Small Tiltrotor UAV Development and Conversion Flight Test

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Abstract A small tiltrotor UAV (2-m span) has been developed and flight test is underway. Conversion flight was successfully achieved as a result of systematic approach in development of the vehicle and flight control system.
Sizing and performance analysis of the tiltrotor is presented, where simple codes based on blade element and momentum theory were utilized. Conversion corridor of the tiltrotor was predicted and the nacelle tilt angle and air speed were compared with flight test results. This paper also presents design and fabrication feature of the small tiltrotor vehicle. Ground testing activity is presented including rotor-drive-engine iron bird test and frame vehicle hovering test. After a series of progressive flight tests, conversion flight from helicopter to fixed-wing mode was accomplished. This verified that the stability and control augmentation algorithm work properly in the flight control software. This small tiltrotor flight test is expected to reduce risks in flight test of the 5-m span full-scale tiltrotor UAV called 'Smart UAV'. The full-scale Smart UAV is being tested on the ground and flight test is scheduled in 2009.

1. INTRODUCTION

The Smart UAV(SUAV) development program, which is one of the '21st Frontier R&D Program' being supported by Korean government, has selected tiltrotor as a UAV platform [1]. Among various sub-systems of the SUAV, rotor, drive and flight control system have been considered as major challenging items for KARI to develop due to lack of previous experience with tiltrotor development. Ironbird test of the rotor/drive system was adopted to reduce development risk. Development risk of the flight control system was considered to be mitigated by flight simulation but still need to be verified by flight test. Small-scale platform was decided to be developed to reduce the risk in full-scale flight test.

The small scale tiltrotor flight was also expected to help understand the realistic feature of the tiltrotor vehicle. Furthermore, the small-scale flight test was expected to be used in training of the external and internal pilots for the full scale flight test.

A 40%-scale (2-m span) of the full-scale SUAV (5-m span) was selected to mount the flight control computer and navigation system while utilizing the off-the-shelf items such as an engine and actuators. Aerodynamic performance of the 40%-scaled tiltrotor was calculated and analyzed using in-house developed performance code. The calculated performances are rotor performances in hover, speed performance in forward flight, flight performance during transition flight, and mission performance along mission profile. The performance data have been used for scheduling of the various control surfaces such as collective pitch of the rotors and flaperon deflection in flight control logic.

The scaled tiltrotor was designed to maintain 40% in geometric scale but rotor rpm, blade mass and stiffness were not dynamically scaled. Rotor control components were designed similar to that of the full-scale SUAV using gimbal hub for three blades and tension-torsion straps for centrifugal force transmission [2]. Early version of the small tiltor was fabricated using many RC helicopter control devices. After successful RC flights in helicopter mode and limited nacelle-tilting flight, a flight control computer (FCC) and a navigation device were installed to enable evaluation of the control law.

After control software was loaded on the FCC, ground test and flight test of the small tiltrotor were performed using a rate stability augmentation system(SAS) and an attitude stability and control augmentation system(SCAS) feedback[3,4].

The tiltrotor flies in helicopter, airplane and conversion modes. In conversion mode, transition occurs in configuration from helicopter to airplane mode and also in control law structure, which causes discontinuity and unexpected flight motion. Hence common structure of the control law for the different configurations is desirable. SUAV adopted attitude SCAS control law in all flight modes. Main purpose of the small tiltrotor flight test was to prove the effectiveness of attitude SCAS control for all configurations. For the control law design, nonlinear simulation model was developed based on the manned tilt rotor mathematical dynamics model.

The flight test procedures including tethered hover test and hardware-in-loop simulation (HILS) helped fast evaluate the modified operational flight program (OFP) before flight test (Fig.1). During the tethered hover test, hidden problems were found occasionally which were not observed in HILS simulation. Those problems could be fixed before flight test. The conversion flight test was accomplished after a series of progressive flight tests.

Fig. 1 40%-scaled tiltrotor UAV in hover

2. SIZING

The small tiltrotor was geometrically scaled by 40% of the SUAV as shown in Fig. 2 and Table 1. The rotor system was not designed in dynamic scale but rotor control and hub components were designed similar to those of the SUAV using gimbaled hub and hub spring. The major difference between the scaled vehicle and the full scale vehicle is installed engine and rotor speed. While a 550 horse-power turbo-shaft engine is installed in the full scale vehicle, a 16.5-hp 2-cycle 2-cylincer reciprocating engine is installed in the scaled vehicle. The reciprocating engine is cooled by axial fan installed in front of the engine. Although dual rotational speeds are used for the full scale rotor; 1,604 rpm in helicopter mode and 1,284 rpm in airplane mode, the scaled vehicle is designed to operate with a single rotor speed for simplicity of the control system. The 40% Mach-scaled rotor should have the rotor speed over 4,000 rpm, which is excessive when utilizing the off-the-shelf mechanical components. Hence 2,000rpm of rotor speed was chosen for both helicopter and airplane mode flights.

Although calculation indicates that 60kg of gross weight is available form 16.5-hp engine, 38kg of gross weight was chosen for typical flight. Disk loading and wing loading of the scaled aircraft are less than one third of those of the full scale vehicle.

Fig. 2 Full scale vs. 40% scale of the Smart UAV

Table 1 Specification of aircraft

		Full Scale	40% Scale
Weight	GW (kg)	995	38
	Payload (kg)	40	N/A
	Fuel (kg)	280	3.2
Engine	Type	Turbo-Shaft	Reciprocating
	Power (hp)	550	15
Rotor	Hub Type	Gimbal	Gimbal
	Radius (m)	1.433	0.573
	Area/Rotor (m^2)	6.451	1.032
	Disk Loading (kg/m^2)	77.1	18.4
	RPM (HC)	1604	2000
	RPM (AP)	1284	2000
	Gimbal Spring (Nm/rad)	359.0	11.1
	Flapping Inertia (kgm^2)	1.561	0.012
	DEL3 Angle (m^2)	-15.0	-15.0
Wing	Chord (m)	0.80	0.32
	Span (m)	4.00	1.60
	Area (m^2)	3.20	0.51
	Wing Loading (kg/m^2)	310.9	74.2
Fuselage	Length (m)	4.96	1.98

3. PERFORMANCE ANAYSIS

Performance analysis code named SPAC(Smart UAV Performance Code) was developed and used for performance prediction. The code has capability to calculate the three modes of tiltrotor flight. Generalized input module enables calculation of various types of mission profiles. The aerodynamic performance module for rotor is based on a blade element and momentum theory. Rotor flapping equations and aircraft trim equations are combined to calculate attitude of the rotor and airframe. Rotor model adopted various inflow models and accuracy of each model has been investigated correlating with numerical and wind tunnel test data. The performance code was used both in full-scale and small-scale vehicle design. Fig.3 shows the structure of the performance code – SPAC.

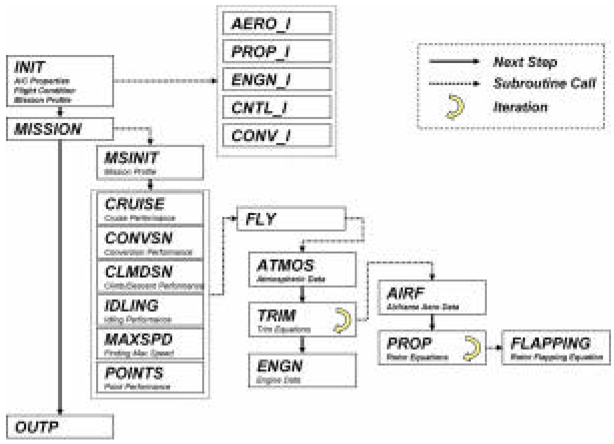

Fig. 3 Structure of performance code SPAC

Hover flight performance of the 40%-scaled proprotor was calculated for investigation of hovering capability as well as for sizing of the rotor at initial stage of development. The rotor performance was calculated varying the rotational speed between 1,500 and 2,500 rpm. Fig. 4 shows thrust curves for the collective pitch at 75% blade span of the rotor in hover mode. The two points marked on the plot indicate test data obtained from hovering test of the frame vehicle, which is composed of rotor-drive system and engine as shown in Fig. 12 [3]. The test point 1 is a case of gross weight 40kg with rotor speed of 2,000rpm and point 2 is for the gross weight 50kg. The two points marked on the curve of 2,000 rpm show good correlation with the prediction. Considering 12% download ratio, which is downward force on wing and body due to rotor downwash near hover mode, and 5% lift-up margin allocated for the 50kg vehicle, the required thrust was predicted near 60kg. Fig. 5 shows curves for collective pitch versus required power per a rotor. The two measured points are also marked on the plot and show good correlation with the data predicted. Required power for two rotors is 11 hp for 15 degrees of the collective pitch at the 60-kg required thrust.

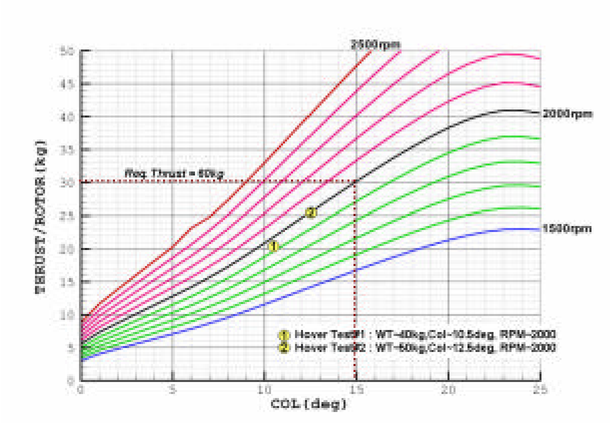

Fig. 4 Collective pitch – thrust curve for hover

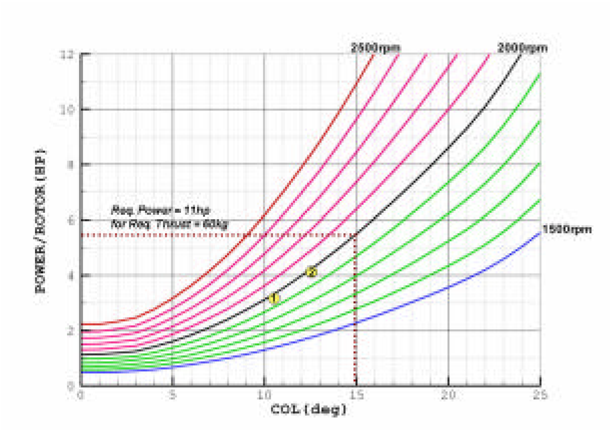

Fig. 5 Collective pitch – power curve for hover

Performance for conversion flight was predicted as the nacelle tilts from 80 degrees to 0 degrees to find proper vehicle attitude during the conversion flight. The vehicle attitude is controlled by scheduled command from a flight control computer (FCC). Fig. 6 shows nacelle tilt angle versus vehicle speed at various vehicle angles of attack. The conversion path moves to left side as the angle of attack increases, which approaches the vehicle stall boundary. On the other hand as the angle of attack decreases, the conversion path moves to right side, where the engine power limit approaches. Considering the two boundaries, a conversion corridor was recommended at 4 degrees of angle of attack. Summary of the small tiltrotor performance is shown in Table 2.

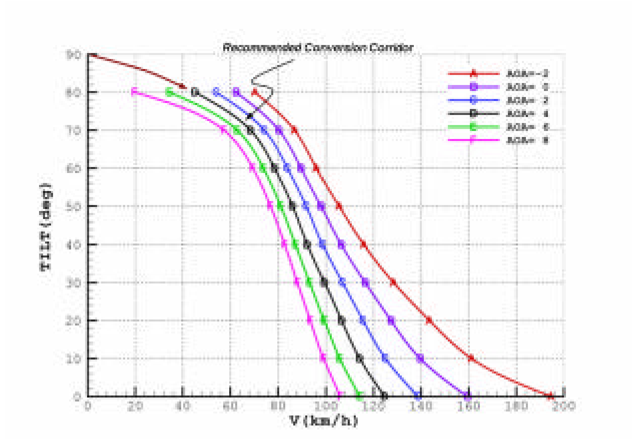

Fig. 6 Speed – tilt angle curve for conversion flight

Table 2 Performance summary of the 40% scaled vehicle of Smart UAV

Stall Speed (Flap = 10 deg)	92 km/h
Maximum Speed	176 km/h
Max Endurance Speed	140 km/h
Entry Speed of Conversion	50 km/h
Exit Speed of Conversion	125 km/h
AOA of Conversion	4 deg
Maximum Endurance	53 min
Maximum Range	104 km

4. DESIGN AND FABRICATION

The scaled vehicle was designed and fabricated to maintain 40% scale in geometric similarity but not in dynamic similarity. Rotor rpm, blade mass and stiffness were selected so that the vehicle could be fabricated utilizing components available in RC model rotorcraft community (Fig. 7).

A 2-cycle reciprocating engine was selected and located at fuselage. The engine has maximum power of 16.5 hp, which is widely used in RC model vehicle. The engine was designed to be cooled by air not by water, raising issue in engine cooling during hover flight. Engine cooling was more difficult since the engine was located away from rotor unlike model helicopter. Engine cooling fan was installed adjacent to the engine and cooled the engine successfully after several modifications.

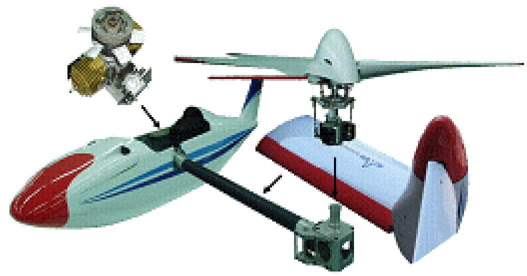

Fig. 7 Small tiltrotor components

Gimbal hub as shown in Fig. 8 has a hinge at the rotational center. Tension-torsion strap was used as a means of transmitting blade centrifugal forces to the hub while providing negligible resistance to feathering motion. The gimbal hub and tension-torsion strap concept were adopted from the full scale SUAV design.

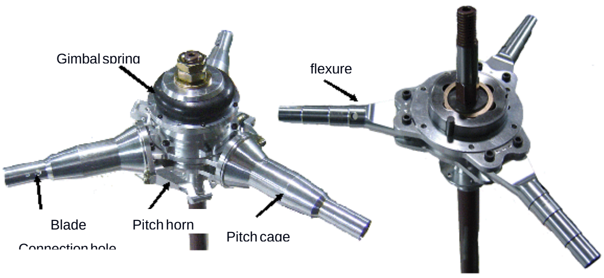

Fig. 8 Rotor hub components for small tiltrotor

Center gear box reduces rotational speed and is connected to pylon gear box with wing shaft (Fig.9). The wing shaft and gear boxes are coupled by universal joints to be flexible while the wing is variably loaded.

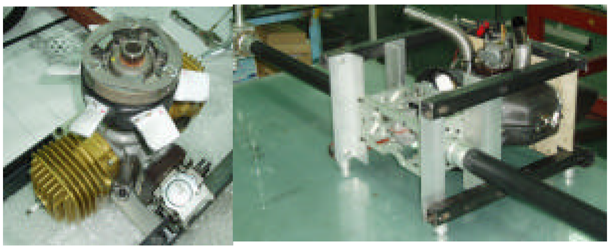

Fig. 9 Engine and drive components

Fuselage skin was fabricated with balsa sandwiched between carbon-fiber fabrics. Bulkhead and longeron were used to reinforce the structure.

The tension-torsion strap was identified as a most critical part in rotor components and tested structurally. The structural test indicates that strap has sufficient safety margin as shown in Fig. 10.

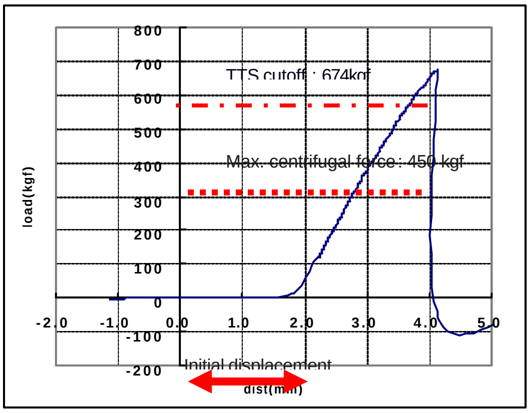

Fig. 10 Structural test result for tension-torsion strap

Rotors, drive and engine were connected to form a iron bird as shown in Fig. 11. Swash plate actuators and nacelle actuators were installed and were remotely controlled through radio control devices. Nacelle tilting was tested while the rotor was at flying condition. The ground test showed that two nacelles were tilted in synchronous manner although the they are not synchronized mechanically but electronically. After the ironbird test, the rotor-drive-engine ironbird was modified to form a frame vehicle (Fig. 12) and tested in helicopter flight mode. At this stage contol mixer from RC device was tuned so that hovering flight can be maintained. Fuselage, wings, empenage were installed later and form a complete tiltrotor platform. The vehicle reliabity was tested at high powered hovering condition for up to 40 minutes (Fig. 13)

Fig. 11 Rotor tilting tested on the rotor-drive-engine iron bird

Fig. 12 Frame vehicle in hovering test

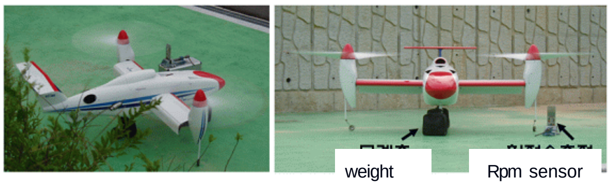

Fig. 13 Endurance test on the ground

5. FLIGHT CONTROL

One of the main purpose for the small tiltrotor flight was to to evaluate the tiltrotor aircraft control law. Ground and flight tests were performed using rate SAS and attitude SCAS feedback [4, 5].

Three different flight modes in tiltrotor require different control structures in each flight mode. Transition in configuration from helicopter to airplane mode has tendency to cause discontinuous flight motion. Common structure in control law for different flight mode configurations was used in the flight control. SUAV uses attitude SCAS control law in three flight modes. Effectiveness of the attitude SCAS control for all configurations was evaluated through the small scale flight test. For the control law design, nonlinear simulation model was developed based on the manned tilt rotor mathematical dynamics model [6].

Rotor governor was used to keep constant rotor speed during all flight modes. In a rotor governor, the pilot controls the engine through a throttle command, while the governing system regulates blade pitch so as to control rotor speed. For the tiltrotor aircraft, the rotor governor is known to be more effective than engine governor since flight speed sensitivity to the rotor blade pitch control is excessive in airplane flight mode [7].

In early flight tests by an external pilot (EP), only the rate feedback SCAS control law was used in order to evaluate flight characteristics of the tiltrotor. In later flight test, attitude SCAS was added to relieve EP's workload by maintaining pitch and roll attitude automatically. At that stage, nacelle tilt angle was still commanded by the EP. At the same time airspeed also had to be controlled by the EP to stay in conversion corridor, which gave another workload. After successful flight tests reaching down to 0 degree of nacelle tilt angle by EP's manual tilt command, the airspeed control was implemented in the ground control station (GCS) to have automatic tilting algorithm as a function of airspeed. The GCS was originally developed for the full scale vehicle but was used for the small scale flight, which enabled evaluation of the GCS in advance.

The FCC of the scaled model was developed to control 11-servo actuators. The FCC also processes all of the interface signals from the flight control sensors. Cross-bow NAV420CA-100 was used as a gyro and GPS sensor. Servo actuators were off-the-shelf items from RC model community.

The attitude SCAS on the pitch, roll and yaw axes were designed based on linearized model from the 40%-scaled nonlinear simulation software. The structure of the attitude SCAS in pitch axis is shown in Fig. 14. Pilot input and pitch attitude feedback make attitude error command and it is augmented by proportional and integral gain. Due to pitch up tendency at transition in high tilt angle and pitch down tendency in low tilt angle, the integrator gain was chosen to handle this special situation efficiently. The integrator gain in pitch and roll axis was designed to remove the steady state errors and at the same time to give more controllability to the pilot. The pitch rate feedback also was included in the inner loop of the pitch attitude SCAS to increase damping in pitch motion.

Speed hold control loop shown in Fig. 15 is engaged by IP with touching speed hold knob button on knob screen. Speed hold control loop generates pitch attitude command and automatic tilt switch command when discrepancy between speed command and current speed is bigger than 5km/h.

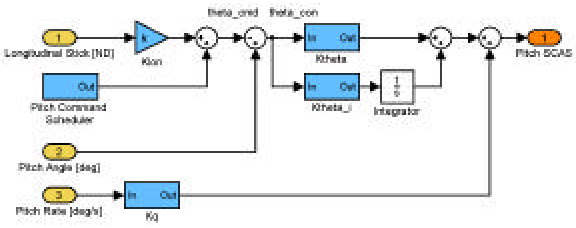

Fig. 14 Block diagram of the pitch attitude SCAS

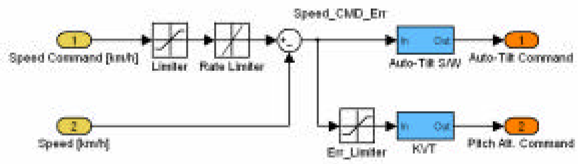

Fig. 15 Block diagram of the speed hold control

Fig. 16 Monitoring screen of the pilot bay

Fig. 17 Electronic map screen of the pilot bay

Fig. 15 shows HILS simulation and Fig. 16 shows the replay of real flight test and electronic map around the KARI flight test center at South Coast. IP could monitor all the flight critical parameter in lower screen of the pilot bay.

6. FLIGHT TEST

Early flight tests were performed using manual tilting control logic where only rate feedback SCAS control law was used. The EP had to control the vehicle attitude, tilt angle and flight speed. Fig. 18 shows flight trajectory with varying nacelle angle. The flight test result was depicted on the predicted conversion flight performance (Fig. 19). It can be noted that the scattered manual flight test data are within the predicted performance range and well correlated.

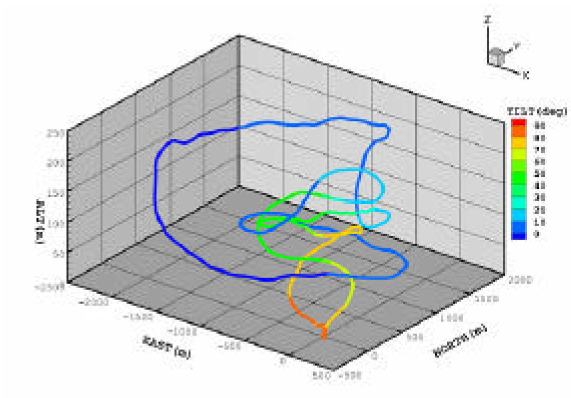

Fig. 18 Nacelle tilt angle and flight trajectory acquired from manual tilt flight test

Manual and automatic tilt controls in the conversion flight are compared by depicting flight test result on the conversion corridor.(Fig. 20, 21)

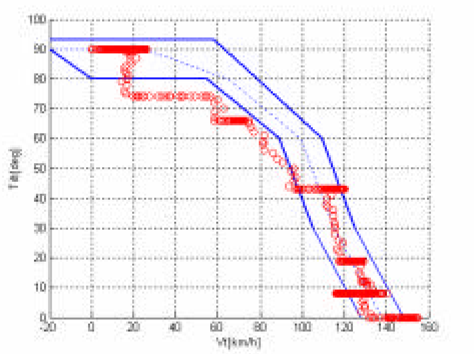

Fig. 20 Conversion corridor plot from manual tilt flight test

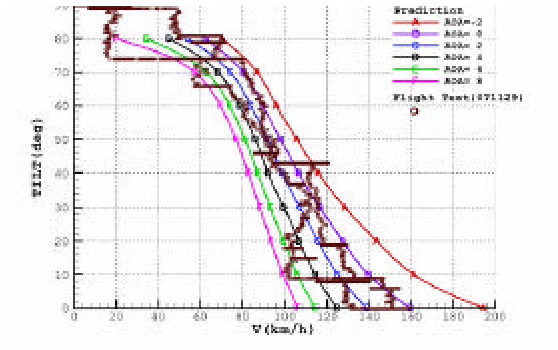

Fig. 19 Conversion corridor prediction and flight test result

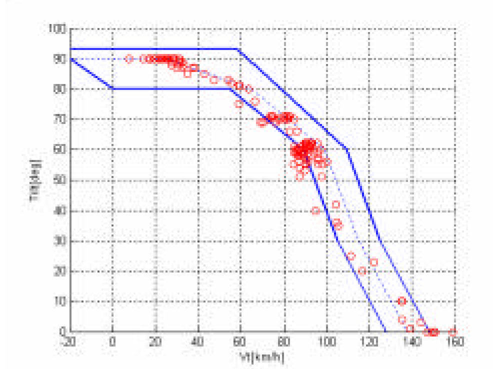

Fig. 21 Conversion corridor plot from auto tilt flight test

During the flight test by manual tilt command, pilot had to maintain air speed within the range in the conversion corridor, but the speed varied in a wider band than was arranged (Fig. 20)

Fig. 21 shows the test result from automatic tilt flight. Nacelles were automatically tilted depending on airspeed. It can be noted that the speed variation at given nacelle tilt angle is much narrower than that of the manual tilt flight. Scattered data in left side of the corridor boundary was caused by abrupt deceleration in airplane mode flight. The limited pitch attitude authority in airplane mode could not decelerate the vehicle within the conversion corridor. IP commanded very low speed command to decrease airspeed instead of commanding lower altitude to decrease engine power. The limiter in conversion control loop restricted nacelle tilt slightly lower than was required.

The populated data points in Fig. 6 shows the preflight check on ground (tilt angle = 90 deg) and the control authority transition between EP and IP(tilt angle = 70 and 60 deg).

7. CONCLUSION

A 2-m span small tiltrotor has been developed maximizing available parts from RC helicopter community. The tiltrotor vehicle was modified to a UAV by installing flight control computer in the fuselage. The vehicle was successfully controlled by ground control system, which was developed for full-scale flight test. Control logics progressively implemented on the FCC enabled conversion flight of the tiltrotor. This small-scale tiltrotor flight test verified that stability and control augmentation algorithm works well in flight control software. Simple aerodynamic performance prediction and vehicle sizing based on first principles contributed in reduction of design period of the small tiltrotor. Flight test experience with small vehicle before the full scale flight test gave tremendous lessons to designers and flight test staffs who never had previous experiences with tiltrotor. The small-scale test experience is being reflected in full-scale flight test program.

ACKNOWLEDGMENTS

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