Quad Tilt Wing VTOL UAV: Aerodynamic Characteristics and Prototype Flight Test

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A QTW VTOL UAV, featured tandem tilt wings and propellers mounted at the mid-span of each wing, is one of the most promising UAV configurations having both a VTOL capability and high cruise performance. A small prototype QTW UAV has been constructed to prove the concept and full transition between vertical and horizontal flight has been successfully demonstrated under remote manual control. The essential aerodynamic characteristics of the QTW derived from wind tunnel data are summarized in this paper, and a tandem wing concept which achieves both hovering and cruising stability has been applied to design the prototype UAV. A flight control system allowing continuous control through all flight phases enabled a pilot to perform vertical take-off, accelerating transition, cruise, decelerating transition and hover landing, with sufficient flying qualities.

Nomenclature

\[ \begin{align*}
A & = \text{propeller disk area, m}^2 \\
D & = \text{drag} \\
D_p & = \text{propeller diameter, m} \\
C_L & = \text{lift coefficient} \\
C_D & = \text{drag coefficient} \\
C_m & = \text{pitching moment coefficient} \\
C_T & = \text{thrust coefficient based on free-stream velocity and wing area} \\
C_{TS} & = \text{thrust coefficient based on slipstream velocity and propeller disk area} \\
C_{lf} & = \text{lift coefficient (forward wing)} \\
c & = \text{mean chord length, m} \\
J & = \text{propeller advance ratio} \\
L & = \text{lift} \\
M & = \text{pitching moment} \\
n & = \text{propeller rotation speed, RPM} \\
S_{\text{ref}} & = \text{wing planform area (total of the forward and the rear wings), m}^2 \\
S_f & = \text{forward wing planform area, m}^2 \\
T & = \text{thrust} \\
V & = \text{free stream velocity} \\
\Delta L_W & = \text{lift generated by flaperon} \\
\Delta N_W & = \text{yawing moment generated by flaperon} \\
\alpha & = \text{angle of attack (body), deg} \\
\alpha_W & = \text{angle of attack (wing), deg} \\
\tau_W & = \text{tilt angle, deg}
\end{align*} \]

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I. Introduction

Applications of the Unmanned Aerial Vehicle (UAV) are becoming popular based on rapid technological advances and growth in operational experience. Potential civil and commercial UAV applications include scientific research such as meteorology and earth science, environmental observation such as air sampling, vegetation survey, and wildlife tracking, law enforcement, disaster support, and industrial support such as crop dusting, fish finding and power line maintenance. Indeed, several UAVs have already been applied to border patrol, forest fire mapping and so on. It is expected that the application of UAVs will keep expanding and the market will grow dramatically within the decade.

Existing fixed-wing and helicopter UAVs can be applied to meet the demands of these missions, but these have inherent operational disadvantages. Fixed-wing UAVs generally have good cruise performance but require runways or special launch and recovery equipment such as catapult launchers, parachutes or nets. Helicopter UAVs can takeoff and land without runways but have poor cruise and payload carrying performance compared to fixed-wing UAVs. Vertical Takeoff and Landing (VTOL) UAVs are one means to overcome these disadvantages. They can takeoff and land without runways like a helicopter, and cruise at high speed like a fixed-wing vehicle. Of the VTOL configurations, the proposed Quad Tilt Wing (QTW), featuring a tandem tilt wing and four propellers, one mounted at the mid span of each wing, is one of the most promising. Unlike current and previous tilt rotor or twin engine tilt wing vehicles, the quad tilt wing does not require a tail rotor or a main rotor mechanism, and has advantages over them in payload carrying performance and maintenance costs.

With these considerations, the Japan Aerospace Exploration Agency (JAXA) has been developing a QTW VTOL UAV as one of its research programs aimed at extending civil UAV operational capabilities and applications. The aim is to establish a technological basis for QTW VTOL UAV vehicle system design, and the goal of the present research was to construct a small proof-of-concept UAV prototype to demonstrate the full transition capability of the quad tilt wing configuration from hover takeoff through accelerating transition, cruise, and decelerating transition to a hover landing.

A series of wind tunnel tests first investigated the QTW configuration’s essential aerodynamic characteristics, with measurements carried out of power-on high angle of attack (wing alpha from -90 deg to +180 deg) characteristics, thrust of the tandem propeller layout in airplane mode, and wing-propeller downwash using PIV (particle image velocimetry). These tests confirmed the aerodynamic feasibility of the configuration, but suggested a need to improve the tandem wing design for better stability and control, especially in the cruise.

In the present research, an improved tandem wing design was then developed and used in the design of the proof-of-concept vehicle, and a primary flight control system (PFCS) was designed to allow the vehicle to be manually controlled throughout its wide flight envelope. A series of test flights of the prototype successfully demonstrated full transition. Furthermore, wind tunnel tests to analyze the detailed flight characteristics of the prototype and to review the aerodynamic characteristics of the tandem wing design scheme were conducted.

In the next chapter, the QTW concept is introduced and the design of the prototype QTW, called "QUX-02", is described in chapter III. In chapter IV, the principal aerodynamic characteristics of the QTW configuration obtained from wind tunnel tests are summarized. The flight test and its result are described in chapter V, and chapter VI discusses the flight and wind tunnel tests.

![Diagram of Quad Tilt Wing UAV](image)

Figure 1. Quad tilt wing UAV.
II. Quad Tilt Wing Aircraft

The basic configuration and concept of the QTW are presented in Fig. 1. The QTW has a tandem wing configuration with four propellers, one mounted on each of the front and rear wings. Fig. 1b illustrates the QTW flight profile. The vehicle takes off in VTOL mode with the leading edges of its wings directed vertically upwards. The vehicle climbs and then accelerates while rotating its wing gradually towards the horizontal. This flight phase is termed “accelerating transition” and the vehicle’s configuration during transition is said to be in a “conversion mode”. The QTW cruises in “airplane mode” with the main wings fixed horizontally at a downstop. In the “decelerating transition” phase, the wings tilt back to the vertical, and the vehicle finally lands in VTOL mode.

In the hover, the vehicle is controlled in pitch and roll via differential thrust. Yaw is controlled via flaperon surfaces on the front and rear main wings which are immersed in the propeller slipstream. In airplane mode, the vehicle is controlled in pitch via elevators (or flaperon), in roll via flaperon and in yaw via a rudder or differential thrust.

One advantage of the QTW configuration is that the QTW propeller and wing combination does not require main or tail rotor mechanisms, which are heavier and more complex than propellers. Also, a cross shaft mechanism to compensate for asymmetric thrust in a one-engine-inoperative hovering situation could be eliminated by an automatic engine control function that reduces the thrust of the operating engine diagonally opposite the failed one. A tilt wing vehicle generally has higher disc loading and smaller diameter propellers than a tilt rotor vehicle, and therefore generates higher downwash and noise while hovering but has better cruise performance. A tilt wing configuration allows various design options for the wing planform for cruise efficiency, whereas tilt rotor vehicles generally have the rotors mounted at the wing tips, forcing a shorter wing span.

III. Prototype QTW UAV for Proof-Of-Concept

The main goal of the prototype QTW-UAV, called QUX-02, was to demonstrate full transition through all the phases of the conceptual flight profile in Fig. 1b, including vertical takeoff and landing, transition, and cruise flight. Further aims were to study the vehicle’s aerodynamic characteristics and flight control system design. To this end, a QTW driven by electric motors weighing 3-4 kg was designed taking advantage of current Radio Control (RC) technologies. The tandem wing design was based on the findings of preliminary research on the QTW configuration, and a Primary Flight Control System (PFCS) was developed to allow manual flight control over the entire flight envelope.

A. Tandem Wing Configuration Design

A tandem wing layout that achieves good longitudinal stability and control characteristics in both VTOL and airplane modes is one of the most important design issues for a QTW configuration. Previous research suggested that a tandem wing configuration with identical front and rear wings has reduced payload capability because of negative static stability at the desired center of gravity (CG) position in airplane mode. In VTOL mode, lift is generated by propeller thrust and pitching motion is controlled using thrust differential between the front and rear propellers. To obtain optimum maneuvering and payload lift capability in the hover, the CG should be located at around the midpoint between the front and rear propellers with the wings in the vertical position (tw=90deg). In airplane mode, a tandem wing configuration layout including wing planform sizing, location etc. that achieves aerodynamic static stability is required.

For the QUX-02 wing design, the scheme illustrated in Fig. 2 was applied to satisfy both the VTOL and airplane mode requirements. Once wing loading is determined, the static margin in airplane mode at the reference CG is calculated by varying the fore-and-aft distance between the front and rear wings and by varying front and rear wing area ratio. The contribution of the rear wing to stability is estimated assuming the forward wing's downwash at the rear wing position. Fig. 3 shows a three views diagram of the QUX-02 tandem wing layout design generated by this process. The fore-and-aft distance and wing area ratio between the front and rear wings was determined to obtain a positive static margin for manual flight control in airplane mode. Horizontal tail and elevator surfaces were then appended to secure otherwise unproven static stability and pitch control capabilities in airplane mode for flight tests.

![Figure 2. Tandem wing configuration design procedure.](image-url)
B. QUX-02 Specification  
Based on the tandem wing configuration design, a prototype vehicle was constructed taking advantage of current RC technologies. Table 1 summarizes specification of the QUX-02 and Fig. 4 illustrates its system architecture. A fuselage, main wing tilt units and an on-board thrust mixing computer were specially built. The fuselage was made mainly from balsa wood. The semi-span wings were connected by tilt shafts passing through the fuselage. Tilt units on the main wings driven by RC servo motors allowed the tilt angle to be varied between zero and 90 degrees. The vehicle was powered by four electric motors driving fixed-pitch propellers. Actuators were provided for power control, the flaperon, elevator, rudder control surfaces, wing tilt angle, and nose wheel steering. A thrust mixing computer was developed to generate power command outputs to each motor by mixing average power and differential pitch and roll power-command inputs from the pilot through a radio remote control system. Pitch and roll rate gyros were added to augment stability when using differential power control.

C. Primary Flight Control System  
Fig. 5 depicts the flight control system of the QUX-02. As described in chapter II, the attitude control method need to be changed according to whether the vehicle is in VTOL mode, conversion mode or airplane mode. Since this would be extremely difficult for a pilot, a PFCS was designed to enable manual control. The PFCS, installed in the radio control system, automatically changes the transfer function from pilot command input to surface deflection output according to the wing tilt angle.

Fig. 6 shows the logic of the longitudinal PFCS. In VTOL mode, the wings are at 90 degrees tilt and pitch attitude can be controlled only by the difference between front and rear thrust, so the pilot's pitch command is purely
linked to differential thrust control. In conversion mode, the control gains from the pitch command to thrust differential and aerodynamic surface deflections are gradually varied by the PFCS according to tilt angle. The aerodynamic lift and control power on the flaperon and elevator are scheduled by airspeed, and as forward speed increases, the tilt angle is reduced and the longitudinal PFCS increases the control gains for the aerodynamic surfaces and decreases the gain for differential thrust. In airplane mode, the tilt angle is zero and pitch attitude is controlled purely by the elevators and flaperons, so the pilot's pitch command is linked only to the aerodynamic surfaces. In addition to these logics, stability augmentation in pitch and roll using commercial rate gyros is added to thrust differential control, especially at higher tilt angles.

As shown in Fig. 5, the pilot controls the vehicle through a RC system controller. The flap angle (which is equivalent to setting the neutral position of the flaperons) and the wing tilt angle are changed using multipurpose switches, while pitch, roll, yaw and average power control commands are input using joysticks.

IV. Aerodynamic Characteristics of the Quad Tilt Wing Configuration

This chapter describes some of the intrinsic aerodynamic characteristics of the QTW configuration based on the aerodynamic data obtained from a series of wind tunnel tests. Characteristics investigated were yaw control power during hover, power-augmented lift characteristics during transition, effects of the tandem propeller layout on thrust characteristics, and longitudinal characteristics in airplane mode.

A. Wind Tunnel Tests

A series of wind tunnel tests was performed to investigate the fundamental aerodynamic characteristics of the QTW configuration and to validate the improved tandem wing layout design. The tests were carried out in JAXA’s 2 m x 2 m low-speed wind tunnel, a closed-circuit tunnel with a 2 m x 2 m cross-section and 4 m-long test section. The components of the QUX-02 vehicle itself were used as the test model except for the fuselage. The test model fuselage was of the same size and shape as the QUX-02’s balsa wood fuselage but was made from steel to allow it to withstand high speed and high angle of attack flight beyond the flight envelope of the actual vehicle. Alpha and beta sweep tests were carried out for each flight mode, motor RPM setting and flap angle. Tilt angle (wing angle of attack) sweep tests were also carried out on the forward and rear wings in isolation to obtain data for each of these components.

For the results presented below, the reference point of the aircraft was set at the reference CG position shown in Fig. 3, and no wall correction was applied to the wind tunnel output.

B. Aerodynamic Characteristics of the QTW Configuration

1. Yaw Control in VTOL mode

During hover, the QTW uses flaperons immersed in the propeller slipstream and these allow the aircraft to be controlled without a tail rotor or a rotor mechanism. Fig. 8a shows the control power generated by a flaperon on a semi-span of the forward wing in zero-wind conditions. The data show that an axial force in the forward direction is generated in proportion to flaperon deflection and propeller thrust. This is the same as the propeller slipstream effect described in Ref. 8. The flaperon can provide sufficient yaw control power and axial (fore and aft) forces during hover.
2. Power Augmented Lift in Conversion Mode

Fig. 8b shows the lift curve of the front wing. The lift coefficients plotted in the figures include both aerodynamic wing lift and lift generated by propeller thrust. The QTW configuration takes advantage of the power-augmented lift characteristics of the propeller-wing combination due to the propeller slipstream which always flows over part of the wing surfaces. In Fig. 8b, no sharp edged stall is observed in power-on conditions, unlike a conventional fixed wing vehicle (fixed wing condition without propeller in Fig. 8b).

3. Tandem Wing and Propeller Layout in Airplane Mode

In airplane mode, the rear propellers lie in the wake of the front wing and front propellers. Investigation of the effects of the wake on the rear propellers and wings was one of the main objectives of the wind tunnel tests. Axial (fore-and-aft) forces in a no power configuration, a front propellers only powered configuration and an all propellers powered configuration were measured and the thrust generated in each powered condition was estimated by subtracting the force (drag) of the no-power configuration. Fig. 8c suggests that the all propellers powered configuration generates almost twice the thrust of the front propellers only powered configuration when each powered propeller turns at the same RPM, and no significant adverse effects such as vibration or excessive thrust loss were observed. Fig. 8c also suggests that the rear propellers generate less thrust than the front propellers. Since the RPM of each propeller was the same, it is considered that the inflow at the rear propellers was higher than the general flow because it was accelerated by the front propellers.

4. Lift, Drag and Pitching Moment Characteristics in Airplane Mode

Fig. 8d shows the longitudinal aerodynamic coefficient in airplane mode. The overall lift and drag characteristics are almost same as those of a conventional airplane. There is no significant difference in the lift curve between power-on and power-off cases except for the stall angle of attack. It is also found that the QUX-02 has static stability ($C_{m_{\alpha}}<0$) in the cruise angle of attack region. The curves for configurations with and without a horizontal tail suggested that the horizontal tail was not essential to ensure static stability and could be deleted.
Positive static stability was achieved by the tandem wing design method described in chapter III. However, the static margin at the reference CG was about 74.7% and it is significantly higher than we had intended or expected. This point will be discussed in chapter VI in conjunction with the result of the flight test.

V. Flight Test for Proof Of Concept

A. Flight Test Summary

A series of the flight tests were performed using the QUX-02. The goals of the flight test in this phase were to demonstrate the full transition concept of the QTW configuration and to evaluate the basic flying qualities of the QUX-02 configuration based on pilot comments. A pilot who had a lot of experiences and excellent skills in model helicopter control was involved in the tests. Pilot comments and ratings on the flying quality in each flight mode (tilt angle) and the video images were recorded. No data recording device were on board due to the limitation of system complexity at the time flight tests were planed and performed. Each test was performed under calm wind speed from 0 to 5 m/sec and enough visibility (5 km or more) condition.

During the tests step-by-step approach extending flight envelope was taken. Before conducting full transition flight, flight test runs of each preset tilt angle were performed. In those runs, tilt angle was fixed at 0, 15, 25 ..., 70 or 90 degrees through entire flight from takeoff to landing. Hovering test in VTOL mode(\(\theta_w=90\text{deg}\)) was firstly conducted. Then the airplane mode test was performed which begun from takeoff ground run and end with full-stop landing after flying the traffic pattern. Test runs were proceeded in both ways from \(\theta_w=0\text{deg}\) to increased tilt angle and from 90 deg to decreased tilt angle. In the course of these test process

Table 1. Flight test record.

<table>
<thead>
<tr>
<th>Flight Mode</th>
<th>(\theta_w) (deg)</th>
<th>First Flight</th>
<th>Total FLT Hours(mm:ss)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VTOL</td>
<td>90</td>
<td>June 30, 2008</td>
<td>02:57</td>
</tr>
<tr>
<td>Conversion</td>
<td>70/50/40</td>
<td>July 16, 2008</td>
<td>15:43</td>
</tr>
<tr>
<td>Conversion</td>
<td>30/25/15</td>
<td>July 30, 2008</td>
<td>14:48</td>
</tr>
<tr>
<td>Airplane</td>
<td>0</td>
<td>July 15, 2008</td>
<td>09:55 (including taxi test)</td>
</tr>
<tr>
<td>Full Conversion</td>
<td>90-0-90</td>
<td>July 30, 2008</td>
<td>15:49</td>
</tr>
</tbody>
</table>

Total: 59:12

Figure 9. Snapshots of the flight test.

a) Takeoff hover.  
b) Accelerating transition.  
c) Cruise.  
d) Decelerating transition.
detailed gains of the PFCS were adjusted based on the pilot comments. After all the configuration were accomplished, full transition flight tests comprising vertical takeoff, accelerating transition, cruise, decelerating transition, approach and vertical landing, were performed.

B. Flight Test Results

Table 1 summarizes the result of these flight tests. After 43 minutes of flight test runs, the first full transition flight was accomplished on July 30, 2008. Fig. 9 shows snapshots of a full transition flight. After taking off with the wings at 90 degrees (VTOL mode), the pilot changed the tilt angle gradually through the preset tilt angle switch of the radio controller. The aircraft accelerated and climbed in accordance with the decrease of tilt angle from 90 to 0 degree (conversion mode). When the tilt angle reached 0 degrees (airplane mode), stabilized straight and level flight was performed with acceptable flying qualities. While changing the tilt angle back to VTOL mode, deceleration and approach descent were conducted at tilt angles mainly between 30 to 50 degrees, final approach was flown at 70 degrees tilt and the vehicle then landed vertically with the wings at 90 degrees (VTOL mode).

Table 2 contains a summary of pilot comments and ratings for each transition flight mode. These suggested that full transition was attainable with satisfactory flying qualities using all the preset tilt angles.

VI. Discussion

A. Full Transition Capability

This section discusses the flight characteristics of the QUX-02 prototype in each flight mode and over the entire flight profile based on the pilot comments and the wind tunnel test results.

In VTOL mode, pilot comments suggest that QUX-02 has adequate stability and control characteristics for
hovering. Sufficient yaw control power is provided through the flaperons immersed in the propeller slipstream as shown in Fig. 8a of chapter IV. Also, sufficient pitch and roll control are provided by thrust differential between the front and rear propellers. When there is a wind, the pilot commented that a certain amount of pitch down into the wind is required with $\theta_w=90\text{deg}$ selected, and hovering at a tilt angle of 80 or 70 degrees was considered to be a reasonable option for windy conditions.

During conversion at tilt angles from 70 to 40 degrees, the pilot commented he could recognize aerodynamic forces operating on the wings at below 70 degrees tilt. The vehicle was stable and controllable by applying a technique similar to that for controlling helicopters, and pitch stability augmentation applied from 90 to 40 degrees tilt was effective for reducing control workload. For conversion at tilt angles from 30 to 10 degrees, the pilot reported that he controlled the aircraft using a fixed-wing technique and that it had sufficient stability and control characteristics.

For accelerating transition to airplane mode, the pilot reported that did not need to pay much attention to speed or flight path control; he simply decreased the tilt angle using the preset switch, and the vehicle automatically climbed away and accelerated. The pilot maintained average thrust and just made adjustments to pitch attitude. On the other hand, the decelerating and approach transition phase required increased workload; increasing the tilt angle while keeping the thrust constant sometimes produced a positive climb, and the pilot needed to reduce thrust while holding pitch attitude to maintain the airspeed. As shown Fig. 8b, the wing lift characteristics and maximum angle of attack of the QTW greatly change according to the thrust level. In the decelerating condition there is less thrust and a lower safety margin than in the accelerating condition where a higher thrust is maintained.

The current QUX-02 system has no means to display flight parameters such as airspeed, attitude or flight path, and the pilot could comprehend the vehicle’s state only through its motion and responses to his control inputs. Based on further analysis of the QUX-02 flight envelope, a flight profile and tilt schedule with a reasonable safety margin need to be established. Also, a sensor system and instrumentation to enable a pilot or automatic flight control system to control the aircraft within a safe flight envelope needs to be developed.

In airplane mode, the pilot commented that the QUX-02 has sufficient stability and maneuverability similar to that of a conventional fixed-wing aircraft. No stability augmentation system was used in this mode; the aircraft had adequate natural static stability and the flaperons provided adequate control power.

Pilot comments regarding overall full transition flight suggest that QUX-02 has a smooth transition response during tilt angle change and is controllable using normal control skills. The PFCS enabled the pilot to control the vehicle through all the flight modes with sufficient flying qualities.

B. Tandem Wing Layout Design

The static margin of the QUX-02 estimated from wind tunnel data was 74.6%. This is much greater than the design requirement we applied in the tandem wing design scheme. Analytical review of the contributions of the forward and rear wings on the static margin suggests that this discrepancy was mainly due to a large difference between the estimated downwash and actual downwash at the rear wing position. When applying the tandem wing design scheme on the QUX-02, the estimated downwash derived from a previous wind tunnel model was used. This model used identical rear and front wings, and had longer engine nacelles to be used as landing gear in VTOL mode that extended close to the leading edge of the rear wing in airplane mode. The wake at the rear wing position in airplane mode is considered to be affected by the relative size of the front and the rear wings and their separation. The tandem wing design scheme therefore needs to be improved to account for the wake at the rear wing position more accurately.

The static margin of the QUX-02 was far greater than that of typical fixed-wing aircraft. A lack of maneuverability might therefore be expected, but there were no comments from the pilot suggesting that this was the case. QUX-02's longitudinal control in airplane mode uses both elevators and the flaperons on the forward wing. Since the flaperons were almost full span, they provided a greater moment than the ailerons of a conventional fixed wing aircraft and gave enough control power for maneuvering.

C. Configuration Layout for Cruise Efficiency

Fig. 8d suggests that the lift-drag ratio of the QUX-02 is extremely low. Since the QUX-02 was constructed without considering cruise efficiency, there was no streamlining of the fuselage, fillet or engine nacelle, and cables and structural parts were exposed. These would significantly reduce the lift-drag ratio. This kind of construction was applied because this research is only focused on proof-of-concept. A configuration design for cruise efficiency should be incorporated to the experimental aircraft design in the next phase.
VII. Concluding Remarks

The concept of a quad tilt wing UAV, which takes off and lands vertically and cruises similarly to a fixed-wing airplane, has been proved by flight tests using a small proof-of-concept model. The aerodynamic characteristics of the QTW configuration that enable it to fly over a wide flight envelope were confirmed from wind tunnel data. Based on this information, a proof-of-concept vehicle was constructed using a tandem wing designed for both hovering and cruising stability. A primary flight control system for continuous control through all flight modes was also designed and implemented. These enabled a pilot to accomplish full transition flight by visual remote control. During full transition flight, vertical takeoff, accelerating transition, cruise, decelerating transition and hover landing were all accomplished with sufficient flying qualities.

We will progress this research to further improve the performance and operational capabilities of the QTW UAV. An automatic flight control system will be designed using a mathematical model of the QUX-02 and will be implemented as the outer loop of the PFCS. The tandem wing design scheme will be improved by further experiments and analysis of the QUX-02. Also, preliminary design work on a follow-on experimental UAV will be started applying the further improved tandem wing design process and a more cruise efficient design.

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