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Paper:

Flight Characteristics of Quad Rotor Helicopter with Thrust Vectoring Equipment

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A quad rotor helicopter (QRH) is a radio controlled (RC) aircraft that tilts its attitude to generate a horizontal force component to move in a certain direction. Using autonomous control, the attitude control system tilts the airframe against disturbances, such as wind. Thus, the attitude of a flying QRH is always slanted. In this study, three types of deflecting thruster were compared to maintain the position and horizontal attitude of the QRH. The extra thrusters are tilted to generate a thrust against disturbances without causing the airframe to incline. It is suitable for precise measurements for which the airframe posture should remain horizontal.

Keywords: quad rotor, UAV, ducted fan, extra thruster, tilting rotor

1. Nomenclature

- g : Gravitational acceleration
- T_R : Thrust of rotors
- L : Lift force
- F : Centrifugal force
- F_O : Centripetal force
- F_H : Force in horizontal direction
- F_C : Force of crosswind
- φ : Banking angle of airframe
- n : Load factor
- R : Turning radius
- T_D : Thrust of ducted fan
- θ : Deflection angle of ducted fan
- w : Weight
- v : Air speed

2. Introduction

Small unmanned aerial vehicles (UAV) of the vertical take-off and landing (VTOL) type, which require no runway, have attracted attention in recent years. For example, radio-controlled helicopters are used for pesticide spraying and aerial photography. Unmanned helicopters can be classified in general as single-rotor and multi-rotor types. In this paper, we focus on the multi-rotor type helicopters, which have greater flight stability and better controllability. In general, an airplane tilts to withstand crosswinds during flight, as shown in **Table 1**, but should retain a horizontal attitude for aerial photography or ground measuring. A general measure is to mount a camera on a gimbal and use a gyro sensor to maintain the ground angle even when the airplane changes attitude. The objective of this study was to develop a quad rotor helicopter (QRH) that can retain a horizontal attitude, even during flight or in crosswinds. For this purpose, three types of thrust vectoring mechanism were individually proposed in preceding studies [1–4]. The flight characteristics of the three types are compared in the present study.

Table 1. Attitude of airframe.

	Forward (Pitch angle)	Turn (Roll angle)
Plane (Fixed wing)		
Helicopter (Rotary wing)		

3. Flight Attitude of Multi-Rotor Helicopter

The attitude of a plane during turning flight is a combination of a forward and a turn motion, as shown in **Table 1**. As in an ordinary helicopter, the attack angle of the pitch axis of a multi-rotor helicopter is determined so that the helicopter tilts forward, and the banking angle of the roll axis is determined as for fixed-wing planes, as shown in **Fig. 1**. In a circular motion, the plane turns by tilting the plane body to the banking angle φ so that the centrifugal force F and centripetal force F_O are equal. φ is deter-

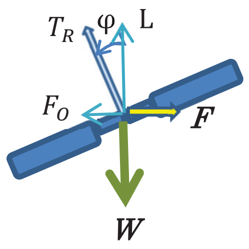

Fig. 1. Forces when turning in flight.

mined from the relational expression of F, as represented in Eqs. (1) and (2). To maintain altitude when turning in flight, T_R is increased n times; n is called the load factor. Additional necessary thrust is obtained by adjusting the attack angle upward.

$$F_O = F = T_R \sin\varphi = \frac{wv^2}{gR} \quad \text{(1)}$$

$$\varphi = \tan^{-1}\left(\frac{v^2}{gR}\right) \quad \text{(2)}$$

$$L = w = T_R \cos\varphi \quad \text{(3)}$$

$$n = \frac{T_R}{w} = \frac{1}{\cos\varphi} \quad \text{(4)}$$

Since no centrifugal force is exerted during straight movement, Eq. (1) gives a horizontal force

$$F_H = T_R \sin\varphi \quad \text{(5)}$$

and the attack angle of the pitch axis is set such that the plane body tilts forward. Therefore, a QRH should tilt its attitude to move, turn, and fly against crosswinds.

It is now possible to capture high-quality images by using equipment called a brushless gimbal together with a camera. The attitude of the camera is controlled by a gyro sensor independently of the plane body. However, when an operator controls the plane in a narrow space or area that requires high-level control skills or when a docking operation that requires accurate positioning is conducted, the stabilization of the plane attitude is the most important factor. For this purpose, a helicopter of our proposed thrust vectoring type has an advantage. In addition, since the brushless gimbal does not operate appropriately against a variation in the center of gravity or load, it is not suitable for the suspension of a robot hand.

4. Thrust Vectoring Mechanism

As mentioned above, ordinary planes fly with their attitude tilted. In the present paper, helicopters with the following three types of thrust vectoring mechanism are proposed. They can maintain their body attitude and hover or fly in a horizontal attitude.

4.1. Extra Thruster Type

A helicopter with an extra thruster (ET), which allows an ordinary QRH to sideslip, is proposed. A ducted fan (DF) is used for the extra thruster and two-axis gimbal mechanisms on the right and left sides are introduced to allow thrust vectoring in an arbitrary direction (**Fig. 2**). **Fig. 3** shows the attitude of the helicopter during hovering in a crosswind and the effect of the ET. When there is no crosswind, the helicopter flies horizontally in the direction opposite to that of the crosswind. The appearance of a prototype is shown in **Figs. 4** and **5**, the rotation direction of the rotor in **Fig. 6**, and the specifications in **Tables 2** and **3**. The specifications of the DF are shown in **Table 4**. The relating references are [5, 6].

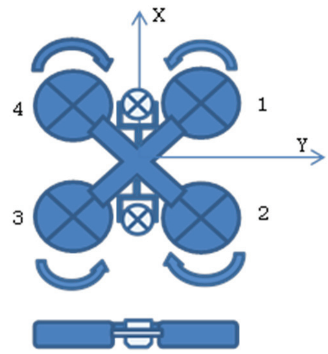

Fig. 2. Layout of extra thruster.

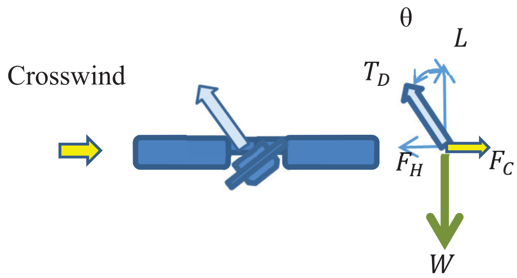

Fig. 3. Effect of extra thruster.

Fig. 4. Experimental setup of quad rotor helicopter.

4.2. Vectoring Nozzle Type

While the quad ducted fan helicopter (QDH) uses the DF as the main thruster, here we propose a helicopter that

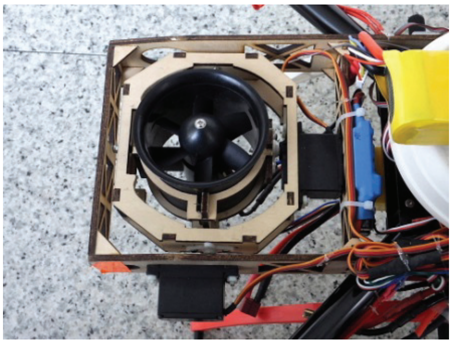

Fig. 5. Extra thruster.

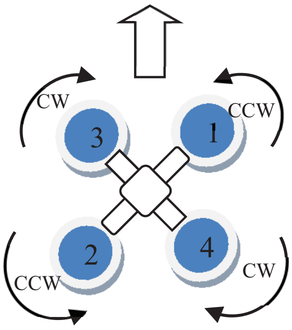

Fig. 6. Rotation direction of rotors.

Table 2. Specifications of quad rotor helicopter with extra thruster.

Rotor axis distance	650 [mm]
Rotor diameter	12 × 3.7 [inch]
Motors	850 [kV], 656[W]
ESCs	40[A]
Height	250[mm]
Width	500 [mm]
Net weight	2.59 [kg]
Battery	LiPo, 4 Cell × 2 (25 C, 3300 mAH)

Table 3. Specifications of quad ducted fan helicopter with thrust vectoring nozzle.

Span of DF		481 [mm]
Height		150 [mm]
Width		497 [mm]
Weight (including batteries)		2.54 [kg]
Battery	For motor	LiPo, 4 Cell × 2 (35 C, 2450 mAH)
	For radio Control	LiPo, 2 Cell × 1 (20 C, 800 mAH)

Table 4. Specifications of ducted fan.

Outer diameter (Max.)	83 [mm]	(1)
Inside diameter	70 [mm]	(2)
Length	58 [mm]	(7)
Diameter of impeller	68 [mm]	(3)
Number of blades	6	
Thrust	1.1 [kgf]	
Motor	3000 [kV]	
ESC	45 [A]	

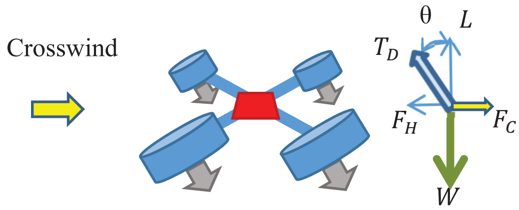

Fig. 7. Quad ducted fan helicopter with thrust vectoring nozzle under crosswind.

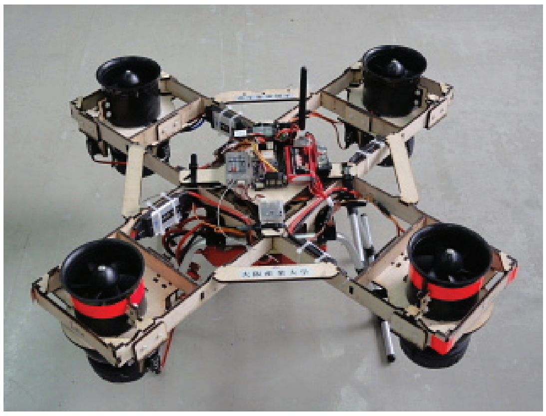

Fig. 8. Experimental setup of quad ducted fan helicopter equipped with thrust vectoring nozzle.

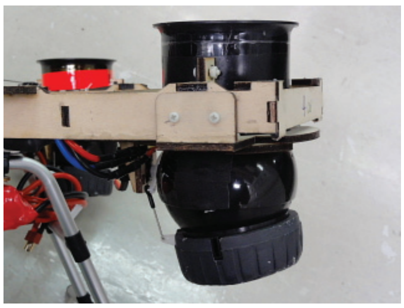

Fig. 9. Thrust vectoring nozzle.

uses a thrust vectoring nozzle (TVN) as the exhaust nozzle of each DF. **Fig. 7** shows the attitude of the helicopter during hovering in a crosswind and the effect of the TVN. When there is no crosswind, the helicopter flies horizontally in the direction opposite to that of the crosswind. The nozzle vectoring is driven by two servo motors mounted perpendicularly to each other. The appearance of our prototype is shown in **Figs. 8** and **9** and its specifications in **Table 4**. Details of the DF and TVN are given in **Tables 4** and **5** and **Fig. 10**. The relating references are [7, 8].

Table 5. Dimension of thrust vectoring nozzle.

Outer diameter (Max.)		80 [mm]	(5)
Inside diameter	Inlet	62 [mm]	(4)
	Outlet	60 [mm]	(6)
Length		87 [mm]	(8)

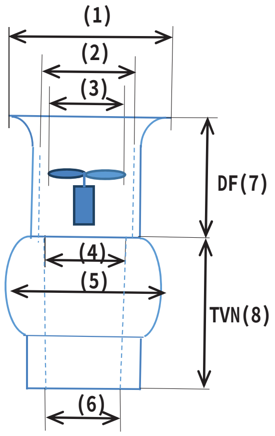

Fig. 10. Section of thrust vector control system.

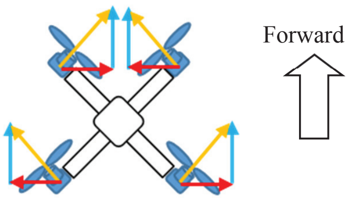

Fig. 11. Resultant vector of impellent with tilting mechanism for the rotor.

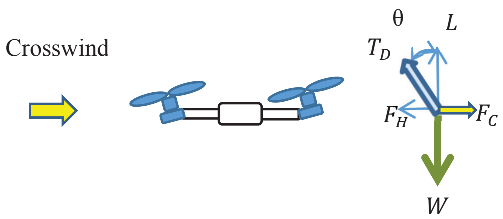

Fig. 12. Quad rotor helicopter with tilting mechanism for the rotor under crosswind.

4.3. Tilting Rotor Type

A tilting-rotor type QRH specified for the present purpose is proposed. The tilting mechanism for the rotor (TMR) proposed in this study tilts the rotors on the boom to directions that differ from each other by 90°, in order to achieve the desired impellent vector, as shown in **Fig. 11**. **Fig. 12** shows the attitude of the helicopter during hovering in a crosswind and the effect of the TNR. When there is no crosswind, the helicopter flies horizontally in the direction opposite to that of the crosswind. The appearance of a prototype is shown in **Figs. 13** and **14** and the specifications in **Tables 6** and **7**. The relating references are [9–11].

Fig. 13. Experimental setup of equipped quad rotor helicopter with tilting mechanism for the rotor.

Fig. 14. Assembled tilting mechanism for rotor.

Table 6. Specifications of quad tilting rotor helicopter.

Span of rotor		610 [mm]
Height		120 [mm]
Width		425 [mm]
Weight (including batteries)		1.41 [kg]
Battery	For motor	LiPo, 3 Cell (35 C, 2450 mAH)
	For radio Control	LiPo, 2 Cell (25 C, 350 mAH)

Table 7. Specifications of tilting mechanism for rotor.

Rotor	11 × 4.7 [inch]
Motor	1000 [kV], 235 [W]
Servo motor	3.5 [kg-cm], 0.2 [s/60°], 6[V]
ESC	20 [A]

4.4. Control Flow

The three types of helicopters use the same control system and have thee flight modes: manual, normal, and skid. The manual mode is used for takeoff and landing and allows the same flight as that of an ordinary QRH. Only attitude control is performed in this mode. In the normal

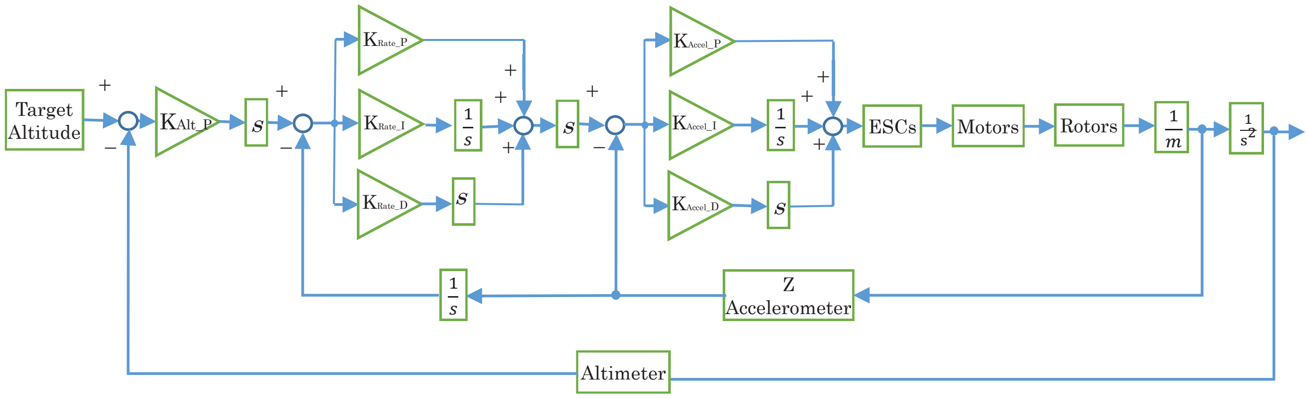

Fig. 15. Altitude hold function.

Table 8. Gain of PID.

Term of deflection	Proportion	Integration	Differential
Altitude	K_{Alt_P}		
Speed of Z	K_{Rate_P}	K_{Rate_I}	K_{Rate_D}
Acceleration of Z	K_{Accel_P}	K_{Accel_I}	K_{Accel_D}

mode, attitude control and altitude maintenance control are conducted, but the thrust vectoring mechanism does not operate. In the skid mode, attitude control and altitude maintenance control are performed and the thrust vectoring mechanism operates to allow sideslip flight. In the skid mode, the flight controller automatically controls the roll, pitch, and throttle by using the attitude stabilization control and altitude maintenance control to keep the body attitude horizontal. The operator controls the thrust vectoring mechanism by using an RC transmitter to achieve sideslip in the desired direction. The flow of the altitude maintenance control is shown in **Fig. 15**. The following triple feedback controls to the altitude command are performed by the operator.

(1) PID control for acceleration in Z direction

(2) PID control for velocity in Z direction

(3) P control for altitude measured by barometer

Table 8 shows the symbols of PID gains.

5. Flight Experiment

A prototype QRH with three types of thrust vectoring mechanism to maintain its horizontal attitude was built. Two flight experiments were conducted to compare the three types of thrust vectoring mechanism.

5.1. Flight Experiment 1 (Ex. 1): Alternating Straight Motion

The plane alternates its motion between two points (6 m apart) at a constant speed and a constant altitude (1.5 m).

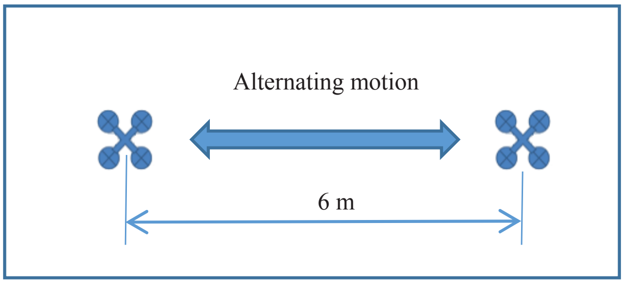

Fig. 16. Flight pattern of Experiment 1.

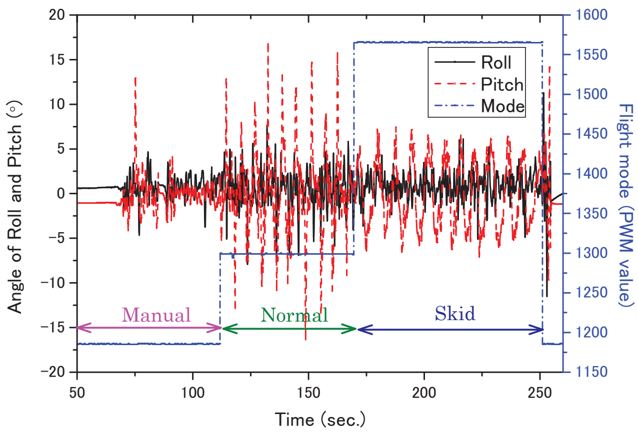

Fig. 17. Attitude angle of airframe by ET type in Experiment 1.

The flight attitude is compared in the skid and in the normal mode (**Fig. 16**). The attitude change about the pitch axis was observed in the experiment.

5.1.1. Extra Thrust Type

The change in the attitude angle was measured in two flight modes. The results are shown in **Fig. 17**.

Since the plane's motion alternates back and forth, an attitude improvement due to the mode change was observed for the pitch axis. However, the influence of the vectoring operation of the DF on the yaw axis was weak.

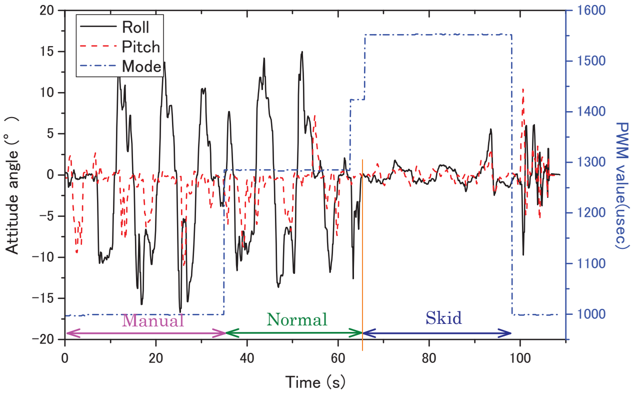

Fig. 18. Attitude angle of airframe by TVN type in Experiment 1.

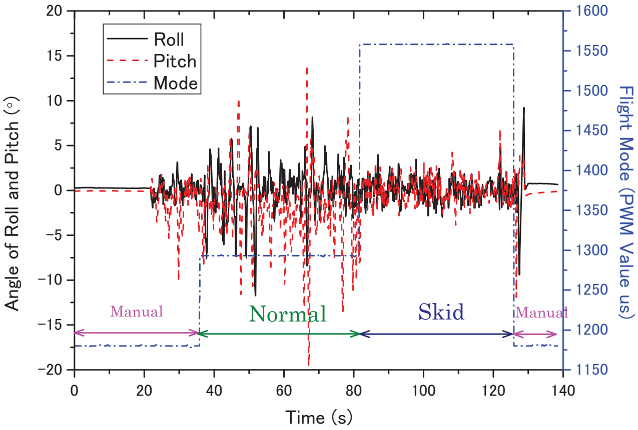

Fig. 19. Attitude angle of airframe by TMR type in Experiment 1.

5.1.2. Vector Nozzle Type

The change in the attitude angle was measured in two flight modes. The results are shown in **Fig. 18**.

Since the plane's motion alternated back and forth, an improvement due to the mode change was observed for the roll axis. Since there was also a considerable improvement in the pitch angle variation, the experiment could be performed when the yaw axis was a little rotated.

5.1.3. Tilting Rotor Type

The change in the attitude angle was measured in two flight modes. The results are shown in **Fig. 19**.

Since the plane's motion alternated back and forth, an improvement in the attitude angle fluctuation due to the mode change was observed for the pitch axis. The mode change also suppressed the attitude angle fluctuation for the roll axis; however, the suppression was small.

5.2. Flight Experiment 2 (Ex. 2): Crosswind Test

The plane hovered at a constant position and constant altitude and the attitude change was observed in the skid mode and in the normal mode (**Fig. 20**). It was expected that the attitude angle variation about the pitch axis would be suppressed in the case of frontal wind and that about the roll axis in the case of a crosswind.

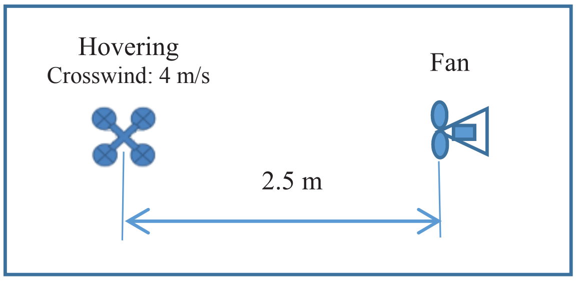

Fig. 20. Flight pattern of Experiment 2.

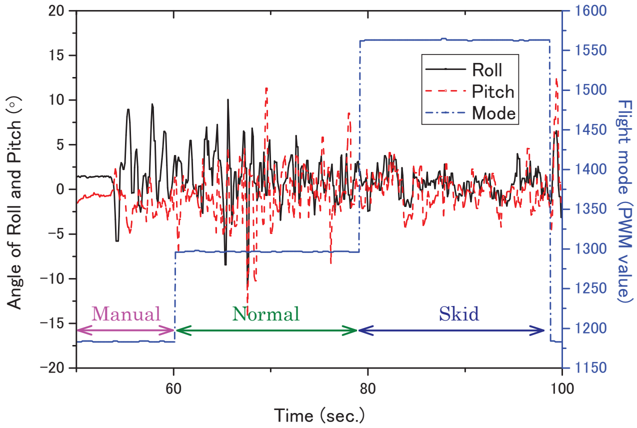

Fig. 21. Attitude angle of airframe by ET type in Experiment 2.

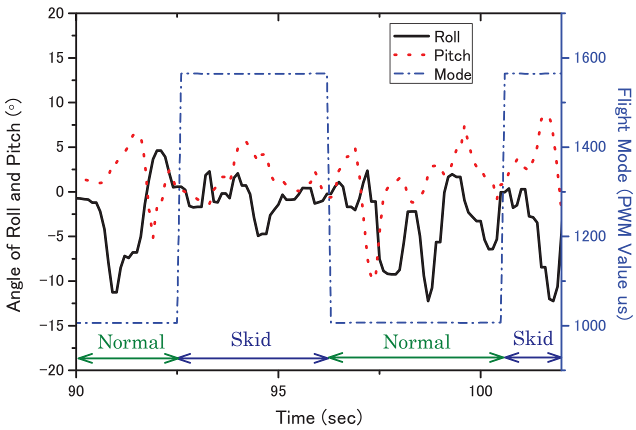

Fig. 22. Attitude angle of airframe by TVN type in Experiment 2.

5.2.1. Extra Thrust Type

The change in the attitude angle was measured in two flight modes. The results are shown in **Fig. 21**.

Since the flight experiment was performed in a frontal wind, the improvement due to the mode change was slightly larger for the pitch axis than for the roll axis.

5.2.2. Vector Nozzle Type

The change in the attitude angle was measured in two flight modes. The results are shown in **Fig. 22**.

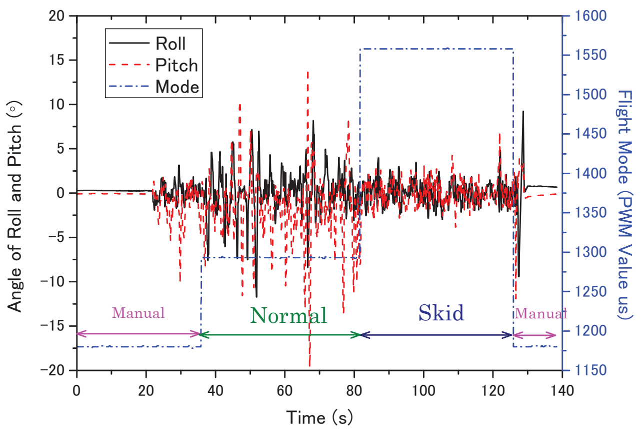

Fig. 23. Attitude angle of airframe by TMR type in Experiment 2.

Table 9. Statistical comparison of angle in Experiment 1.

		QRH with ET		QDH with TVN		QRH with TMR	
		Standard Deviation	Deviation Range	Standard Deviation	Deviation Range	Standard Deviation	Deviation Range
Roll	Normal	2.09	15.56	7.52	28.65	1.96	14.88
	Skid	1.46	11.22	1.20	8.07	0.71	4.51
	Ratio	0.679	0.721	0.160	0.282	0.364	0.303
Pitch	Normal	4.70	33.17	2.59	16.04	8.00	37.71
	Skid	3.66	14.61	0.79	5.49	2.37	9.15
	Ratio	0.779	0.441	0.304	0.342	0.296	0.243

Unit: degree

Since the flight experiment was conducted in a crosswind, the improvement in the attitude angle fluctuation due to the mode change was more significant for the pitch axis than for the roll axis. However, this tendency is not definite, since the flight time was shorter than in the other experiments.

5.2.3. Tilting Rotor Type

The change in the attitude angle was measured in two flight modes. The results are shown in **Fig. 23**.

Since the flight experiment was performed in a frontal wind, the improvement due to the mode change was slightly larger for the pitch axis than for the roll axis.

5.3. Statistical Comparison of Three Types

The results of the change in the attitude angles (roll angle and pitch angle) obtained in Exs. 1 and 2 are compared for the three kinds of mechanism by using statistical values (standard deviation and deviation range). Since the three planes have different mechanisms, dimensions, weights, directions, and completion levels, a direct comparison of the figures is not appropriate. Therefore, the improvement ratio for switching from the normal mode to the skid mode is presented in **Table 9**, where the values to be compared are shaded.

Table 10. Statistical comparison of angle in Experiment 2.

		QRH with ET		QDH with TVN		QRH with TMR	
		Standard Deviation	Deviation Range	Standard Deviation	Deviation Range	Standard Deviation	Deviation Range
Roll	Normal	2.75	21.04	3.99	14.60	2.70	19.90
	Skid	1.41	8.22	1.71	7.21	1.22	7.79
	Ratio	0.514	0.391	0.429	0.494	0.453	0.392
Pitch	Normal	3.15	25.40	3.55	17.13	3.95	33.61
	Skid	1.99	10.66	1.94	6.98	1.51	14.89
	Ratio	0.633	0.420	0.546	0.407	0.381	0.443

Unit: degree

5.3.1. Comparison in Experiment 1

A statistical comparison for Ex. 1 is shown in **Table 9**. Since the plane's motion alternated in Ex. 1, the standard deviation is the mean tilting angle of the plane body, and half of the deviation range is the maximum tilting angle. A comparison in terms of the ratio gives the following magnitude relation of the improvement:

$$\text{(QRH with ET)} \ll \text{(QRH with TMR)} < \text{(QDH with TVN)}.$$

5.3.2. Comparison in Experiment 2

A statistical comparison for Ex. 2 is shown in **Table 10**. A comparison in terms of the ratio gives the following magnitude relation of the improvement, although the difference is small:

$$\text{(QDH with TVN)} \leq \text{(QRH with ET)} \leq \text{(QRH with TMR)}.$$

6. Conclusions

Three types of the helicopter were proposed for the purpose of this study and prototypes were created for conducting flight experiments. The results of the experiments were examined in terms of the nine items in **Table 11**.

The skid effect, which was the most important target of the present study, was found in Ex. 1 to be maximized in the vectoring nozzle type. However, the vectoring nozzle type and the tilting rotor type showed poor crosswind resistance in Ex. 2. A correlation exists between the crosswind resistance and the weight of the helicopter body, and a heavier helicopter shows better crosswind resistance. For example, even a light weight manned helicopter is not very resistant to a strong wind. In the comparison of the power efficiency (power consumption per sec), the tilting rotor type showed a much better result than the others.

The above comprehensive comparison analysis indicates that the tilting rotor type QRH is optimal for the purpose of the present study.

Since the influence of the thrust vectoring operation of a QRH with an ET on the yaw axis is weak, its cause should be clarified in future studies. Since the energy con-

Table 11. Comparison of three methods.

Comparison item	QRH with ET	QDH with TVN	QRH with TMR
Skid Effect	○	◎	◎
Robustness of Crosswind	◎	○	△
Structural simplicity	△	×	○
Required battery	2×3300mAH 4Cell	2×2450mAH 4Cell	1×2450mAH 3Cell
Flight duration	4 min.	2 min.	5 min.
Effect of Power (Rate)	1465 W (4.5)	2161 W (6.6)	326 W (1)
Cost	△	×	○
Lightweight	×	△	○
Quietness	△	×	○

sumption of a QDH with a TVN is large, the variation in the electric and magnetic fields is large, and hence, the influence on the direction sensor should be a matter of concern. A reduction in power consumption and the simplification of the control mechanism of the TVN are also necessary. The QRH with a TMR is the most promising type, although the control method should be improved, because a large vectoring angle affects the constant-altitude control.

Horizontal attitude maintenance, analyzed in this study, is the most necessary function for the purpose of capturing aerial photographs. The superiority of the proposed method is degraded by the high-quality brushless gimbal. However, the attitude control by the thrust vectoring proposed in this paper would be the most promising method for robot hand or accurate positioning, which will be required for future flying-types robots.

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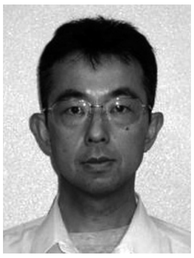

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