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Paper:

Arbitrary Attitude Hovering Control of Quad Tilt Rotor Helicopter

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The quad tilt rotor helicopter (QTRH), a tilt-rotor aircraft prototype, has fixed wings for long-range high-speed flight. Its rotor-tilt mechanism controls 4 rotor-tilt angles independently and controls its roll and pitch angles similarly to a multirotor helicopter. It controls yaw angle by thrust vectoring and moves forward and backward by tilting its rotors. Rotor-tilting maneuvers are the initial stage of flight-mode transition between helicopter and fixed-wing modes.

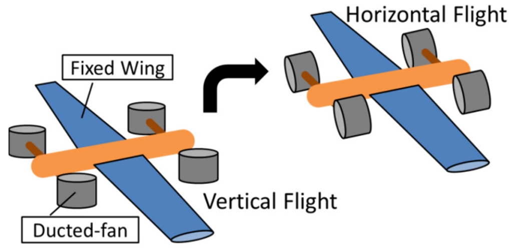

Fig. 1. MDH-based tilt rotor aircraft.

Keywords: attitude control, tilt rotor helicopter, quad rotor helicopter

1. Introduction

Unmanned aerial vehicles (UAVs) such as multirotor helicopters (MRHs) are increasingly replacing manned aircraft uses of aerial photographing in proportion to the improvement of the radio control and flight controller technology. Operation cost of MRH is less than that of manned aircraft, and MRH uses a smaller heliport. MRHs such as quad-rotor helicopter (QRH) are widely used in research such as real-time vision-based localization [1, 2] and onboard laser range finders for indoor QRH position control [3]. MRHs are thus reported used in automatic control systems. Some autopilot units are even available on the market.

However, MRH operation involves risks of fatal accidents and serious injury due to operator inexperience, radio wave interference, or wind disturbance. MRH thrust is generated by the blades rotating at very high speed, which may also be dangerous. To minimize the risk of rotor blade and thruster backwash influence on payloads, we have presented flying machines using ducted fans instead of rotor blades. We developed a quad-duct fan helicopter (QDH) as a flying object for tests using 4 ducted fans instead of 4 rotor blades [4]. QDH flight performance is similar to that of quad rotor helicopters and decreases rotor blade risk. We also developed ducted fan flying objects (DFOs) [5, 6] – a type of inverted pendulum. We realized vertical take-off/landing (VTOL), hovering, and horizontal flight.

The fact that ducted-fan power consumption is higher than that of propellers, however, makes multiduct-fan helicopter (MDH) unsuitable for long-range flight. One goal of our research is thus to develop MDH-based tilt-rotor aircraft such as shown by the model in **Fig. 1**. Tilt-rotor aircraft has both fixed-wing and helicopter features, meaning they can take off and land vertically like helicopters and fly with the aid of fixed wings. Tilt-rotor aircraft with fixed wings uses less energy in flight. As the similar research, tilt-wing aircrafts are reported [7, 8]. Tilt-wing aircraft equips rotors on its wing, and tilts its wings. This mechanism makes attitude control difficult during the state transition between vertical and horizontal modes due to the relatively large drag generated by the tilted wing.

On the other hand, tilt-rotor aircraft has a fixed wing and flies horizontally by tilting its rotors while keeping the attitude horizontal. Since the wing is also kept horizontal, lift is generated proportional to the speed of movement and drag is relatively small, leading to the expectation that tilt-rotor aircraft will perform state transition stably.

We developed the quad tilt rotor helicopter (QTRH) as the tilt-rotor aircraft prototype. We selected propeller rotors instead of ducted fans to keep long endurance for experiments. QTRH's rotor tilt mechanism controls tilt angles for its 4 rotors independently. Roll and pitch angles

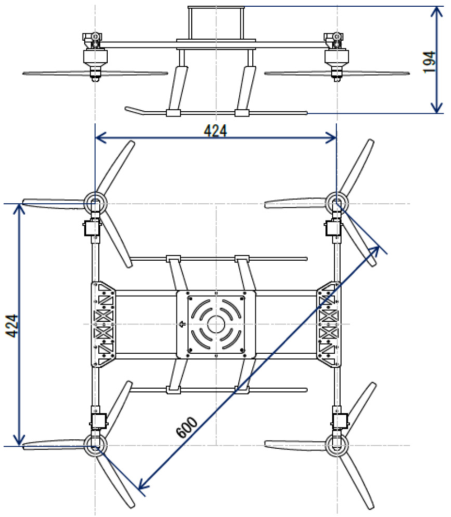

Fig. 2. Quad tilt rotor helicopter design.

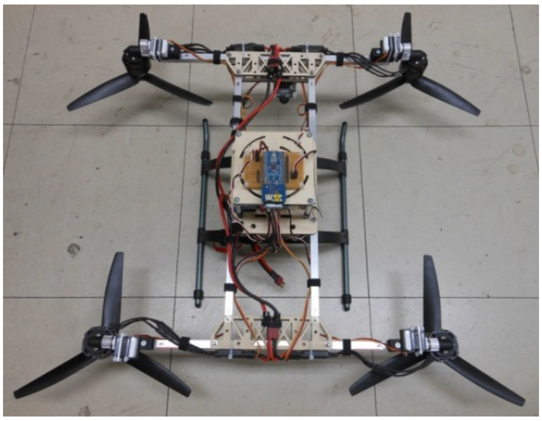

Fig. 3. Quad tilt rotor helicopter.

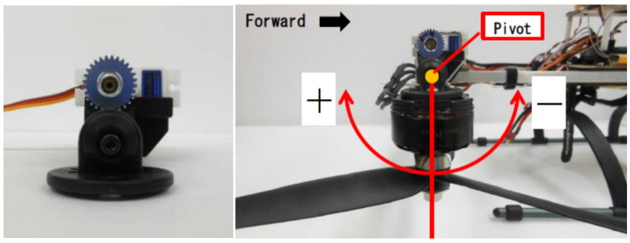

Fig. 4. Rotor tilt system.

Table 1. QTRH specifications.

Weight (include battery) [kg]	1.94
Rotor axis distance [mm]	600
Rotor diameter [mm]	254
Payload [kg]	1.00
Flight time [min]	10.0

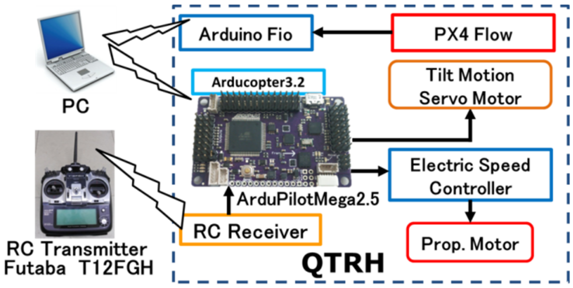

Fig. 5. System configuration.

of QTRH are controlled similarly to MRH. Yaw angles are controlled by thrust vectoring. QTRH moves forward and backward by rotor tilting, which is the initial stage of flight mode transition between helicopter and fixed-wing modes.

2. Experimental Setup

Figures 2 and **3** show the test QTRH, which is based on the quad MRH. In a previous study of quad rotor helicopters with thrust vectoring [9], a rotor tilting mechanism set on the motor mount arm enables horizontal flight suppressing the airframe inclination. The thrust vectoring nozzle on the QDH's ducted fan unit [10] enables the same flight characteristics. In our study, we had to change the thrust tilt from a vertical 0° (multi-copter mode) to horizontal 90° (airplane mode), which is why we used the rotor tilt mechanism on the motor mount arm. Individual rotors and motors on the tilt mechanism, shown in **Fig. 4**, control tilt angles independently.

Table 1 shows QTRH specifications. ArduPilotMega2.5 (APM2.5: 3DRobotics) was selected as the flight controller. Modified ArduCopter 3.2 flight control software was introduced on the APM2.5. QTRH flight tests were done manually basically in attitude mode control. In manual control, we used the radio controller (14SG: Futaba). We used wireless transmitter (Xbee Pro ZB S2B: Digi International) for the telemetry system with a PC. We used an optical flow sensor (PX4 Flow: 3DRobotics) set on the bottom of the QTRH to measure ground speed. **Fig. 5** shows the system configuration.

3. Horizontal Flight Tests

In horizontal flight tests, the QTRH first hovers the same as a QRH. The 4 rotors are then tilted at the same angles as synchronously.

This test was done as the initial transition flight stage.

3.1. Experimental Method

We detail QTRH level flight with tilting rotors as follows:

When the multicopter moves forward, it first reduces the rotational speed of the front rotors and increases that of the rear rotors to have them tilt forward. The horizontal

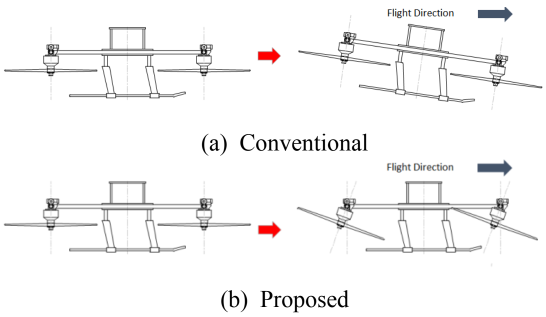

Fig. 6. QTRH movement.

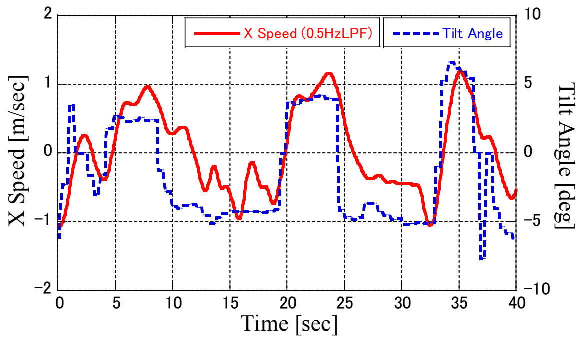

Fig. 7. Flight speed and tilt angle.

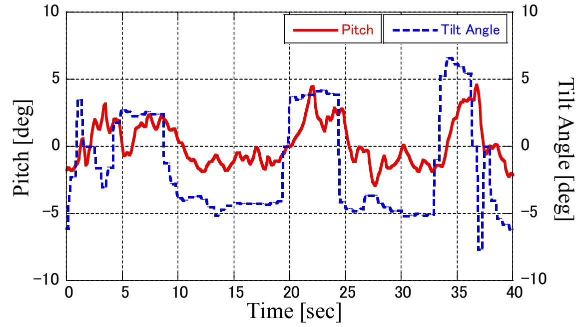

Fig. 8. Pitch and tilt angles.

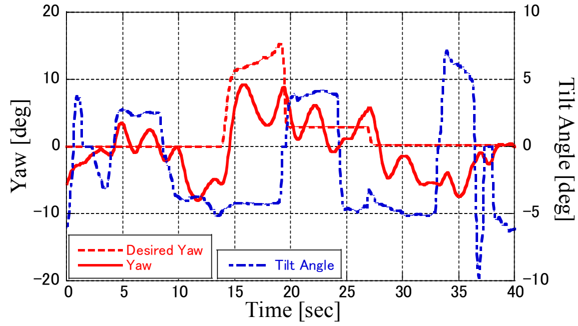

Fig. 9. Yaw and tilt angles.

thrust component is generated by this anteversion.

By maintaining this posture, it then starts moving forward using the horizontal component of thrust, keeping the same direction of movement, as shown in **Fig. 6(a)**. To move a small distance in this way, e.g., while keeping the distance between the multi copter and other objects (such as building, bridge, etc.), steering becomes difficult because the attitude must be changed frequently. The method we present for generating the horizontal component of thrust is by tilting the propeller rotors instead of tilting the vehicle itself. We fabricated the airframe with tilting mechanism as shown in **Figs. 3** and **4**. The level was hold by attitude control code of Arducopter 3.2. We set the QTRH angle at 0° in relation to the attitude controller, and tilted the 4 QTRH rotors manually by using the radio control transmitter.

All rotors were tilted synchronously at the same angle to generate horizontal thrust, as shown in **Fig. 6(b)**.

3.2. Results

Figure 7 shows the flight speed and tilt angle. The rotor-tilt angle is 0° when the rotor shaft is vertical to the QTRH airframe. We used a low-pass filter to eliminate noise in optical sensor velocity data. **Fig. 7** shows that the flight speed changes with the tilt angle. **Fig. 8** shows the rotor tilt angle and the QTRH pitch angle.

During flight tests, the pitch angle varied from $-3°$ to $+5°$ at desired pitch angle of 0°. **Fig. 9** shows the QTRH tilt and yaw angles. Note the vibration and steady state error in yaw axis motion. These results show that rotor tilting affects roll and yaw axis control.

Pitch angle interference is caused by torque around the

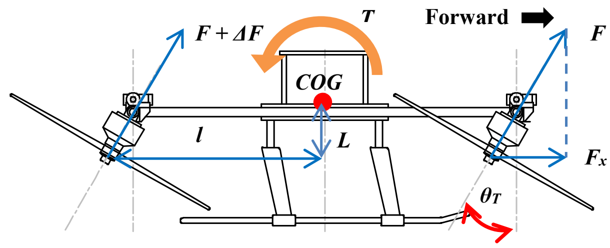

Fig. 10. Torque generated around the pitch axis by tilting the rotors.

pitch axis. In **Fig. 10**, the horizontal thrust component F_x is generated by rotor tilting, then F_x and vertical length L between the COG and the thrust origin generate torque T_P, which affects QTRH pitch angle control.

$$\begin{aligned} T_P &= FL\sin\theta_T + (F+\Delta F)L\sin\theta_T \\ &= (2F+\Delta F)L\sin\theta_T \quad \ldots \ldots \ldots \ldots (1) \end{aligned}$$

F is front rotor thrust, $F+\Delta F$ is rear rotor thrust, and ΔF is attitude control output. Torque T_{AC} generated by attitude control is

$$\begin{aligned} T_{AC} &= (F-(F+\Delta F))\,l\cos\theta_T \\ &= -\Delta F\,l\cos\theta_T. \quad \ldots \ldots \ldots \ldots (2) \end{aligned}$$

T_p is commensurate with T_{AC}, yielding the following:

$$T_P + T_{AC} = 0 \quad \ldots \ldots \ldots \ldots (3)$$

$$\Delta F = \frac{2FL\sin\theta_T}{l\cos\theta_T - L\sin\theta_T}. \quad \ldots \ldots \ldots \ldots (4)$$

Because P control is used for attitude control, ΔF is $K_P\theta_P$, where K_P is P control gain and θ_P is the QTRH pitch an-

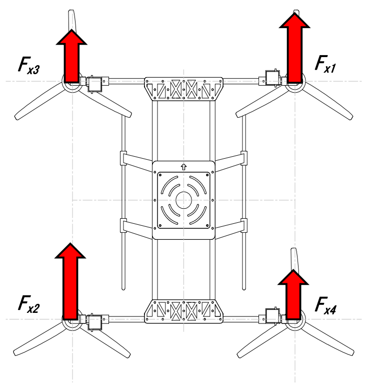

Fig. 11. Thrusts of QTRH with rotor tilting.

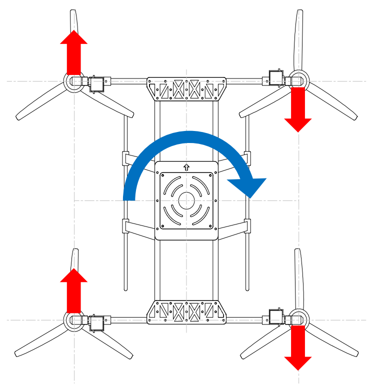

Fig. 12. Thrust vectoring yaw control.

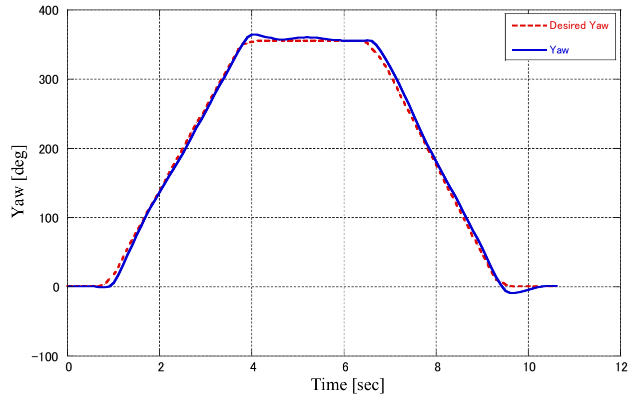

Fig. 13. Thrust vectoring yaw control behavior.

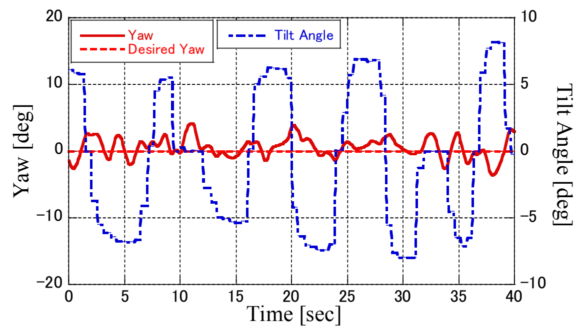

Fig. 14. Yaw and tilt angles with the improved yaw controller.

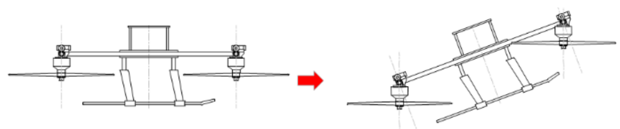

Fig. 15. Arbitrary attitude hovering principle.

gle. As a result, the pitch angle of QTR converges at θ_P.

$$\theta_P = \frac{2FL\sin\theta_T}{K_P(l\cos\theta_T - L\sin\theta_T)} \quad \ldots \ldots \ldots \quad (5)$$

To realize horizontal flight, i.e., θ_P is 0°, L must be close to zero.

Interference with the yaw angle is caused by the horizontal component of the tilted rotor. Rotor speeds of the 4 rotors differ because attitude control for 3 axes decides rotor speed and each thrust differs from the others.

Figure 11 shows those thrust on the QTRH. Horizontal thrust components act as torque T_Y around the yaw axis.

$$T_Y = a(-F_{X1} + F_{X2} + F_{X3} - F_{X4}) \quad \ldots \ldots \quad (6)$$

where, a is the distance between the COG and the thrust origin. T_Y prevents control of the yaw axis performed by reaction torque of 4 rotors.

We therefore present a new yaw axis control method that uses rotor tilting as thrust vectoring, as shown in **Fig. 12**. Yawing torque is generated by tilting the right and left rotor pairs in directions opposite to each other.

We modified the yaw axis control program to tilt the rotor for rotation around the yaw axis. The control algorithm is the same as for Ardurcopter 3.2. **Fig. 13** shows yaw control results. **Fig. 14** shows the QTRH tilt and yaw angles with the new control program. "Tilt angle" shows the rotor tilt angle in manual control without the tilt angle for yaw control. There is a tiny vibration of 2° to 3°, but steady-state error is no longer observed. Compared to **Fig. 9**, yaw axis variation is reduced and interference caused by rotor tilting is suppressed.

4. Arbitrary Attitude Hovering

To conduct arbitrary attitude hovering tests, the QTRH first hovers in the same way as a QRH, then pitch control tilts the QTRH by thrust control and the 4 rotors are tilted synchronously at the same angles.

4.1. Experimental Method

We tried to realize arbitrary QTRH attitude hovering by tilting the rotors. The QTRH pitch angle was held by the Ardurcopter 3.2 attitude control code. The desired QTRH pitch angle was changed from 0° to 30° in 3 seconds and the 4 QTRH rotors were tilted synchronized with the desired QTRH pitch angle. All rotors were tilted the same as the desired QTRH pitch angle. **Fig. 15** shows the arbitrary attitude hovering principle and **Fig. 16** actual arbitrary attitude hovering.

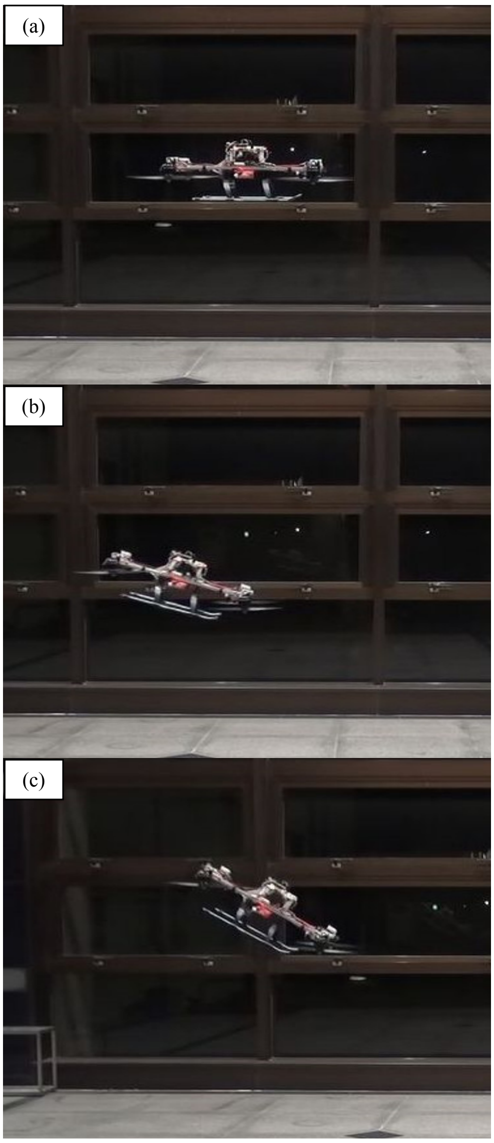

Fig. 16. Arbitrary attitude hovering.

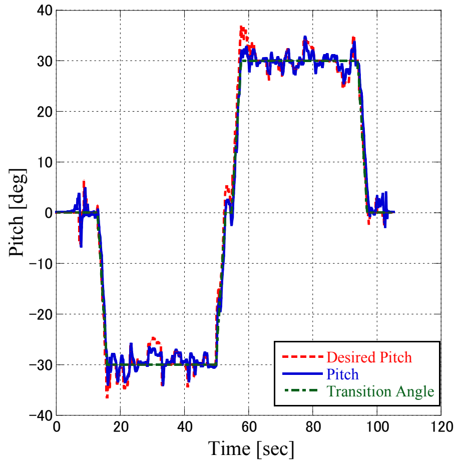

Fig. 17. Pitch angle response.

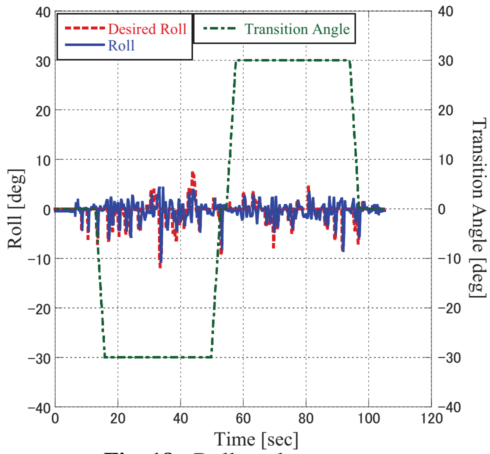

Fig. 18. Roll angle response.

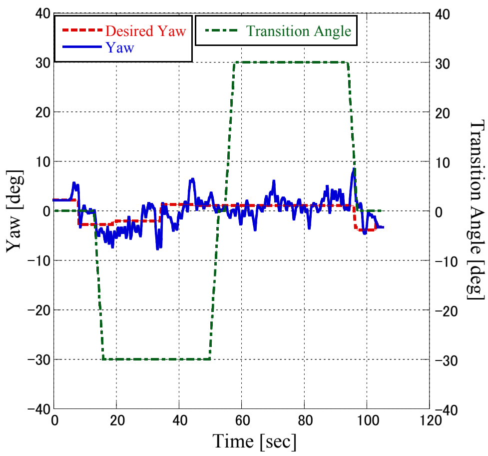

Fig. 19. Yaw angle response.

4.2. Results

Figure 17 shows the QRTH pitch angle during arbitrary attitude hovering. The transition angle varied automatically by manual start signal input. The desired pitch is the sum of the transition angle and manual pitch angle input. Pitch is the QTRH pitch angle. The transition angle is changed from 0° to −30°, −30° to 0°, 0° to 30°, and 30° to 0° followed by the pitch angle. The QTRH then hovers during pitch angle transition. The pitch angle also follows the desired angle when the QTRH is tilted at −30° and 30° in pitch angle 16–50 secondsand 56–94 seconds.

Figure 18 shows the QRTH roll angle during arbitrary attitude hovering. The desired roll is manual roll angle input. Roll is the QTRH roll angle. Although there is minute vibration in the roll angle, the roll angle follows the desired roll angle when QTRH is tilted at −30° and 30° in pitch angle.

Figure 19 shows the QRTH yaw angle during arbitrary attitude hovering. The desired yaw is manual yaw angle input. Yaw is the QTRH yaw angle. Minute error occurs in the yaw angle, but the yaw angle still follows the desired yaw. A comparison of **Figs. 14** and **19** shows that the yaw angle error range increases from 5° to 10°, but hovering remains stable. We moved the test airframe back and forth and left and right at an arbitrary attitude.

These results indicate that attitude control with the tilting rotor realizes arbitrary attitude hovering by the QTRH.

5. Conclusions

The experimental quad tilt rotor helicopter test frame we developed with an arbitrary attitude control system and a rotor tilting mechanism succeeded in flying horizontally with a minute error of 3° to -5° in the pitch angle, and succeeded in hovering at an arbitrary attitude.

We now plan to add a fixed wing and to implement control for transition to horizontal flight as a fixed-wing aircraft.

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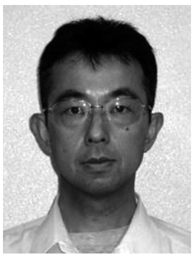

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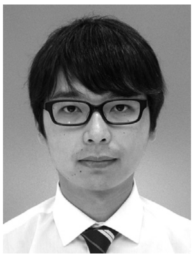

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