Lift Control of Electric Airplanes by Using Propeller Slipstream for Safe Landing

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Abstract—Aircrafts are desired to be more energy efficient and safer due to the increasing demand for air transportations. However, generally speaking, nowadays commercial airplanes tend to loss stability under wind disturbances, especially during landing. On the other hand, electric airplanes (EAs) are believed to satisfy the two demands because electric motors are used for the propulsion. Especially, as the actuators, electric motors can improve the control performances of EAs compared with internal combustion engines (ICEs). In this paper, by utilizing electric motors’ advantages, lift control method using propeller slipstream is proposed for safe landing, which might be a key technology to innovate the design of EAs. Moreover, simulations and experiments are conducted to verify the effectiveness of the proposed method.

I. INTRODUCTION

A. Background

Considering the increasing demand for air transportation, aircrafts are desired to be more energy efficient and safer. Electric airplanes (EAs) are believed to satisfy these demands due to the utilization of electric motors for propulsion [1]–[4]. Compared with internal combustion engines (ICEs), motors have the following remarkable advantages [5].

- Response of motor torque is much faster than that of internal combustion engines (over 100 times).
- Distributed installation and independent control are easy.
- Motor torque can be measured precisely from the current.
- The electric motors are more efficient than ICEs.

There are some studies [6] [7] on safety and efficiency control for EAs by utilizing these advantages and it is widely recognized that EAs will have multiple motors and propellers.

B. Objective

Although nowadays airplanes including EAs are designed to have higher stability and controllability, over 60% accidents of light airplanes were occurred during approaching and landing [4] [8]. Besides, landing weight of EAs is larger than that of a normal airplane, because the weight of battery-powered EAs is not decreased during the flight. Solving this problem is challenging, and current works focus on making temporary

II. MODELING OF MULTIPLE PROPELLERS ELECTRIC AIRPLANE

In this section, the dynamics for an airplane with multiple propellers is explained.

A. Propeller Dynamics

Figure 1 shows the cross section of a propeller blade at distance r from hub. During flying, the propeller cross section moves as a composition of rotation and forward motion. Therefore, the cross section moves as a spiral. Assume the airflow is parallel to the axis of propeller. Airspeed $V_x$ is the relative velocity between the air and airplane. Counter torque $R$ is generated by the blade of propeller, and $R$ can be resolved into the direction of the motion of the airplane “thrust” $F$ and the direction of propeller revolution “counter torque” $Q$. Assume the air density is $\rho$, the propeller whose diameter $D_p$ rotates at the propeller revolution speed $n$, and generates the
thrust $F$ and the counter torque $Q$ which can be express as

$$ F = C_F(J) \rho n^2 D_p^4, \quad (1) $$

$$ Q = C_Q(J) \rho n^2 D_p^5, \quad (2) $$

where $C_F$ is propeller thrust coefficient, and $C_Q$ is propeller counter-torque coefficient. Generally, each of them is a function of advance ratio $J$ which is defined as

$$ J = \frac{V_x}{nD_p}. \quad (3) $$

B. Propeller Slipstream

When a propeller rotates and generates thrust, propeller slipstream occurs and velocity of slipstream is amplified with respect to velocity of airspeed. Figure 2 illustrates the diagram between airspeed and propeller slipstream. $V_x$ is airspeed, $V_p$ is wind speed through propeller, and $V_s$ is propeller slipstream. $P_{\infty}$ is the pressure outside propeller stream, $P_F$ is the pressure of the front face of propeller, and $P_R$ is that of the rear face. Eq. (4) is realized from infinite direction ahead to the front face of the propeller, and Eq. (5) is realized from the rear dace of the propeller to infinite direction of back, based on Bernoulli’s theorem.

$$ \frac{1}{2} \rho V_x^2 + P_{\infty} = \frac{1}{2} \rho V_p^2 + P_F, \quad (4) $$

$$ \frac{1}{2} \rho V_p^2 + P_R = \frac{1}{2} \rho V_s^2 + P_{\infty}. \quad (5) $$

Because thrust is basically the force on a propeller caused by the pressure difference between front face and rear face of the propeller, Eq. (6) is obtained as propeller thrust by multiplying the disk-area of the propeller and the pressure difference,

$$ F = \frac{\pi}{4} D_p^2 (P_R - P_F). \quad (6) $$

From Eq. (4) ~ Eq. (6) are reformulated as Eq. (7).

$$ F = \frac{\pi}{4} D_p^2 \frac{\rho} {2} (V_s^2 - V_x^2) $$

$$ = \frac{\pi}{8} \rho V_x^2 D_p^2 \left( \frac{V_x}{V_s} \right)^2 - 1 \right). \quad (7) $$

By reformulating Eq. 7, slipstream $V_s$ is obtained as

$$ V_s = V_x \sqrt{1 + \frac{8}{\pi} C_F(J) \left( \frac{nD_p}{V_x} \right)^2}. \quad (8) $$

Fig. 2. Propeller slipstream diagram.

C. Aerodynamic Force of Wing

When an airplane has $N$ propellers, some propellers are on the right wing, and the others are on the left wing, and the subscript $j$ represents $j$th propeller. $S$ is wing area, $S_s$ is area which slipstream of a propeller blows against, and $S_a$ is area which airspeed blows against. $S$ can be expressed in short as

$$ S = \sum_{j=1}^{N} S_{s_j} + S_a. \quad (9) $$

$C_L$ is lift coefficient and $C_D$ is drag coefficient. Total lift $L_{all}$ is a summation of lift $L_{s_j}$ by each propeller slipstream and lift $L_a$ by airspeed as Eq. (10). In the same way, total drag $D_{all}$ is a total of drag $D_{s_j}$ by each propeller slipstream and drag $D_a$ by airspeed as Eq. (11).

$$ L_{all} = \sum_{j=1}^{N} L_{s_j} + L_a $$

$$ = \frac{1}{2} \rho C_L \sum_{j=1}^{N} S_s V_x^2 + \frac{1}{2} \rho C_L S_a V_x^2, \quad (10) $$

$$ D_{all} = \sum_{j=1}^{N} D_{s_j} + D_a $$

$$ = \frac{1}{2} \rho C_D \sum_{j=1}^{N} S_s V_x^2 + \frac{1}{2} \rho C_D S_a V_x^2. \quad (11) $$

Fig. 3. Model block of plane with multiple propellers.

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**Note:** The diagrams and equations in the original text are complex and involve multiple variables and functions related to aerodynamics and propulsion systems. The text provides a foundational understanding of the concepts involved, such as propeller thrust, slipstream velocity, and aerodynamic forces on wings and propellers. The equations and figures are integral to understanding the mechanics of flight and propulsion systems, particularly in aviation and engineering contexts.
It is assumed that propeller slipstream are not interfered with each other and the slipstream speed $V_{s_j}$ is spreaded over the slipstream area $S_{s_j}$.

**D. Motion Equation of Plane**

When the airplane with $N$ propellers moves straight at airspeed $V_x$ and accelerates at $a_x$ and $a_z$, the equations of plane dynamics on horizon axis is expressed as Eq. (12) and the equation on vertical axis is expressed as Eq. (13).

$$Ma_x = F_{all} - D_x$$

$$Ma_z = L_{all} - D_z - Mg$$

The model of airplane with multiple propellers can be expressed as Fig. 3. In this paper, the wind speed $V_{wind}$ is ignored, and $V_x$ is equal to $V_E$.

**III. DESIGNING OF LIFT CONTROL OF MULTIPLE PROPELLERS ELECTRIC AIRPLANE**

In this section, designing lift control by slipstream is explained as a proposed method. The controller has a disturbance observer (DOB) to compensate for propeller counter torque which is regarded as disturbance, a propeller revolution speed controller $C_P$ at the inner loop, and a lift controller $C_I$ at the outer loop.

**A. Designing of Propeller Counter Torque Observer and Revolution Speed Controller**

In this part, counter torque observer (CTO) and revolution controller are designed in a dotted line box on Fig. 4 by referring to [13].

The propeller counter torque can be expressed as

$$Q = T - 2\pi J_\omega \dot{n}.$$  

Therefore, if motor torque $T$ and revolution speed $n$ is detected, propeller counter torque $\dot{Q}$ can be estimated with a propeller counter torque observer as shown in a dotted line box on Fig. 4. In this paper, it is assumed that the current controller is adequately fast to use motor torque reference $T^*$ for estimation. By adding the estimated value to the torque command, the plant is nominalized as Eq. (16) at frequency ranges below the cut-off frequency $\omega_c$ of the low pass filter of the CTO.

$$P_{norm} = \frac{1}{2\pi J_\omega s}.$$  

The revolution speed control is done by proportional controller. The gain $C_P$ of the controller is decided so that the pole is placed at $-\omega_n$. Here, the plant is assumed to be the nominal plant as shown in Eq. (16).

The transfer function from $n^*$ to $n$ is expressed as Eq. (17) and is defined $G_n$.

$$\frac{n}{n^*} = \frac{\omega_n}{s + \omega_n} = G_n.$$  

Therefore, $K_P$ becomes as

$$K_P = 2\pi J_\omega K_p.$$  

**B. Designing of Lift Controller**

In this part, the lift controller is designed and considered to be able to measure or estimate the lift of wing by calculating Eq. (10) and Eq. (13).

The controller is designed as a two-degree-of-freedom controller as shown in Fig. 4. $C_F$ can be quadratically approximated using coefficients $a_{CF}$, $b_{CF}$, and $c_{CF}$ as

$$C_F = a_{CF}J^2 + b_{CF}J + c_{CF}.$$  

From Eqs. (1), (8), and (19), $L_s$ can be written as

$$L_s = \alpha_L n^2 + \beta_L n + \gamma_L,$$

where

$$\alpha_L = \frac{4}{\pi} C_L \rho S_s C_F p D_p^2,$$

$$\beta_L = \frac{4}{\pi} C_L \rho S_s D_p b C_F V_x,$$

$$\gamma_L = \frac{1}{2} C_L \rho S_s \left( \frac{8}{\pi} \alpha C_F + 1 \right) V_x^2.$$

Define function $f$ as a function between revolution speed $n$ and $L_s$ as

$$L_s = f(n).$$

Feed forward controller $C_{FF}$ is designed as follows. $L_s$ is a function of the revolution speed reference $n^*$ as

$$L_s = f(G_n \cdot n^*).$$

Therefore,

$$n^* = G_n^{-1} \cdot f^{-1}(L_s) = \frac{s + \omega_n}{\omega_n} f^{-1}(L_s).$$

Eq. (23) is non-proper, so feed forward controller $C_{FF}$ is designed using reference model $G_g(s)$.

$$G_g(s) = \frac{\omega_g}{s + \omega_g},$$

$$n^* = f^{-1}(L_s) \cdot G_n^{-1} \cdot G_g(s).$$

Here, $\omega_g$ is the pole of the reference model. Feed forward controller $C_{FF}$ is a nonlinear variable controller as shown in Eq. (25), because $f^{-1}(L_s)$ varies by $V_x$ and is non-linear.

Next, feedback controller $C_I$ is designed as follows. Feedback reference $L_s^*$ is created by multiplying reference model $G_g(s)$ to lift reference $L_s^*$ as $L_s^* = G_g(s) L_s^*$. By using Taylor series at operating point $n = n_o$, $f(n)$ can be approximated to its first order.

$$L_s \approx (\alpha_L n_o + \beta_L) n + (\gamma_L - \alpha_L n_o)^2.$$ (26)

The revolution speed controller is assumed to be fast enough so $n^* = n$. The feed back controller uses the difference of the reference and output, so when $\beta_L$ is regard as a constant, Eq. (27) can be obtained as a transfer function $G_L$ from $n^*$ to $L_s$.

$$G_L = \frac{\Delta L_s}{\Delta n^*} = \frac{\Delta L_s}{\Delta n} = \alpha_L n_o + \beta_L.$$ (27)

Lift control uses an integral controller, and the gain $K_I$ is designed the placing the pole at $-\omega_{lift}$ while the plant is assumed to be $G_L$.

$$\frac{L_s}{L_s^*} = \frac{K_I (\alpha_L n_o + \beta_L)}{1 + K_I (\alpha_L n_o + \beta_L)} = \frac{\omega_{lift}}{s + \omega_{lift}}.$$ (28)

Therefore, $K_I$ becomes as

$$K_I = \frac{\omega_{lift}}{\alpha_L n_o + \beta_L}.$$ (29)

Here, $K_I$ is function of $n_{FF}$ and $V_x$, so lift feedback controller $C_I$ is variable.

C. Controller Design Concept

In this part, controller design concept on this paper was explained. Assume that $N = 3$ propellers airplane shown in Fig. 5. 2 propellers on wing are controlled by the proposed method. A propeller on head is used for airspeed control [14] to keep airspeed constant by compensating thrust addition of the proposed method for future works.

ICE airplanes can only control propeller revolution speed. Accordingly, the conventional lift control method is set up as follows. Assume that pilot can give a revolution speed reference based on airspeed and lift reference feed forwardly without delay. The revolution speed control response speed is generally 2~3 seconds. This time needs to be ensured to keep safely according to the inertia moment of the reciprocal engine and the setting time of the fuel-air ratio.

In the simulation and experiments of this paper, the revolution speed controller is a proportional and integral controller whose pole is $\omega_{conv}$ instead. The revolution speed reference is same as the proposed one.

IV. SIMULATION OF LIFT CONTROL

Lift control method proposed in section III is verified by simulation.

A. Simulation Condition

The simulation model uses the parameter of APC10×10 E model propeller. The $J-C_P$ and $J-C_Q$ curves are shown in Fig. 6. The parameter including the airplane constants and the poles of each controller are as listed in Table I.
**B. Step Response Simulation**

Step response simulation was conducted to the thrust controller. The airspeed was changed by the propeller thrust, and a step reference was given. When the airspeed $V_x$ was set at $V_x = 10.0$ m/s, the simulation started at a steady state of lift $L_{all}$ = 6.0 N. At $t = 5.0$ s, lift reference changed from 6.0 N to 7.0 N.

The simulation result is shown in Fig. 7. Figure 7(a) is total lift $L_{all}$ and Fig. 7(b) shows $L_x$ and $L_a$ of one side wing which are separated from $L_{all}$. The response is very fast for 0.2 s, because revolution speed response of the proposed method is quicker than that of conventional one in Fig. 7(c). Figure 7(d) shows the airspeed $V_x$ and the propeller slipstream $V_s$ which is depend on the propeller revolution.

From the comparison with the conventional method, the proposed one was verified to have quick and accurate response to the reference.

**V. EXPERIMENT OF LIFT CONTROL**

In this section, lift control in use of propeller slipstream is verified by experiment.

**A. Experimental Setup**

The experimental units for this research are explained. Located in the aerospace engineering department at the University of Tokyo, one part of the units is a Goettingen type wind tunnel shown in Fig. 8(a) with a 1.5 m diameter of the opening. The wind tunnel reuse the wind which it generates, so there is less influence of the surrounding environment. The measuring of lift and drag is called 'wire balance method.' First, the airplane was supported by wires and the wires kept tension by counterweights as shown in Fig. 8(b). And then the wires were connected to strain gages to measure the difference tension as lift and drag. Lift and drag were calculated from Eq. (30) and Eq. (31).

$$L = L_{right} + L_{left} + L_{rear}, \quad (30)$$

$$D = D_{right} + D_{left}. \quad (31)$$

Lift was occurred to upside of airplane, so the model airplane was supported to be upside down to keep wires tension. It is able to change the attack angle of airplane by moving the position of strain gage CH3.

The model airplane specification is same as the simulation in Table. I, and lift coefficient $C_L$ and drag coefficient $C_D$ were measured as shown in Fig. 9(b).

Two motors and two propellers are placed above the wing whose location is in propeller slipstream shown in Fig. 10. The motor mounts are able to adjustable angle of attack depending on the model plane attitude.

**B. Measurement of Propeller Slipstream**

In this part, propeller slipstream was measured in order to confirm the propeller slipstream theorem in Section II-B.

The propeller was rotated by a motor and the propeller slipstream was measured by an anemometer. Figure 11 showed the results about airspeed of wind tunnel and propeller slipstream depend on propeller revolution. Figure 11(a) is the simulation result and Fig. 11(b) is the experimental result. Between the simulation and the experiment, value was different, but the relationship between propeller revolution and slipstream was adjustable to theory.

**C. Lift Control Experiment Results**

In this part, in order to confirm the lift control proposed method, experiment was carried out. The airspeed was fixed and step reference was given.
<table>
<thead>
<tr>
<th>Speed [m/s]</th>
<th>Lift [N]</th>
<th>Drag [N]</th>
<th>Propeller Revolution [rpm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>3000</td>
<td>10</td>
<td>5</td>
<td>2000</td>
</tr>
<tr>
<td>4000</td>
<td>12</td>
<td>6</td>
<td>3000</td>
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</tr>
<tr>
<td>6000</td>
<td>18</td>
<td>8</td>
<td>5000</td>
</tr>
</tbody>
</table>

When the airspeed $V_a$ was set at $V_a = 10$ m/s, the experiment started at lift reference $L_{ref} = 6.0$ N. At $t = 5.0$ s, lift reference changed from 6.0 N to 7.0 N.

The results were shown in Fig. 12. Figure 12(a) and Fig. 12(b) are the response of total lift and drag on wing, and Fig. 12(c) is the propeller revolution. At $t = 5.0$ s, propeller revolution was enlarged depend on step reference, and the slipstream was increased in Fig. 12(d). Compare to the conventional method, the response speed and accuracy was improved by the proposed method.

From considering scaling rule, 1.0 N increase for this experiment model airplane means 0.169 increase of lift coefficient $C_l$ as non-dimensional value. If commercial airplanes adopt the proposal method, 800 N $\sim$ 5000 N will be increased as lift depending on airspeed. The effectiveness of the lift control by using propeller slipstream was confirmed from these results.

**VI. Conclusion**

This paper aimed at landing weight reduction by controlling the motors and propellers. In order to achieve the aim, the propeller slipstream was modeled and then used for the lift control. The reliability of the propeller slipstream theory was verified by experiments, and the effectiveness of the proposed method was verified by simulations and experiments.

The proposed method can improve the response speed and landing accuracy, compared to the conventional approaching and landing methods like powered lift system and flaring, and the method might be a key technology for landing assist in the future.

Future works include but not limit to: 1) further experiments of the lift control using wind tunnel, 2) design of a vertical velocity control without using the information of lift, 3) introducing an airspeed control approach into the proposed method of this paper by using extra propellers might be desirable.

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