STUDY ON CONTROL PERFORMANCE OF A NEW TYPE OF TILT-ROTOR AIRCRAFT

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Abstract

A new type of tilt-rotor aircraft is introduced in this study, whose rotors are tilted by arm-mechanisms. The effect and benefits of the arm-mechanisms are explained by comparing with the standard tilt-rotor aircraft. The most evaluable feature is that the new tilt-rotor aircraft can enhance the stability during the transitional mode between its vertical take-off/landing and cruising modes by reducing the interference between the rotor-wakes and the fixed-wing. In addition, simple control strategy is effective because independent control for the three attitude motions is possible for the tilt-rotor aircraft. The advantages are verified in numerical simulations, and the stability in the transition mode is examined by using an experimental aircraft.

Keywords: Tilt-rotor aircraft, Arm-mechanism, Translation mode, Stability, Interaction

1. General Introduction

Tilt-rotor aircraft are capable of vertical take-off/landing and hovering by directing its rotors upward, as well as efficient flight in cruising mode by utilizing the lift and thrust generated by the fixed-wings and forward-directed rotors. Thus, they are actively researched and developed in many countries for mission applications; e.g., efficient flight systems connecting various locations (urban/island areas), or transportation systems in times of disaster occurrence [1]. This is because they can take-off/landing without airports, and because longer/faster flight is achievable than rotary-wing aircraft, like helicopters or “drones”.

Meanwhile, it is known as a critical problem that tilt-rotor aircraft tends to lose its attitude stability during the transition mode between vertical and cruising modes. In the transition mode, the flow of the rotor-wakes generates complex interference with the fixed-wings or fuselage according to the rotor-tilt angles, and it changes the lift and drag characteristic of the fixed-wing [2],[3]. In the previous studies [4],[5],[6], since accurate modeling of this aerodynamic change is very difficult, complex controllers with robustness for nonlinearity and uncertainties are investigated.

In recent years, electrification has made it possible to realize various shapes of aircraft [7]. This is because electrically powered aircraft have a greater degree of freedom in the number and layout of rotors than engine-driven aircraft [8]. Meanwhile, an important problem of electric aircraft is that batteries have low energy density and heavy weight. Therefore, electrified tilt-rotor aircraft attracts attention of researchers to overcome the limited battery problem by utilizing highly efficient flight, although standard tilt-rotor aircraft has an instability problem in its transition mode.

In this study, we propose a new layout for tilt-rotor aircraft, whose rotor-directions are fixed to arms and tilted with the arm-mechanisms. In this layout, the rotor-wakes have little interactions with the wing or fuselage of the aircraft. Thus, the proposed arm-mechanisms enhance the stability during the transition mode between vertical take-off/landing and cruising modes. Moreover, by differentiating the tilt angles of the front and rear arms, the aircraft can generate independent control torques for the three attitude motions by only rotor thrusts. Consequently, the proposed tilt-rotor aircraft can keep the aerodynamic characteristics of the fixed-wings even when the tilt-rotor angles change, and simple control strategy is effective for the motion control of the aircraft.

2. Overall layout of tilt-rotor aircraft

2.1 Standard tilt-rotor aircraft

Recently developed tilt-rotor aircraft often have multiple rotors in front of the fixed-wings and the rotor-direction are tilted at that positions (e.g., AMSL Aero's Vertiia [9], Wisk Aero's Generation6 [10], supernal's S-A2 [11], etc.). This rotor-layout requires complex controllers due to the following reasons.

(1) The rotor-wakes in front of the fixed-wings change the flow patterns around the wings. Thus, as described above, the lift/drag characteristics of the wings change significantly according to the tilt-angles of the rotors. However, the accurate modeling of the lift/drag change is very difficult, and experimental attempts to measure the interference are extremely complicated, because they are also influenced by aircraft' shapes and flight speed, wind disturbance, and so on. Consequently, controllers should be robust for aerodynamic changes due to the interferences and modeling errors.

(2) Besides the interaction or modeling errors, the pitching moment generated by the rotor-thrusts of the standard tilt-rotor is gradually decreases according to the tilt-angle and approaches to zero when the rotor-directions are in horizon. This is because the moment-arm of the pitching torque becomes small when the rotors tilted at the same positions. This requires to use its control surfaces together with the rotor-thrusts. However, the effects of the rotor-thrust on the control surfaces are nonlinear and complicated, thus controllers should combine the rotor-thrust with the interfered control surfaces properly [12].

These complexities make it difficult to control tilt-rotor aircraft with a simple controller. Thus, robust control strategy is used for inaccurate model and disturbances, but this process is complicated and the controllers sometimes too conservative for large modeling errors.

2.2 The new type of tilt-rotor aircraft

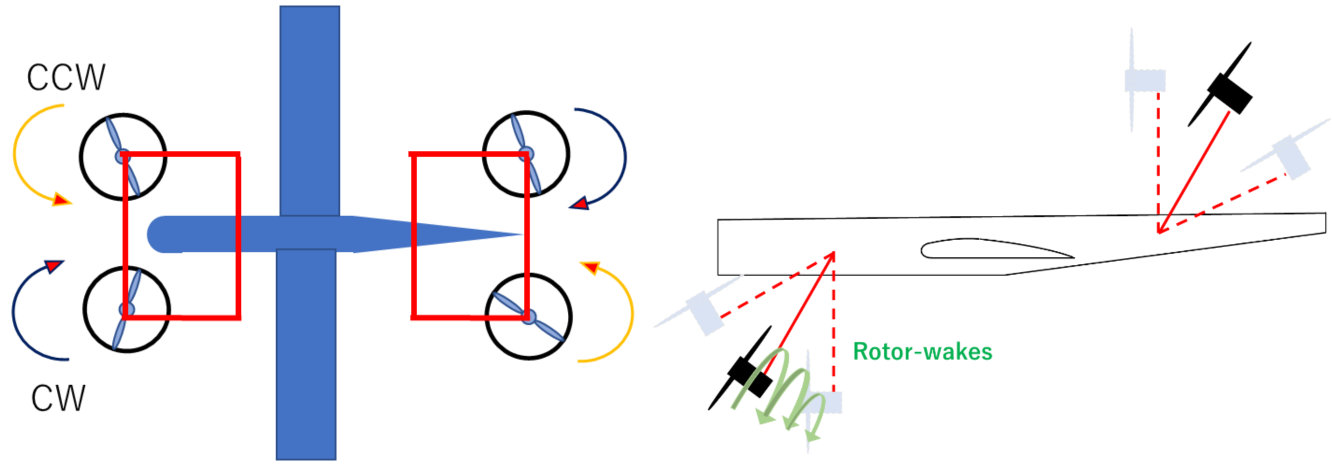
We are studying an overall layout of tilt-rotor aircraft in which the rotors are separated from the fixed-wing and tilted by arm-mechanisms, as shown in the Figure 1. The rotor-directions are fixed to the arms, and the rotors are tilted by tilting the arm-mechanisms. This layout makes the following advantages.

(1) Interference between the rotor-wake and the fixed-wing can be dramatically reduced. Regardless of the rotor's tilt-angle, the rotor-wake flows perpendicular to the plane of the arm-mechanism. Besides, the rotor-wake is apart from the fixed-wing by the arm length. As a result, in spite of the tilt-rotor angles, the aerodynamic characteristics of the fixed-wing can be maintained in the transition mode.

(2) Since the rotors are separated by the arms from the tilting pivot, the moment arm of the pitching motion is maintained. As a result, even when the tilt-angle approaches to horizon, the rotor thrusts can generate the pitching moment.

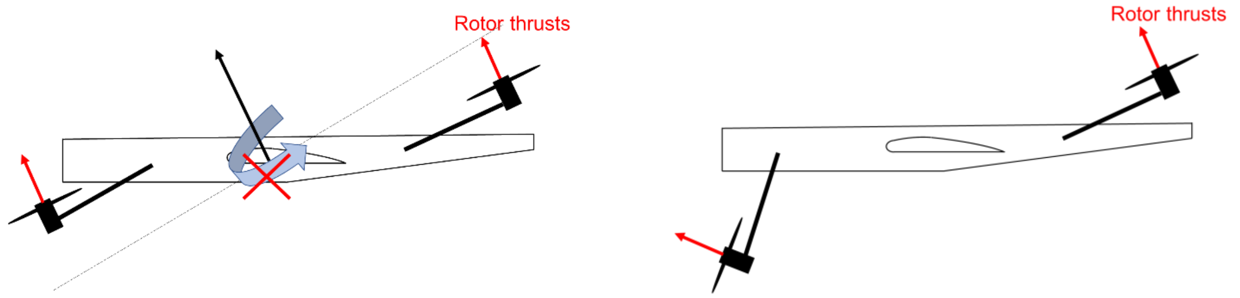
(3) In addition to the above two advantages, this arm-mechanisms make it possible to generate independent attitude control torques around the three axes by the rotor thrusts when the front and rear tilt-angles are different. When the tilt-angles are the same as shown in Figure 2(a), all the rotor-thrusts are parallel. As a result, they cannot generate torque around the rotational direction. Thus, usual multi-rotors aircraft utilizes the rotors' counter-torques for rotating around the rotor-axis, but the magnitude of the counter-torque is small and the rotational motion is slow.

Contrary to the above configuration, the new tilt-rotor aircraft can generate independent torques for the pitch, roll, and yaw motions by the rotor thrusts, when the tilt-angles of the front and rear arm-mechanisms are different as shown in the Figure 2(b). This implies that attitude control around three axes is possible without the control surfaces (elevator, rudder, and aileron). Furthermore, since the control torques generated by the rotor-thrusts are much larger than counter-toques, much faster attitude control becomes possible.



(a) Top view (b) Side view

Figure 1 – Layout of the proposed aircraft with two tilt-arm mechanisms.



(a) Same tilt-angles (b) Different tilt-angles

Figure 2 – The tilt-angles of the front and rear arm-mechanisms of the new tilt-rotor aircraft.

3. Dynamics of tilt-rotor aircrafts

3.1 Definition of coordinates and symbols

A ground-fixed coordinate system $(\mathrm{X}, \mathrm{Y}, \mathrm{Z})$ is defined as an inertial system. And as non-inertial systems, the body-fixed system (x, y, z) whose origin is placed at the gravity center of the aircraft and the rotor-fixed system (x_r, y_r, z_r) whose origin is the rotational center of the rotor are used in the following equations. Some of the main symbols used in the equations of motion are summarized in Table 1.

3.2 Newton-Euler's equation of motion

The equation of motion for the translation of the aircraft is expressed in the inertial force as the following.

$$\boldsymbol{m\ddot{X}} = \boldsymbol{C_{EB}F_B} - \boldsymbol{mge_3^E} \tag{1}$$

And the rotational motion of the aircraft is expressed as

$$\boldsymbol{J\dot{\Omega}} + \boldsymbol{\Omega} \times \boldsymbol{J} = \boldsymbol{T} \tag{2}$$

3.3 External force

The external force $\boldsymbol{F_B}$ in Eq. (1) is composed of the lift force $\boldsymbol{L_w}$ and the drag force $\boldsymbol{D_w}$ generated by the fixed-wing, and the thrust forces generated by the tilt-rotors. Thus, by using the transformation matrix $\boldsymbol{C_{BR}}$, the force $\boldsymbol{F_B}$ is expressed as follows.

Table 1 Symbols used in equations

Overall mass of aircraft	m	-
Position of aircraft (center of gravity)	$\boldsymbol{X}$	w.r.t. inertial frame
Angular velocity of aircraft	$\boldsymbol{\Omega}$	w.r.t. body frame
Moment of inertia of aircraft	$\boldsymbol{J}$	w.r.t. body frame
External force	$\boldsymbol{F_B}$	w.r.t. body frame
External torque	$\boldsymbol{T}$	w.r.t. body frame
Unit vector in z-axis direction	$\boldsymbol{e_3^E}$	w.r.t. inertial frame
Gravity acceleration	g	w.r.t. inertial frame
Tilt-angle (Front, Rear)	α, β	-
Transformation matrix from rotor frame to body frame	$\boldsymbol{C_{BR}}$	-
Transformation matrix from body fame to inertial frame	$\boldsymbol{C_{EB}}$	-
Lift coefficient of rotors	C_L	-
Drag coefficient of rotors	C_D	-
Rotor's thrust coefficient	b	-
Anti-torque coefficient of rotors	d	-
Rotor's moment of inertia	J_r	w.r.t. body frame

$$\boldsymbol{F_B} = \begin{bmatrix} -\frac{1}{2}\rho S C_D U^2 \\ 0 \\ -\frac{1}{2}\rho S C_L U^2 \end{bmatrix} + \Sigma \boldsymbol{C_{BR_i}} \begin{bmatrix} 0 \\ 0 \\ -b\omega_i^2 \end{bmatrix} \tag{3}$$

3.4 Torque applied to aircraft

The total moment $\boldsymbol{M}$ applied to the aircraft is composed by followings: the torque $\boldsymbol{T_p}$ due to the rotor thrust, the rotor's counter-torque $\boldsymbol{T_a}$, the gyro moment $\boldsymbol{T_g}$, the moment $\boldsymbol{T_b}$ due to the variation of the rotor-speed, and the moment $\boldsymbol{T_{l_{ac}}}$ of the lift-force which is caused by the distance between the gravity center and the aerodynamic center. Thus, the total moment is expressed as follows.

$$\boldsymbol{M} = \boldsymbol{T_p} + \boldsymbol{T_a} - \boldsymbol{T_g} + \boldsymbol{T_b} + \boldsymbol{T_{l_{ac}}} \tag{4}$$

In the above expression, the torque T_p is evaluated by using the position vectors $r_i(\alpha, \beta)$ $(i = $1-4$)$ from the gravity center to each rotor as follows.

$$\boldsymbol{T_p} = \boldsymbol{\Sigma}\left(\boldsymbol{r_i} \times \boldsymbol{C_{BR_i}} \begin{bmatrix} \boldsymbol{0} \\ \boldsymbol{0} \\ -\boldsymbol{b\omega_i^2} \end{bmatrix}\right) \tag{5}$$

The counter-torque of the each rotor $\boldsymbol{T_a}$, which is induced in the opposite direction of the rotor's rotation, is expressed as

$$\boldsymbol{T_a} = \boldsymbol{\Sigma C_{BR_i} sgn(i) d} \begin{bmatrix} \boldsymbol{0} \\ \boldsymbol{0} \\ \boldsymbol{\omega_i^2} \end{bmatrix} \tag{6}$$

The gyro moment $\boldsymbol{T_g}$ is induced to the rotational rotors when the aircraft changes its attitude as well as the arm-mechanism tilts the rotating rotors. Thus, the moment is evaluated as follows. $(j = $1-2$, k = $3-4$)$

$$\boldsymbol{T_g} = \boldsymbol{\Sigma}\left(\boldsymbol{\Omega} \times \boldsymbol{C_{BR_i} Jr} \begin{bmatrix} \boldsymbol{0} \\ \boldsymbol{0} \\ \boldsymbol{\omega_i} \end{bmatrix}\right) + \boldsymbol{\Sigma}\left(\begin{bmatrix} \boldsymbol{0} \\ -\dot{\boldsymbol{\alpha}} \\ \boldsymbol{0} \end{bmatrix} \times \boldsymbol{C_{BR_j} Jr} \begin{bmatrix} \boldsymbol{0} \\ \boldsymbol{0} \\ \boldsymbol{\omega_j} \end{bmatrix}\right) + \boldsymbol{\Sigma}\left(\begin{bmatrix} \boldsymbol{0} \\ -\dot{\boldsymbol{\beta}} \\ \boldsymbol{0} \end{bmatrix} \times \boldsymbol{C_{BR_k} Jr} \begin{bmatrix} \boldsymbol{0} \\ \boldsymbol{0} \\ \boldsymbol{\omega_k} \end{bmatrix}\right) \tag{7}$$

The torque $\boldsymbol{T_b}$ is generated as inertia when the rotor changes the rotational velocity, and it is expressed by the following

$$\boldsymbol{T_b} = \boldsymbol{\Sigma}\left(-\boldsymbol{C_{BR_i}}\boldsymbol{Jr}\begin{bmatrix}\boldsymbol{0}\\ \boldsymbol{0}\\ \boldsymbol{\dot{\omega}_i}\end{bmatrix}\right) \tag{8}$$

Finally, the pitching moment $\boldsymbol{T_{lac}}$ due to the lift force generated by the distance between the gravity center and the aerodynamic center is expressed as follows

$$\boldsymbol{T_{lac}} = \begin{bmatrix}\boldsymbol{0}\\ \boldsymbol{0}\\ -\frac{1}{s}\boldsymbol{\rho S C_L U^2 L_{ac}}\end{bmatrix} \tag{9}$$

By inserting Eqs. (3)-(9) into Eqs. (1) and (2), the translational and rotational motions of the new tilt-rotors are expressed in the inertial coordinate.

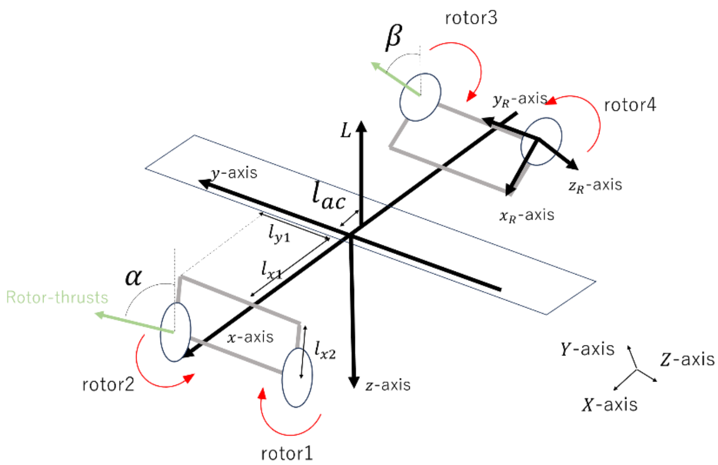


Figure 3 – Geometry of the forces generated in the aircraft.

4. Numerical simulations

The advantages of the new type of tilt-rotor aircraft has been explained in Sec. 2.2. The first one could be understood from the geometric relation between the tilt-rotors and the fixed-wing. Thus, this section verifies the second and third advantages for the flight performance of the proposed aircraft by using numerical simulations for four tilt-rotor configuration as shown in Figure 1.

In the practical design of the new tilt-rotor aircraft, three control surfaces (elevator, aileron, rudder) would be implemented as well as the arm-mechanisms to enhance its static stability and to improve control robustness for attitude motions. However, to emphasize the control ability of the new tilt-rotor aircraft, this paper does not consider any control surface. Thus, the control devises of the new aircraft are two tilt-mechanism and four rotor speeds. Note that the tilting mechanisms changes the arm-angles, but their motion should be slow because of its large inertia. Thus, the tilt-angles are mainly used for controlling the aircraft speed. Meanwhile, the four rotor-speeds are used for attitude control, because their rotational speeds are rapidly controlled by electric motors. Moreover, the total thrust of the four rotors should be balanced with the gravity force for level flight. Thus, keeping the balance with gravity, the distribution of each rotor-thrust is changed to generate control moment for the attitude motion of the aircraft. In the following simulations, the motion of the tilt-rotor in the transition mode is controlled by a simple PD controller to indicate that even a simple control strategy is effective for the new tilt-rotor aircraft.

In the following simulations, the values listed in the Table 2 are used.

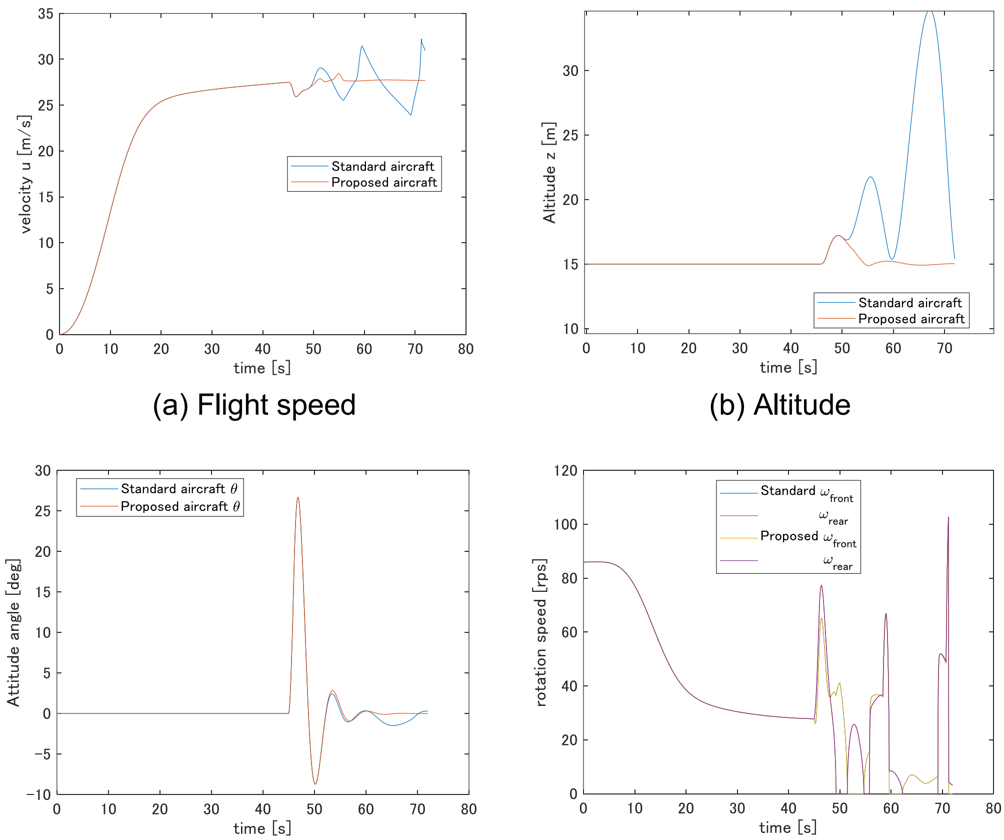
Table 2 Simulation conditions and variables

Overall mass	m	[kg]	13.0
Target velocity	v	[m/s]	0 to 25
Inertia tensor	$(I_{xx}\ I_{yy}\ I_{zz})$	$[\mathrm{kg}\cdot\mathrm{m}^2]$	(1.93 6.83 8.69)
Inertia tensor	$(I_{xy}\ I_{yz}\ I_{zx})$	$[\mathrm{kg}\cdot\mathrm{m}^2]$	(0 0 0.254)
Feedback gain (Height)	$(K_{P_z}\ K_{D_z})$	[−]	(3 3.5)
Feedback gain (Pitch)	$(K_{P_\phi}\ K_{D_\phi})$	[−]	(6 8)
Feedback gain (Roll)	$(K_{P_\theta}\ K_{D_\theta})$	[−]	(12 2)
Feedback gain (Yaw)	$(K_{P_\psi}\ K_{D_\psi})$	[−]	(4 10)

4.1 Control performance in longitudinal motion

In the longitudinal motion of the tilt-rotor aircraft, the vertical component of the total rotor-thrust and combined with the lift force of the fixed-wing are balanced with the gravity force in level flight. Since the lift force of the wing can be decided by a function of the flight speed, and since the lift force specifies the vertical component of the rotor thrust, eventually the tilt-angle of the rotors can be decided for the level flight. This means that under a specified total rotor-thrust, the flight speed is specified according to the tilt-angle of the rotors.

In the first simulation, the tilt-angles of the front and rear arm-mechanisms are supposed to be same for simplicity. The tilt-angle changes from 0 deg to 90 deg constantly for 50 seconds. The tilt-angle 0 deg indicates that the rotors are facing to upward (i.e., hovering mode), 90 deg means the rotors are facing to the flight direction (i.e., cruising mode), and the intermediate duration indicates the transition mode of the tilt-rotor aircraft. To verify the stability during the transition mode, a disturbance torque with 0.8 N is applied around the pitch axis for 1 second at t=45 s.



(a) Flight speed (b) Altitude

(c) Pitch angle (d) Rotor speed

Figure 4 – Flight performance of tilt-rotor aircraft in a vertical plane.

The result of the new tilt-rotor aircraft is shown in Figure 4 in red lines; (a) is the time history of the flight speed, (b) and (c) indicate the altitude and attitude (: the pitch angle) histories respectively, and (d) is the rotors' rotational speeds. Due to the disturbance torque applied at t=45 s, the results temporarily fluctuate but returns to their steady states. This implies that the new tilt-rotor aircraft is stable during the transition mode.

Meanwhile, for comparison with the new tilt-rotor aircraft, the results of a standard type tilt-rotor aircraft whose rotors are tilted at the rotor-positions are shown in the figure in light-blue lines. It should be noted that the interaction between the rotor-wakes and the wing/fuselage is not included in this simulation, because the modeling of the interaction is difficult. This implies that the results of the standard tilt-rotor aircraft would be more disturbed (or unstable) because the interaction makes very severe effects on the attitude motion. Moreover, even without the interaction, the simulation results show large fluctuated responses in the longitudinal motion around/after 50 s. This is because that the standard tilt-rotor aircraft becomes harder to generate the pitch control moment according the tilt-angles approach to 90 deg.

4.2 Three-axis attitude angle control performance

For the new tilt-rotor aircraft, the independent control ability around its three axes is examined when the tilt-angles are different between the front and rear arm-mechanisms. As a different tilt-angles, let us suppose that the front arm-mechanism is +15 deg and the rear one is -15 deg for the initial state and the aircraft is hovering. Then, keeping this tilt-angle difference, the tilt-rotor aircraft rotates the arm-mechanisms until 90 deg for the front and 60 deg for the rear during 50 second constantly. As in the previous simulation, a level flight and PD controllers are also supposed in the following simulations. To indicate the attitude motion stability for three axes, three disturbance torques with the magnitude of 0.8 N, 0.8 N, and -0.8 N are added around the roll, pitch, and yaw axes for 1 s at t=20 s.

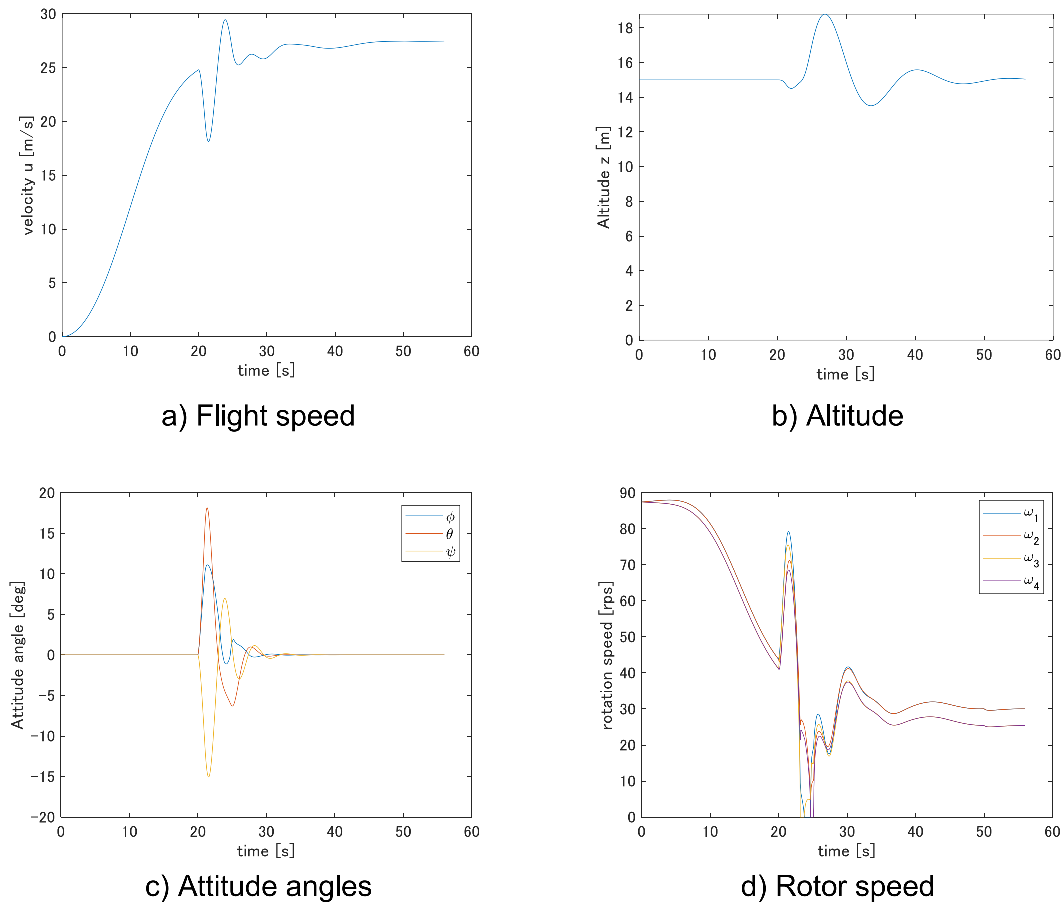


Figure 5 – Flight performance of tilt-rotor aircraft in three-attitude.

Figure 5 shows the result; (a) and (b) are the time histories of the flight speed and the altitude of the aircraft, (c) indicates the attitude motion for the three axes, and (d) is the rotor's speed variations. Figure 5(c) implies that the PD controllers work independently for three axes, because each attitude history shows a simple damping motion.

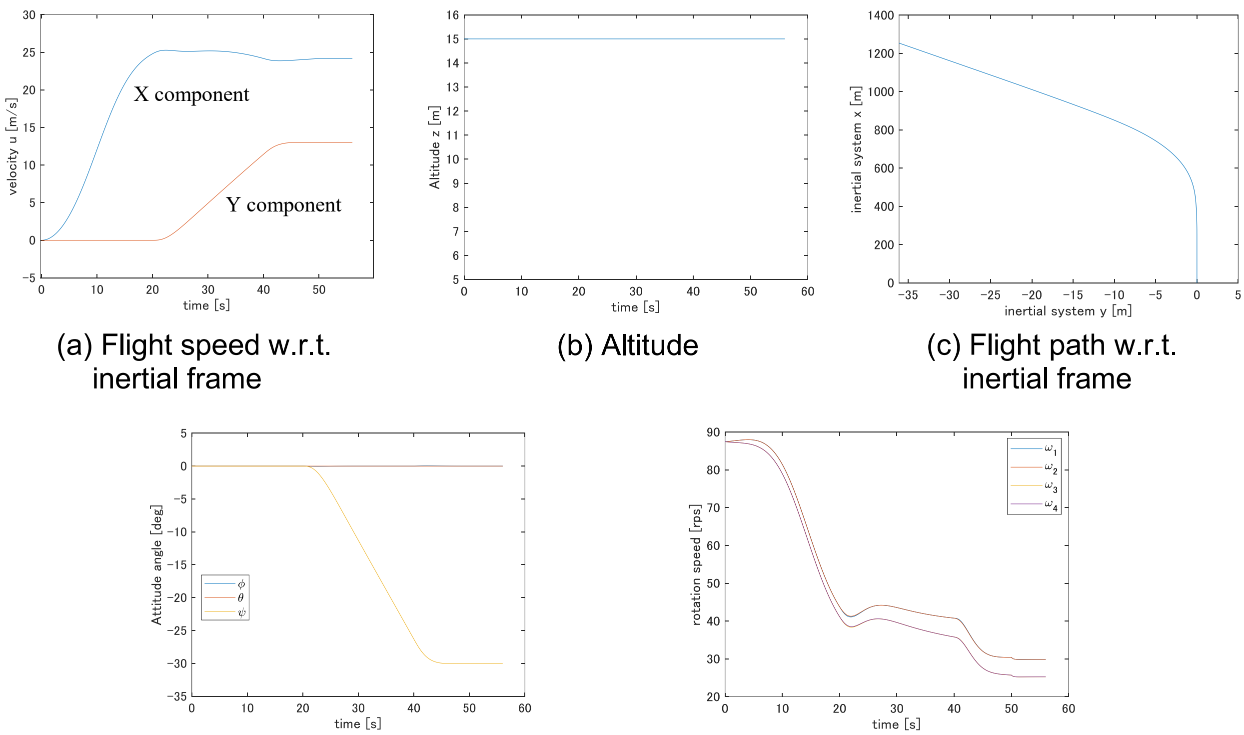
Moreover, the new tilt-rotor aircraft can generate control torque around the rotor-axis not by the reaction torques of rotors but by the rotor-thrusts. Thus, rapid attitude control is possible when the front and rear rotors have different tilt-angles. The third simulation examines the aircraft motion when the yaw angle is controlled by the rotor-thrusts.

In the simulation, suppose the following motion; the aircraft is hovering at t=0 s, and its flight path angle in a horizontal plane is changed to -30 deg in a constant speed for 20 seconds starting at t=20 s. Figure 6 shows the result;(a) and (b) are the time histories of the flight speed and altitude of the aircraft's gravity center in the ground-fixed coordinate system, (c) is the flight path of the aircraft, (d) is the attitude angle (Euler angle) of the body-fixed system in the ground-fixed coordinate system, and (e) is the rotor speed variation.

Figure 6(d) implies that the aircraft can control its yaw motion and stable by the rotor-thrusts. The aircraft changes direction and has a velocity in the y axes as shown in Figure 6(a). Therefore, the aircraft can fly a path in Figure 6(c) without reaction torques or control surfaces.

5. Experiment on interference of rotor-wake flow

In the simulations in the previous section, some effects being practically important but difficult to model have not be considered; i.e., the interaction between the rotor-wakes and fixed-wings/fuselage, or the nonlinear effect of the rotors' speed changes. Thus, an experimental tilt-rotor vehicle equipped with the proposed arm-mechanisms for rotor-tilting has been developed and investigated its motion in some transition modes experimentally. Note that the controller so that "Alt Hold mode" in ArduPilot is applied to the flight system [13]. This mode automatically controls the attitude angle and altitude, but not the aircraft position. Therefore, when the aircraft moves forward by tilting the rotors, its attitude angles and altitude are controlled to be stable by the controller.



(a) Flight speed w.r.t. inertial frame

(b) Altitude

(c) Flight path w.r.t. inertial frame

(d) Flight path angles w.r.t. inertial frame

(e) Rotor speed

Figure 6 – Flight performance for a path change in a horizontal plane.

5.1 Experimental aircraft and circumstances

Figure 7 shows the developed experimental aircraft, which is based on the F450 kit by DJI equipped with two tilting mechanisms at the roots of the front and rear arms. These tilt-mechanisms are controlled by servo motors. The overall height is 250 mm, the distance between rotors is 590 mm, and the total weight is 1.8 kg. On the aircraft, a Pixhawk6c and ArduPilot are mounted for control, and open-source programs are used as the flight code.

In the flight experiments for examining the interaction between the rotor-wakes and fixed-wing, a plate imitating a wing is placed in each side at the same height as the rotating pivot of the arm-mechanism. Meanwhile, for the experiment supposing a standard tilt-rotor aircraft for comparisons, the plates are placed in a lower positon to receive some portion of rotor-wakes. Note that in the Figure 7, the plates have been removed for better visibility.

It should be noted that the flight experiments have been conducted indoor to avoid unexpected wind disturbances. Thus, the available experimental space is limited about 5 meters for the moving direction. As a result, the aircraft motion during only the beginning from hovering to transition mode can be examined in the experiment.

Figure 7 – Overview of the experimental aircraft with rotor-tilting.

5.2 Results of experiments

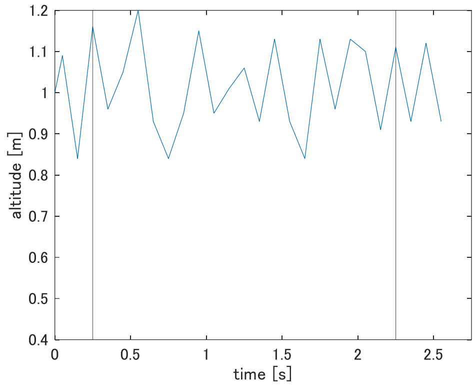
In each experiment, the tilt-rotor aircraft starts in a hovering state with 0 deg tilt-angle for the front and rear arm-mechanisms. Then, the front-arm is tilted until 12 deg for 2 seconds, while the rear-arm is tilted to 5 deg in a constant speed (this time-interval corresponds to 0.25 s to 2.25 s in Figures 8 and 9).

Figure 8 is a typical experimental result; (a) is the altitude history, (b) indicates the attitude motions, and (c) is a snapshot in the experiment. Let us note that the altitude in Figure 8 (a) looks fluctuated, but it could be caused mainly the characteristics of an onboard sensor; the output is always fluctuated in experiments, although the movie of a video camera for the same experiment shows little change for the altitude. Figure 8(b) indicates also little change for the attitude motion. (Currently, we are preparing to measure the altitude and attitude from a motion capture system.)

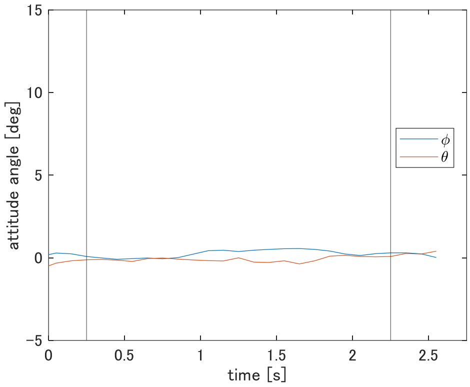
For comparison, an experimental result for a standard tilt-rotor aircraft is shown in Figure 9. In this experiment, to imitate the interaction between the rotor-wake and fixed-wing, the plates are placed to a lower place to receive about 20 % of the rotor-wake for the maximum tilt-angle. The position is calculated by the momentum theory [14]. Compared with the results of Figure 8, both the altitude and the attitude show larger variations. Therefore, these results imply that the new tilt-rotor aircraft has little interaction between the rotor-wake and fixed-wing.

6. Conclusion

Although the tilt-rotor aircraft is attractive for its vertical take-off/landing and effective flight performance, the stability in the transition mode is an essential problem for the aircraft. This study deals with a new tilt-rotor aircraft, which tilts the rotors by two arm-mechanisms. The attractive features of the new tilt-rotor aircraft have explained by comparing the standard tilt-rotor aircraft. Then, the features have been verified in several numerical simulations. One eminent feature is that the effect of the interaction between the rotor-wakes and the fixed-wing is negligible. Another one is that



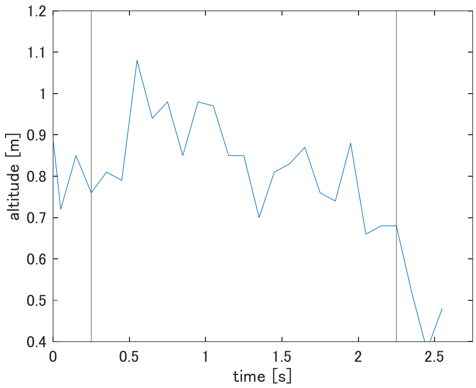
(a) Altitude history



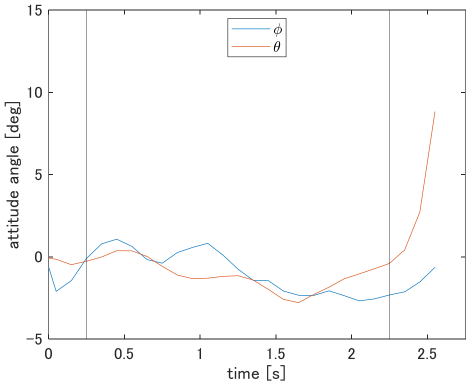
(b) Attitude history

(c) Experimental aircraft

Figure8 – Experimental result of the new tilt-rotor aircraft.



(a) Altitude history



(b) Attitude history

(c) Experimental aircraft

Figure 9 – Experimental result of a standard tilt-rotor aircraft.

simple control procedure is effective, because the new aircraft can generate independent control toques for three-axes attitude motions. Finally, some experimental results obtained by a developed new tilt-rotor aircraft have been shown. The results imply that the new tilt-rotor aircraft has little interaction between the rotor-wake and fixed-wing.

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