

Flight Characteristics of Quad Rotor Helicopter with Tilting Rotor

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Abstract—A quad rotor helicopter (QRH), a type of unmanned aerial vehicle (UAV), uses a tilted attitude to generate a horizontal thrust component in the flying direction. In the case of autonomous control, the attitude control system is used to tilt the airframe against disturbances such as crosswinds. Consequently, the flying attitude of a QRH is always inclined. In this study, a tilting mechanism for rotors (TMR) was mounted on a QRH to maintain a horizontal attitude. The TMRs were tilted to generate thrust against disturbances without inclining the airframe. The system was constructed using a QRH and TMRs tilted around only one axis and allocated every 90°. Because the airframe is always horizontal, this system can be used for the precise measurement of, e.g., landforms and buildings.

Keywords—UAV, multi rotor, quad rotor, helicopter, tilt rotor.

I. INTRODUCTION

SMALL vertical take-off and landing (VTOL)-type unmanned aerial vehicles (UAVs) have recently been used for tasks such as spraying agricultural chemicals in croplands of mountainous areas. However, operations such as the inspection of high-voltage electrical power lines and aerial photography continue to require manned helicopters.

In operations utilizing UAVs, it becomes more difficult to fly safely with increasing distance from ground control. In particular, single-rotor helicopters face a high risk of colliding with surrounding objects because the rotor diameter is larger than the airframe. At the same time, multi-rotor helicopters with only small-diameter rotors have been widely developed for recreational and industrial use. Most current multi-rotor helicopters are equipped with various sensors for attitude control. Therefore, their flight stability and controllability are better than those of a conventional single-rotor helicopter. This study aimed to design a control mechanism that maintains the horizontal attitude of a quad rotor helicopter (QRH) under all circumstances. Toward this end, we propose a quad tilt rotor helicopter (QTRH), which we call “hummingbird,” in which a tilting mechanism is installed in each rotor. This mechanism rotates the mount of the motor around only one axis. Each tilting mechanism for rotors (TMR) is controlled by a servo motor. Therefore, four servo motors together enabled the

helicopter to be tilted in order to generate thrust against crosswind disturbances while maintaining the horizontal attitude of the airframe. Because the airframe is always horizontal, the system can be used for aerial photography and precise measurement. Moreover, many studies have focused on a mechanism to enable a rotor to tilt a fixed wing in the direction of the same axis, such as that in the Bell Boeing Quad Tilt Rotor V-44. In our proposed method, the tilt axis of each rotor is allocated at every 90°. As for [7], because the purpose is different, the control techniques are also different though the basic structure of the TMR is the same. A basic study of the QTRH can be obtained in [6] and [8]. The control techniques and effectiveness of the TMR were verified by an experimental model.

II. TILT ROTOR HELICOPTER

The single-rotor radio-controlled (R/C) helicopter is of the variable pitch type, and the number of joints in the rotor heads is minimized. Most types of R/C helicopters use hingeless blades for their rotors. Thus, even under a little movement and crosswind, it becomes necessary to incline the airframe. A similar situation holds, even though the multi-rotor helicopter is of the fixed pitch type (see **Figures 1** and **2**).

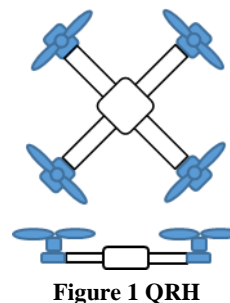


Figure 1 QRH

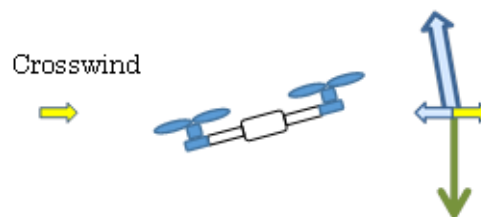


Figure 2 Airframe inclinations under crosswind

A QRH continually adjusts its inclination to maintain its attitude. When a camera is installed using a stabilized gimbal system attached to a QRH, the camera attitude is maintained by the gimbal device. A similar effect was achieved in this study by installing a TMR in the multi-rotor helicopter. A QRH generally uses rotors with fixed-pitch blades, and it is possible to easily apply a TMR to them for thrust vectoring. There are two types of frames in which a TMR can be installed (see **Figure 3**). The “H”-type does not sustain any loss caused by the generation of thrust and allows for travel in only certain directions. The “X”-type sustains loss caused by the generation of thrust and can allow for travel in any direction. Therefore, in this study, the TMR is installed in an “X”-type QRH, and it allows for travel even under crosswind (see **Figure 4**).

The QTRH should compensate so that the lift may decrease according to the vectoring angle when TMR is used. The thrust margin of the QTRH should also increase because it is assumed that the vectoring angle increases in strong-wind outdoor environments. When using a TMR in practice, strength and accuracy are important, and therefore, the mechanism should not resonate.

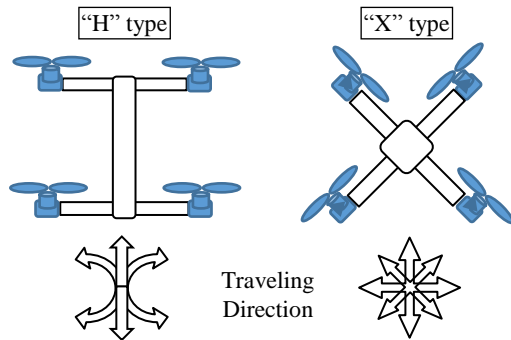


Figure 3 Tilt axis of QTRH

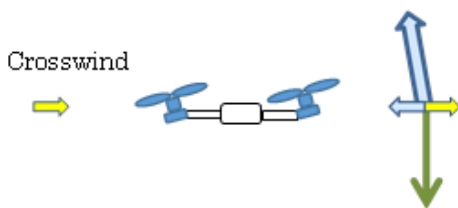


Figure 4 QTRH under crosswind

A. Quad Rotor Helicopter

Four TMRs were installed in an “X”-type configuration in the QRH. The rotation directions of the TMRs were set such that their anti-torques neutralize each other: diagonally opposite rotors rotate in the same direction and adjacent ones, in opposite directions (**Figure 5**).

B. Tilting Mechanism for Rotor

Each TMR was driven by a servo motor (see **Figures 6** and **7**), and all four servo motors were controlled through two R/C channels. Accurate phase adjustment of the TMRs was required in the QTRH because a phase error would result in thrust wastage.

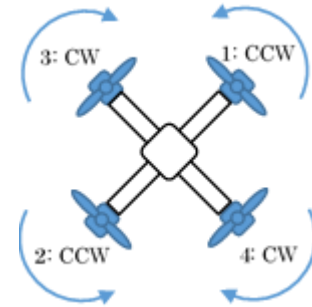


Figure 5 Rotation directions of rotors

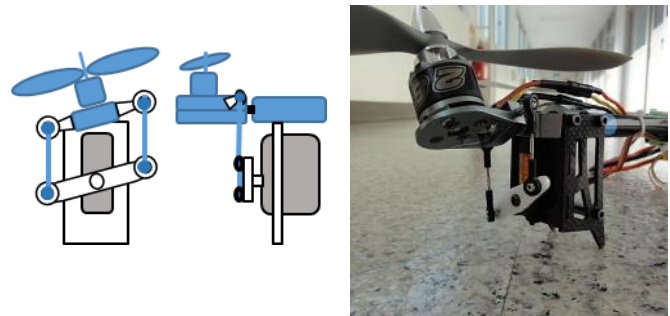


Figure 6 Structure of TMR

Figure 7 Assembled TMR

Installing the TMRs produces skid and stabilization effects, among others. The skid effect of the TMR is manifested by the horizontal component of the total thrust, whereas the vertical component provides lift. The relation between these components and the vectoring angle is expressed in (1) and (2).

$$H = T \sin\theta \tag{1}$$

$$L = T \cos\theta \tag{2}$$

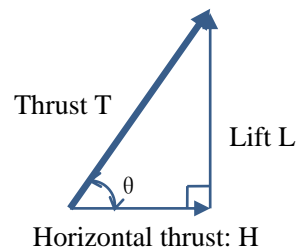


Figure 8 Orthogonal components of total thrust

The horizontal thrust element acts against the crosswind, resulting in a stabilization effect that is also effective against turbulent flow (see **Figure 4**). The thrust of each rotor is individually slanted by the TMR, and the traveling direction is determined by the resultant vectors, as shown in **Figure 9**. Furthermore, the TMS system increases the robustness against disturbances.

However, installing the TMRs on the QTRH has some disadvantages:

- Increase in weight
- More complicated mechanism and control

- Altitude loss under tilt angle
- Counterbalance loss by resultant vector

The most significant disadvantage is the weight increase. However, because this mechanism is simpler than two previously reported methods [2], [5], there is only a slight increase in the weight when the TMR method is employed.

Two TMR methods for controlling the vectoring are as follows:

- Anti-phase method (skid effect, see **Figure 9**)
- In-phase method (yaw control effect, see **Figure 10**)

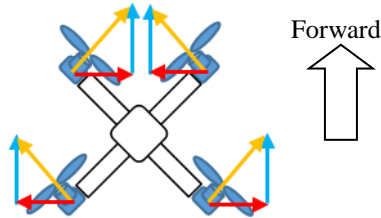


Figure 9 Resultant vector of impellent with TMR (Anti-phase)

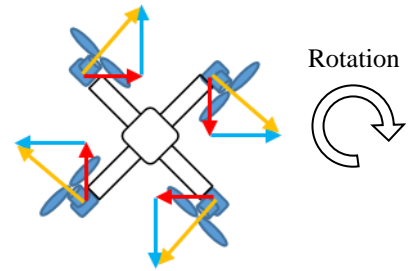


Figure 10 Resultant vector of impellent with TMR (In-phase)

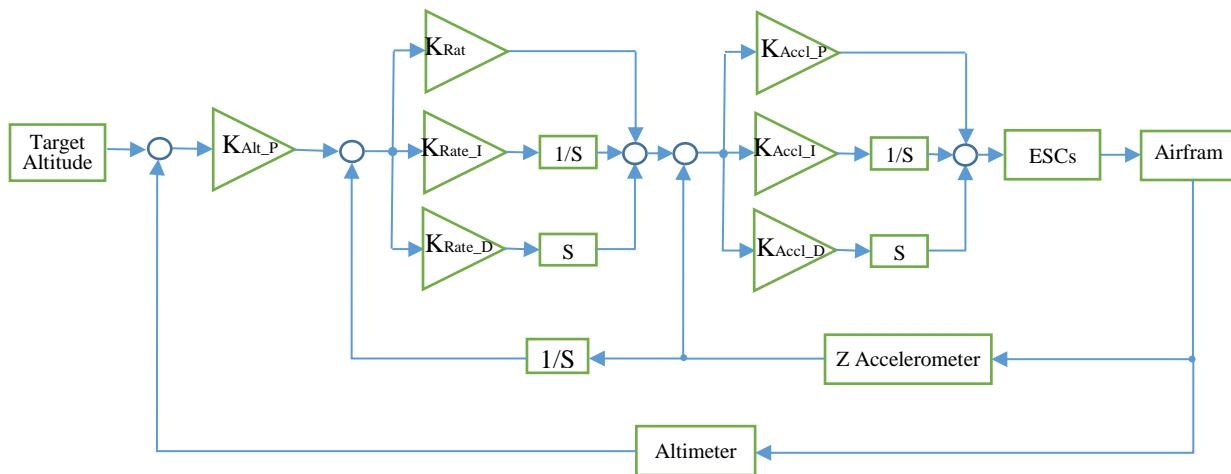


Figure 11 Attitude stabilizing function

III. EXPERIMENT

A conventional QTRH inclines its attitude to generate a horizontal thrust component in the flying direction. To maintain flight, the attitude control system inclines the airframe against disturbances such as wind. Consequently, the attitude of the flying QTRH is always inclined. In this study, TMRs were installed to maintain the horizontal attitude of the QTRH. An indoor experiment (see **Figure 12**) was set up to evaluate the performance of our TMRs-equipped QTRH against crosswind disturbances.

A. Experimental Setup of QTRH

It is quite dangerous to use a QTRH around humans and animals because its rotor is not shielded. Safety can be improved by substituting the rotor with ducted fans, which also enabled miniaturization in the previous study [5]. The four

Anti-phase vectoring of the TMR control system was applied to prepare the airframe for test flights in this study. Skidding of the TMRs was enabled by the automatic attitude holding control of the QTRH. The control system has two flight modes, normal and skid, as shown in **Figures 17** and **18**, respectively. In the normal flight mode, the TMRs are fixed. In the skid flight mode, the operator manually controls the thrust and vectoring of the TMR system, whereas the flight controller automatically controls the roll, pitch, and throttle by the attitude stabilizing function (see **Figure 11**).

TMRs used in this experiment were developed for an electric model aircraft. Two were operated with positive rotation and the other two, with negative rotation. The outlet of each rotor was installed in a TMR, and its tilting motion was controlled by a servo motor. The X-type frame construction (see **Figure 13**) was chosen to prioritize axial movement performance. The specifications of the QTRH are listed in **TABLES 1** and **2**.



Figure 12 Scene of experiment



Figure 13 Experimental setup of TMR-equipped QTRH

TABLE 1 SPECIFICATIONS OF QTRH

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 2 SPECIFICATIONS OF TMR

Rotor	APC Slow Flight 11 x 4.7 [inch]
Motor	NTM 28-26 1000 [kV], 235 [W]
Servo motor	JR Propo DS359HV 3.5 [kg-cm], 0.2 [s/60°], 6[V]
ESC	Turnigy Multistar 20 [A]

TABLE 3 EXPERIMENTAL CONDITIONS

Environment	Indoor
Area	4 [m] × 8 [m]
Altitude	1.5 [m]
Velocity	Constant
Motions	Alternating Motion Rotary Motion Hovering Motion

B. Flight Controller and Radio Control Unit

An ArduPilot Mega 2.6 (APM2.6, 3D Robotics Co.) flight controller, the architecture of which is publically available, was used. The firmware of APM2.6 was open source, and ArduCopter 3.1 was installed. APM2.6 was used to control the airframe by incorporating four types of sensors (a three-axis gyro sensor, a three-axis acceleration sensor, a three-axis magnetometer, and an atmospheric pressure sensor) and placing a GPS module outside it. Data communication with the PC of the ground station was achieved by adding the Xbee telemetry device. Recording of the flight log and setting of the

control parameters were carried out by installing an open source GUI mission planner onto the PC.

The R/C equipment was a 14-channel system (XG14, RG731BX, XB1-CV4, JR Propo Co.), seven of which were used for operation (four channels), TMR (two channels), and flight mode (one channel). The structure of each TMR is the same, and the rotation is allocated at every 90° (see Figure 14). Therefore, a reverse rotation circuit and Y-type harness are made by the XBus system, and the control signal diverges because the servo motor allocated in opposition to the TMR assumes the opposite direction (see TABLE 5). Moreover, the control system was powered by a separate battery owing to the increased power consumption. Conversion from the “+”-type to the “X”-type TMR is performed by the program mixing of the RC transmitter (see TABLE 6).

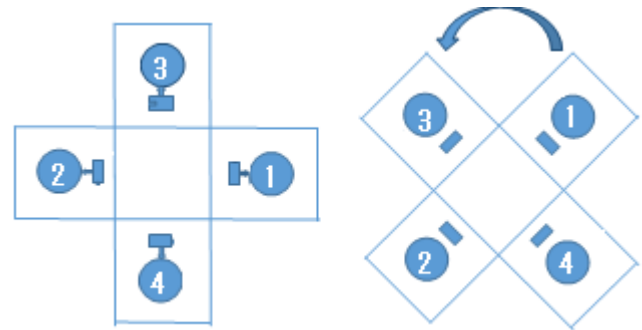


Figure 13 Layout of servo motor for TMR

TABLE 4 SERVO MOTOR NAME FOR TMR

RC Channel	Aux2	Aux3
Rotor Axis	1-2 Axis	3-4 Axis
Rotor No.	1	XBus 7-1
	2	XBus 9-1
	3	XBus 7-2 (Reverse)
	4	XBus 9-2 (Reverse)

TABLE 5 PROGRAM MIXING FOR RC TRANSMITTER

Program No.	Primary > Secondary	High Position (%) Low Position (%)
1	Roll > 1-2 Axis	Down -100 Up -100
2	Pitch > 3-4 Axis	Left +100 Right +100
3	Pitch > 1-2 Axis	Down +100 Up +100
4	Roll > 3-4 Axis	Left +100 Right +100

C. Flight Mode

Two vectoring control methods are used for the TMR. In this study, we assumed anti-phase tilting for the TMR control system. The skidding operation by the TMR was enabled by the automatic attitude holding control of the QTRH. The control system included two flight modes, normal and skid, as shown in **Figure 19** and **20**, respectively, and **TABLE 6**. In the normal flight mode, the TMR was non-operational, and it was the same as the QRH. The takeoff and landing were executed in the manual mode. In the skid flight mode, the operator manually controlled the TMR, and the flight controller automatically controlled the roll, pitch, and throttle using the attitude stabilization function.

Loss occurs during lift because of slanting, even though the airframe moves by slanting the TMR in the skid mode. Altitude is measured by the acceleration and atmospheric pressure sensors, and it is controlled by double PID feedback, to maintain a constant altitude.

TABLE 6 OPERATION IN FLIGHT MODE

Operation item		Flight mode	
		Normal	Skid
QRH	Roll Pitch	Manual (Operator)	Automatic (APM)
TMR	Forward/Backward Right/Left	Non-operational	Manual (Operator)

D. Experimental Procedure

In this study, three experimental test flights were conducted:

Test flight 1: Linear alternating motion

The airframe was flown back and forth, and the attitude change in the skid mode was compared with that in the normal mode (see **Figure 15**). The attitude change owing to the fixed velocity movement at 6 m and the reversing movement was observed.

Test flight 2: Rotary motion

The direction of the nose was not changed, and it flew in a circle of 2.5 m diameter, and the attitude change in the skid mode was compared with that in the normal mode (see **Figure 16**). The attitude change owing to the angle of the roll axis and the pitch axis simultaneously changing was observed.

Test flight 3: Crosswind testing

To measure the stability level with respect to the crosswind, a test flight was carried out indoors with a large fan. The wind velocity was 4 m/s and the QTRH was 2.5 m away from the fan. The QTRH was maintained in the hover condition. The attitude change was measured as the flight mode was switched between the normal and the skid modes (see **Figure 17** and **18**).

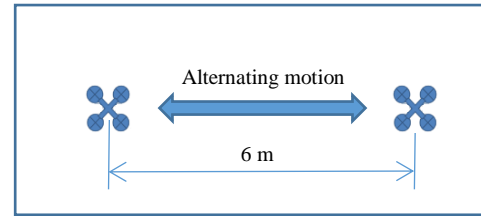


Figure 15 Flight pattern of test flight 1

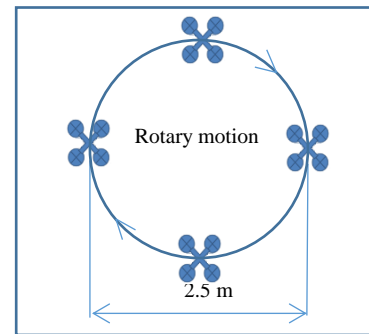


Figure 16 Flight pattern of test flight 2

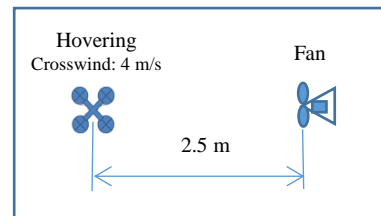


Figure 17 Flight pattern of test flight 3



Figure 18 Scene of crosswind test

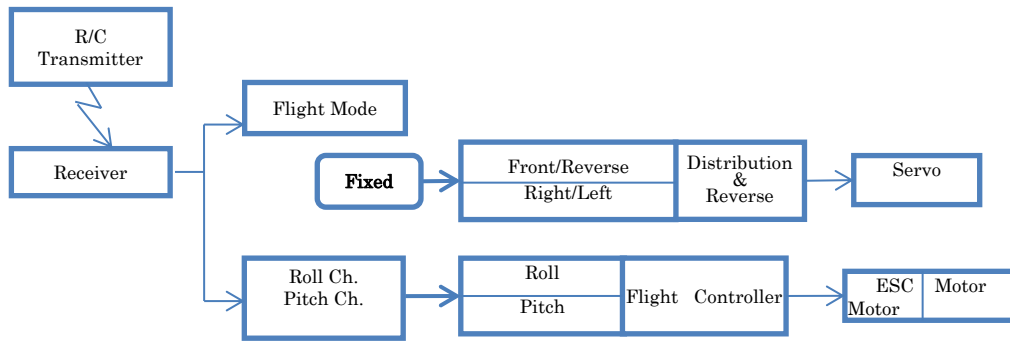


Figure 19 Flow of normal flight mode

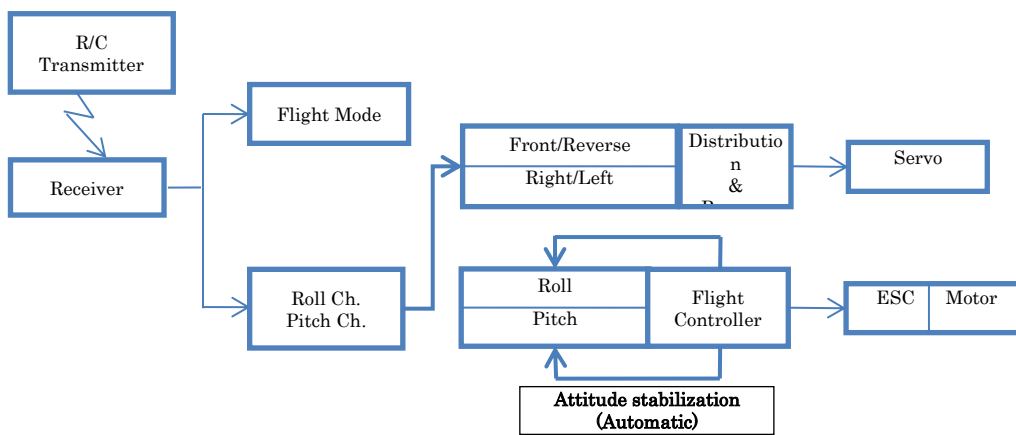


Figure 20 Flow of skid flight mode

IV. RESULTS

The flight modes observed from the outcome of an experiment are as follows:

- Manual mode: During takeoff and landing.
- Normal mode: During slanted flying, similar to a QRH.
- Skid mode: Flying in which attitude is maintained, similar to a hummingbird.

A. Test flight 1: Linear alternating motion

The transition in the slant angle in test flight 1 is shown in Figs. 21 and 22 and Tables 7 and 8. The changes in the roll and pitch of the angles and angular velocity of the airframe attitude over time can be observed in the figures.

The difference between the two flight modes descends obviously: there is a difference of about 330% in the attitude angle and a difference of about 150% in the angular velocity.

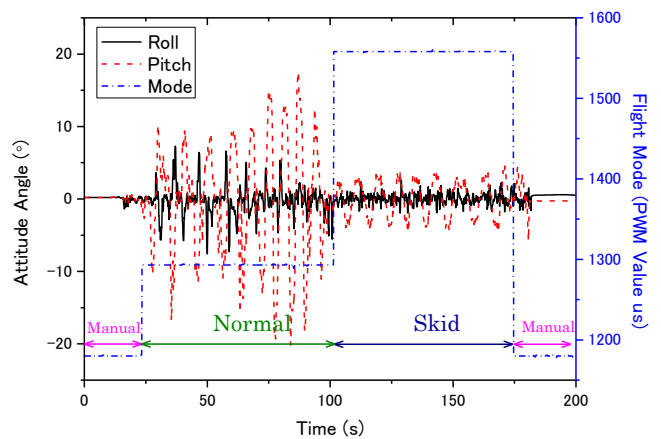


Figure 21 Attitude angle of airframe in test flight 1

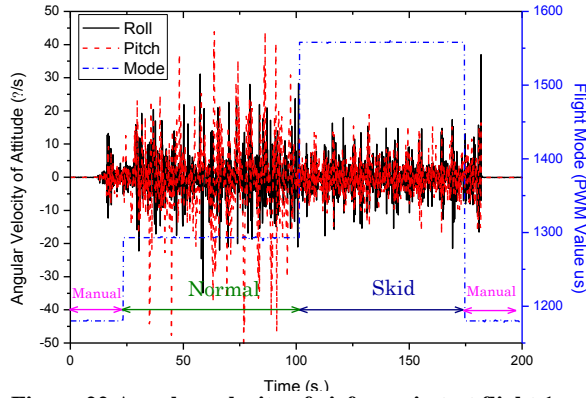


Figure 22 Angular velocity of airframe in test flight 1

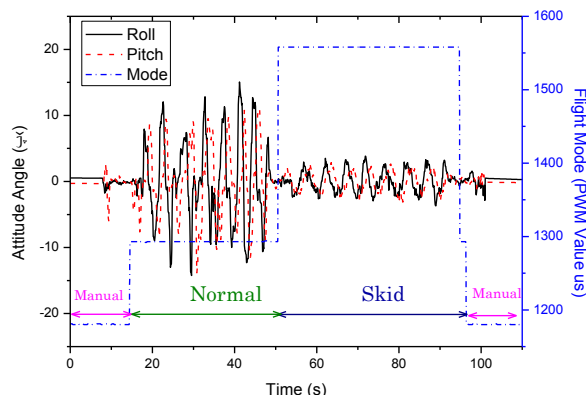


Figure 23 Attitude angle of airframe in test flight 2

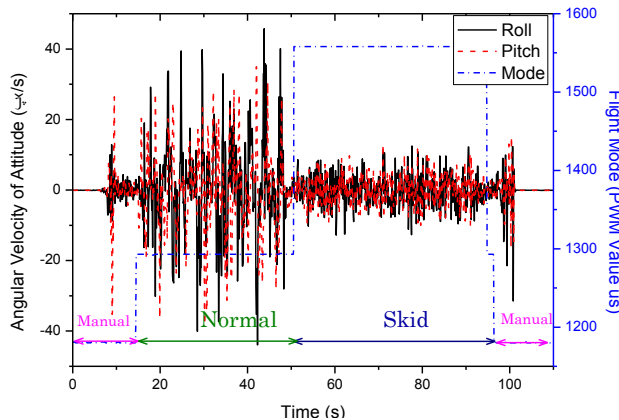


Figure 24 Angular velocity of airframe in test flight 2

B. Test flight 2: Rotary motion

The transition in the slant angle in test flight 2 is shown in **Figure 23** and **24** and **TABLE 9** and **10**. The changes in the roll and pitch of the angles and angular velocity of the airframe attitude over time can be observed in the figures.

The difference between the two flight modes descends obviously: there is a difference of about 390% in the attitude angle and a difference of about 310% in the angular velocity.

TABLE 7 STATISTICAL COMPARISON OF ATTITUDE ANGLE IN TEST FLIGHT 1

	Normal Mode		Skid Mode	
	Roll	Pitch	Roll	Pitch
Mean	-0.20937	-0.2996	0.04181	0.01855
Std. Dev. (Skid/Norm)	1.9569	8.00195	0.71284 (0.364)	2.36941 (0.296)
Min.	-7.5908	-20.16367	-1.94418	-4.5809
Max.	7.28805	17.55057	2.56513	4.56553
Range (Skid/Norm)	14.87885	37.71425	4.50931 (0.303)	9.14642 (0.243)

(unit: °)

TABLE 8 STATISTICAL COMPARISON OF ANGULAR VELOCITY IN TEST FLIGHT 1

	Normal Mode		Skid Mode	
	Roll	Pitch	Roll	Pitch
Mean	0.04122	-0.11521	-0.15245	0.00804
Std. Dev. (Skid/Norm)	7.6325	12.85318	5.19962 (0.697)	4.96681 (0.778)
Min.	-34.9215	-51.3314	-21.446	-17.09382
Max.	31.1147	43.88147	17.91355	18.85111
Range (Skid/Norm)	66.0362	95.21291	39.35955 (0.721)	35.94493 (0.441)

(unit: °/s)

TABLE 9 STATISTICAL COMPARISON OF ATTITUDE ANGLE IN TEST FLIGHT 2

	Normal Mode		Skid Mode	
	Roll	Pitch	Roll	Pitch
Mean	-0.0674	-0.11887	0.04781	0.01936
Std. Dev. (Skid/Norm)	6.24917	5.32648	1.64573 (0.263)	1.39015 (0.261)
Min.	-14.24075	-13.85588	-3.67705	-3.13592
Max.	15.07907	10.82511	3.82034	2.88473
Range (Skid/Norm)	29.31982	24.68099	7.49738 (0.256)	6.02064 (0.244)

(unit: °)

TABLE 10 STATISTICAL COMPARISON OF ANGULAR VELOCITY IN TEST FLIGHT 2

	Normal Mode		Skid Mode	
	Roll	Pitch	Roll	Pitch
Mean	0.12144	-0.32399	-0.1401	-0.01874
Std. Dev. (Skid/Norm)	13.70731	11.72268	4.61474 (0.337)	4.25788 (0.363)
Min.	-43.94588	-38.22176	-12.78751	-10.05117
Max.	45.77925	34.97907	12.48675	12.99748
Range (Skid/Norm)	89.72513	73.20083	25.27426 (0.282)	23.04865 (0.315)

(unit: °/s)

C. Test flight 3: Crosswind testing

The transition in the slant angle in test flight 2 is shown in **Figure 25** and **26** and **TABLES 11** and **12**. The changes in the roll and pitch of the angles and angular velocity of the airframe attitude over time can be observed in the figures.

The effect is visible, though a clear difference as observed in the other flight tests is not observed; there is a difference of about 240% in the attitude angle and a difference of about 130% in the angular velocity.

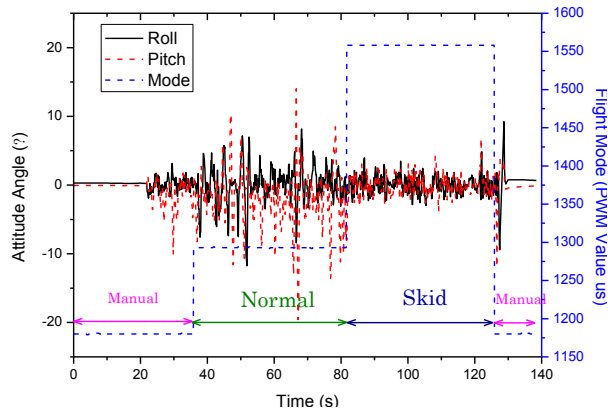


Figure 25 Attitude angle of airframe in test flight 3

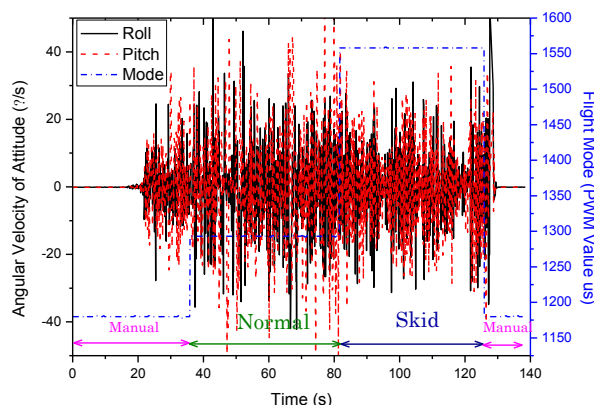


Figure 26 Angular velocity of airframe in test flight 3

TABLE 11 STATISTICAL COMPARISON OF ATTITUDE ANGLE IN TEST FLIGHT 3

	Normal Mode		Skid Mode	
	Roll	Pitch	Roll	Pitch
Mean	0.07788	-1.73365	-0.00397	0.00142
Std. Dev. (Skid/Norm)	2.69584	3.95487	1.22131 (0.453)	1.50552 (0.381)
Min.	-11.7322	-19.60615	-2.96932	-8.04982
Max.	8.16957	14.0026	4.82437	6.83743
Range (Skid/Norm)	19.9017	33.60875	7.79369 (0.392)	14.88725 (0.443)

(unit : °)

TABLE 12 STATISTICAL COMPARISON OF ANGULAR VELOCITY IN TEST FLIGHT 3

	Normal Mode		Skid Mode	
	Roll	Pitch	Roll	Pitch
Mean	-0.75029	0.00422	0.13008	0.09363
Std. Dev. (Skid/Norm)	14.51303	14.51303	11.34671 (0.782)	13.39952 (0.923)
Min.	-42.1775	-54.68509	-31.29351	-35.56933
Max.	56.32798	69.97889	35.50492	40.25344
Range (Skid/Norm)	98.50557	124.66397	66.79843 (0.678)	75.82277 (0.608)

(unit : °/s)

V. CONCLUSION

In this paper, we proposed a tilting rotor for realizing thrust vectoring of a QRH. It was experimentally confirmed that the proposed system could be used to fly the QTRH without inclining the airframe. Under a skid effect, a more steady mechanism was obtained than that that obtained in two previous studies [2], [5]. Moreover, because the mechanism is simpler than the two previously reported methods, there is only a slight increase in the weight when the TMR method is employed. Because a large skid effect is achieved, the practicality of this method, although simple, is high.

Because the thrust loss increases with the increase in the tilt angle, the altitude decreases. Therefore, it is necessary to correct the altitude in the skid mode. This loss can be disregarded, though the counterbalance element is generated to generate thrust in the vector.

In this study, anti-phase vectoring of the TMR control system was employed. In a future work, we will employ in-phase vectoring.

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