the rear fuselage also increased the thrust, but led to a significant increase in drag with an increase in flow rate, which eliminated any benefits.

An analysis of the results of numerical studies of the initial PRE [11] with various shapes of the rear fuselage showed that with optimal regime of $V = 35...40$ m/s and Reynolds number $Re \approx 7$ million, the thrust can be significantly increased without optimizing the entire system (fuselage + RPE). However, for flights with higher speeds ($V > 50$ m/s), it is necessary to change the shape of the ring profile due to the growth of its drag. Additionally, in order to achieve the possibility of flying at these speeds and compensate for the increasing drag due to increased thrust it is necessary to holistically optimize the outline of the rear fuselage, the profile and the angle of ring position.

In an earlier study [12], the influence of the shape of the rear fuselage on the thrust of a rotor-propulsion engine had been investigated. The results showed that a change in the shape of the rear fuselage affected the local angle of attack, at which the flow ran onto the ring, as a result of which the PRE thrust changed. In this study the investigations continued.

2. Aerodynamic design of new ring profile shape to increase PRE thrust

The aerodynamic design of a new ring shape was carried out for the same outlines of the fuselage, the unchanged chord of the ring and the fixed distance ($L = 0.017$ m, Fig. 2 a) from the tip of the blade to the spot where the profile of the inner side of the ring had the largest thickness.

According to the above limitations, a new ring profile was designed for numerical studies of the fuselage assembly with the PRE (Fig. 2b), which had the same chord $b = 0.176$ m as the initial profile, the angle of the profile of the ring is $\delta_{pr} = -5$ deg., and the relative curvature $f = 5\%$, but it differed from the initial profile because of its lower relative thickness $c_{\text{mod}} = c / b = 14\%$ ($\Delta c = -2\%$) whereas the maximum relative thickness and curvature equally shifted backward. Moreover, for the initial profile of the ring, the position of the maximum relative thickness and curvature was $x_{c_{\text{ref}}} = x_{f_{\text{ref}}} = 23\%$, and for the modified profile - $x_{c_{\text{dom}}} = x_{f_{\text{mod}}} = 53\%$.

The angle of the ring aperture was selected based on the analysis of the distribution of flow rates in the area where the ring was installed so that the flow ran onto the ring at an angle corresponding to the regime of maximum lift-to-drag ratio of the ring profile.
Earlier calculations [12] had showed that the local angle of attack of the ring profile $\alpha = 5$ deg corresponded to the maximum lift-to-drag ratio of the isolated profile. Therefore, in the calculated parameters, $\alpha = -1$ deg. corresponded to the local angle of attack of the ring profile with the modified fuselage, and $\alpha = 7$ deg. corresponded to the local angle of attack of the profile with the initial fuselage, in which the isolated profile had the greatest rarefaction on the upper surface and the maximum lift-to-drag ratio. To make calculations of the designed profile of the ring, these angles were chosen as the base.

3. Numerical studies of new PRE shape
Numerical studies of the initial and modified fuselage shapes with the initial and modified ring profiles were performed using RANS-equations on the structured mesh containing about 17 million cells (Fig. 3). For the simultaneous calculation of the translational motion of the fuselage and the rotation of the propeller, two computational domains were chosen: the first domain simulated the air flow onto the studied model, and the second domain – the rotational air motion simulating the rotation of the propeller. [15]. Due to the fact that the simulation models were bodies of rotation and the pusher propeller had 6 blades with a fixed angle the calculation grids for 1/6 of the model with areas of rotational and translational air flow and periodic boundaries were built. Finally, the full model was simulated in RANS-equations. For a more correct comparison of the calculation results, one such computational grid was adapted to the geometry of all the studied models.
The calculations were carried out at a fixed rotor speed $N = 6000$ rpm, in the range of free-stream velocities $V = 0 \div 50$ m/s in accordance with the experimental conditions in the T-102 wind tunnel. The propeller was not modified.

It is worth noting that, according to the calculations, when the free-stream velocity was $V \leq 35$ m/s, the modification of the rear fuselage led to an increase in the efficiency of the propeller without a ring, however, at a speed of $V \geq 40 \div 50$ m/s, the propeller thrust decreased below the level of the initial fuselage (without ring), which was shown in the paper [12];

The numerical studies showed that the maximum thrust of modified propeller ring was obtained at speeds of $V = 35 \div 40$ m/s, and a further increase in speed to $V = 50$ m/s led to a decrease in thrust by $\Delta T = 0.5$ kg from the maximum (for the initial rings $\Delta T = 1$ kg) (Fig. 4).
The PRE thrust values of the computational models, representing as the sum of propeller thrust and ring thrust, at \( V = 35 \) m/s, are presented in Table 1. It was shown that at a given free-stream velocity, a change in the ring profiling had a negligible effect on the thrust of the propeller itself, but had a significant effect on the thrust of the ring.

**Table 1.** PRE thrust at \( V = 35 \) m/s.

| Model Description                                                                 | \( T_{prop} \) (kg) | \( T_{ring} \) (kg) | \( T_{total} = T_{prop} + T_{ring} \) (kg) |
|----------------------------------------------------------------------------------|---------------------|--------------------|-------------------------------------------|
| Initial fuselage model with an initial ring                                     | 1.80                | 0.87               | 2.67                                      |
| Initial fuselage model with a modified ring                                     | 1.87                | 2.10               | 3.97                                      |
| Modified fuselage model with an initial ring                                    | 1.64                | -0.12              | 1.53                                      |
| Modified fuselage model with a modified ring                                    | 1.62                | 0.40               | 2.02                                      |
| Initial fuselage model with a pusher propeller without rings (experiment)      | 2.05                | -                  | 2.05                                      |
| The isolated propeller (experiment)                                             | 0.93                | -                  | 0.93                                      |

The table shows that the total thrust of the PRE with a modified profile significantly exceeded the thrust of a conventional propeller (pulling and pusher) with the exception of the modified fuselage model with a modified ring. In this case, the thrust of the PRE was comparable to the thrust of the pusher propeller, however, at lower speeds (\( V \) up to 20 m/s), this solution also had advantages (see Fig. 4), which allowed us to recommend the proposed solution for low-speed aircraft.

Figures 5-7 show the pressure distribution on the surface of the simulation models and in the XOY section plane \( z = 0 \) at flow velocity of \( V = 35 \) m/s. Figure 6 shows the distribution of the pressure coefficient in the XOY section plane, \( z = 0 \) for the modified fuselage and the initial ring at flow velocity of \( V = 35 \) m/s, and Figure 7 shows the case of the initial fuselage and the modified ring. It can be seen that at the given flow velocity (\( V = 35 \) m/s), rarefaction was observed on almost the entire inner surface of the modified ring, and the area of greatest rarefaction occupied up to 60% of the chord of the ring profile, whereas the initial profile - only 30% (Figures 6, 7).
Figure 5. Pressure distribution at airflow velocity of $V = 35$ m/s.

Figure 6. Pressure distribution in the XOY section plane, $z = 0$ for the initial fuselage with initial and modified rings, $V = 35$ m/s.

Figure 7. Pressure distribution in the XOY section plane, $z = 0$ for the modified fuselage with initial and modified ring profiles, $V = 35$ m/s.
According to the calculation results, the rarefaction on the inner surface of the modified ring took the shape of roof-top pressure distribution (Fig. 7), at which a maximum increase in the PRE thrust was observed. Whereas the dependency $C_p(x)$ assumed a peak distribution (Fig. 6), an increase in the flow velocity was accompanied by a decrease in the PRE thrust.

![Image](image.jpg)

**Figure 8.** Velocity distribution in the XOY plane, $z = 0$, $V = 35$ m/s.

The velocity distribution in the wake behind the PRE showed the direction of flow from the propeller blades at higher speeds: an even strongly inhibited wake behind the hub, convergent in the far region behind the model (Fig. 8, b).
4. Conclusion

The numerical studies showed that to design a PRE-equipped aircraft it was necessary to select parameters such as: profile thickness, chord and angle of the ring, taking into account the flow conditions and interference.

The analysis of the results of computational studies showed that at low flight speeds $V < 20$ m/s, the maximum thrust of the PRE was mainly affected by the shape of the rear fuselage, and not by the profile of the ring. The highest thrust was obtained at flow velocity of $V = 35$ m/s for the model with the initial fuselage shape and with the modified ring profile. With an increase in flight speed $V > 35$ m/s, it was necessary to take into account the increasing drag of the PRE and the operating conditions of the propeller in a thin boundary layer.

Reducing the thickness of the boundary layer and increasing the velocity in it due to a change in the shape of the fuselage allowed reducing the drag of the fuselage itself, but led to more significant loss of PRE thrust, limiting the range of applicable speeds.

The analysis of the pressure distribution data on the surface of the ring showed that the rarefaction on the inner surface of the ring, which takes the shape of a roof-top pressure distribution, corresponded to the maximum thrust of the propeller. If the dependence $C_p(x)$ assumed a peak distribution, then, with an increase in the flow velocity, the PRE thrust decreased. Therefore, the assumption can be made that designing a propeller ring for a certain flight speed requires the solution of the inverse problem of determining a roof-top pressure distribution on the inner surface of the ring.

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