TRANSITION FLIGHT OF QUAD TILT WING VTOL UAV

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Abstract

The QTW VTOL UAV, which features tandem tilt wings with propellers mounted at the mid-span of each wing, is one of the most promising UAV configurations, having both VTOL capability and high cruise performance. A six-degree-of-freedom dynamic simulation model covering the full range of the QTW flight envelope was developed and a flight control system including a transition schedule and a stability and control augmentation system (SCAS) was designed. The flight control system was installed in a small prototype QTW and a full transition flight test including vertical take-off, accelerating transition, cruise, decelerating transition and hover landing was successfully accomplished.

1 Introduction

The Japan Aerospace Exploration Agency (JAXA) has been developing Quad Tilt Wing (QTW) VTOL UAV technology as one of its research programs aimed at developing an advanced vehicle configuration to extend civil UAV operational capabilities and applications[2)]. The proposed QTW features a tandem tilt wing and four propellers, each one mounted at the mid span of a wing. The QTW is one of the most promising UAV configurations as it can overcome the inherent operational disadvantages of fixed-wing and helicopter UAVs: it can take off and land without runways like a helicopter, and cruises at high speed like a fixed-wing vehicle. The research aims to establish a technical foundation for QTW VTOL UAV vehicle system design including tandem wing layout, flight operations, and flight control systems.

In our previous research, a tandem tilt wing design procedure that achieved good stability and control characteristics in both VTOL and airplane modes was created and used to construct a small prototype QTW UAV (QUX-02). A flight test demonstrated full transition between vertical and horizontal flight under remote manual control, but flight data were not obtained because the effort was concentrated on proving the concept and on validating the proposed layout design procedure.

To further progress the research on QTW vehicle design technologies, one of the most important issues is accurate prediction and analysis of flight characteristics. Therefore, the goals of the present research are to develop a flight simulation model and to design a flight control system which enables safer full transition with a Stability and Control Augmentation System (SCAS).

Using data obtained through wind tunnel tests performed after the previous flight test, a flight simulation model which covers the whole flight envelope was constructed. Based on this model, the vehicle's transition flight characteristics were analyzed in detail and an auto-flight system was designed. An updated wing tilt angle schedule and new attitude hold controllers were installed in a newly added on-board computer, and a full transition flight test was carried out to evaluate the validity of the flight control system designed using the simulation model.

In the next section, the QTW concept and the prototype QTW, called "QUX-02A", is introduced and the QTW dynamic characteristics modeling is described in section 3. The design of the flight control system comprising transition schedule, Primary Flight Control System (PFCS) and SCAS controller is summarized in section 4. The flight test and its results and discussions are presented in sections 5 and 6.

2 Prototype QTW UAV for Proof-of-Concept

2.1 QTW Aircraft

The basic configuration and concept of the QTW are presented in Fig. 1. The vehicle takes off in VTOL mode with the leading edges of its wings directed vertically upwards. It initially climbs vertically and then accelerates while rotating its wing gradually towards the horizontal. This flight phase is termed "accelerating transition" and during transition the vehicle's configuration 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 wings which are immersed in the propeller slipstream. In airplane mode, the vehicle is controlled in pitch via elevators (or flaperons), in roll via flaperons, and in yaw via a rudder or differential thrust.

One advantage of the QTW configuration is that the propeller-and-wing combination does not require main or tail rotor mechanisms, which are heavier and more complex than simple propellers. Also, while a twin engine tilt rotor vehicle requires a cross shaft to avoid asymmetric thrust in a one-engine-inoperative hovering situation, this may be eliminated in a QTW 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 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.

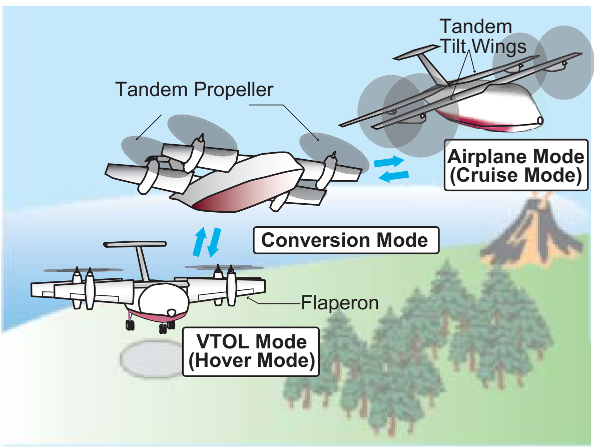

Fig. 1. Quad Tilt Wing UAV.

2.2 The QTW-UAV Prototype (QUX-02A)

Fig. 2 and Table 1 summarize the specifications of the small prototype[2]. The main goal of the prototype QTW-UAV was to demonstrate full transition capability including vertical takeoff and landing, transition, and cruise flight. Further aims were to study the vehicle's aerodynamic characteristics and to establish a flight control system design methodology. To this end, a QTW driven by electric motors was designed taking advantage of off-the-shelf Radio Control (RC) systems, and no aerodynamic design features for cruise efficiency such as streamlining of the fuselage, fillet or engine nacelle, were applied.

The present research added on-board data acquisition and auto-flight computer and sensors to the QTW-UAV prototype to obtain quantitative flight data and to realize auto-flight system functions. The full capability of the on-board computer developed by JAXA for small UAS research purposes was used, which features 16 input and 24 output PWM channels and a flexible programming capability[2]. The resulting QUX-02A vehicle has a gross weight of about 4,200 grams and thrust-to-weight ratio of approximately 1.2:1.

Fig.2. Small Prototype QTW QUX-02A

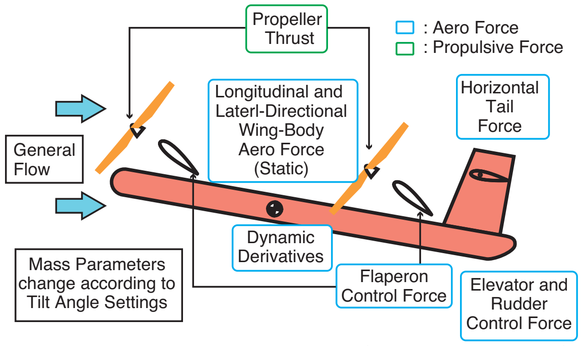

Fig. 3. Aerodynamic and Propulsive Force Model Architecture

Table 1. QUX-02A Specifications

L x W x H	1,100 x 1,381 x 435 mm
Gross Weight	4,200g
Wing Area	Sref = 0.294 m^2
Chord	c=0.132 m
Propellers	12 inch x 5.5 pitch
Electric Motor	4 x AXi 2814/20 Goldline (277Wmax)
On-board Computer ("AP03M")	PFCS, SAS(power & flaperon axes*) SCAS*,Data Recording* 16input/24output PWM channels
Sensors	GPS/INS*, RPM*, airdata*, RC-gyros

*Note: Newly equipped in the present research.

3 Vehicle Dynamics Modeling for Full-Fight Simulation

A six-degree-of-freedom nonlinear flight simulation model was constructed using QTW-UAV wind tunnel test data. The model was intended to be used both for analysis of flight characteristics such as trim, transition scheduling, stability and controllability, and for pilot-in-the-loop real time simulation.

The model developed in this research comprises an analytic aerodynamics model, a mass properties model, a propulsion system model, a flight control system model, an equations of motion model, an atmospheric model, winds and turbulence models, and a ground contact model. The analytic aerodynamics model and mass properties model incorporated the QTW's powered-lift and configuration features which are summarized below.

(1) The propeller-wing combination provides both the forward and rear wings with power-augment high-lift characteristics. There is a certain amount of flow interference between the wings. The aerodynamic coefficients change according to wing tilt angles, body angle of attack and flap angles as well as engine thrust.

(2) The wings are immersed in the propeller slipstream and so generate lift even while hovering in zero wind. Flaperons can therefore generate yaw control and axial (forward and aft) forces during hover.

(3) The mass parameters including center of gravity, inertial moment and inertial product vary with wing tilt angle.

Fig. 3 shows the architectures of the aerodynamic and propulsive models constructed using wind tunnel test data. Total aerodynamic forces and moments are calculated by summing the basic wing-body component, control surface component, dynamic component excited by aircraft rotational motion and tail wing component. Table 2 provides summary descriptions of each aerodynamic component. The wing-body component involves aerodynamic interference between front and rear wings, and longitudinal aerodynamic coefficients are assumed to depend on body angle-of-attack, wing tilt angle, the average angle of the left and right flaps on the front wing, and the average thrust of the four propellers. A set of data tables obtained from the wind tunnel tests was used for the basic longitudinal and lateral wing-body models. Fig. 4 illustrates an example of the lift coefficient of the wing-body model at tilt angle, τ_W=30 deg. The model of the control forces and moments generated by each flaperon are based on wind tunnel tests of a propeller-and-wing unit (e.g. a front wings-only configuration). The models include power-augment lift features in which coefficients depend on wing angle-of-

Table 2. Descriptions of Aerodynamic force component

(a) Longitudinal Aerodynamic Model

Force & Moment Components	Coefficients	Attributes	Data Source
Wing-Body (w/o horizontal tail)	C_{LB}, C_{DB}, C_{mB}	$\alpha_B, \tau_W, C_{Tave}, \delta_{Ff}$	Wind Tunnel
Control Surface (unit wing-propeller)	$\Delta C_{L\delta f}, \Delta C_{D\delta f}, \Delta C_{m\delta f}$	$\alpha_W, C_T, \Delta\delta_F$	Wind Tunnel
Dynamic	$\Delta C_{Ldyn}, \Delta C_{Ddyn}, \Delta C_{mdyn}$	$\alpha_B, \tau_W, C_{Tave}, \delta_F$, q, $\dot{\alpha}_B$	Estimated
Horizontal Tail	$\Delta C_{LHT}, \Delta C_{DHT}, \Delta C_{mHT}$	$\alpha_B, \tau_W, \delta_e$	Wind Tunnel

(b) Lateral Aerodynamic Model

Force & Moment Components	Coefficients	Attributes	Data Source
Wing-Body (with vertical tail)	C_{YB}, C_{lB}, C_{nB}	$\alpha_B, \beta_B, \tau_W, C_{Tave}, \delta_{Ff}, \delta_r$	Wind Tunnel
Control Surface (unit wing-propeller)	$\Delta C_{Y\delta f}, \Delta C_{l\delta f}, \Delta C_{n\delta f}$	$\alpha_W, C_T, \Delta\delta_F$	Wind Tunnel
Dynamic	$\Delta C_{Ydyn}, \Delta C_{ldyn}, \Delta C_{ndyn}$	$\alpha_B, \tau_W, C_{Tave}, \delta_F$, p, r	Estimated
Vertical Tail	Included in Wing-Body Model		

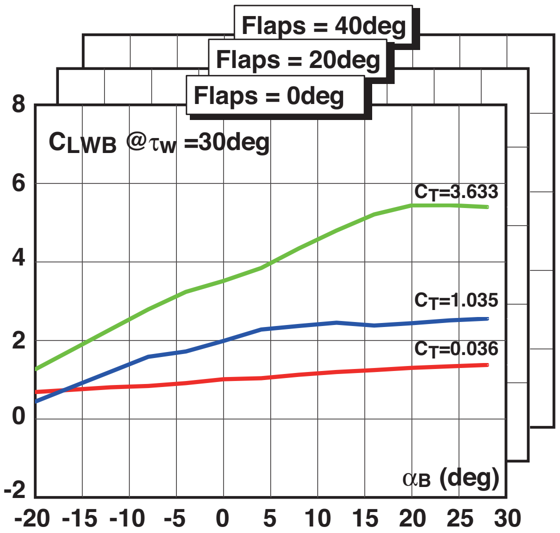

Fig. 4. Wing-body C_{LB} model at τ_W=30deg.

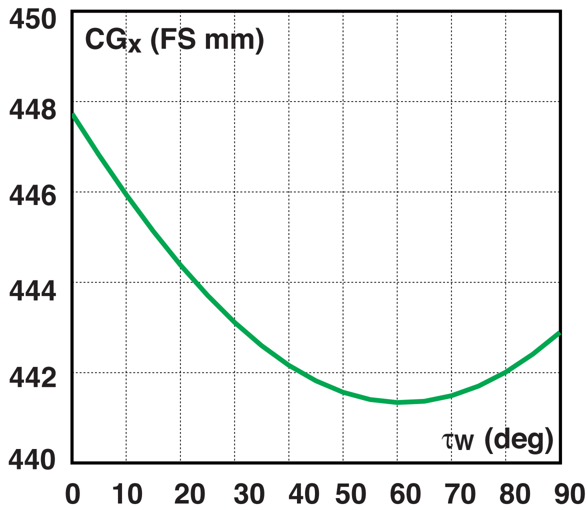

Fig. 5. CG_x Mass Property Model

attack and engine thrust. It is assumed that left and right flaperon deflections for roll control induce no significant local flow changes between the front and rear wings. For the aerodynamic control surfaces, only deflection of the front flaperons from neutral for longitudinal control is considered to affect the interference between the wings and is included in the wing-body model. Dynamic derivatives are estimated based on analysis of (static) wind tunnel data and aircraft geometry. The aerodynamic force of the horizontal tail is separately calculated by assuming a downwash angle which depends on the wing tilt angle.

Mass properties model comprise CG_x, CG_z, I_{xx}, I_{yy}, I_{zz}, and I_{xz} models. These properties vary with wing tilt angle. Fig. 5 shows the CG_x model as an example of the mass property model.

4 Design of the Flight Control System for Transition Flight

The flight characteristics of a VTOL aircraft, such as trim conditions and stability, vary greatly over the wide flight envelope range[3]. The design of the flight control system and transition schedule are therefore key to achieving safe flight and good handling qualities. This section summarizes the design of the QTW's flight control system.

Fig. 6 depicts the overall flight control system designed for the QUX-02 comprising PFCS, transition schedule, SAS, SCAS, and actuators.

The flight control system has two modes: manual mode and SCAS mode. In both modes, control sticks on the RC system controller are

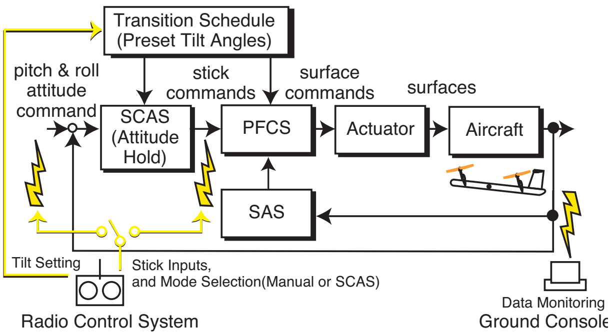

Fig. 6. Flight Control System Architecture

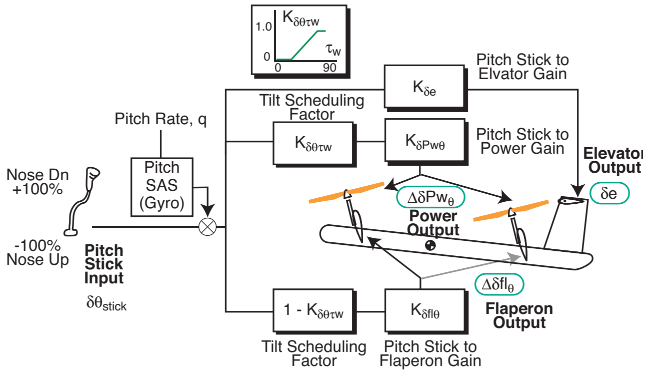

Fig.7. Longitudinal PFCS.

used for control command inputs, and the pilot selects the operational mode through an auto/man switch. In manual mode, the pilot's stick inputs are input directly to the PFCS which generates corresponding control surface deflection commands. In SCAS mode, pitch and roll stick inputs are converted to attitude commands and the SCAS controller commands the required control surface deflections from the PFCS to acquire and maintain the commanded attitude.

In the present research, the SCAS mode is designed as an integral part of the auto-flight system, and manual mode with SAS is used mainly for safety purposes when testing the SCAS mode. The PFCS and the SCAS design are described in sections 4.4 and 4.3 respectively.

The wing tilt angle and flap angle (which is equivalent to setting the neutral position of the flaperons) are also selected by the pilot through preset tilt switches on the RC system controller. The preset angles along transition schedule were determined from the analysis explained in section 4.2.

4.1 The PFCS: Primary Flight Control System

As described in section 2, the attitude control method needs 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[2)]. The PFCS automatically changes the transfer function from pilot stick command input to control surface deflection command output according to the wing tilt angle. This architecture is also used in the present research with the SAS gain redesigned based on the dynamics model. Also, the SCAS was designed as an outer loop of the PFCS.

Fig. 7 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 propeller 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 the wing tilt angle. The aerodynamic lift and control power of the flaperons and elevators increase with airspeed. As forward speed increases, the tilt angle is scheduled to reduce 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 stick command is linked only to the aerodynamic control surfaces.

4.2 Transition Schedule

The tilt angle schedule against airspeed in transition mode was designed based on trim analyses of each wing tilt angle generated from the simulation model. Fig. 8 shows an example trim plot when τ_W=15deg and the front and rear flaps are at 25 and 20 deg respectively (denoted as "T15F25/20").

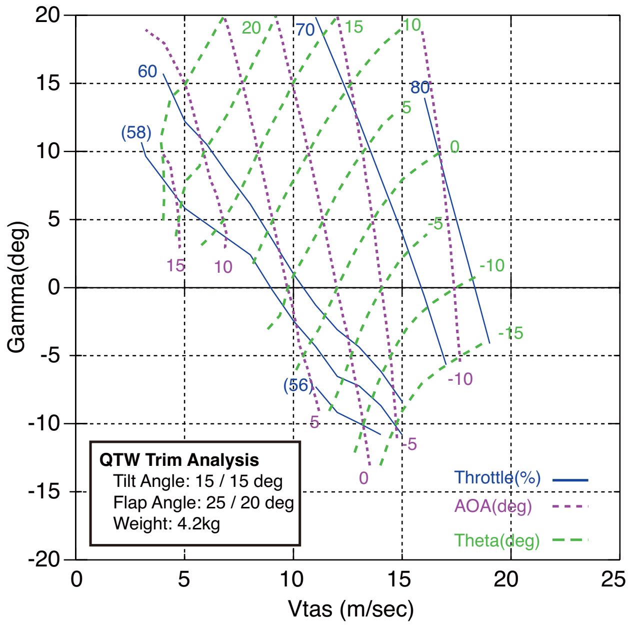

Fig. 8. Trim plot at T15, F25/20 (V-Gamma Diagram)

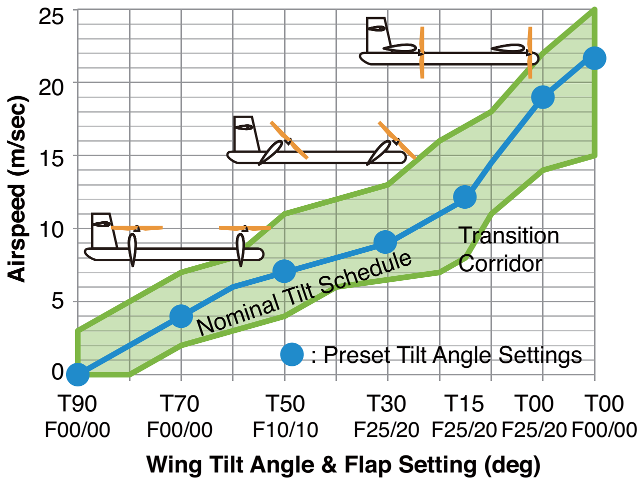

Fig. 9. Transition corridor

The corridor for the transition schedule shown in Fig. 9 was determined based on trim pitch angles ranging from -15 to +15 deg. The corridor in this research phase is only for the all-engines-operative condition and does not consider a one-engine-out situation.

The nominal wing tilt angle schedule shown in Fig. 9 was used to determine target speeds for flight operations and design points for the controller design. Preset wing tilt and flap angles along the transition schedule were determined so to allow a pilot to change airspeed smoothly at constant pitch angle when selecting a new tilt angle configuration. Also, the flap setting schedule was designed so that smaller pitch stick inputs are required to compensate for trim changes during transition.

4.3 SCAS Design

In the present research, an SCAS including pitch and roll attitude hold controllers was newly designed as an integral part of the auto-flight system. The SAS controller was designed with the requirement that a pilot can manually control the vehicle with an acceptable workload. The pitch and roll attitude hold controller was designed as the outer loop of the SAS and the PFCS to reduce pilot workload in transition flight. In both the SAS and attitude hold controller designs, multiple equilibrium points were used as design points and gains were scheduled according to the wing tilt angle settings. An attitude command-type stick input was adopted instead of a rate command type since flight simulation test results suggested this brings better awareness of pitch and roll attitude to a remotely controlling pilot. Since the remote control pilot does not use the attitude indicator on the ground console, it is easier for him/her to understand how much attitude command is being applied to the vehicle and to judge the correct functioning of the SCAS by comparing stick position with the vehicle's attitude.

5. Flight Test

5.1 Flight Test Overview

A series of flight tests was carried out to evaluate the tilt schedule design and the SCAS. A pilot highly experienced and skilled in model helicopter control participated in the tests. Flight data and pilot comments were recorded for each preset wing tilt angle. Tests were performed in conditions of calm winds of less than 5 m/sec and sufficient visibility (1 km or more).

During the tests, an incremental approach to expanding the flight envelope was taken. Before attempting full transition, the SCAS controller was evaluated at each preset wing tilt angle. In these runs, after vertical takeoff under manual mode the SCAS was engaged by the pilot and then transition was performed until the wing tilt reached a prescribed test angle.

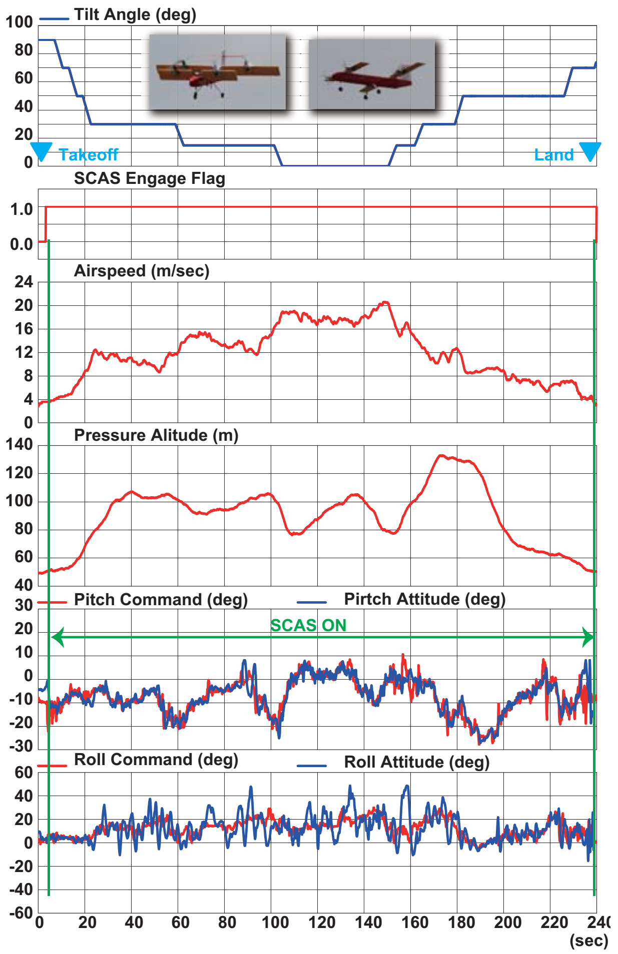

Fig. 10. Flight Test Results (T90~T00)

Straight flight and turn maneuvers then were performed to evaluate the handling qualities of the SCAS at the test wing tilt angle. At any time the pilot was able to revert from SCAS back to manual mode, or to select another preset wing tilt angle for safety. Tilt angles of 90 deg or 70 deg were used for takeoff depending on the wind conditions; if there was certain amount of head wind then a wing tilt angle of 70 deg was used to perform a vertical takeoff relative to the ground.

5.2 Results

Fig. 10 shows the time histories of a full transition flight using the SCAS. The data indicate that the SCAS successfully controlled the aircraft to follow the pitch and roll commands through all wing tilt angle settings. Table 3 shows pilot ratings of the handling qualities of the SCAS at each preset wing tilt

Table 3. Pilot Ratings Summary

Axis	T90	T70	T50	T30	T15	T00	CLN
Pitch	S	S	S	S	S	S	S
Roll	S	S	S	A	A	A	S

S: Satisfactory (PR=1~3), A: Adequate (PR=4~6)

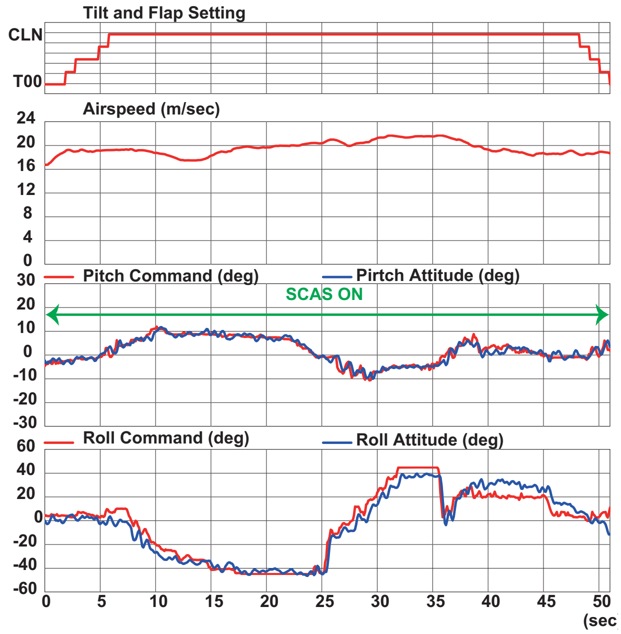

Fig. 11. Flight Test Results (CLN)

angle. The pilot also commented that the workload was remarkably reduced by the SCAS.

6. Discussions

6.1 SCAS Controller

In manual mode, the pilot’s workload involves tasks such as attitude and stability control, airspeed control and path control, as well as wing tilt angle change. The SCAS mode made the attitude and stability control task much easier and it made possible to pay more attention to airspeed and flight path control and wing tilt angle change. It is considered that this accounts for the pilot’s comment on workload reduction.

In Fig. 10, pitch attitude well followed pitch commands at each the wing tilt angle setting. Roll attitude also followed the commands but degraded damping and followability were observed in T30, T15, T00 in contrast to T90, T70 and T50 in Fig. 10 and CLN in Fig. 11. These performance degradations of the controller resulted in pilot ratings of "adequate" in the roll axis, which means that flying quality improvements are desirable. This could be achieved by additional tuning of the control gains at the problem wing tilt angles. However, for this phase of the research we did not pursue tuning the SCAS gain settings because the goal of this study was to develop the technical foundations of an auto-flight system for the QTW configuration. In this regard, the results of the present research attained our goals. The pitch hold and roll hold control loops in the SCAS worked well and can be applied as the inner loops of a more sophisticated auto-flight system such as automatic guidance and navigation. Technologies acquired in the present research have been applied to the development of the next prototype, which has already commenced. Fig. 12 shows the next prototype, which is aimed at mission capability technology development and demonstrations, and has just started a series of flight tests.

Fig. 12 The Next Prototype
(Mission capability technology demonstrator, Gross Weight = 43kg, Span=2.4m)

6.2 Transition Schedule Design

In the flight test, full transition was successfully achieved with the transition schedule designed in the present research. The number of preset wing tilt angles was sufficient for the pilot to perform a smooth transition while retaining awareness of the selected wing tilt angle. If the preset angles were too numerous, the pilot's task would be complicated and there would be a risk of losing awareness of the selected tilt angle. The remote control pilot must constantly watch the aircraft which makes it difficult to check a tilt angle indicator or the position of the tilt switch. On the other hand, if the number of the preset tilt angles were too small it would be difficult for the pilot to compensate the transient motions that arise during tilt angle changes.

It was found that the aircraft deviated from the boundary of the transition corridor; higher negative pitch (nose down) angles were applied by the pilot during wing tilt angle change and descent at T50. This might have been because pilot was unable to check the vehicle's attitude or thrust status on the ground console and was overly concerned with avoiding sudden pitch up or stall, even although such events did not occur. The boundary of the transition corridor was defined based on the tentative maximum and minimum pitch angles, and the attitudes attained during the flight tests did not exceed the safety boundary. However, the excursions from the nominal corridor suggested that a function such as flight envelope protection might be useful for operations.

6.3 Simulation Model Applicability

Detailed analysis of the fidelity of the flight simulation model has not been conducted since no flight data including static trim status and step responses were obtained due to the limited size of the flight test area and QUX-02A's system configuration. Simple comparisons of flight data with trim conditions calculated by the simulation model were carried out and no significant discrepancies were found. Also, the pilot commented that the flight simulation was sufficiently similar to the vehicle's actual behavior to allow him to conduct pre-evaluation of the handling qualities and was useful for understanding the vehicle's flight characteristics before actual flight tests.

Since the analysis and design processes using the simulation model resulted in successful full transition in actual flight, it can be said that the simulation model enabled analysis and design that were safer, easier and more reasonable than in the previous research. It can therefore be concluded that the simulation model of the QTW is applicable to the design and analysis process including aircraft trim, transition schedule, flight control design and pilot-in-the-loop simulation.

7. Concluding Remarks

A QTW vehicle dynamics simulation model was constructed to allow the accurate prediction of flight characteristics, which is one of the most important issues in VTOL design. Also, the vehicle's flight control system, which is also a key component for achieving safe and efficient VTOL operations, was designed with SCAS capabilities. Full transition flight to evaluate the flight control system and transition schedule were successfully accomplished by a remotely controlling pilot using the SCAS.

The simulation model developed in this research has the following features:

(1) The model simulates the nonlinear six-degree-of-freedom characteristics of the QTW covering the full flight envelope ranging from hover at τ_w =90 deg to cruise at τ_w =0 deg.

(2) The model incorporates the QTW's unique powered lift aerodynamic features and configuration features.

(3) The model is applicable to design and analysis such as transition scheduling, flight control system design and pilot-in-the-loop simulation.

Furthermore, the flight tests demonstrated the following features of the flight control system:

(1) The system comprising a PFCS, transition schedule and SCAS makes safe and smooth full transition possible.

(2) The PFCS automatically changes transfer functions from stick inputs to control surfaces, which is required due to the unique configuration of the QTW.

(3) The QTW has a transition corridor which is sufficiently large for safe and smooth transition both for acceleration and deceleration.

(4) The SCAS maintains aircraft pitch and roll attitudes according to pilot commands and reduces the pilot workload over manual mode. The control loops developed here will be applicable to the inner loops of more sophisticated auto-flight systems which involve guidance and navigation controllers.

The research program has proceeded to the next stage to develop a follow-on prototype for mission capability technology and demonstration. The technologies developed here are being applied to the design of the next prototype and the development of features such as a higher level auto-flight control system with as guidance and navigation, and a high speed and cruise efficient propulsion system.

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Symbols

τ_w	Tilt Angle	(deg)
α_w	Wing Angle of Attack	(deg)
α_B	Body Angle of Attack	(deg)
β_B	Body Sideslip Angle	(deg)
q	Pitch Rate	(deg/sec)
p	Roll Rate	(deg/sec)
r	Yaw Rate	(deg/sec)
C_{Tave}	Thrust Coefficient (average of 4 propellers)	
δ_F	Flap Angle	(deg)
δ_{Ff}	Flap Angle (average of the left and right front flaps)	(deg)
$\Delta\delta_F$	Flaperon Angle	(deg)
δ_e	Elevator Angle	(deg)
δ_r	Rudder Angle	(deg)
CG_x , CG_x	Center of Gravity	(mm)
I_{xx} , I_{yy} , I_{zz} , I_{xz}	Moment of Inertia and Product of Inertia	

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