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Flight Characteristics of Quad Ducted Fan Helicopter with Thrust Vectoring Nozzles

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***Abstract*—**As an unmanned aerial vehicle (UAV), a quad rotor helicopter (QRH) 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, thrust vectoring nozzles (TVNs) were mounted on a quad ducted fan helicopter (QDH) to maintain a horizontal attitude. The TVNs were tilted to generate thrust against disturbances without inclination of the airframe. The system was constructed using a QDH and TVNs inclined to two axes. Because the airframe is always horizontal, the system can be used for precise measurement e.g. landform and building.

***Keywords*—**UAV, multirotor, quad rotor, helicopter, ducted fan, thrust vectoring nozzle.

I. Introduction

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

In operations utilizing UAVs, it gets more difficult to fly safely as it gets more distant to the ground control. Especially for single rotor helicopters, the risk of colliding with surrounding objects and structures is high because the rotor diameter is larger than the airframe. In the mean time, multirotor-type helicopters using only small diameter rotors have been widely developed for recreational and industrial use that they become attractive. The flight stability and controllability of a multirotor helicopter are better than those of a conventional single rotor helicopter. Most multirotor helicopters nowadays are equipped with various sensors for attitude control. Therefore despite their simple rotor control mechanism, multirotor helicopter stability is better than their single rotor counterpart. The present study started from UAV with a ducted fan [1]. The basic studies were done in [3], and [4].

The purpose of this study was to design a control mechanism that will maintain the horizontal attitude of quad rotor helicopter (QRH) under all circumstances. Previous work [2] that added Extra Thruster for the QRH was done. The process of this paper is reported by [5]. For this purpose, we propose a thrust vectoring mechanism using thrust vectoring nozzles (TVNs) installed in a ducted fan (DF) instead of a conventional rotor. The system comprises a QDH with TVNs, each can be inclined on two axes. Each TVN is controlled by two servo motors, totaling of eight servo motors enabling them to be tilted to generate thrust against cross wind disturbances while maintaining horizontal attitude of the airframe. Because the airframe is always horizontal, the system can be used for aerial photography and precise measurement. The control techniques and the effectiveness of the TVCS were verified by an experimental model. Moreover, the investigative purpose and airframe construction are different from ours though [6] and [8] are presented in the same field as the present study, and a similar component is used as study [6], and [7]. It seems that the purpose of that of [9] is similar with the present study, and the same result can be achieved limitedly. Basic study that used the ducted fan for UAV ware referred to [7] and [8]. Theoretical study of the helicopter with a ducted fan was referred to [6]. The attitude control of QRH was referred to [10]. Reference [11] was referred to for ducted fan's characteristic to the cross wind.

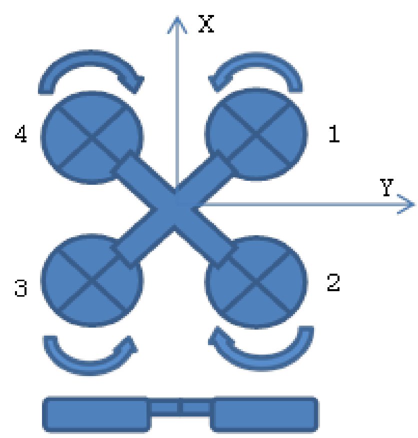

Figure 1 QRH

II. Thrust Vector Control System

The single rotor radio-controlled (R/C) helicopter is a variable pitch type, and the number of joints of rotor heads is minimized. Most types of R/C helicopter use hingeless blades on its rotor. Thus, even if a little movement and crosswind are present, it would be necessary to incline the airframe. A similar situation is applied, even though the multi rotor is a fixation pitch type (see **Figure 1** and **Figure 2**).

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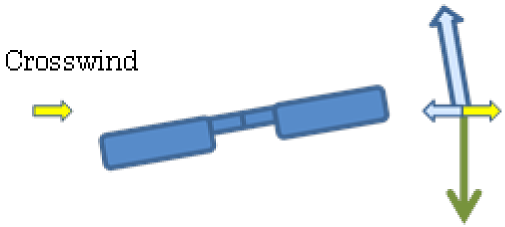

Figure 2 Airframe inclination under crosswind

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 attitude of the camera is maintained by the gimbal device. A similar effect was achieved in this study by installing a TVCS in the multirotor helicopter. QRH generally uses rotors with fixed-pitch blades, and it is not possible to apply TVCS on them. The TVCS was therefore installed in a DF in this study (see **Figure 3** and **Figure 4**).

The thrust of the DF should compensate so that the lift may decrease according to the vectoring angle when TVN is used. The thrust margin of the DF should also increase because it is assumed that the vectoring angle increases in strong-wind outdoor environments. In the practical use of a TVN, the estimate of the thrust margin of the DF is important.

Figure 3 TVCS

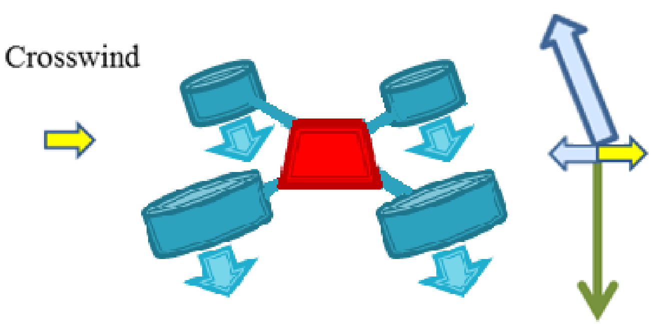

Figure 4 QDH with TVCS under crosswind

A. Quad Ducted Fan Helicopter

Four ducted fans were installed in an X configuration in the QDH. The rotation directions of the DFs were set as such that their anti-torques neutralize each other: Diagonally-opposite DFs rotate in the same direction, and adjacent ones rotate in opposite directions (**Figure 5**). The pitch angles of the impeller and the stationary blade of each DF had opposite directions (**Figure 6**). The stationary blade changes thrust in the direction of the twist into straight advancement. The twist can be increased to compensate any direction error in thrust output.

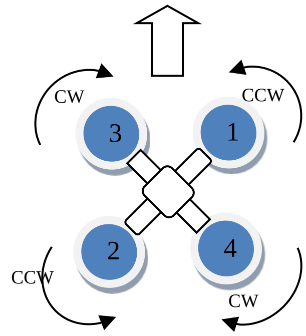

Figure 5 Rotation direction of DF

Figure 6 Impeller and straightening vane of DF

B. Thrust Vectoring Nozzle

Each TVN was driven by two servo motors (**Figure 7**), and all eight servo motors were controlled through two R/C channels. Accurate phase adjustment of the DFs and TVNs was required in the TVCS because a phase error would result in thrust wastage.

Figure 7 TVN

The effects of installing the TVNs include skid and stabilization. The skid effect of the TVN is manifested by the horizontal component of the total thrust, while the vertical component serves as lift. Relation between these components and vectoring angle is expressed in (1) and (2).

$$H = T \cdot \sin\theta \quad (1)$$

$$L = T \cdot \cos\theta \quad (2)$$

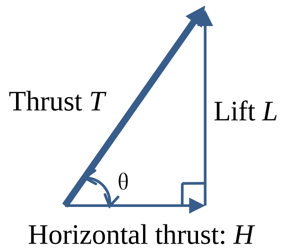

Figure 8 Orthogonal components of total thrust

The horizontal thrust element acts against the crosswind, resulting in stabilization effect, which is also effective against turbulent flow. The same effect as increasing the airframe span is achieved by inclining the thruster as shown in **Figure 4** and **Figure 9**, which increases the robustness against disturbances.

However, installing the TVNs on QRH brings some disadvantages:

- Increase in weight
- More complicated mechanism and control
- High frequency noise produced by the DF.

The most significant disadvantage is the weight increase. In order to reduce overall weight, lightening holes were created and mortise and tenon joints were used on the airframe structure.

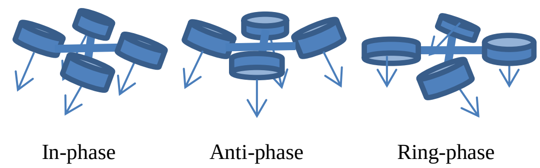

Figure 9 Control Method of TVN

Three TVN methods for controlling the vectoring are as follows (**Figure 9**):

- In-phase method (skid effect)
- Anti-phase method (stabilization effect)
- Ring-phase method (yaw control effect).

In-phase vectoring of the TVN control system was applied in preparing the airframe for test flights in this study. Skidding of the TVNs was enabled by automatic attitude holding control of the QRH. The control system has two modes, namely normal flight mode and skid flight mode, as shown in **Figures 16** and **17**. In the normal flight mode, the thruster is fixed and only the thrust effect is used to generate lift. In the skid flight mode, the operator manually controls the thrust and vectoring of the thruster, whereas the flight controller automatically controls the roll, pitch, and throttle by the attitude stabilizing function (see **Figure 10**).

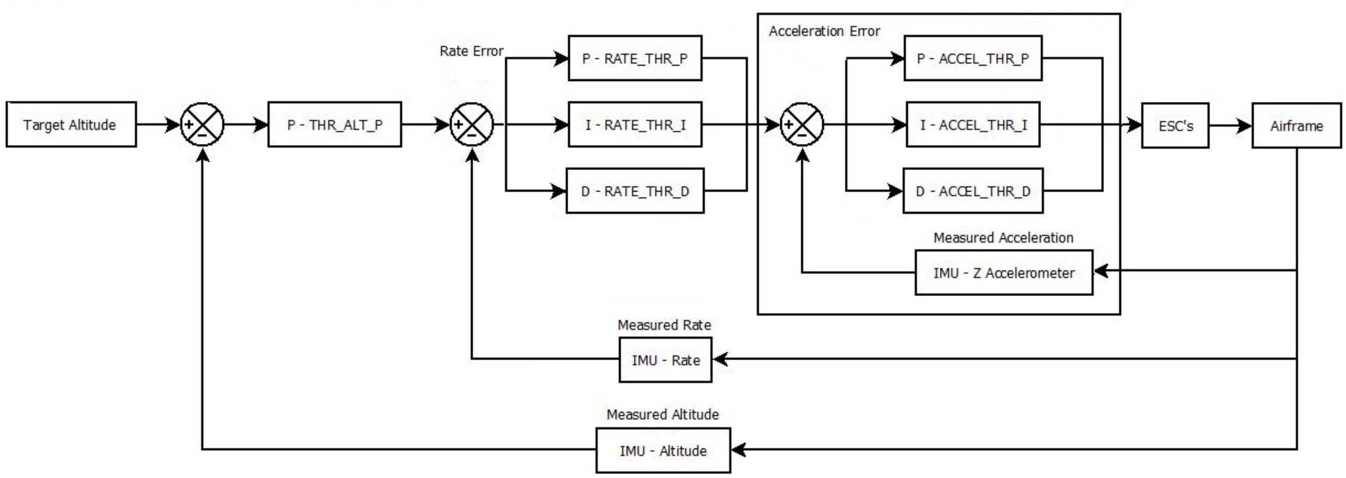

Figure 10 Attitude stabilizing function

III. Experiment

A conventional QRH inclines its attitude to generate a horizontal thrust component in the flying direction. And to maintain flight condition, the attitude control system inclines the airframe against disturbances such as wind. Consequently, the attitude of the flying QRH is always inclined. In this study, TVNs were installed to maintain a horizontal attitude of the QDH. An indoor experiment (Figure 11) was set up to evaluate the performance of our TVNs-equipped QDH against crosswind disturbance.

Figure 11 Scene of experiment

A. Experimental Setup of QDH with TVNs

It is quite dangerous to use a QRH around humans and animals because its rotor is not shielded. Safety can be improved by substituting the rotor with DFs, which also enabled miniaturization in the present study. The four DFs of this experiment were developed for an electric model aircraft. Two were operated with positive rotation and the other two were operated with negative rotation. The outlet of each DF was installed in a TVN, and its thrust inclination was controlled by two servo motors. The x-type frame construction (Figure 12) was chosen to give priority to axial movement performance. Specification of the QDH, DF and TVN is shown in **TABLE I**, **TABLE II**, **TABLE III**, and **Figure 13**. The experimental condition is shown in TABLE IV.

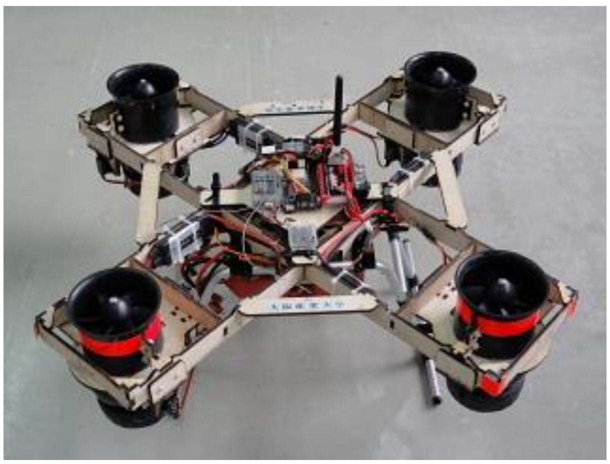

Figure 12 Experimental setup of QDH equipped with TVN

TABLE I Specifications of QDH with TV

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, 3300 mAH)
	For radio Control	LiPo 2 Cell × 1 (20 C, 800 mAH)

TABLE II Specifications of DF

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	DC Brushless 3000 [kV]	
ESC	45 [A]	

TABLE III Dimension of TVN

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

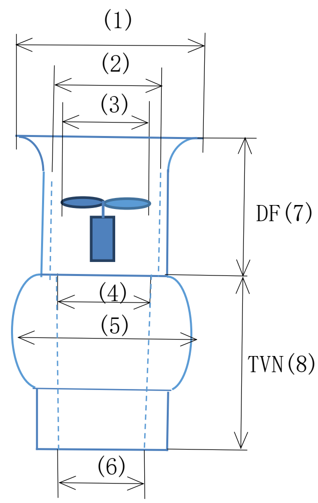

Figure 13 Section of TVCS

TABLE IV Experimental conditions

Environment	Indoor
Area	4 [m] × 8 [m]
Altitude	1.5 [m]
Speed	Constant
Motion	Straight line

B. Flight Controller and Radio Control Unit

The flight controller was ArduPilot Mega 2.5 (APM2.5, 3D Robotics Co.), the architecture of which is publically available. The firmware of APM2.5 is an open software and ArduCopter 3.01 was installed. APM2.5 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 a telemetry device, namely XBee. Recording of the flight log and setting of the control parameters were carried out by installing a mission planner onto the PC, which is an open software for a GUI environment.

The R/C equipment was an eight-channel system (XG8, RG831B, JR Propo Co.), and seven channels were used: for operation (four channels), TVN (two channels), and flight mode (one channel). The structure of each TVN is the same, and the rotation is allocated every 90° (see **Figure 14**). Therefore, a reverse circuit is combined with Y-type harness in the divergence of the control signal because the servo motor allocated in opposition to the TVN becomes the opposite direction (see **TABLE V**). Moreover, the control system was powered by a separate battery owing to the increased power consumption. Conversion from the '+'-type to 'x'-type TVN is done by the program mixing of the RC transmitter (see **TABLE VI**).

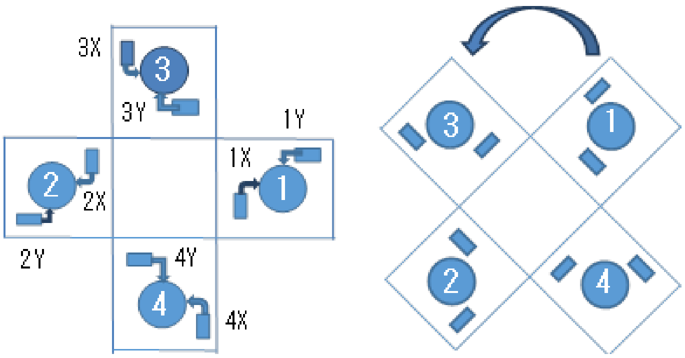

Figure 14 Layout of servo motor for TVN

TABLE V Servo motor name for TVN

(RC Ch.) DF No.	(Aux2) X Axis	(Aux3) Y Axis
1	1X	1Y
2	2X (Reverse)	2Y (Reverse)
3	3X	3Y
4	4X (Reverse)	4Y (Reverse)

TABLE VI Program mixing for RC transmitter

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

C. *Flight Mode*

There are three vectoring control methods for the TVN. In this study, we assumed in-phase vectoring for the TVN control system. The skidding operation by the TVN was enabled by automatic attitude holding control of the QDH. The control system included two flight modes namely normal flight mode and skid flight mode, as presented in **Figure 16** and **Figure 17** and **TABLE VII**. In the normal flight mode, the TVN was fixed and was the same as in a conventional QDH. The takeoff and landing were executed in the normal mode. In the skid flight mode, the operator manually controlled the TVN, and the flight controller automatically controlled the roll, pitch, and throttle using the attitude stabilization function. Loss occurs in the lift because of slanting, even though the airframe moves by slanting TVN in the skid mode. Altitude is measured by the acceleration and atmospheric pressure sensors, and is controlled by double PID feedback to maintain a constant altitude.

TABLE VII Operation in flight mode

Operation Item		Flight Mode	
		Normal	Skid
QDH	Roll	Manual	Automatic
	Pitch	Manual	Automatic
TVN	Forward/Back ward	Automatic	Manual
	Right/Left	Automatic	Manual

D. *Cross-wind Test*

To measure the stability level with respect to the crosswind, a test flight is carried out indoors with a large fan. The velocity of the wind is 3.5 $m.s^{-1}$ at 3 m distance from the fan. The QDH was maintained in hover condition. Attitude change was measured as the flight mode was switched between normal mode and skid flight mode.(see **Figure 15**).

Figure 15 Scene of cross-wind test

E. *Experiment procedure*

The experiment on this study does four test flights shown as follows.

Test flight 1: Example of normally operating

Test flight 2: Example of saturating motor output

Test flight 3: Example of failing yaw control

Test flight 4: Cross-wind testing

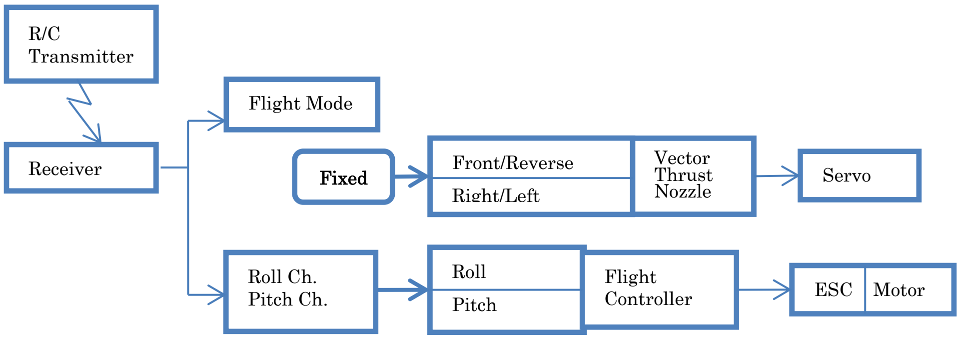

Figure 16 Flow of normal flight mode

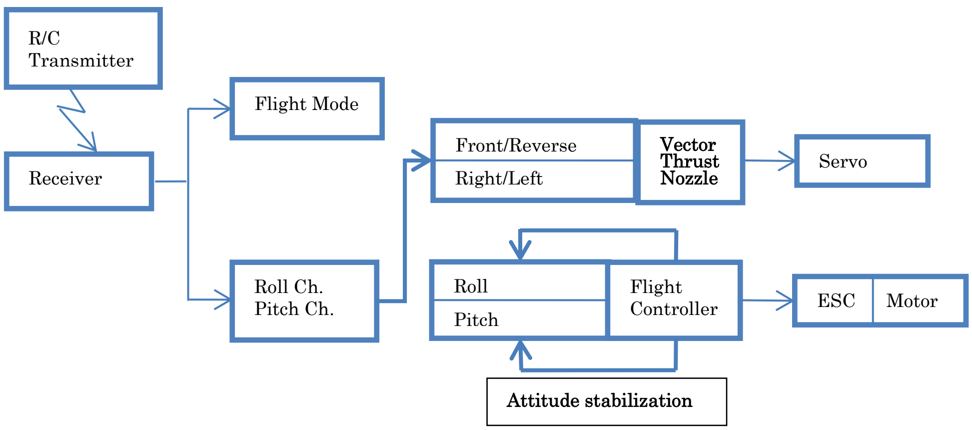

Figure 17 Flow of skid flight mode

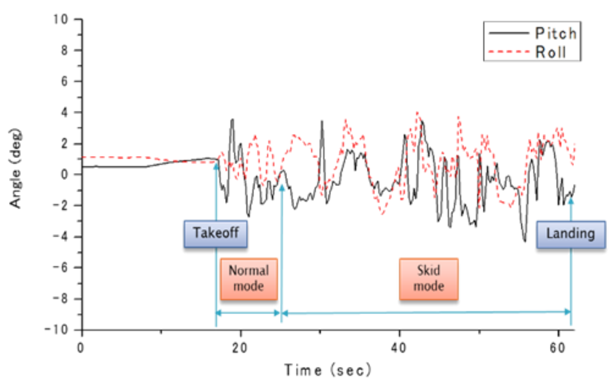

Figure 18 Attitude angle for Test flight 1

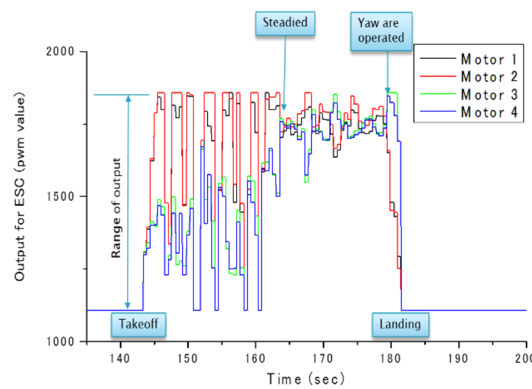

Figure 19 Output to ESCs for Test flight 2

IV. RESULTS

A. Test flight 1

The transition of the slant angle in Test flight 1 is shown in **Figure 18**. The change in of the roll and pitch angles of the airframe over time can be observed in the figure.

In the skid flight mode, the offset is caused by insufficient adjustment of the control parameter. The effect has not become visible though the flight mode is switched in Test flight 1.

The experimental helicopter was relatively heavy, and the situation in which the thrust margin was insufficient was characterized by the following:

- Slow takeoff speed
- Weakness against disturbances such as cross-winds
- Impossible control of the yaw axis motion.

B. Test flight 2

Figure 19 is an example of control of the yaw axis exceeding the limit, because the synchronous error margins between each TVNs are large. The pulse width modulation (PWM) value of output to the electric speed controller (ESC) for motors 1 and 4 are saturated, although the yaw axis motion is controlled for attitude stabilization during takeoff.

Afterwards, the ESC output to each motor became stable at constant value. Moreover, this example shows thrust shortage of the DF, it is not possible to fly the helicopter by operating the yaw controller. Because the output of motors 3 and 4 was saturated by the yaw operation, the control is impossible. The landing was due to the failure to achieve the thrust difference required to operate the yaw controller. This situation will be considered later because it is important.

C. Test flight 3

An example in which the effect of the stabilized attitude by the skid mode becomes very apparent is shown in **Figure 20**. The data shows the transition of the slant angle of the airframe. The operation was in the normal mode during the transition, and the variance in the attitude angle is large. In the skid mode, the variance in the attitude angle is small. The difference between the attitude angles of the normal and skid modes can be observed. Moreover, it is understood that the operation of the yaw controller created instability in the airframe.

The transition of the motor output for test flight 3 is shown in **Figure 21**. It is understood that the motor output should not be saturated when the airframe is steady. Motors 3 and 4 of the motor outputs are saturated by the operation of the yaw controller.

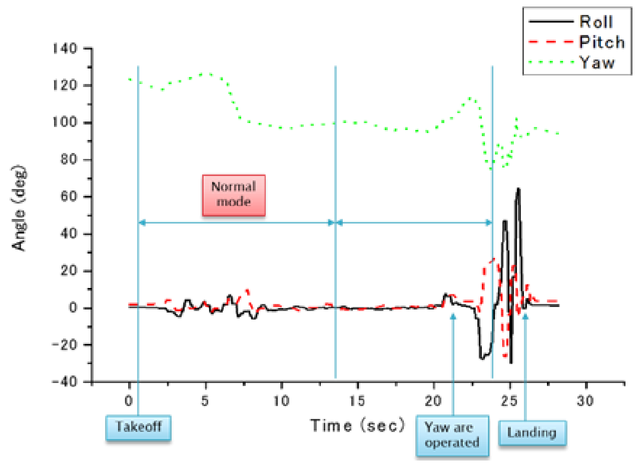

Figure 20 Attitude angle for Test flight 3

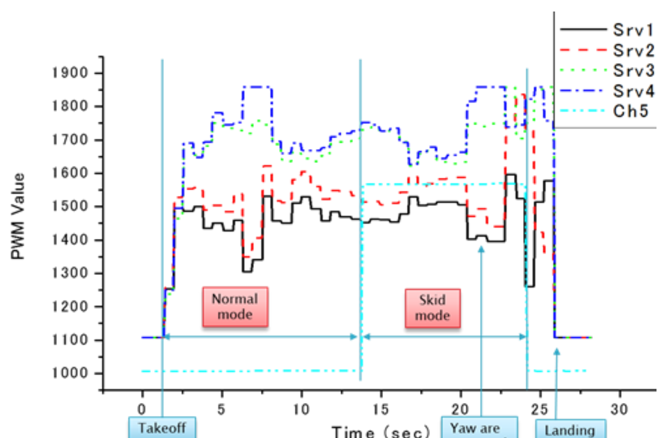

Figure 21 Output to ESCs for Test flight 3

D. Test flight 4

The results of the crosswind test are shown in **Figure 22**. The skid mode is represented by the positive valued curve, and the normal mode is represented by the negative valued curve. It is shown that flight attitude deviation under crosswind disturbance was reduced, both in roll and pitch direction, during skid mode.

During all test flights, power of about 1.5 times are necessary for the weight of the airframe, and, in addition, the thrust 1.5 times is necessary also for the yaw axis control. On the other hand, an anti-torque of DF can be counterbalanced by the normal rotation and the reversal. However, moment of inertia on the yawing axis generated by the attitude of flight depends on weight and an angle acceleration of the impeller. The weight ratio of the impeller of DF and the propeller of QRH is about 1.5 times. It is necessary to consider two elements though these three factors are not simultaneously caused. Therefore, the thrust margin 2.25 times every 1.5 time two power is necessary. The power consumption for hovering is summarized in **TABLE VIII**.

TABLE VIII Power Consumption at the hovering

Current	80 [A]
Voltage of Battery	14.8 [V]
Power consumption	1184 [W]

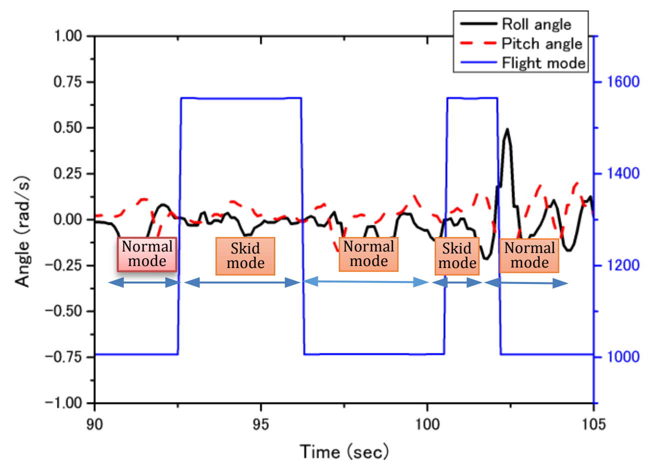

Figure 22 Attitude angle of cross-wind test

V. Conclusion

In this paper, we proposed a TVCS comprising DFs and TVNs for use as the thrust device of a QRH. It was experimentally confirmed that the proposed system could be used to fly the QRH without inclination of the airframe. However, a satisfactory outcome was not obtained because the control parameters were insufficiently adjusted.

The addition of the TVCS made the structure of the air frame more complex, and also increased the control parts and overall weight. The weight of the test helicopter was a major problem and the cause of the crash. However, its flight characteristics such as the skid were efficient and are suitable for aerial photography and precise measurement.

A thrust margin is necessary for the QDH to achieve the flight expectations when the yaw motion is controlled. Because the impellers of the DFs were smaller than that of a normal rotor, significant rotational speed differences, including in opposing directions, are required to generate the necessary moment. The control of the yaw motion is therefore ineffective. A ratio of the maximum thrust to the weight of the helicopter greater than two is necessary to achieve the thrust margin. This value of two was presumed from the power consumption.

A large effect during flight was noted, although a clear difference was not observed in the graph of the cross-wind test. Flying became unstable because the wind contained turbulent flow, even though the airframe was slanted in the normal mode because of the cross-wind. On the other hand, the influence of turbulent flow on the skid mode was minimal.

In this study, the TVN was used in-phase. In a future work, we will apply the anti-phase and the ring-phase. The anti-phase contributes to positional hold, and the ring-phase contributes to the yaw control. As for the airframe in the next generation in the present study, [9] is referred to.

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