Performance Analysis of Smart UAV Using CAMRAD II

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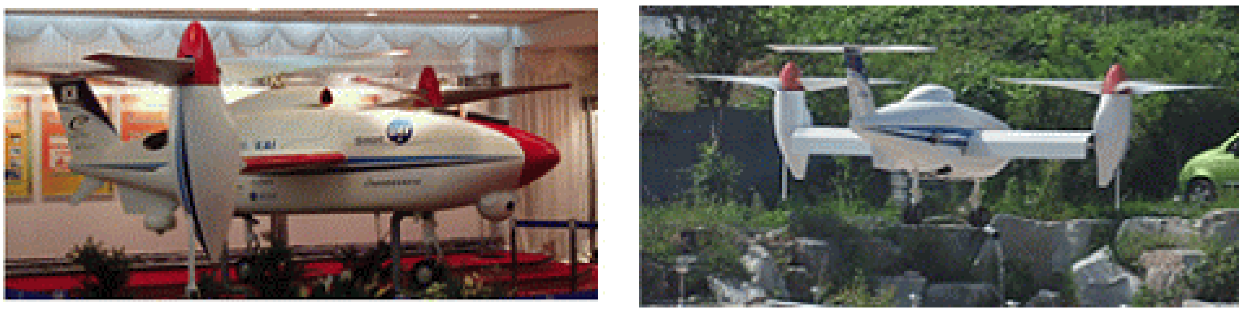
Abstract: Smart UAV is the tilt rotor type unmanned aerial vehicle system developed in KOREA since 2002. In this study, the performance of Smart UAV is analyzed using CAMRAD II coupled with engine deck. The airplane mode performance analysis shows that the target maximum speed of 500 km/h is achieved at an altitude of 3.4 km, and the flap deflection of about 5° to 15° is needed to maintain the adequate stall margin during loitering flight. The helicopter mode maximum speed is 277 km/h and the helicopter mode maximum endurance is 2.97 hours. Through the conversion mode performance analysis, the conversion corridor of SUAV is generated and it is shown that about 25° flap deflection is required for the safe conversion. Putting those performance analyses results together, the mission performance of SUAV is carefully assessed. Through this mission performance analysis, it is clearly shown that the loitering time on station is greater than 3 hours and also the maximum endurance is greater than target endurance of 5 hours. From these results, it can be concluded that the target performances of SUAV are well achieved.

INTRODUCTION



(a) SUAV Mockup *(b) SUAV Small Scale Flight Demonstrator*

Figure 1: Tilt Rotor Unmanned Aerial Vehicle (SUAV)

These days, various configurations of unmanned aerial vehicle have been designed and utilized in many applications. The tilt rotor UAV is one of the noticeable applications (Ref.1 and Ref.2). Figure 1 shows Smart Unmanned Aerial Vehicle (SUAV) that Korea Aerospace Research Institute (KARI) has developed since 2002 for a robust and intelligent tilt rotor UAV exhibiting high-speed cruise and vertical take-off and landing capabilities. The nominal mission weight is 1,000kg. The maximum and maneuver speeds are 500 km/h and 400 km/hr, respectively. Highly reliable design and operating concepts were implemented in the critical subsystems such as power train, flight control and avionics systems. SUAV can fly in three flight modes; helicopter, conversion, and airplane modes. The typical mission of SUAV would be performed in airplane mode because the primary mission of SUAV is surveillance. The power plant, P&W X206 turbo shaft engine, is located at center fuselage and drives both rotor systems through center and pylon gearboxes. The static and dynamic wind tunnel tests with and without proprotor have been performed to gather aerodynamic performance and stability & control data. Figure 1(a) shows the full scale mockup of SUAV. Small scaled flight demonstrators have been developed and tested as shown in Figure 1(b).

In this study, the performance of SUAV is carefully assessed using CAMRAD II coupled with the engine deck. Through CAMRAD II trim analysis, the required power, vehicle attitude and the control settings are calculated at a given flight condition. Based on the calculated required power and flight condition, the engine performances are calculated such as the fuel flow and engine torque limit. The performances of SUAV such as endurance and range are finally determined by coupling those trim analysis results and engine performances.

1. PERFORMANCE ANALYSIS TOOL

1.1 Overview of CAMRAD II

The rotary wing aircraft has a little bit different flight characteristics compared with the fixed wing aircraft. In case of the fixed wing aircraft, the flight characteristics can be analyzed using 6-DOF (Degree of Freedom) equations of motion derived from the forces and moments equilibrium. In case of the rotary wing aircraft, however, the forces and moments equilibrium of the rotor systems should be added to the conventional 6-DOF equations of motion to calculate the flight characteristics accurately. Therefore, CAMRAD II, the comprehensive analysis code for the rotorcraft, is adopted for the trim analysis of SUAV in this study.

CAMRAD II is an aeromechanical analysis of the helicopters and rotorcrafts developed by Dr. Wayne Johnson (Ref. 3). It incorporates a combination of advanced technology, including the multibody dynamics, nonlinear finite elements, structural dynamics, and the rotorcraft aerodynamics. It can be used for the design, testing, and evaluation of rotors and rotorcraft and can be applied to all stages, including research, conceptual design, detailed design, and development. CAMRAD II can calculate the performance, loads, vibration, response, and the stability with a consistent, balanced, yet high level of technology in a single computer program. So it can be applied to a wide range of problems, and a wide class of rotorcraft. Especially it has very convenient analysis environment for the tilt rotor because it has been originally developed to analyze the whirl flutter phenomenon of the tilt rotor since 1980s (Ref. 4).

1.2 Performance Analysis Process

The performance analysis process of SUAV is shown in Figure 2. The whole aircraft configuration is designed, generated and modified using CATIA. The blade section airfoil geometry is transferred to CORDAS, and CORDAS calculates the blade section structural properties such as the sectional mass, inertia, polar radius of gyration, stiffness. Through the wind tunnel test and CFD using the blade section airfoil geometry and the whole aircraft configuration transferred from CATIA, the blade section aerodynamic properties and the whole airframe aerodynamic properties are measured and calculated. NASTRAN calculates the airframe structural properties based on the airframe configuration generated by CATIA. The generated blade section structural properties and the blade section aerodynamic properties mainly construct the rotor inputs of CAMRD II. Also the generated airframe aerodynamic properties combined with the airframe structural properties mainly construct the airframe inputs of CAMRD II. The trim analysis is performed using the generated rotor and airframe inputs to calculate the required power, vehicle attitude and the control settings at a given flight condition. The trim results are finally combined with the engine deck to accurately estimate the performances of SUAV.

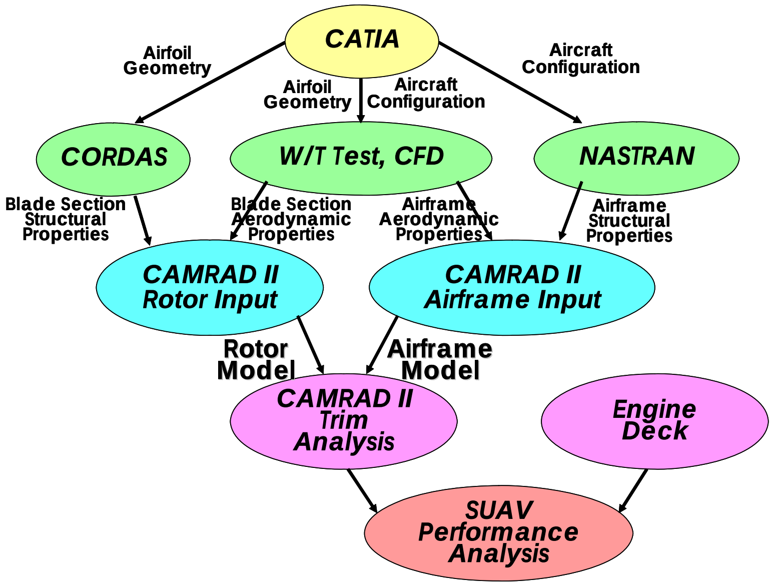


Figure 2: Performance Analysis Process of SUAV Using CAMRAD II

2. AERODYNAMIC CHARACTERISTICS OF SUAV

	Component	CDmin	Counts	%
W/T	Body	0.00908	90.8	13.0%
	Wing	0.01864	186.4	26.6%
	Nacelle	0.01075	107.5	15.4%
	Empennage	0.00550	55.0	7.9%
	Air Intake (drag)	0.00184	18.4	2.6%
	EO/IR	0.00727	72.7	10.4%
	Ventral Fin	0.00029	2.9	0.4%
	VHF	0.00005	0.5	0.1%
	KU-band	0.00178	17.8	2.5%
	Ant1	0.00063	6.3	0.9%
	Ant2	0.00006	0.6	0.1%
	Ant3+Ant4	-0.00016	-1.6	-0.2%
	Aux. L/G	0.00079	7.9	1.1%
	H.E.1	0.00099	9.9	1.4%
	H.E.2	0.00049	4.9	0.7%
	W/T-SUM	0.05800	580.0	82.9%
Extra	Exaust	0.00400	40.0	5.7%
	Cooling I/Os	0.00200	20.0	2.9%
	L/G Cavity	0.00100	10.0	1.4%
	Misc	0.00500	50.0	7.1%
	EX-SUM	0.01200	120.0	17.1%
Total		0.07000	700.0	100.0%

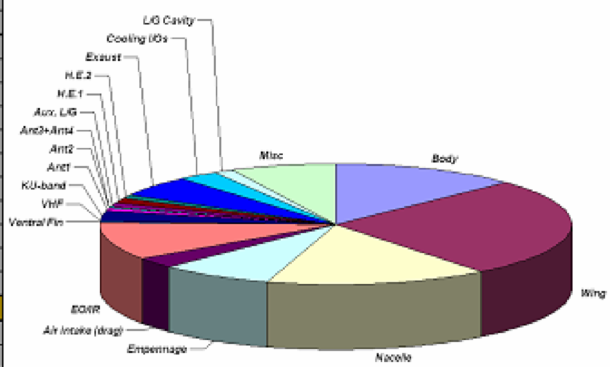


Figure 3: Minimum Drag Coefficient Breakdown

Figure 3 shows the minimum drag coefficient breakdown of SUAV generated through the unpowered wind tunnel test and CFD. Here, “unpowered” means that the rotor wake effects on the airframe aerodynamic coefficients are not considered during the wind tunnel test. The minimum drag measured through the wind tunnel test is 580 counts. The biggest portion of the drag is from the wing and it amounts to 27% of the total minimum drag. The drag of extra parts such as engine exhaust, cooling inlet/outlet and the landing gear cavity is estimated by CFD and it amounts to 120 counts. Total minimum drag coefficient of SUAV is 700 counts at last.

The lift curve and the drag polar of SUAV are depicted in Figure 4 and 5, respectively. The solid line denotes the powered data and the dashed line denotes the unpowered data. As can be seen clearly in those figures, the powered effect has a favorable effect on the aerodynamic coefficients; increases the lift and reduces the drag.

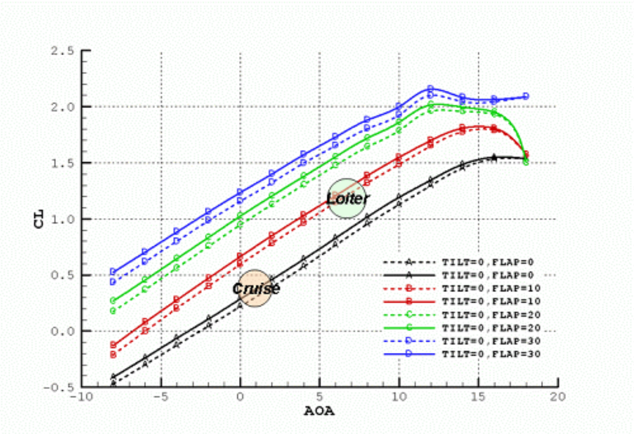


Figure 4: Lift Curve of SUAV

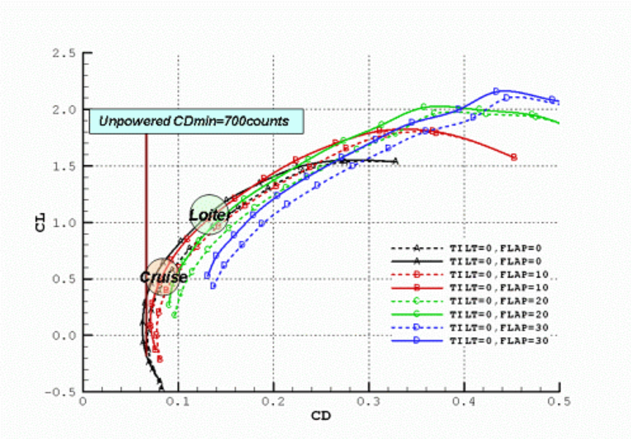


Figure 5: Drag Polar of SUAV

3. AIRPLANE MODE PERFORMANCE

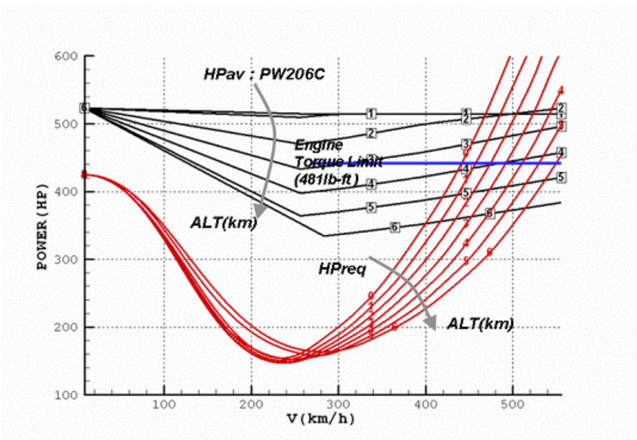


Figure 6: Speed vs. Required Power

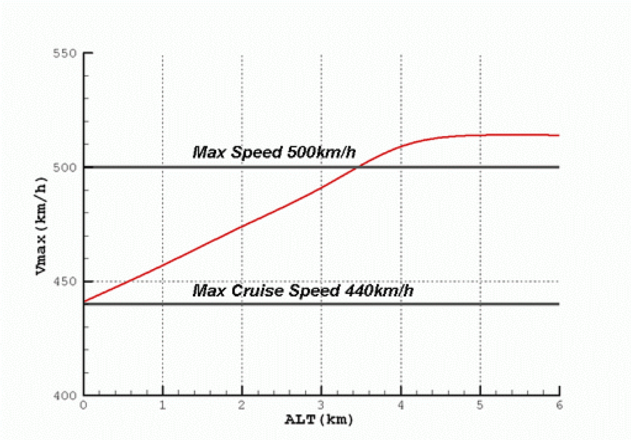


Figure 7: Altitude vs. Max. Speed

Figure 6 shows the required power variation with altitude. Here, small number label denotes the altitude. The required powers are calculated at V = 0 km/h (Hover Mode) and over V = 250 km/h, and the curves between 0 km/h and 250 km/h are just smooth connections between those two points. The required power at hover mode is calculated at sea level, 35°C and 8 ft/sec climb condition. As can be seen clearly in Figure 6, the maximum speed is limited by the engine torque limit below an altitude of 4 km, and above 4 km the available power limits the maximum speed of SUAV.

As a result, the maximum speed variation with altitude is shown in Figure 7. The maximum speed increases as the altitude increases and the maximum speed shows no variation over 4.2 km. The target maximum speed of SUAV is 500 km/h and it can be reached at the altitude of 3.4 km.

Figure 8 shows the endurance parameter variation and figure 9 shows the range parameter variation with speed and altitude. The number label also denotes the altitude. As shown in figure 8, the endurance decreases as the speed increases and the endurance increases as the altitude increases. Therefore, the low speed and high altitude are favorable for the long endurance. In case of range parameter, the range increases as the altitude increases, and there exists an optimal flight speed for the best range at each altitude. The optimal flight speed ranges from 330 km/h to 380 km/h.

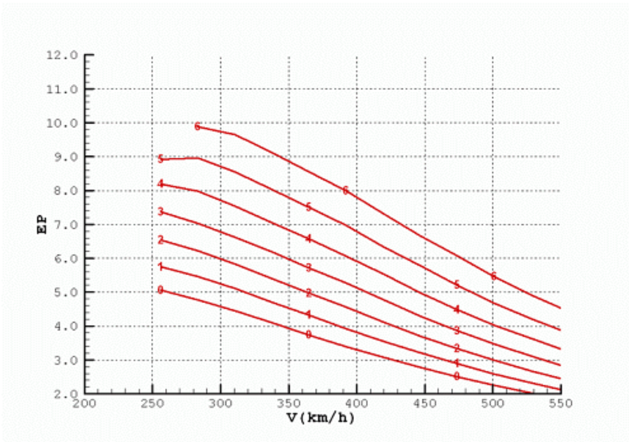


Figure 8: Speed - Altitude – EP

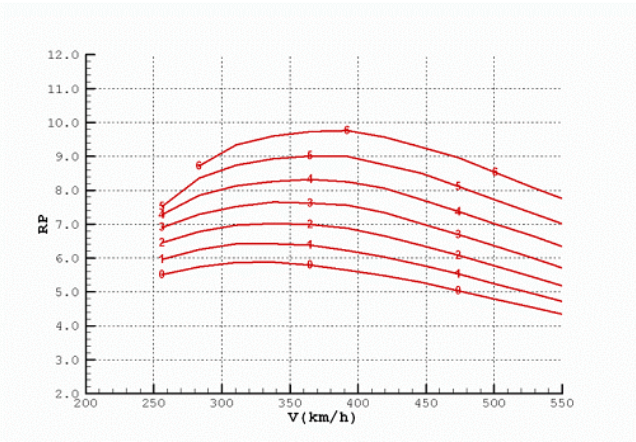


Figure 9: Speed - Altitude - RP

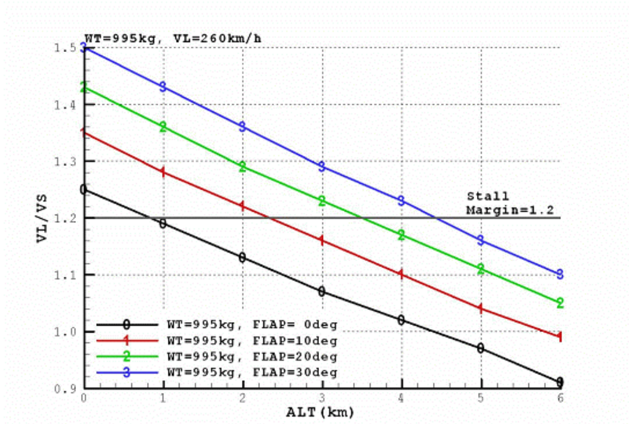


Figure 10: Altitude vs. Stall Margin (Weight =995kg)

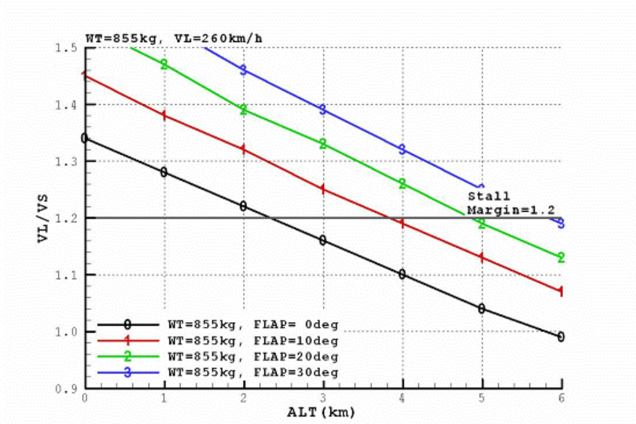


Figure 11: Altitude vs. Stall Margin (Weight=855kg)

The stall margin is defined as a ratio of a flight speed to a stall speed at a given flight condition, and the target stall margin of SUAV is over 1.2. The optimal loitering speed of SUAV for the long endurance is 260 km/h, and figure 10 and 11 show the stall margins of SUAV at that speed. As you can see clearly in figure 10, in order to maintain the stall margin over 1.2 at an altitude of 3 km or more with the maximum take-off weight of 995 kg, about 15° or more flap deflection angle is required. In case of 855 kg half-fuel weight, about 5° or more flap deflection angle is needed to secure the stall margin. From these results, it can be concluded that during loitering flight, about 5° to 15° of flap deflection is needed to maintain the adequate stall margin.

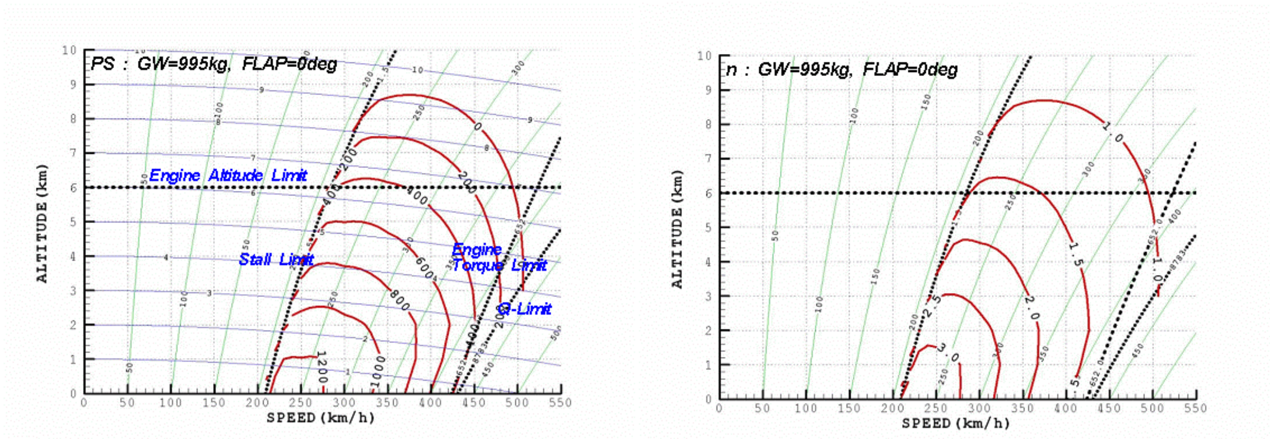


Figure 12: Flight Envelope (Weight=995kg, Flap =0°, Specific Excess Power (PS) & Load Factor (n))

The flight envelope of SUAV is shown in figure 12. The flight envelope can be depicted by the specific excess power (PS) contour and load factor (n) contour as follows.

- Specific excess power (PS) contour: the specific excess power contour where the load factor n = 1

$$\begin{bmatrix} V \\ H \\ n \end{bmatrix} \Rightarrow \begin{bmatrix} L = nW \Rightarrow C_L \Rightarrow C_D \Rightarrow D \\ T_{AV} \end{bmatrix} \Rightarrow \begin{bmatrix} PS = \dfrac{V(T-D)}{W} \end{bmatrix} \tag{1}$$

- Load factor (n) contour: the load factor (n) contour where the specific excess power PS = 0

$$\begin{bmatrix} V \\ H \\ PS \end{bmatrix} \Rightarrow \begin{bmatrix} W \Rightarrow C_L \Rightarrow C_D \Rightarrow L/D \\ T_{AV} \end{bmatrix} \Rightarrow \begin{bmatrix} n = \left(\dfrac{T}{W}\right)\left(\dfrac{L}{D}\right) \end{bmatrix} \tag{2}$$

The limit lines on the flight envelope are defined as follows

- Engine altitude limit: 6 km
- Stall limit: $C_{L_{\max}}$ at flap deflection angle = 0°
- Engine torque limit: 652 Nm
- Max. q limit: 8,783 N/m^2 (q at altitude = 3 km, speed = 500 km/h)

As shown clearly in figure 12, the maximum speed of SUAV is limited by engine torque limit, not by q limit.

4. HELICOPTER MODE PERFORMANCE

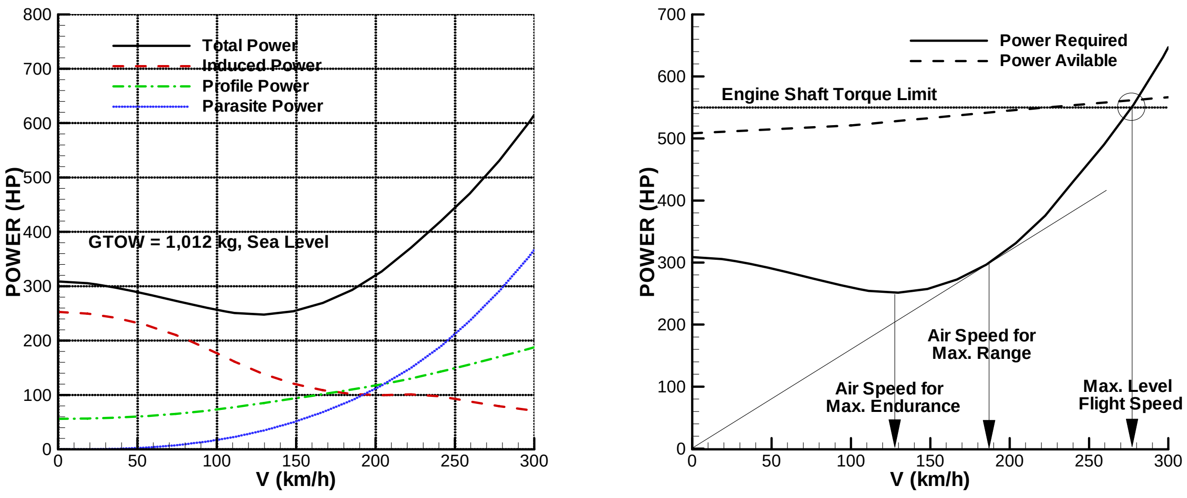


Figure 13: Speed vs. Required Power

Figure 13 shows the required power variation with a forward speed in helicopter mode. In addition to the total required power, the induced power, profile power and parasite power are also depicted in the left figure. Among the total power, the induced power takes a large portion at the low speed region, but as the speed getting faster, the portion of the induced power is going down and the portion of the other profile power and parasite power is going up. The profile power originated from the blade drag has a tendency to increase in proportion to the square of the advancing speed. Also the parasite power required to overcome the airframe drag tends to increase in proportion to the cube of the advancing speed. From the right figure, the maximum speed of SUAV in helicopter mode is 277 km/h and limited by the engine torque limit, not by the available power limit. The optimal speeds for the best endurance and best range are also depicted in the right figure. The resulting helicopter mode performances of SUAV are well summarized below.

- Maximum level flight speed: 277 km/h
- Optimal speed for best endurance: 128 km/h
- Endurance in helicopter mode: 2.97 hours
- Optimal speed for best range: 187 km/h
- Range in helicopter mode: 510 km
- Hover ceiling: 2.4 km

5. CONVERSION MODE PERFORMANCE

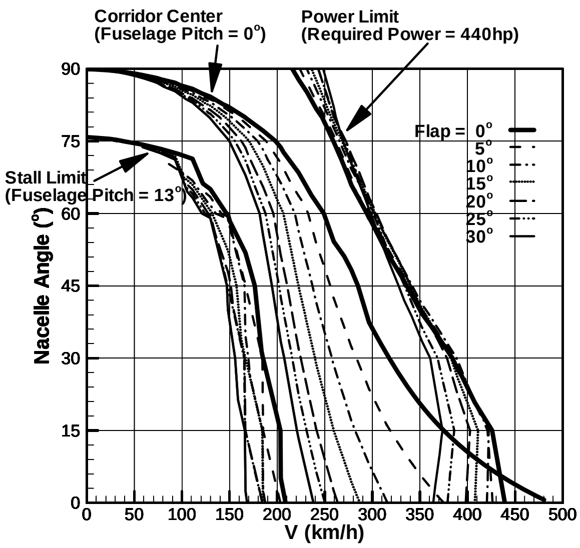


Figure 14: SUAV Conversion Corridor Variation with Flap Deflection

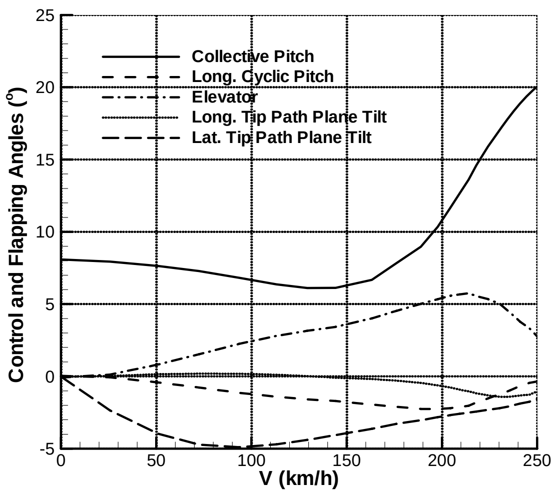


Figure 15: Control and Flapping Angle Variation along Corridor Center (Flap=25°)

The tilt rotor aircraft transforms its configuration through conversion mode. During conversion mode, the nacelle rotates from the vertical position (nacelle angle 90°) to the horizontal position (nacelle angle 0°) and conversely to transform the configuration between helicopter mode and airplane mode. Figure 14 shows the conversion corridor of SUAV. The conversion corridor of SUAV is generated as follows. At first, fix the nacelle angle at 90° and perform velocity sweep trim analyses from a low speed to a high speed. The conversion corridor is generated by repeating this velocity sweep trim analyses with changing the nacelle angle from 90° to 0°.

The stall limit in figure 14 is defined as the limit where the fuselage pitch equals to 13°, and the aircraft stalls below this stall limit. The power limit is the line where the required power equals to the available power, and aircraft can’t fly beyond the power limit due to the lack of power. In this study, the corridor center is defined as the passage where the fuselage pitch equals to 0°, and the conversion flight between helicopter and airplane mode follows this corridor center. As the flap deflection angle is getting smaller, the corridor center is moving closer to the power limit and the overall conversion speed is getting faster, and the fast speed during the conversion flight is unfavorable for the safe conversion. The moderate flap deflection is, therefore, required for the safe conversion but the excessive flap deflection makes the corridor center too close to the stall limit, so about 25° flap deflection is appropriate for the safe conversion.

Figure 15 shows the variation of the control and flapping angles along the corridor center. The flap deflection is 25° in this case. The flapping angle limit of SUAV is ±10° and the lateral and longitudinal tip path plane tilts during conversion do not exceed the flapping limit. In case of collective pitch, it decreases gently until the speed reaches 150 km/h and increases abruptly above that speed.

6. MISSION PERFORMANCE

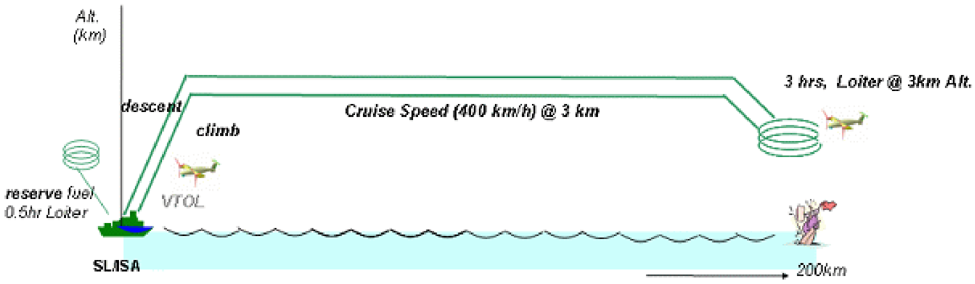


Figure 16: Standard Mission Profile of SUAV (Emergency Catch Up)

Table 1: Segments of Mission Profile

Mission Segment	Mode	Time (min)	Time (%)	Altitude (km)	Speed (km/h)
Pre-check & Taxi	HC	8	2.7%	0.0	0
Vertical Takeoff	HC	1	0.3%	0.0	0
Climb to TR Alt.	HC	1	0.3%	0.0 ~ 0.2	0 ~ 100
Transition	HC-AP	1	0.3%	0.2	100 ~ 250
Climb to Mission Alt.	AP	8	2.7%	0.2 ~ 3.0	250 ~ 400
Cruise	AP	30	10.0%	3.0	400
Loiter	AP	180	60.0%	3.0	250
Cruise	AP	30	10.0%	3.0	400
Descent to TR Alt.	AP	7	2.3%	3.0 ~ 0.2	400 ~ 250
Transition	AP-HC	1	0.3%	0.2	250 ~ 100
Descent to LD Alt.	HC	1	0.3%	0.2 ~ 0.0	100 ~ 0
Landing	HC	2	0.7%	0.0	0
Emergency	HC,AP	30	10.0%	0 ~ 1.0	0 ~ 250
Total		300	100.0%		

The standard mission profile of SUAV is shown in figure 16. The standard mission profile is defined as follows. At first, SUAV makes a flight of 200 km mission range distance in 30 minutes and it loiters for 3 hours on station for the reconnaissance and surveillance mission, and then it returns. Besides this mission profile, there are other performance requirements such that the maximum speed should be greater than 500 km/h and the endurance should be greater than 5 hours. Table 1 summarizes the flight mode, time, altitude and the speed of each mission segment.

The basic mission performance is analyzed under the following flight conditions.

- $C_{D_{\min}}$: 700 counts
- Loitering altitude: 3.5 km
- Loitering speed: 250 km/h
- Loitering radius: 2 km
- Loitering flap deflection: 10°

The mission performance analysis results are well summarized in table 2 according to the target weight of each development phase. The final target weight of SUAV is 945 kg and the phase 2 target weight is 995 kg. In all cases, the loitering time on station is greater than 3 hours and also the maximum endurance is greater than target endurance of 5 hours. Figure 17 shows the variation of angle of attack following the mission profile.

Table 2: Mission Performances of SUAV

Phase	MTOW (kg)	FUEL (kg)	CDmin (cts)	Mission E (hrs)	Max E (hrs)	Max V (km/h)
2	995	280	700	3.07	5.35	514
3	945	280	700	3.21	5.56	516

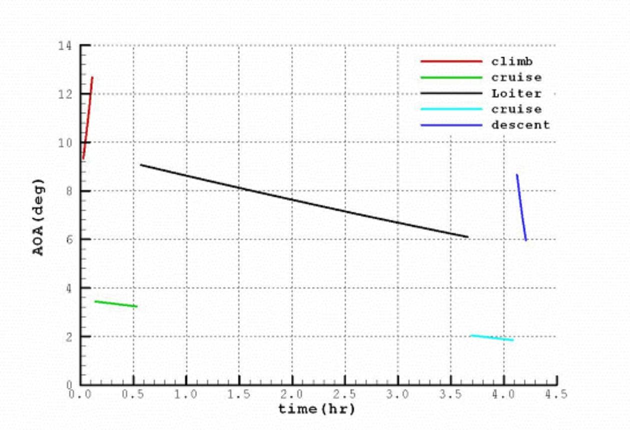


Figure 17: Angle of Attack Variation along Mission Profile

7. CONCLUSION

- Smart UAV System with innovative technology has been developed since 2002 in KOREA. The target maximum speed and endurance of SUAV are 500 km/h and 5 hours, respectively. Smart UAV System also has the smart capabilities such as the autonomous and sense & avoid flight.
- The performance of SUAV is estimated using CAMRAD II coupled with engine deck.
- During loitering flight (250 - 260 km/h), the flap deflection of about 5 ° to 15 ° is required to maintain adequate stall margin.
- 20°- 25 ° flap deflection is appropriate for the safe conversion.
- Through the performance analysis, it is clearly shown that the maximum speed of SUAV is over 510 km/h, and the maximum endurance is greater than 5.3 hours.
- It can be concluded that the target performances are well achieved.

REFERENCES

[1] Mike Hirschberg, “Bell Makes First Flight with New Eagle Eye Demonstrator,” Vertiflite, Vol.52, No.1, Spring 2006.

[2] Soojung Hwang, Myeong Kyu Lee, Soohun Oh and Seongwook Choi, “Collision Avoidance Maneuver Simulation of Tilt Rotor Unmanned Aerial Vehicle,” 44th AIAA Aerospace Sciences Meeting and Exhibit, Reno, January 2006.

[3] Wayne Johnson, "Rotorcraft Aeromechanics Applications of a Comprehensive Analysis," Heli Japan 98, April 1998.

[4] Wayne Johnson, “Calculation of Tilt Rotor Aeroacoustic Model (TRAM DNW) Performance, Airloads, and Structural Loads,” AHS Aeromechanics Specialists' Meeting, November 2000.