TILT ROTOR/WING CONCEPT FOR MULTI-PURPOSE VTOL UAV

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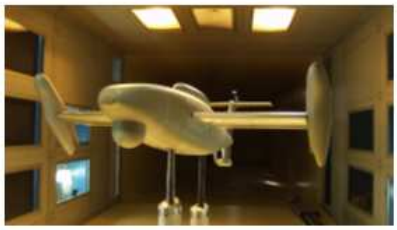
Abstract: Tilt rotor/wing concept to show enhanced performance in low speed mission is presented. Three types of stud wing on the existing tilt rotor configuration are suggested and their characteristics are compared. Aerodynamic analysis indicates that the stud wing concept gives significant performance improvement in the endurance and range at low speed regime when compared with the tilt rotor. Penalties of the stud wing are discussed from the perspectives of conversion corridor, structural weight, configuration design, and cross wind stability. This study concludes that the advantage of the stud wing in general UAV mission performance is so significant as to surpass the penalties in other perspectives investigated.

1 INTRODUCTION

Tilt rotor has risen recently as a strong alternative for the future high speed VTOL air vehicle concept in civil and other applications. The best advantage of the tilt rotor concept is known to have higher flight speed and endurance performance superior to the conventional helicopter. Nevertheless, the tilt rotor could not reach the conventional fixed wing airplane in the performance of range and endurance since it has some inherent limits caused by relatively small aspect ratio wing, complicated pylon conversion system, high fuel consumption.

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 475 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 wind tunnel test model of SUAV without proprotor installed in the test section of the KARI subsonic wind tunnel. Small scaled flight demonstrators have been developed and tested as shown in Figure 1(b).



(a) SUAV Wind Tunnel Model

(b) SUAV Flight Demonstrator

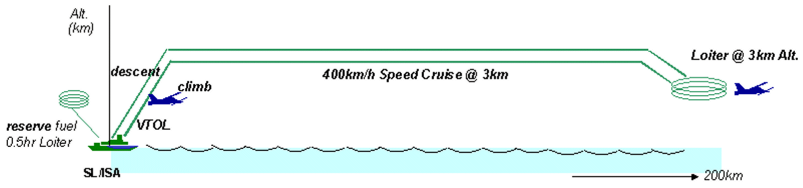
Figure 1. Tilt Rotor Unmanned Aerial Vehicle (SUAV)

This study was motivated to expand wider range of UAV application by surmounting the limited tilt rotor UAV performance such as endurance and range.

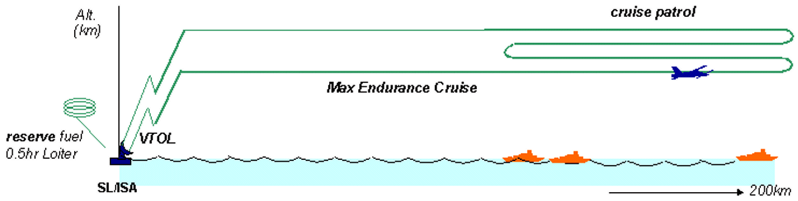
2 RESULTS AND DISCUSSION

2.1 Mission Analysis

SUAV has two primary missions of emergency catch-up (ECU) and long endurance patrol (LEP) as shown in Figure 2. The ECU mission requires high speed capability over the range of 200km, while the LEP mission requires long endurance performance to patrol over the broad mission area. These two missions may be contradictory to each other in the aircraft design perspective. For example, the short and thin wing is better for the high speed, but the long and high-cambered wing is preferred for the long endurance. Basically, the tilt rotor has short wing to efficiently mount the power train and rotor system at the end of the wing. And its wing section is relatively thick to accommodate the transmission shafts inside. The short and thick wing of the tilt rotor shows relatively poor aerodynamic performance when compared with the fixed wing aircraft. The drag rise due to the thick wing can be offset by the high propulsion power because the tilt rotor has powerful propulsion to have VTOL capability. However, there is no compensation in the inferior endurance performance. Thus, the poor endurance of the tilt rotor is one of primary penalties when compared with fixed wing aircraft. Especially, it can be a critical penalty in the UAV applications, which most of missions can be found by surveillance or patrol. The tilt rotor/wing concept presented in this paper was derived from the necessity to improve the endurance performance for the surveillance UAV application.



(a) Emergency Catch-UP (ECU) Mission



(b) Long Endurance Patrol (LEP) Mission

Figure 2. Primary Mission Profiles of SUAV

Figure 3 shows the aspect ratio values of various air vehicles with some birds. Tilt rotors show the aspect ratio range of 4~6, while the fixed wing UAVs show the double times higher aspect ratio than the tilt rotors. The aspect ratio of the tilt rotors is even lower than the commercial aircrafts. As well known in the aerodynamics, high aspect ratio wing shows high lift to drag ratio, thus gives long endurance and range performance. Especially, the increase of aspect ratio much improves the endurance rather than the range because the endurance factor is mainly influenced by the lift in the propeller driven aircraft. The main idea of tilt rotor/wing is to increase the wing aspect ratio to improve the endurance performance of the tilt rotor.

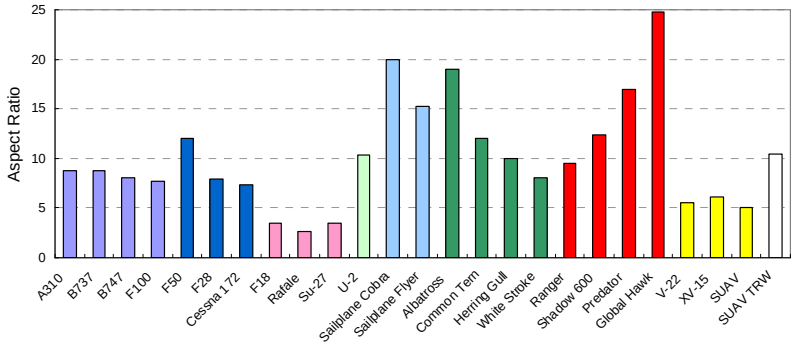
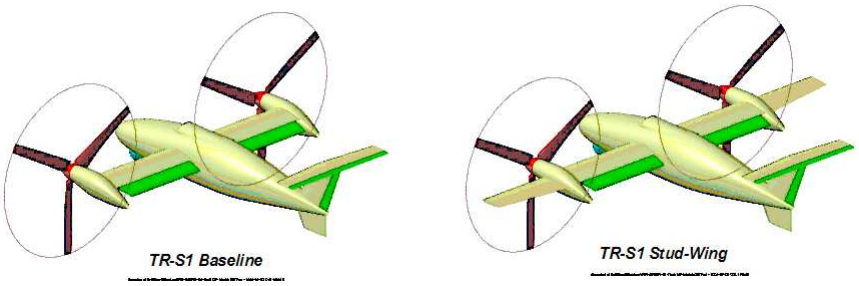


Figure 3. Aspect Ratios of Air Vehicles with Some Birds

2.2 Configuration Design

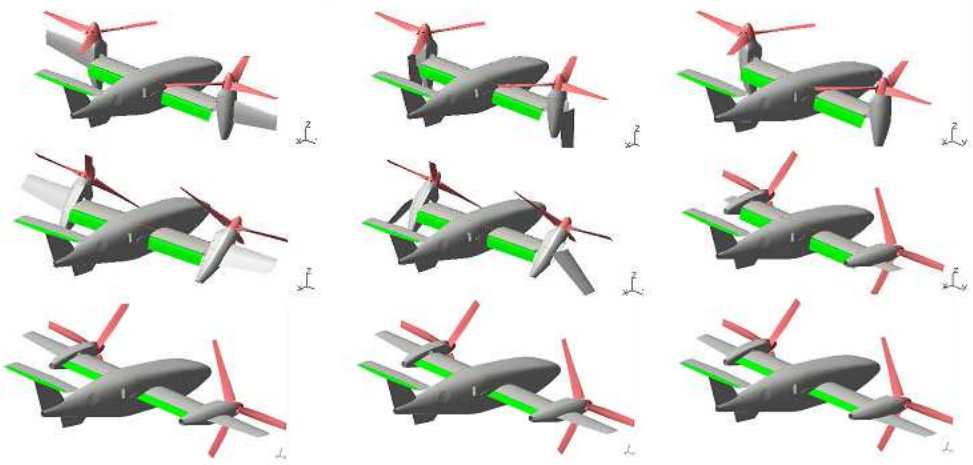
As can be seen from Figure 2, the most of SUAV missions are performed in the airplane mode. The helicopter mode is mostly confined to the take off and landing, and there is no hover requirement in the primary mission profiles. From this reason, the performance in the airplane mode is the most significant in the tilt rotor mission analysis. Figure 4 shows the configuration of tilt rotor/wing concept in the airplane mode. The wing was extended out from the nacelle to the outboard end of the proprotor tip trace. This is to keep the geometric width of the air vehicle because the portability is one of important factors in UAV operation. The extended wing can be easily separated from the nacelle as the rotor blade can be easily disassembled from the rotor hub. It means that the optimum configuration can be chosen dependent on the each different mission. The extended wing was named as stud-wing in this study. The wing section of the stud wing is thinner than the main wing because it does not need to accommodate the drive shaft inside. The thickness and camber of the stud wing can be optimized for the minimum drag and the best air load distribution. From the design as shown in Figure 4, the aspect ratio of the tilt rotor/wing is 10.5, whereas that of the original tilt rotor is 5.0.



(a) Tilt Rotor (b) Tilt Rotor with Stud Wing

Figure 4. Tilt Rotor/Wing Concept in Airplane Mode

It is important to reduce the blockage effect of rotor wake by wing for the maximum rotor performance in the helicopter mode. Figure 5 shows three types of stud wing in the helicopter and transition modes. The first type as seen from Figure 5(a) shows the stud wing attached and fixed to the nacelle. From this concept, the tilt rotor/wing was named because it seems to be a hybrid configuration between tilt rotor and tilt wing. This is the simplest concept which gives the minimum impact on the existing tilt rotor design. It is easy to assemble and disassemble the stud wing from the nacelle. The main wing should be strengthened by considering the additional weight and load of the stud wing. But, its effect would be small because the load on the stud wing acts in the opposite direction against the nacelle weight in the wing design flight condition. On the other hand, the disadvantage of this concept is to give worse stability and performance in the hover and conversion flight conditions. Although the SUAV has no requirement of hover during the specified mission profiles as shown in Figure 2, the stability should be carefully investigated for the precise landing in the cross wind or moving deck environments. Also, the drag rise due to the stud wing in the helicopter mode may cause an issue during the conversion flight.



(a) Fixed Type Stud Wing (b) Fold Type Stud Wing (c) Slide Type Stud Wing

Figure 5. Tilt Rotor/Wing Concepts in Helicopter and Transition Modes

Figure 5(b) and Figure 5(c) show the fold and the slide types of stud wing concepts to minimize the stability and performance degradation in the hover and conversion flights. The fold

type of stud wing as shown in Figure 5(b) can play a role of the landing gear strut in the helicopter mode. When the air vehicle converts from the helicopter to airplane modes, the nacelle with rotor rotates to the wing spanwise axis, and the nacelle conversion actuator folds up to the airplane mode configuration. The stud wing is mechanically linked to the nacelle conversion actuator. This concept has no penalty in the hover stability and little drag rise in the conversion flight. And, the auxiliary landing gear system under the nacelle can be simplified if it can be well compromised with the stud wing design. However, the mechanical pivot system linked to the nacelle conversion actuator to rotate the stud wing can be complicated when compared with the first concept of nacelle fixed stud wing. The third one is the slide type of stud wing as shown in Figure 5(c). The stud wing is located under the wing in the helicopter mode. After the conversion of nacelle, the stud wing is slide out through or under the nacelle by the mechanical system linked to the nacelle conversion actuator. The vertical location of the stud wing would be lower than the main wing. This concept can solve the disadvantages of the other two concepts, while it needs the space which the stud wing can pass through or under the nacelle. The actuating system to slide out the stud wing could be more complicated than the fold type one.

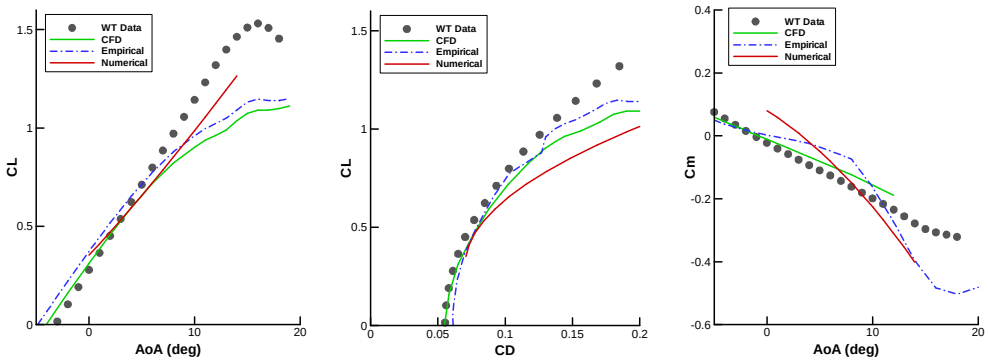
Summing up, the first option of stud-wing fixed to the nacelle is the most efficient and simplest concept for the tilt rotor/wing only if it does not have a significant negative impact on the other design and operational areas.

2.3 Aerodynamic Performance

The aerodynamic performance of the tilt rotor/wing was estimated and compared with the tilt rotor. The aerodynamic performance in this paper is confined to the airplane mode because the missions of the tilt rotor UAV were mostly performed in the airplane mode. As mentioned earlier, one of the penalties of tilt rotor is the inferior performance in the low speed flight condition when compared with the fixed wing aircraft. It is mainly due to the high fuel consumption and low aerodynamic efficiency. The relatively high fuel consumption of the tilt rotor is unavoidable because the tilt rotor engine should be selected based on the vertical take off condition. As a result, the available propulsion power is excessively higher than the require power in the airplane mode. This causes the high fuel consumption in the most part of mission flight. In addition, the wing design point of the tilt rotor is generally the high speed cruise condition because the high speed capability is one of the main advantages compared with the helicopter. The wing of the tilt rotor designed under the high speed condition needs relatively high angle of attack in the low speed condition. As a result, it gives lower performance of endurance and range in the low speed flight. Although the flap deflection for the higher lift in the low speed can help to improve the endurance performance, it has a limit due to the rapid drag rise when the flap deflection angle goes up over a certain value.

Figure 6 shows the predicted and measured aerodynamic characteristics of SUAV tilt rotor configuration. The result of some numerical methods shows good agreements with the wind tunnel test data. For the simplicity of the analysis, the panel method with viscous correction was applied to the aerodynamic performance prediction for the tilt rotor/wing. Figure 7 shows the predicted endurance and range factors for the SUAV tilt rotor and tilt rotor/wing configurations. From these results, the endurance of the tilt rotor shows the peak around the angle of attack of 5 degree, while the range factor shows the peak around 3 degree. In the primary mission profiles, the high cruise speed of SUAV is defined by 400 km/h, while the low cruise or loitering speed is 250 km/h. The angle of attacks required in the high and low cruise speeds

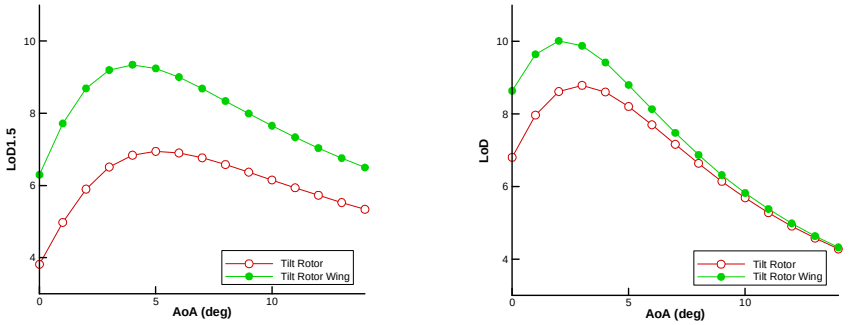
are 0 degree and 9 degree, respectively. Figure 7 shows that the low speed performance is degraded by 10% ~ 30% due to the deviation from the optimum operational points.



(a) lift curve (b) drag polar (c) pitching moment

Figure 6. Aerodynamic Characteristics of SUAV Tilt Rotor

From the estimated results of the tilt rotor/wing as shown in Figure 7, the stud wing successfully improves the aerodynamic performance. With the stud wing, the peak value of endurance and range factors are increased by 25% and 15%, respectively. Additionally, the endurance and range factors are improved by the decrease of the required angle of attack due to the extended wing. For example, the required angle of attack of the tilt rotor/wing in the low speed is 5 degree, while the tilt rotor needs 9 degree. Figure 7 shows that the total improvement of endurance factor due to the stud wing can be about 40%. This is a significant enhancement of the low speed performance even if the analysis results have some uncertainty. On the other side, the stud wing degrades the maximum cruise speed capability. From the drag rise due to the stud wing, the maximum cruise speed was estimated to be decreased by 5%~10% when compared with the original tilt rotor.



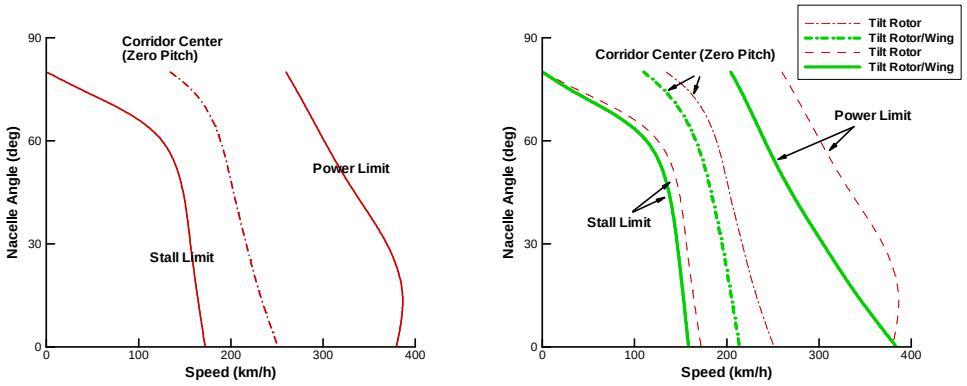
(a) Endurance Factor (b) Range Factor

Figure 7. Predicted Performances of SUAV Tilt Rotor and Tilt Rotor/Wing

If the maximum speed degradation due to the stud wing cannot be accepted in the specific mission, the stud wing can be taken out before the mission flight. On the other hand, in case of the mission which the other general performances except the speed are important, the stud wing configuration can be easily provided for the great improvement of mission performance.

2.4 Conversion Characteristics

The conversion from the helicopter to the airplane modes is a peculiar feature of the tilt rotor. The reliability in the conversion flight is directly related to the safety and reliability of the tilt rotor aircraft. In the conversion flight, not only the hardware of conversion system but also the software such as conversion corridor and flight control algorithm is important for the reliability. In case of the SUAV, the conversion scenario is scheduled by many flight control parameters such as nacelle angle, proprotor pitches, elevator, engine throttle, etc. Figure 8(a) shows the conversion corridor of the SUAV tilt rotor defined by CAMRAD simulation (Ref.3). The three lines shown in Figure 8(a) mean respectively stall limit, corridor center, and power limit. Figure 8(b) shows the estimated results of the SUAV tilt rotor/wing configuration. It can be seen from Figure 8(b) that all three corridor lines of the tilt rotor/wing shift to the left when compared with the tilt rotor. Especially, the power limit boundary is much shrunk by the drag rise in the helicopter mode. There is a significant drag rise due to the stud wing in the forward helicopter flight, but it decreases as the conversion completes. The analysis result showed that the addition of the stud wing decreased the maximum speed in the helicopter mode by 23%. However, the absolute magnitude of the maximum speed in the helicopter mode is insignificant in the tilt rotor UAV application. On the other hand, Figure 8(b) shows that the stud wing improves the stall limit boundary a little because the stall characteristics get better by the stud wing. As a result, the conversion corridor envelop was shrunk due to the stud wing, and the corridor center line was shifted to the left direction a little. However, it can be concluded that the tilt rotor/wing still shows satisfactory conversion corridor characteristics for the reliable conversion flight.



(a) Tilt Rotor (b) Tilt Rotor/Wing

Figure 8. Conversion Corridors of SUAV Tilt Rotor and Tilt Rotor/Wing

2.5 Other Aspects

One of penalties by the stud wing is the weight increase. The weight increase due to the stud wing can be attributed to three things ; the stud wing itself, mounting structure, and the main wing reinforcement. With several assumptions, the weight prediction was performed from the computed load distributions at the same design condition with the tilt rotor. One of the assumptions is that the main wing should be strengthened to have the same deflection of main wing tip inside the nacelle. From the weight analysis results, the weight increase due to the stud wing is 1.5% of the total aircraft weight. This value corresponds to approximately 5% of the total fuel weight of SUAV. The increased weight came from the main wing reinforce, stud wing itself, and mounting structure in the order of size. As a result, it was concluded that the

amount of the weight increase due to the stud wing was acceptable because the performance gain by the stud wing is much bigger than the loss of the fuel due to the weight increase.

The other penalty by the stud wing is the complexity of configuration design. For example, the nacelle of the tilt rotor is generally full of many complicated components such as transmission, nacelle conversion system, rotor control system, sensors, tubes, wires, and so on. The nacelle is designed to have the smallest cross sectional area for the minimum drag in the airplane mode. And the sealing between the main wing and the nacelle of moving part is to be carefully designed to minimize the interference drag. Therefore, the addition of stud wing with its mounting system may increase the nacelle size, thus and the drag. Especially, the fold or slide types of stud wing can give higher additional drag due to the actuating system.

The stability in the hovering flight can be deteriorated by the addition of stud wing. In the helicopter mode, the tilt rotor/wing configuration of the nacelle fixed type shows the inboard wing of tilt rotor and the outboard wing of tilt wing. Therefore, it is more susceptible to the cross winds due to the exposed area of the stud wing and higher use of available control power to maintain stability and alleviate gusts when compared with the tilt rotor. The stability level in hover mode, especially the cross wind susceptibility, of the tilt rotor/wing would be between tilt rotor and tilt wing. From the simple cross area analysis, it was found that the tilt rotor/wing showed the similar level of cross wind susceptibility with the helicopter. But it is difficult to quantify the hover mode stability and compare with the other UAVs because configurations of UAV are too diverse. Anyway, the tilt rotor/wing needs more robust stability augmentation system to have the same envelope of low speed operation in the helicopter mode with the tilt rotor. It can be important for the precise landing in the severe wind or on the moving deck environments.

3 SUMMARY

Tilt rotor/wing concept is suggested and investigated to enhance the mission performance of the tilt rotor UAV. The addition of the stud wing to the existing tilt rotor configuration shows significant improvement in endurance and range performance in the UAV mission especially at low speed cruise or loitering flight. Of the three stud wing configurations, the nacelle fixed concept gives the least impact on the existing tilt rotor design. The penalties of the stud wing are discussed considering aspects of conversion corridor contraction, weight increase, nacelle design complexity and cross wind susceptibility. As a result, it can be concluded that the gain in mission performance by the stud wing can be far superior to its penalties, especially when the tilt rotor UAV is to be utilized for the multi-purpose missions.

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