Unsteady Numerical Simulation of the Mutual Disturbance between Propeller and Wing*

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This paper presents the unsteady numerical simulation and analysis of the slipstream generated by distributed propellers on a solar-powered UAV using the CFD method based on structured/unstructured hybrid grids. Sliding mesh technology and a transition model are used for the numerical simulation of a NACA propeller and an Eppler 387 airfoil, the results of which are well compatible with the experimental data, proving the calculation method to be highly credible and accurate. Numerical simulations are run for configurations with the propeller in front of and behind the wing, and comparative analyses are conducted with a pure propeller and pure wing. The results suggest the existence of mutual disturbance between the propeller and the wing, as the propeller, either in front of or behind the wing, causes an increase in cyclical fluctuation of the wing’s lift, drag and nose-down moment. The wing, in return, gives rise to an increase in fluctuation of the propeller’s pulling force, absorbing power and efficiency, with propeller oscillation being triggered by the discontinuity of the flow field. The configuration with the propeller posed behind the wing is proven to be of smaller disturbance to the whole system.

Key Words: Propeller, Wing, Mutual Disturbance, Unsteadiness, Sliding Mesh, Transition

Nomenclature

\[ V_{\infty} \]: inflow velocity
\[ \rho \]: atmospheric density
\[ Re \]: Reynolds number
\[ Ma \]: Mach number
\[ y^+ \]: distance in wall coordinates
\[ \alpha \]: angle of attack
\[ C_{Tf} \]: frictional drag coefficient
\[ C_{Tf} \]: propeller thrust coefficient
\[ C_{Pp} \]: propeller absorbing power coefficient
\[ \eta \]: propeller efficiency
\[ T \]: propeller thrust
\[ Q \]: propeller torque
\[ P_{p} \]: propeller absorbing power
\[ P_{e} \]: propeller effective power
\[ D \]: propeller diameter
\[ n_{i} \]: propeller rotating speed
\[ C_l \]: lift coefficient
\[ C_d \]: drag coefficient
\[ C_p \]: pressure coefficient
\[ f \]: turbulence intensity
\[ \mu_{t}/\mu \]: turbulent viscosity ratio
\[ P_{\text{input}} \]: power input of propeller/wing system
\[ L_{\text{output}} \]: lift output of propeller/wing system
\[ T_{\text{output}} \]: thrust output of propeller/wing system

1. Introduction

Solar-powered Unmanned Aerial Vehicles (UAVs) have been proven to be a viable solution for those seeking long cruising hours, high cruising altitude, large region coverage, task flexibility and other characteristics beyond the capability of traditional powered aircraft. Such aircraft designs have been under intensive research in many countries.\(^1\) Distributed propellers are typical in solar-powered UAV designs requiring high reliability of the propelling system as a prerequisite for its flying task of months in the air. For example, NASA’s Helios solar-powered UAV had 10 propellers in front of its wing, putting a considerable part of its wing under the propeller slipstream, which significantly influenced the aerodynamic characteristics of the wing.\(^2\)

The propeller and airfoil streams of the solar-powered UAV are also unique to those of traditional propeller-driven aircraft, as an individual propeller among the distributed propellers provides lower pulling force. Furthermore, these propellers are always of a larger diameter to maintain their propelling efficiency, resulting in a lower load on the propeller dish. Laminar separation and transition are typical in solar-powered UAVs with a Reynolds number ranging between 400,000 and 800,000.\(^3\) Therefore, the derived aerodynamic disturbance between the propeller and the wing must be managed for such aircraft designs.

The disturbance between the propeller slipstream and the wing is rather complicated, as the overlapped flow field of the slipstream and the profile flow are highly complicated; especially in the case of low-Reynolds-number airfoils typical in solar-powered UAV designs, in which the influence of the slipstream to the flow transition must be taken into account. The disturbance between the propeller slipstream
and the wing, on the other hand, is mutual as the aerodynamic characteristics of both the airfoil and the propeller blades change at the same time. Many engineering calculation methods have been developed to simulate the mutual disturbance, including attempts to simulate the effect of slipstream on aerodynamic characteristics of the airfoil using the panel method or by introducing the equivalent dish model of the propeller. However, the precise analysis and evaluation of the disturbance in aerodynamic terms, particularly in the unsteady sense, cannot be achieved without precisely simulating the relative motion between the propeller and the wing. Bousquet and Gardarein from ONERA managed to simulate the flow field caused by a multi-zone grid to solve the Euler equation. Stuermer et al. from DLR used the chimera grid to simulate the slipstream of the propeller. The unsteady simulation method, unlike the traditional engineering calculation methods, can provide access to the complicated characteristics of the wing, the influence of propeller slipstream to the aerodynamic performance of the propeller, the disturbance to the structure of the propeller slipstream caused by the wing, and the change in the performance of the propeller/wing system.

2. Numerical Calculation Method

All simulations were performed with ANSYS FLUENT software using Reynolds-Averaged Navier-Stokes (RANS) equation, finite volume method and second-order upwind scheme with the integrated control equation generated as:

\[
\frac{\partial \rho \vec{V}}{\partial t} + \nabla \cdot (\rho \vec{V} \vec{V}) = \nabla \cdot \tau + \frac{\partial}{\partial x_j} \left[ \sigma_{ij} \left( \mu + \mu_t \right) \frac{\partial \vec{V}}{\partial x_j} \right]
\]

where \( \rho \) is the density, \( \vec{V} \) is the velocity vector, \( \tau \) represents the net flux vector, and \( \sigma_{ij} \) is the stress tensor.

In the case of a solar-powered UAV, both the propeller and the wing have a low Reynolds number (10,000-level and 100,000-level, respectively). Therefore, the issue of laminar transition must be taken into account in a numerical calculation. In this paper, the \( \gamma-Re_0 \) transition model, coupled with the SST \( k-\omega \) turbulence model and proposed by Langtry and Menter, is introduced. This transition model integrates the advantages of the empirical transition correlation and the low-Reynolds-number turbulence model, which is available for engineering calculations.

The \( \gamma-Re_0 \) transition model contains two additional transport equations (i.e., the local transition Reynolds number \( Re_0 \) and the intermittency factor \( \gamma \)), with the former to anticipate the initial position of transition and the latter to simulate flow movement in the transition zone.

The equation of the local transition Reynolds number \( Re_0 \) is shown as below:

\[
\frac{\partial (\rho Re_0)}{\partial t} + \nabla \cdot (\rho \vec{V} Re_0) = \frac{\partial}{\partial x_j} \left[ \sigma_{ij} (\mu + \mu_t) \frac{\partial Re_0}{\partial x_j} \right] + P_{\text{fl}} 
\]

Where the source item \( P_{\text{fl}} \) is key to transporting the free flow \( Re_0 \) into the boundary layer, expressed as follows:

\[
P_{\text{fl}} = c_{infl} \rho (Re_0 - Re_{0i})(1.0 - F_{\text{fl}}) 
\]

Where the time scale

\[
t = \frac{500 \mu}{\rho \nu^2} 
\]

The transport scalar \( Re_0 \) diverges from the free flow, due to \( F_{\text{fl}} \), eliminating the source item \( P_{\text{fl}} \) in the boundary layer. \( F_{\text{fl}} \) equals 0 in the free flow, and 1 in the boundary layer.

\[
F_{\text{fl}} = \min \left( \max \left( F_{\text{wake}}, e^{-\left( \frac{\gamma}{\gamma_1} \right)^4}, 1.0 - \left( \frac{\gamma - 1/c_2}{1.0 - 1/c_2} \right)^2 \right), 1.0 \right) 
\]

\[
\theta_{BL} = \frac{Re_{0i} \mu}{\rho U}, \quad \delta_{BL} = \frac{15}{2} \theta_{BL} 
\]

\[
\delta = \frac{50 \Omega V}{U}, \quad Re_0 = \frac{\rho \nu^2}{\mu}, \quad F_{\text{wake}} = e^{-\frac{Re_0}{175}} 
\]

The equation of the intermittency factor \( \gamma \) is:

\[
\frac{\partial (\rho \gamma)}{\partial t} + \nabla \cdot (\rho \vec{V} \gamma) = \frac{\partial}{\partial x_j} \left[ \mu + \mu_t \frac{\partial \gamma}{\partial x_j} \right] 
\]

With the source item defined as:

\[
P_{\gamma} = F_{\text{length}} \rho S_i (\gamma F_{\text{onset}})^{\alpha}, \quad E_{\gamma 1} = c_{1p} P_{\gamma 1} \gamma 
\]

\[
P_{\gamma 2} = c_{2p} \Omega \gamma F_{\text{urb}}, \quad E_{\gamma 2} = c_{2p} P_{\gamma 2} \gamma 
\]

Where \( F_{\text{length}} \) is an empirical correction coefficient that determines the length of the transition zone. \( F_{\text{urb}} \) is used to avoid the regeneration of the laminar flow inside the viscous sublayer, \( F_{\text{onset}} = e^{-\left( \tau_{\text{fl}} / 10 \right)} \). \( \tau_{\text{fl}} \) represents the relative viscosity. \( S_i \) represents the value of the strain rate. \( F_{\text{onset}} \) is used to trigger the intermittency of the turbulent fluctuation.
constant terms in the intermittency factor equation are:

\[ c_{e1} = 1.0, \quad c_{e2} = 50, \quad c_{d1} = 0.5, \quad c_{d2} = 0.06, \quad \sigma_f = 1.0. \]

The detailed interpretation of each parameter is shown in the literature from Langtry and Menter.\(^{11-13}\)

3. Calculation Model and Grid

3.1. Calculation model

The whole wing can be divided into segments by the number of propellers, with each propeller influencing the wing segment behind it significantly and the neighboring segments insignificantly. An individual segment is singled out, with both ends of it treated as a symmetric boundary to simplify the analysis and also to avoid the three-dimensional effect of the limited wing span. In addition, the wing and propeller have a no-slip-wall boundary and the far-field is a pressure-far-field boundary.

The calculation model is based on a solar-powered UAV design with a two-bladed propeller 3.2 m in diameter and a 45° nonlinear geometric twist from the root to the tip of each blade. The x axis represents the rotating shaft in the same direction of the inflow. The propeller rotates counterclockwise from the positive perspective of the x axis at a cruising speed of 800 rpm. The wing section is 3.2 m in chord length with an installation angle of 4°, a relative thickness of 13.42% (maximum thickness at 32% chord length), and a relative camber of 6.27% (maximum camber at 52% chord length). The configurations with the propeller in front of (Model 1) and behind (Model 2) the wing are analyzed, as shown in Fig. 1, and comparison is made between the pure propeller and the pure wing. The rotation angle of the propeller when parallel with the wing is defined as 0°.

3.2. Grid generation

The static zone and rotating zone enveloping the propeller are established in the flow field using hybrid grids to generate meshes of the rotating zone and the static zone. The boundary in-between is defined as the boundary of the sliding meshes, through which the flow field information is transmitted between the two zones, thereby addressing the issue of relative motion between the wing and the propeller. An unstructured grid is used to divide the rotating zone, generating a prism grid around the surface of the propeller blades so as to maintain the accuracy of the simulated boundary layer with the grid mesh tightened at the boundary area. The static zone is divided by a structured grid, with the chordwise nodes slightly tightened to capture the transition point accurately. An O-grid is used to generate the grid of the boundary layer on the wing surface. The y+ value of the first-layer grids should be approximately 1, as pointed by Menter et al.,\(^{12}\) so as to accurately capture the laminar-transition boundary layer.

Figure 2 shows the distribution of the surface and space grid, the grid containing 9.0 million cells. Calculation results based on the grid are compared to results based on a sparser and denser grid before the study. Figure 3 presents the time-average drag of the wing (Model 1), which is the most sensitive to grid numbers, as the grid number changes. It can be seen that drag changes by 3.2% when the grid number changes from 9.0 million to 13.5 million. Therefore, it is believed that 9.0 million is sufficient for this study.

4. Results and Analysis

4.1. Calculation example validation

The experimental data of the pure propeller and pure wing are used to demonstrate the accuracy of the numerical simulation. The full set of data concerning propeller shaping, experimental conditions and results from Reid\(^{14}\) provide the most frequently used calculation examples for propeller validation.\(^{15,16}\) Model 5 (β0.75R = 19°, Test F-10), from Reid,\(^{14}\) is introduced to such examples for numerical simulation. The rotating zone enveloping the propeller is divided by unstructured grids, and the static zone is divided by structured ones in the same way as applied to this study. The sliding mesh is used for the unsteady numerical calculation, using the aforementioned transition model for the turbulence model.

Eppler 387, as a low-Reynolds-number and high-lift airfoil, is commonly used in high-altitude propellers and UAVs, and experimental data of such airfoil is plentiful.\(^{17,18}\)

![Fig. 1. Propeller/wing of two models (mm).](image1)

![Fig. 2. Distribution of surface and space grid.](image2)

![Fig. 3. Time-average drag of wing (Model 1) as grid number changes.](image3)
Numerical simulation is conducted under the condition of $Re = 3.0 \times 10^5$ (airfoil chord of 0.305 m, velocity of 14.62 m/s, in flow turbulence intensity of 0.1%, inflow turbulent viscosity ratio of 5.0, and sea-level atmosphere condition), with the flow domain divided by structured grids using the transitional model for its turbulence model.

Curves in Figs. 4–6 present the correlation between the thrust coefficient, absorbing power coefficient and efficiency of the propeller with its advance ratio, suggesting the calculation results match fairly well with the experimental data at all advance ratios, each showing the same trend of variation.

In this paper, thrust coefficient, absorbing power coefficient, and efficiency are respectively defined as:

$$C_T = \frac{T}{\rho n_s^2 D^4}, \quad C_P = \frac{P_w}{\rho n_s^3 D^5}, \quad \eta = \frac{P_e}{P_w} \quad (10)$$

Where $P_w$ is absorbing power ($P_w = 2\pi n_s \cdot Q$), $P_e$ is effective power ($P_e = T \cdot \nu_0$), $Q$ is torque, $T$ is thrust, $n_s$ is rotating speed (revolutions per second) and $D$ is propeller diameter.

Figure 7 provides the comparison between CFD results and experimental data for the Eppler 387 under $Re = 3.0 \times 10^5$, suggesting the lift/drag result generated by numerical calculation are basically in line with the experimental results. Figure 8 provides the comparison of pressure at the angle of attack of $4^\circ$, suggesting the difference between the two distribution patterns is rather small, except for the minor difference in suction peak near the leading-edge.

Figure 9 presents the frictional drag coefficient curve of the airfoil surface along the drag direction at the angle of attack of $4^\circ$, from which many critical features of the flow can be gathered. The first passing-through of $C_f$ over 0, suggests the lift/drag result generated by numerical calculation are basically in line with the experimental results. The experimental results from Selig et al. suggest that Eppler 387, under such circumstances, has its laminar separation position at 40%, the transition point at 55%, and the reattachment point at 58% of its chord length, which are well in line with the calculation.
results of this study.

4.2. Propeller’s influence on wing

In this study, numerical simulations are performed on cases with the propeller fitted in front of and behind the wing, under the conditions of a 25 km atmosphere, facing a free inflow velocity of $Ma = 0.145$, turbulence intensity of $I = 0.05\%$, turbulent viscosity ratio of $\mu_t/\mu = 5.0$, and a propeller rotating speed of $n_t = 800$ rpm (tip Mach number $M_{tip} = 0.47$).

Figure 10 provides the variation curve of the wing lift with the rotation angle of the propeller. It suggests that, compared to the pure wing, the wing with a propeller experiences an increase in lift, mostly due to the fact that the wing is right in the middle of the accelerated slipstream from the propeller when it is fitted in front (or in the suction flow when the propeller is fitted behind), which increases the flow speed at the wing surface. The sinusoidal fluctuation of the lift generated by the wing with the rotation of the propeller can be observed twice in a single rotation ($360\degree$), as the two blades of the propeller sweep over the leading- (or trailing-) edge of the wing. Such fluctuation matches well with the conclusion of the numerical simulation involving AGARD2, conducted by Stuermer and Rakowitz. It is obvious that the variation magnitude in Model 2 is smaller than that in Model 1, suggesting the rear-mounted propeller configuration generates less acceleration effect and smaller cyclical disturbance than the frontal-mounted configuration does.

Figure 11 provides the variation curves of the total drag, pressure drag and viscous drag with the rotation angle of the propeller. It can be seen that, similar to the wing lift, the drag of the wing changes in a steady sinusoidal pattern, fluctuating twice per revolution. The increment of both the drag and magnitude of the cyclical fluctuation of Model 2 are smaller than those of Model 1, suggesting the rear-mounted propeller has a smaller influence on the drag of the wing. It can be seen from Fig. 11 that, compared to the pure wing, the pressure drag of the wing behind the propeller experiences an increase in drastic, while its viscous drag increases at a modest pace.

Figure 12 presents the pressure distribution of the upper wing surface in Model 1 and the pure-wing case, suggesting that the pressure distribution on the wing is changed by the slipstream from the propeller. As the pressure at the $-\gamma$ leading-edge of the wing is reduced that at the $+\gamma$ leading-edge is increased, which is obviously due to the change in local angle of attack as a result of propeller induction. Compared to a six-bladed propeller ($n_t = 1075$ rpm) in terms of pressure distribution on the wing surface, the low-speed, light-load propeller observed in this study has a much smaller impact on the pressure distribution on the wing surface, suggesting that such propellers typical in solar-powered UAVs have a
weaker flow-induction effect.

Further comparisons are made on cross-section A/B/C/D (Fig. 13). Putting together the pressure distribution from front to 60% chord length, it can be seen that, regardless of the proportional change of such distribution due to the varied lift, the patterns of pressure distribution on section B and section D are basically the same, meaning the propeller’s impact on pressure distribution on the wing behind is relatively small. The negative pressure at the leading-edge of section A is increased compared to the case of section B, while that of section C is decreased compared to section B, which is in line with the above analyses (Fig. 12). The same variation trend is observed in the distribution patterns of sections A/B/C, differed from the case of section D, from 60% chord length to the rear: Compared to the case of section D, the lower surface pressure of sections A/B/C don’t recover quickly; instead a convex is formed on the lower surface, which gives rise to additional pressure drag. It is reasonable to believe that the increased pressure drag is a result of the propeller’s impact on the pressure distribution at the rear lower surface of the wing. Thus, it is recommended to take such issues into account in the inverse airfoil design for solar-powered propeller-driven UAVs.

Figure 14 presents the variation curves of the pitching moment coefficient of the wing when taking moment about the aerodynamic center (i.e., the zero-lift moment coefficient). It is clear that the nose-down moment is increased after adding a propeller, and starts fluctuating in a steady sinusoidal pattern. The nose-down moment is considered mostly as an adverse factor to aerodynamics, as it increases the trim drag. It is believed that the increased nose-down moment is also the result of the pressure convex at the rear lower surface of the wing since the aerodynamic center is in front of the pressure convex. The increment and magnitude of cyclical fluctuation of the nose-down moment in Model 2 are smaller than those in Model 1, suggesting the rear-mounted propeller configuration renders the minimal impact to wing moment.

Figures 15–17 present the surface turbulence kinetic energy distribution in the pure wing and wing configurations with frontal- and rear-mounted propellers, with the blue area representing the laminar flow and the red area the turbulence. It can be seen from Figs. 16 and 17 that the flow pattern on the wing surface rarely changes with the propeller at different rotation angles, suggesting that the impact of the propeller, though cyclically sweeping over the wing, is relatively steady for the surface laminar flow and turbulence. Putting together the three groups of figures, it is clear that the transition point of the pure wing (Fig. 15) is fixed; such point is deviated and turbulence range is increased when a propeller is added in front of the wing (Fig. 16). This results in increased viscous drag as shown in Fig. 11, since the viscous drag of the turbulence is more powerful than that of the laminar

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In the case of the rear-mounted propeller (Fig. 17), the deviation of the transition point is rather small and the viscous drag changes modestly as well (Fig. 11).

Figure 18 presents the spatial distribution of turbulent kinetic energy in the flow field. It can be seen that no significant increase in turbulent kinetic energy is observed before the flow passes the propeller. However, the increase becomes obvious after the pass, mainly due to the transition of the flow when passing the surface of the propeller, similar to the case of the high turbulent kinetic energy zone at the rear part of the wing. The spiral turbulence behind the propeller is blocked by the wing and starts dispersing along the wing surface, impacting the transition of the wing-surface boundary layer. Under the influence of flow viscosity, turbulence reintegrates gradually behind the wing. The level of influence from the propeller on the turbulent kinetic energy in front and behind are varied. As the result, the propeller influences the wing flow significantly when fixed in front of the wing (Fig. 16) and modestly when fixed behind (Fig. 17).

### 4.3 Wing’s influence on propeller

The disturbance to the flow at low speed can diffuse throughout the whole flow field. Similarly, the wing may also influence the aerodynamic performance of the propeller. Figures 19–21 provide the variation curves of the propeller’s thrust, absorbing power and efficiency with its rotation angle. It is obvious that, compared to the case of pure propeller, the average thrust, absorbing power and efficiency of the propeller are increased with a wing in existence, with the increment more drastic in the frontal-mounted configuration. Cyclical fluctuations of the transient thrust, absorbing power and efficiency of the propeller are also observed twice per revolution, as the two blades of the propeller sweep over the leading-edge of the wing one after another.

The above phenomenon is believed to be attributed to the following facts: Firstly, in the frontal-mounted configuration, the flow speed through the propeller dish is lower than the speed of the inflow due to blockage of the wing, resulting in reducing the actual advance ratio of the propeller, as the actual working condition of the propeller is changed. As shown in Fig. 19, the most significant blockage of the wing emerges when the propeller is at the rotation angle of about 0°, almost parallel to the wing, resulting in the greatest thrust...
for Model 1. Such blockage is weakened to the minimum when the propeller is perpendicular to the wing (rotation angle 90°), resulting in the lowest thrust for Model 1. Meanwhile, the wing’s rectifying effect on the slipstream from the propeller is also a critical factor for the aerodynamic performance of the propeller, though the mechanism behind such correlation deserves further observation. Here, we try to explain it in the language of physics: A substantial part of energy consumed by the propeller is for the generation of air eddy, yet the tangential velocity component of the eddy contributes nothing to the thrust of the propeller; rectifying the wing helps to reduce the eddy-induced energy loss, improving the thrust and efficiency of the propeller as a result. Such mechanism has seen its application in the design of contra-rotating propellers and ducted propellers with stators.20) However, wing rectifying will definitely bring about change in the aerodynamic performance of the wing, as discussed before.

Secondly, in the rear-mounted configuration, the propeller is subjected to the low-speed wake flow of the wing, resulting in changing the working condition of the propeller. The wake flow of the pure wing is concentrated at the wing plane behind the wing, but the distribution of the wake flow is changed by the rotating propeller, with the most intensive point of the wake flow no longer existing right behind the wing (when the propeller is at 0°). The thrust of the propeller reaches its peak when it is at around 60°, as shown in Fig. 19, suggesting the propeller is right in the most intensive part of the wake flow.

Propeller vibration is a concern of all propeller-driven aircraft designers, as the high-frequency vibration intensifies the wear of the electric motor and structural elements,21) especially in the case of the solar-powered UAVs featuring low design overload and small structural strength allowance, which deserve equally intensive attention to its effects. Vibration is mainly due to the eccentricity of the propeller, motor vibration, blade flutter and aerodynamic imbalance, which is also a major issue under discussion in this paper. The vibration induced by aerodynamic imbalance can be broken up into relatively independent axial vibration and lateral vibration, with the former derived from torsional vibration and the latter formed by coupling the horizontal and vertical vibrations.22)

Figure 22 presents the variation curve of the propeller torque with its rotation angle. It is clear that the torque of the pure propeller in pure flow is constant, which starts showing cyclical fluctuation when a wing is furnished. Similarly, the lateral force along the blade span also shows cyclical fluctuation (Fig. 23), which along with the fluctuation of propeller torque, gives rise to the axial and lateral vibrations. Such fluctuations emerge twice per revolution, suggesting the vibration frequency is twice the rotation frequency. There is no significant difference between the fluctuation magnitudes of Model 1 and Model 2, suggesting the vibration-triggering incentive from the cyclical aerodynamic forces are barely different in the frontal-mounted and rear-mounted configurations.

### 4.4. Propeller/wing system analysis

It is concluded from the above discussions that the wing and propeller do influence each other. In fact, these two elements are connected to each other by internal forces, and thus should be analyzed as a whole. In a system consisting of a wing and propeller, the input and output are the only items being observed, with the interaction between the two elements being neglected, with the system demand power (meaning the absorbing power of the propeller) as the typical input parameter, and the resultant force as the typical output parameter. It should be noted that the resultant force along the thrust direction is the result of wing drag and propeller pull, with the latter greater than the former, since inducing drag and fuselage drag are not considered in this study.

The inputs and outputs of Model 1, Model 2 and pure wing + pure propeller are put together in Table 1, among which the pure wing + pure propeller combination represents the simple addition of the two, without considering their interactions. In the table, $P_{\text{input}}$, $L_{\text{output}}$, $T_{\text{output}}$ respectively represent power input, lift output, and thrust output of the propeller/wing system. It is clear that, compared to the case of the simple addition, the demand power of the
whole system is increased, with the interaction taken into account, and the lift is increased along with the thrust being reduced. Among such changes, the increased lift is beneficial, and the increased demand power and reduced thrust are adverse. The magnitude of such changes is smaller in the rear-mounted configuration.

Take Model 2 for example. Reducing the thrust of the system by 4.87 N is equal to 4.87 N of additional system drag, while the additional system lift is 33 N. For solar-powered UAVs with a high lift/drag ratio (usually higher than 30), the negative effect from an additional 4.87 N drag outweighs the benefit from an additional 33 N lift.

5. Conclusion

In this study, numerical simulations were conducted based on structured/unstructured hybrid grids and using the sliding mesh method to determine the interaction between a propeller and wing. Comparisons were also made on the performance of the pure propeller and wing, suggesting that:

1) The existence of the propeller causes an increase in and cyclical fluctuation of the wing’s lift, drag and nose-down moment. The increased drag is mainly due to the significant increase in pressure drag.

2) Compared to the case of the frontal-mounted configuration, the lift, drag, nose-down moment and flow pattern of the rear-mounted configuration is less sensitive to the existence of the propeller.

3) The thrust, absorbing power and efficiency of the propeller are increased upon the existence of a wing, mainly due to the air flow blockage, wake flow and trimming effect of the wing.

4) The cyclical fluctuation of the propeller torque and lateral force give rise to vibration. As to the two-bladed propeller observed in this study, its vibration frequency is twice its rotation frequency. There is no significant difference in the magnitude of vibration-triggering incentive from the cyclical aerodynamic force of both the frontal-mounted and rear-mounted configurations.

5) Compared to the simple addition case, the whole propeller/wing system, after taking into account the interactions between the two elements, experiences increased demand power and lift, and reduced thrust. The magnitude of such changes is smaller in the rear-mounted configuration.

In conclusion, the wing and propeller do influence each other. Therefore, the designs and calculations should be made in a manner that cover not the simple propeller or simple wing only, but the propeller/wing system as a whole. It was also proven that the rear-mounted configuration has little impact on the whole system, which may lead to its further application in the design of solar-powered UAVs.

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