Evaluation of rotary wing thrust of small UAVs in high-altitude flight conditions

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1 Introduction

The use of rotary wing-type small unmanned aerial vehicles(UAV) is rapidly increasing because they are easy to control and can be used in various applications. Recently, some organizations have decided to use them in hazardous activities, such as for exploring volcanoes, inspecting bridges, and searching disaster sites.

Some of these activities, in particular, the exploration of volcanoes are conducted at high-altitude locations over 1,000 m. The thrust of rotary wings in high-altitude flight is qualitatively lower than that around sea level. However, the quantitative relation between air conditions in high altitude and the thrust of small rotary wings has not been clarified. Therefore, in this study, we aim to clarify the relationship and the theoretical background for the use of this type of small UAV in exploring mountainous areas. In the first step of this research, we evaluated the changing thrust of small rotary wings in high-altitude conditions over 1,000 m. In this paper, we introduce the thrust theory of rotary wings and report some experimental results regarding the thrust of small rotary wings in different conditions. This information can contribute to the design of optimal wings for the high-altitude flight of small UAVs.

2 Theory

2.1 Thrust theory of rotary wings

The aerodynamics of small rotary wings is very complex compared with that of large-scale jet planes because fluids exhibit viscous behavior. The flow at this small scale is called low Reynolds number flow, and many studies have been conducted to clarify the effect of a low Reynolds number range on fluid phenomena. Thus, the features of flow are different between large and small scales. However, we can apply basic theories of rotary wings to small wings. Thus, the thrust is given by the following equation:

$$T = \rho \Omega^2 C_t S \tag{1}$$

$$\left(\begin{array}{llll} T\text{:} & \text{Thrust [N]} & & \\ \rho\text{:} & \text{Atmospheric density } [\mathrm{kg/m^3}] & \Omega\text{:} & \text{Rotational speed [rad/s]} \\ C_t\text{:} & \text{Thrust coefficient} & S\text{:} & \text{Rotor disk area } [\mathrm{m^2}] \end{array}\right)$$

According to this equation, only the atmospheric density can change with increased height. Therefore, we assume that the primary factor in thrust change for small rotary wings is atmospheric density.

2.2 Atomospheric density

Air density is mainly affected by three factors: temperature, pressure, and relative humidity. Typically, air density decreases with an increase in altitude. According to Murray [2] and atmospheric dynamics, the air density is calculated from the following equation:

$$\rho = \frac{1.293 \times 273.15 \times p}{(273.15 + t) \times 1013.25} \times \left[1 - 0.378 \times \frac{e}{p}\right] \tag{2}$$

$$e = \frac{h}{100} \times e_{sat} \tag{3}$$

$$e_{sat} = 0.1078 \times 10^{At/(B+t)}$$

$$A = 7.5 \; B = 237.5$$

Teten's equation(1930)

$$\left(\begin{array}{l} \rho\text{: Atmospheric density } [\mathrm{kg/m^3}] \\ p\text{: Atmospheric pressure } [\mathrm{hPa}] \\ h\text{: Relative humidity } [\%] \\ e\text{: Water vapor pressure } [\mathrm{hPa}] \\ e_{sat}\text{: Saturation vapor pressure } [\mathrm{hPa}] \end{array} \right)$$

3 Thrust evaluation with respect to density

As mentioned in the previous section, air density is affected by three factors: temperature, pressure, and relative humidity. To confirm this, we conducted some experiments using a single small rotary wing.

In the first experiment, we evaluated the thrust of a small rotary wing from 500 m to over 1,000 m above sea level to clarify the effect of the thin atmosphere on a mountain on the thrust.

3.1 Experimental setup

The experiment was conducted at five different altitudes in Mount Asama. We measured the thrust of the rotary wing with an electronic weighing scale and its rotational speed with an optical sensor. The rotational speeds were set from 3,000 rpm to 8,000 rpm, and we used an APC propeller (13 × 4 p) for this experiment. The thrust was directed upward to avoid effects from the ground.

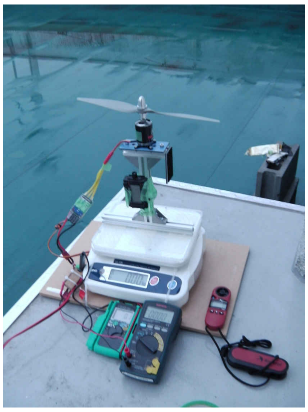

Figure 1: Thrust test stand

3.2 Experimental results and discussions

The results are plotted in Fig. 3. According to the results, the thrust of the wing was smaller than that in thicker air densities (which indicates ascending altitude). At 8,000 rpm, the thrust of the wing at 1,600 m was approximately 9$\%$ smaller than that at 540 m. However, the changes in thrust and atmospheric density were not exactly proportional. This result indicated that other factors play an important role in thrust changes. After precise analysis, we have assumed that the thrust coefficient changes, as shown in the first equation. In general, the thrust coefficient is almost constant for large-scale rotary wings. However, the thrust coefficient of small wings may change at low Reynolds number flows. Therefore, we cannot ignore these changes when estimating the thrust of small rotary wings.

4 Evaluation of thrust coefficient

To precisely evaluate the change of thrust coefficient in a low Reynolds number range, we conducted the same experiment in a decompression chamber. The chamber can artificially create thin density air conditions, and we changed the Reynolds number by not only changing rotational speed, but also atmospheric pressure. The definition of Reynolds number for a rotary wing is

$$Re = LV/\nu \tag{4}$$

$$\left(\begin{array}{c} L\text{: Cord length at 75 \% span of the blade [m]} \\ V\text{: Flow speed at 75 \% span of the blade } [\mathrm{m/s}] \\ \nu\text{: Atmospheric density } [\mathrm{m^2/s}] \end{array} \right)$$

4.1 Experimental setup

We measured the thrust of the wing in a decompression chamber using the same system as in the previous experiment. Pressure was changed from 800 hPa to 1,000 hPa every 50 hPa. According to the initial experiment, we confirmed that interference between the thrust blast and the inside walls of the chamber was negligible.

4.2 Result and discussion

Figure 4 shows the relationship between thrust coefficient and Reynolds number. According to the experiment, thrust coefficient decreases when Reynolds number decreases. Furthermore, thrust coefficient is constant at the same Reynolds number, despite changes in atmospheric density and pressure. This result indicates that the thrust coefficient is dominated only by the Reynolds number. Remarkably, thrust coefficient decreases drastically in a low range of Reynolds number; in other words, because of the decreasing thrust coefficient, the thrust of small rotary wings decreases more strongly than that of large wings in the thin atmosphere above high mountains.

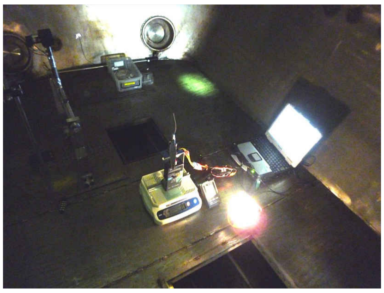

Figure 2: Measurement in a decompression chamber

5 Conclusion

In high-altitude flights over 1,000 m, pressure, temperature, and relative humidity differ from those at sea level. Therefore, the atmospheric density and Reynolds number decrease. Consequently, the thrust of small rotary wings decreases because of decreased air density and thrust coefficient. In particular, in a low Reynolds number range, the thrust coefficient decreases drastically and its mode of change affects the thrust. This behavior is important for small rotary wings.

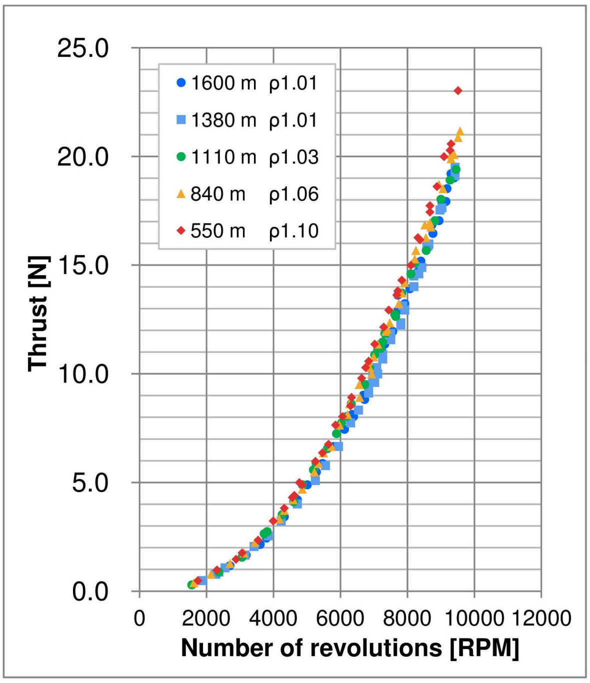

Figure 3: Thrust versus number of revolutions obtained from the experiment in the mountain

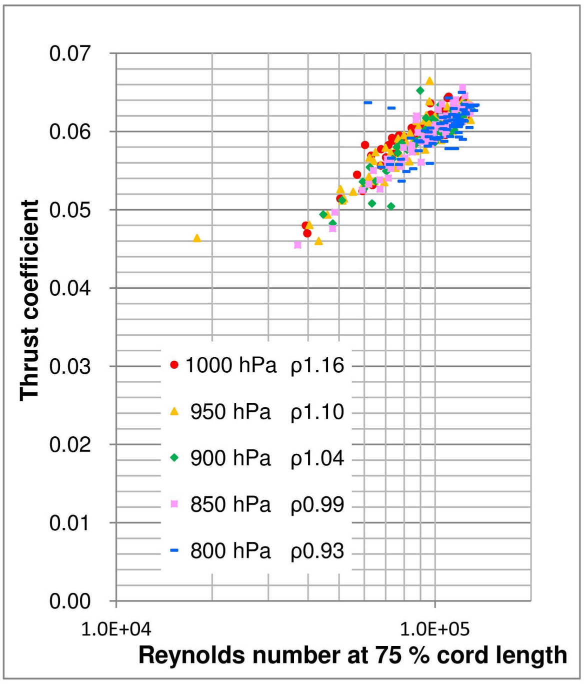

Figure 4: Thrust coefficient versus Reynolds number obtained from the experiment in the decompression chamber

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