Effects of Propeller Position and Rotation Direction on the Ishii Wing at a Low Reynolds Number*

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The aerodynamic characteristics of a wing in a propeller slipstream were investigated at a low Reynolds number. The effects of propeller position and rotation direction on the wing were clarified by aerodynamic measurements and particle image velocimetry. The propeller positions were the center and tip of the wing model, whereas the rotation directions were clockwise and counterclockwise. The center propeller configuration with a clockwise rotation showed a constant pitching moment and increased the lift-to-drag ratio. This was caused by the high-speed propeller slipstream (i.e. 12 and 10 m/s on the upwash and downwash sides, respectively) and the wingtip vortex effect on the slipstream separation. The separation point at an angle-of-attack of 18° was delayed from x/c = 0.1 to 0.3 by the wingtip vortex. Hence, the following two factors must be considered to enhance the aerodynamic characteristics of a Mars airplane: (i) the ratio of the area of the upwash and downwash sides of a wing in a propeller slipstream, and (ii) the effect of the wingtip vortex on the propeller slipstream.

Key Words: Low Reynolds Number, Propeller Slipstream, Wind Tunnel Testing, Aerodynamic Characteristics, Aerodynamics

Nomenclature

- b: span length
- c: chord length
- CD: drag coefficient
- CL: lift coefficient
- CM: pitching moment coefficient
- D: drag
- J: advance ratio, J = U∞/(2RN)
- L: lift
- n: propeller rotation speed
- R: propeller radius
- Re: Reynolds number
- U: flow velocity in main-flow direction
- U∞: main flow velocity
- x: chordwise coordinate
- y: spanwise coordinate
- z: thicknesswise coordinate
- α: angle-of-attack

1. Introduction

Planetary exploration has been actively conducted in recent years. In particular, Mars has attracted attention as a potential planet for human migration. In Japan, the Japan Aerospace Exploration Agency (JAXA) and Japanese universities have been developing a twin-propeller Mars airplane (Fig. 1)1–8) as a new means to conduct Mars exploration. The Mars airplane can explore a wider range than rovers and obtain higher resolution data than satellites.

However, design difficulties arise because a Mars airplane flies in a low Reynolds number (Re = 10^4–10^5) condition owing to the low atmospheric density of Mars. In such an environment, the Ishii airfoil is a candidate for the airfoil of the main wing of the Mars airplane.9) The airfoil shows high performance even in a low Reynolds number condition owing to the flat upper surface and lower surface camber.

The Japanese Mars airplane comprises a propeller propulsion system with a battery and motors. Large propellers are required to obtain sufficient propulsion force for flights in low Reynolds number environments. Because the propellers are large, the propeller slipstream may affect a large area of the wing.

Fig. 1. Mars airplane © JAXA.
The effect of the propeller slipstream on the wing has been investigated for many years. Witkowski et al.\textsuperscript{10,11) investigated the effect of the propeller slipstream on the NACA0012 wing at a wing-chord-based Reynolds number of $47 \times 10^4$. They showed that there are three effects of the propeller slipstream on wing performance: (i) Change in the local effective angle-of-attack by a swirl, (ii) Inclination of the lift force, thereby decreasing the induced drag as the result of changing the inlet flow angle, and (iii) Change in local velocity due to the induced axial velocity. Ananda et al.\textsuperscript{12) investigated the effect of the propeller slipstream on the Wortmann FX63-137 wing at wing-chord-based Reynolds numbers from $6 \times 10^4$ to $9 \times 10^5$. They observed an additional effect in this Reynolds number region. The propeller slipstream induces an early transition to turbulent flow in the regions within the slipstream and the premature formation of a separation bubble in the regions outside of the slipstream; therefore, the lift force increased and the drag force decreased. Deters et al.\textsuperscript{13) measured a velocity field of the propeller slipstream with a flat plate wing when static (without main flow). They observed that the upper and lower slipstreams split by the flat plate wing moved away from each other in the direction of their respective swirl velocities. However, the results when in an advancing flow are not reported.

A Japanese research group for the Mars airplane also investigated the effect of the propeller slipstream on the wing using an even lower Reynolds number. Makino et al. reported that the aerodynamic performance of a NACA0012 wing affected the propeller slipstream at a Reynolds number of $4 \times 10^4$ based on force measurements and flow visualizations.\textsuperscript{14) In this study, the propeller was fixed at the center of the wingspan. Previous studies regarding propeller slipstreams by Ushiyama et al. indicated that the effects of the propeller slipstream on a wing differed depending on the propeller spanwise and chordwise position and rotation direction.\textsuperscript{15,16) In these studies, the propeller at the wingtip disturbed the wingtip vortex and decreased the induced drag; however, the NACA4406 wing was used for the test conducted. Additionally, we intended to investigate the effects on the Ishii wing, which is a candidate for the main wing of the Mars airplane. Matsumoto et al.\textsuperscript{17) performed CFD analysis for a tractor-type propeller and a flat plate wing configuration with several spanwise propeller positions at a wing-chord-based Reynolds number of $5 \times 10^4$. The propeller rotation direction was opposite of the wingtip vortex. The lift-to-drag ratio of the wingtip propeller configuration was higher than the middle spanwise position propeller configuration. Recently, Furusawa et al.\textsuperscript{18) investigated the effect of the chordwise direction position of the propeller, namely, the tractor and pusher configurations. Even though the pitching moment characteristics of the wing are one of the important points for longitudinal stability and control, the effect of the propeller slipstream on the pitching moment of the wing has not been discussed in some studies.\textsuperscript{10–18)}

Although there is some literature that discusses the effect of the propeller slipstream on the wing at a low Reynolds number as shown above, the effect is still unclear. There are many variations of the condition, such as an airfoil, Reynolds number, propeller geometry, propeller position, propeller rotation direction, and propeller advance ratio. These differences sometimes generate conflicting results. Therefore, this study has two objectives. The first objective of this study is to obtain the effect of the propeller slipstream on the wing used for Mars airplanes. Especially, this study aims to clarify the effects of propeller position and rotation direction on the aerodynamic characteristics of the Ishii wing at a low Reynolds number. The second objective is to offer one of the instances about the effect of the propeller slipstream on the wing under low Reynolds number conditions with different experimental conditions from previous literature.

2. Test Equipment

The small low-turbulence wind tunnel at the Institute of Fluid Science, Tohoku University\textsuperscript{19) was used. It is a circulation-type wind tunnel with a regular octagonal measurement section. The opposite side distance of the octagonal cross-section was 0.293 m. The measurement section can either be opened or closed; however, the open-section type was used in this experiment.

The Ishii wing model is shown in Fig. 2. The wing models were created using a three-dimensional (3D) printer (KEYENCE Co., AGILISTA-3100). The z-axis resolution of the 3D printer was 15 µm. The aspect ratio of the model was 1.5 (i.e., the chord length was 100 mm and the span length was 150 mm).

The APC propeller $5 \times 5E$ was used.\textsuperscript{20) The diameter and pitch were both 127 mm.

A brushless DC motor (Maxon Motor, EC-45-flat) was used for the propeller rotation. The number of rotations was controlled using a controller (Maxon Motor, ESCON50/5). Because this study focused on the interaction between the propeller slipstream and the wing, the test under each condition was performed based on the same advance ratio $J$. Therefore, we controlled the propeller rotation to fix the number of rotations, not the input power to the motor.

(a) Cross-section of Ishii airfoil

(b) Picture

Fig. 2. Wing model.
3. Experiment Methods

3.1. Aerodynamic force measurement

Lift, drag, and pitching moment were measured using a three-component balance system (Nissho Electric Works, LMC-3531A). Only the wing force was measured without the propeller thrust. The rated load of the force balance was 5 N for the lift and drag and 0.5 N for the moment. The force measurement results were obtained by subtracting the values in the wind-off condition from the wind-on condition to correct for the model weight.

The test setups for the force measurement are shown in Fig. 3. A half-span main wing of the Mars airplane was simulated using a half-span wing model, propeller, and tip plate. The force measurements were conducted under two experimental conditions. The propeller was set at the center of the wing first and then at the wingtip. In both cases, the axis of the propeller was placed at the center of the wing thickness. The wing model was fixed on a force balance system that was attached to a rotation stage to alter the angle-of-attack. The distance between the propeller and wing leading-edge was 50 mm. The propeller was connected to another rotation stage to prevent the propeller oscillations from affecting the airfoil balance measurements. The axes of the rotation stages coincided with the wing and propeller. The propeller angle-of-attack was changed to match that of the wing angle-of-attack. Hence, the relational position between the wing and propeller was always fixed.

The classification of propeller conditions is shown in Fig. 4. Five conditions for propeller positions and rotation directions were used: no propeller, center_cw, center_ccw, tip_cw, and tip_ccw. The abbreviation cw means that the blade was rotated clockwise as viewed from the downstream side, and ccw means that it was rotated counterclockwise. In this experiment, the area of the slipstream where the propeller blade moved down (shown in Fig. 4) was defined as the downwash side, and vice versa for the upwash side.

3.2. Particle image velocimetry (PIV) measurement

A PIV measurement was performed to visualize the flow around the wing. Tracer particles, which were mixed in the flow and illuminated using a double-pulse YAG laser (Quan-tel, EverGreen 200), were captured using a CCD camera (Dantec Dynamics, FlowSense EO 4M). The velocity was calculated based on the tracer movement distance and the time interval between the two images.

The PIV measurement setups in this experiment are shown in Fig. 5. As shown in Fig. 5(a), to visualize the flow around the wing, it was illuminated using a laser light sheet and depicted from the wingtip direction of the wing. Two sections were measured: the 75% position of the wingspan length from the wing root (2y/b = 0.75) and its 25% position (2y/b = 0.25). The wing root on the side of the force balance system was located at y = 0. This measurement was performed as 2D PIV. As shown in Fig. 5(b), to visualize the flow behind the trailing-edge, the area behind it was illuminated using a laser light sheet, and the flow behind it was depicted from the downstream side. The section was the 10% position of the wing chord length in the flow direction from the trailing-edge (x/c = 0.10). This measurement was performed as stereo PIV; therefore, triaxial velocities were obtained.

The number of images in the set was 300, and the trigger rate was 9 Hz in each of the cases. The average of these images was obtained to yield one image.
4. Experimental Conditions

The experimental conditions are listed in Table 1. Based on a previous study regarding a Mars airplane propeller, the Reynolds number and advance ratio were set to 40,000 and 0.4, respectively. The Reynolds number was determined from the chord length of the wing. The angle-of-attack was changed from $\alpha = 4^\circ$ to $24^\circ$ in $1^\circ$ increments for the force measurements, and $\alpha = 4^\circ$ to $18^\circ$ for the PIV measurements. The propeller rotation speed $n$ was set to 7100 rpm such that the advance ratio $J$ was 0.4.

| Items                        | Values |
|------------------------------|--------|
| Reynolds number $Re$         | 40,000 |
| Angle-of-attack $\alpha$     | $-4^\circ$ to $24^\circ$, $1^\circ$ increments |
| PIV                          | $4^\circ$ and $18^\circ$ |
| Propeller advance ratio $J$  | 0.4    |

5. Results and Discussion

5.1. Force measurement

The lift coefficient ($C_L$) curves of the propeller positions and rotation directions are shown in Fig. 6. $C_L$ differed based on the propeller conditions. For the case of no propeller, $C_L$ increased linearly until the stall angle $\alpha = 15^\circ$ and decreased gradually from $\alpha = 15^\circ$. For the center propeller, stalls were not observed until $\alpha = 24^\circ$. The center_ccw demonstrated a higher level of $C_L$ compared to that of no propeller, whereas the center_cw did not. For the tip propeller, the lift slopes were almost flat from $\alpha = 15^\circ$. The tip_ccw demonstrated a higher level of $C_L$ for every angle-of-attack when compared to no propeller, whereas the tip_cw had a low $C_L$ for $\alpha = 5^\circ$ to $8^\circ$ and a high $C_L$ for $\alpha = 8^\circ$ to $24^\circ$.

The drag coefficient ($C_D$) curves are shown in Fig. 7. $C_D$ depended on the propeller positions. For the case of no propeller, $C_D$ showed a parabolic curve until $\alpha = 15^\circ$ and increased proportionally above $\alpha = 15^\circ$. For the center and tip propellers, $C_D$ showed a parabolic curve and was higher than that of no propeller. This result is conflicting with the results of Ananda et al. They mentioned that the drag coefficient with a Wortmann FX63-137 airfoil, a GWS 5/24 propeller, and a Reynolds number of $6 \times 10^4$ was decreased due to the propeller slipstream effect. This conflicting result may due to the difference in conditions mentioned above. Therefore, this result suggests that more instances are required before further understanding the propeller slipstream effect on the wing under a low Reynolds number condition. In terms of the rotation direction, the $C_D$ of cw was slightly higher than that of ccw until approximately $\alpha = 10^\circ$, and that of ccw was higher than that of cw from approximately $\alpha = 15^\circ$. This tendency for the rotation direction was also reported by Ushiyama and Okamoto. However, in terms of the propeller position, the $C_D$ of the tip propeller configura-
tion was lower than that of the center propeller configuration. This tendency for the propeller position conflicts with that reported by Ushiyama and Okamoto.\textsuperscript{15} Their test was performed using a NACA4406 airfoil with an aspect ratio of 4, a GWS 4.0 \times 4.0 propeller, and a Reynolds number below $2 \times 10^6$. This conflicting result also may be caused by the difference in conditions mentioned above.

The pitching moment ($C_M$) curves are shown in Fig. 8. All of the propeller conditions yielded negative values, indicating a nose-down torque. The conditions except those of center\_cw demonstrated sharp decreases in moment at approximately $\alpha = 15^\circ$. Only center\_cw demonstrated an almost constant moment. This performance is favorable from the standpoint of longitudinal stability and control. This constant moment is a cause of concern for delaying stall; however, the pitching moment of the center\_ccw also dropped as was seen for other conditions as well. This reason is discussed in Section 5.2.

The lift-to-drag ratio ($L/D$) curves are shown in Fig. 9. All of the conditions, including no propeller, showed that the maximum $L/D$ occurred at around $\alpha = 4^\circ$. In particular, center\_cw and tip\_ccw demonstrated higher values, whereas center\_ccw and tip\_cw demonstrated lower values.

Matsumoto et al.\textsuperscript{17} reported that, when the propeller rotates in the opposite direction of the wingtip vortex, the wingtip propeller configuration showed a higher lift-to-drag ratio than the center configuration. Figure 9 agrees with the result of Matsumoto et al.\textsuperscript{17} even though the airfoil, propeller, and Reynolds number are different. On the other hand, the center\_cw condition, which rotates in the same direction as the wingtip vortex, showed a relatively high lift-to-drag ratio even though the propeller was not at wingtip, but rather at the center of the wing.

Ushiyama and Okamoto\textsuperscript{15} stated that the maximum lift-to-drag ratios were almost the same among no propeller, center\_cw, and center\_ccw conditions. However, Fig. 9 indicates that the maximum lift-to-drag ratio of the center\_cw condition is significantly higher than that of the other two conditions. The difference in the results may be due to the difference in the test conditions, such as airfoil, propeller geometry, and Reynolds number.

The results indicate that the aerodynamic characteristics differed according to the position and rotation direction of the propeller. Center\_cw demonstrated the highest performance of the wing under all conditions owing to the constant $C_M$ and high $L/D$. As shown in Section 5.2, flow visualization analysis was performed to determine the reason for contributing to these differences in the next experiments.

### 5.2. Flow visualization

The average velocity distributions around the wing at $\alpha = 4$ are shown in Fig. 10. The colored bar shows $U = 0$ to 12.5 m/s. The velocity distributions differed between the propeller slipstreams on the upwash (in Figs. 10(a), (d), and (f)) and downwash sides (in Figs. 10(b), (c), and (h)). The flow velocity of the slipstream was faster on the upwash side than on the downwash side. The velocity of the propeller slipstream on the upwash side increased to approximately $U = 12.5$ m/s near the leading-edge. Meanwhile, the velocity near the leading-edge on the downwash side decreased to approximately $U = 6.0$ m/s, and the velocity was approximately $U = 10$ m/s in most areas.

These differences affected the wing performance including the $C_L$, as each condition had different area ratios of the propeller slipstream on the upwash and downwash sides. The results suggest that the higher $C_L$ of tip\_ccw, center\_cw, and center\_ccw was caused primarily by the slipstream on the upwash side and that the lower $C_L$ of tip\_cw was caused primarily by the slipstream on the downwash side.

The positions of the propeller slipstream separation differed from those on the upwash sides in Figs. 10(a), (d), and (f). The separation points of center\_ccw, center\_cw, and tip\_ccw were $x/c = 0.3$, 0.7, and 0.5–0.6, respectively. The slipstream separation position of center\_cw was the closest to the trailing-edge. These differences suggest that the highest $C_L$ of center\_cw was caused by the large slipstream area size on the upwash side on the wing.

The main-flow-direction velocities, the $y$-$z$ plane velocity vector fields, and the vorticity distributions behind the trailing-edge at $\alpha = 4^\circ$ are shown in Fig. 11. The interference effects between the wingtip vortexes and the propeller slipstream differed in each case, as shown in Fig. 11.

Firstly, the results of the no propeller condition are shown
in Fig. 11(a) as a baseline. The main-flow-direction velocity field was almost uniform in the visualized area. The blue area at the bottom right corner of the main-flow-direction velocity field is unmeasured. This area appears at the top right or bottom right of the figure depending on the setup. On the other hand, strong and small wingtip vortex is shown in the vorticity figure.

For tip.ccw in Fig. 11(d), the main-flow-direction velocity also shows that the propeller slipstream does not attach on the upper surface of the trailing-edge, as shown in Fig. 10(f). The propeller slipstream on a lower surface side expanded in the wing root direction because the swirling flow was prevented by the wing. As mentioned in the Introduction, Deters et al.\textsuperscript{13)} reported that the upper and lower slipstreams were split by the wing and moved away from each other in the static atmosphere. Figure 11 shows that the splitting and moving away from each other occur even in the advancing flow under this low Reynolds number condition. This moving effect made a difference in the flows on the upper and lower sides. In the vorticity result in Fig. 11(d), a horizontal blue structure is shown on the right side. This structure suggests the upper-surface flow is a straight shear flow in the spanwise-direction and the lower-surface slipstream flow is sliding in the wing root direction. Moreover, the clockwise flow of the wingtip vortex was wrapped by the counterclockwise flow of the propeller slipstream. This result suggests that the effect of the propeller slipstream was stronger than that of the wingtip vortex.

On the other hand, for tip.cw, large clockwise vorticity was observed on the wingtip. This is caused by the fusion of the wingtip vortex and the clockwise-rotating propeller slipstream. The propeller slipstream structure in the main-flow-direction velocity was almost the same as the vertically reversed state of the tip.ccw.

For center.ccw, the wingtip vortex generated a clockwise flow at the wingtip, whereas the propeller slipstream generated a counterclockwise flow at the center of the wing. The wingtip vortex extended in the wing root direction by merging with the downwash flow of the counterclockwise-rotating propeller slipstream at the center of the wing; therefore, the area of the wingtip vortex was larger but the magnitude was weaker than for the no propeller condition. The main-flow-direction velocity shows that the propeller slipstream on the upper side also extended in the wingtip direction. This extension is the effect of not only the prevented swirling flow, but also the fusion with the wingtip vortex.

For center.ccw, the wingtip vortex generated a strong clockwise flow at the wingtip, whereas the propeller slipstream generated a clockwise flow at the center of the wing. However, the slipstream on the upwash side flowed not from the lower side to the upper side, but from the upper side to the lower side owing to the effect of the wingtip vortex. The downwash flow generated by the wingtip vortex mitigated the slipstream separation of center.ccw on the upwash side. This result corresponds to the result shown in Fig. 10(d). On the other hand, the main-flow-direction velocity shows that the propeller slipstream on the lower side extended to the upper side of the wingtip. This also affects the prevention of swirling and the suction of the wingtip vortex.

Based on the force measurement and flow visualization results, center.ccw showed a high lift coefficient and lift-to-drag ratio because of the following:

(i) In the center configuration, a large area of the wing was in the high-speed slipstream;
(ii) In the center.ccw configuration, the flow separation on the upwash side was suppressed by the effect of the wingtip vortex.

The average velocity distributions on the wing at $\alpha = 18^\circ$ are shown in Fig. 12. All of the slipstreams on the downwash sides were not separated from the wings at a high angle-of-attack, as shown in Figs. 12(b), (c), and (h). As shown in Figs. 12(a) and (f), the slipstreams on the upwash sides of center.ccw and tip.ccw were separated near the leading-edge.
Areas of extremely slow flow appeared on the wings as well. Meanwhile, as shown in Fig. 12(d), the slipstream on the upwash side of center cw flowed around the wing owing to the strong effect of the wingtip vortex. The separation point was delayed to \( x/c = C_25\) : 3. These differences suggest that the high \( C_L \) and the constant \( C_M \) of center cw at the high angle-of-attack were caused by the prevention of complete slipstream separations on the upwash and downwash sides, as shown in Figs. 12(c) and (d), respectively.

As for the drag coefficient, PIV measurements could not determine the effects of the propeller position and rotation direction on \( C_D \).  

6. Conclusion

This study aimed to elucidate the effects of propeller position and rotation direction on the Ishii wing at a low Reynolds number. Two types of measurements were conducted: force and PIV measurements. Five conditions of propeller position and rotation direction were used: no propeller, center cw, center ccw, tip cw, and tip ccw.

The velocity of the propeller slipstream on the upwash side was 12 m/s. This was higher than the velocity on the downwash side of 10 m/s. Therefore, the lift coefficient of tip ccw was higher than that of tip cw.

Meanwhile, center cw showed a lift coefficient that was 0.2 higher than that of center ccw, even though both conditions had the same sizes for upwash and downwash areas.
This difference can be explained by considering the effect of the wingtip vortex. The obtained PIV results indicated that the flow separation on the upwash side was delayed to $x/c = 0.7$ at $4\degree$ and 0.3 at $18\degree$ due to the wingtip vortex.

The pitching moment coefficient of center_cw did not change significantly at a high angle-of-attack. This might also be attributed to the delay in flow separation owing to the interaction effect of the wingtip vortex.

The drag coefficient showed conflicting results with those reported in other literature. The propeller slipstream increased rather than decreased the drag coefficient at the center of the wing. The drag coefficients of the center propeller configurations were higher than those of the tip propeller configurations rather than lower. These conflicting results may be caused by difference in the experimental conditions. Therefore, this result suggests that more instances are required to further understand propeller slipstream effect on a wing under low Reynolds number conditions.

In terms of the lift-to-drag ratio, when the propeller rotates in the opposite direction of the wingtip vortex, the tip propeller configuration showed a higher lift-to-drag ratio than the center propeller configuration. This result agrees with the previous study even though the airfoil, propeller shape, and Reynolds number are different. On the other hand, the lift-to-drag ratio of the center $\_c w$ was significantly higher than that of the center $\_c c w$, contrary to the previous study.

From the standpoint of the flow field, this study clarified that the propeller slipstream moves in a spanwise direction even in the advancing flow under this low Reynolds number condition. This spanwise sliding effect encouraged interaction between the propeller slipstream and the wingtip vortex.

Hence, the following two factors must be considered to increase the aerodynamic characteristics when designing a Mars airplane: (i) the ratio of propeller slipstream areas on the upwash and downwash sides of the wing, and (ii) the effect of the wingtip vortex on the propeller slipstream.

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