The Development of 4-blades new rotor system for an unmanned helicopter with 100kg-class MTOW

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ABSTRACT

KARI has developed a new advanced rotor system with a hingeless hub and a new planform shaped blade. This research aims at the condensation of the previous accumulated rotor technologies by developing a new rotor system for an unmanned helicopter with 100kg-class MTOW. KARI adopted 4-bladess hingeless rotor system and a new fuselage for this unmanned helicopter with 100kg-class MTOW. This new developed rotor system is called as KURS (KARI Unmanned Rotor System). This paper will describe the newly developed advanced rotor system mainly. This hingeless hub and 4-bladess with advanced shape were installed on the existing Yamaha R-Max unmanned helicopter by replacing the existing 2-bladess rotor system and fuselage. For this development, The initial sizing of rotor was performed on using the existing 2-bladess geometric data and analysis. Basic performance analysis was conducted by using FLIGHTLAB. Dynamic analysis was conducted by using CAMRAD II. Blade design was done by using CORDAS which was developed in KARI. Fully composite blade was developed and the hingeless hub design was performed by modifying an existing small-scaled hingeless hub system. Advanced blade was developed through being optimized to the unmanned helicopter. This blade has three airfoils and advanced tip shape for reduction of noise. Ground test was conducted on the KARI GSRTS (General small-scale rotor test system) and LSWT (Low speed wind tunnel). The thrust and torque was measured at each collective pitch angle and rotor rotating speed. The loads were measured from 2-axis rotating balance installed between the hub and rotating shaft in the ground test. Also, before flight test, the tie-down test was performed. For this tie-down test, KARI developed special tie-down test bench which can estimate thrust and torque. Fundamental flight test was also performed at KARI flight test center at Goheung site. The test results show that vibratory load and noise were reduced. General performance improvement of KURS helicopter was achieved by about 5%~10% compared to that of the original R-Max.

Introduction

The application of unmanned helicopters to the usual human life is increased. Especially in agricultural application, these unmanned helicopters can be easily applied. The demands of this agricultural unmanned helicopter are increasing in Korea since the population of agricultural people is decreasing as times goes by. Also, this agricultural unmanned helicopter can be applied to commercial observation of land and building which human has a difficulty and danger to access. In KARI, the research program of unmanned helicopter was launched last five years. This program has two main targets. The first is to develop and acquire the key technology which can be applicable to improve performance of helicopter. The second is to prepare the future national demands of unmanned helicopter for agricultural applications or commercial observation and photos.

This paper will describe the some part of the first target which was focused on the advanced rotor system to the unmanned helicopter with 100kg-class MTOW. KARI has developed has several small-scaled rotor system which has various hingeless hub system. KARI also has designed its own blade. These works had done in the several research and development program in KARI. KARI built a research program to develop a new rotor system to be applied to a real flight helicopter to demonstrate its accumulated technology and to improve the existing rotor system. Also, our environmental situations were changed. The first, Korean farmer started to use unmanned helicopter for the purpose of spraying agricultural chemicals. Furthermore, some companies started to develop unmanned helicopter for domestic agricultural purpose.

The basic platform helicopter was selected considering the possibility of future application and stable flight capability. Also this basic platform helicopter should have sufficient payloads for the application of agriculture, land observation and photos. As a basic platform helicopter, the R-Max helicopter developed by Yamaha was selected after considering several candidates. This helicopter has sufficient payloads(30kg) for future application and its stable flight capability was already verified. Also this helicopter has two blades with rigid hub system. So, it is more convenient to show a new rotor system with four blades hingless rotor system. The general characteristics of this R-Max helicopter are described in the following table 1 and Fig 1 [1].

Fig. 1. The R-Max helicopter

Table 1. General Specification of R-Max Helicopter

Specification		Unit
Empty Weight	58	kg
Payload	30	kg
Endurance (Full payload)	60	min
Control Range	150	m
Main Rotor Diameter	3115	mm
Main Rotor RPM	830	rpm
Tail Rotor Diameter	545	mm
Overall Length	3630	mm
Body Width	720	mm
Overall Height	1080	mm
Engine RPM	6350	rpm
Engine Size	246	ccm
Installed Power	21	PS

The several rotor hub systems KARI has developed were described in the following.

The first hub system is MHHS which is a metallic hingeless hub system. This hub system was developed for the purpose of Mach small-scale test for 2-m GSRTS. The general configuration is shown in Fig 2. The main idea came from the Lynx rotor head [2, 3].

Fig. 2. The hub system : MHHS

The second hub system is MHHHS which is a metallic-hybrid hingeless hub system. This hub system was developed for the purpose of froude small-scale test. The flexure was made of engineering material like torlon to optimize dynamic characteristics. The general configuration is shown in Fig 3 [4].

Fig. 3. The hub system : MHHHS

The third hub system is ACHHS which is a advanced composite hingeless hub system. This hub system was developed for the purpose of froude small-scale test to demonstrate the improvement of aeroelastic stability and the weight reduction to replace existing flexure of MHHHS metioned above with advanced composite materials. The output was that the more than 40% aeroelastic stability improvement was achieved without any loss of rotor performance. In addition, the weight reduction of composite hub compared with existing metallic hybrid hub was also 56% without any loss of performance [5]. The general configuration is shown in Fig 4.

Fig. 4. The hub system : ACHHS

The fourth hub system is the NRSHS which is the Next–generation Rotor System hub system. This NRSHS has a fully composite hingeless hub system with an elastomeric bearing and damper. This hub system was developed for the purpose of froude small-scale test to demonstrate the improvement of aeroelastic stability and the weight reduction for the next future advanced rotor system. The general configuration is shown in Fig 5.

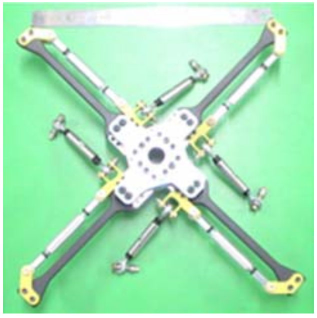


Fig. 5. The hub system : NRSHS

The fifth hub system is the NRLHS which is the National Research Laboratory Hub System. This NRLHS has an adaptive hingeless hub system which can apply various composite flexures to optimize the composite stacking sequence and aeroelstic tailoring. This hub system is very simple but heavy structure. This hub system was developed for the purpose of froude & mach small-scale test to demonstrate the optimized composite flexure design. The general configuration is shown in Fig 6.

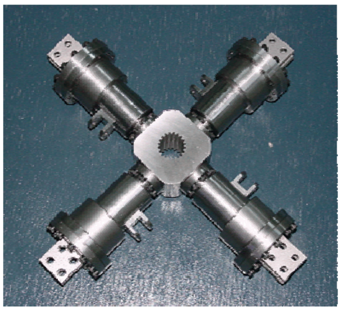
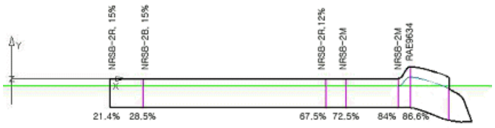


Fig. 6. The hub system : NRLHS

KARI had developed its own unique advanced composite blade [6, 7]. This advanced blade has a paddle-type tip but has a kink to reduce noise. The chord length is also variable from 84%R to tip. This blade was designed using 3 airfoils. This advanced blade was designed to have low vibration characteristics by optimizing the mass distribution. The general layout of advanced tapered blade is shown in Fig 7.



(a) Airfoil Distribution of the Blade

(b) Fabricated blades

Fig. 7. The general layout of KARI advanced blade

This paper will describe the development process of the new advanced rotor system with hingeless hub and advanced planform shaped blade for an unmanned helicopter with 100kg-class MTOW. The design and analysis process will be described first. Next, the ground test results will be shown. Finally, the flight test results will be shown.

Design and Analysis

Rotor Sizing

The rotor diameter of R-Max is 3115mm. This rotor has 2-bladess rotor. KURS rotor system has 4-blades hingeless rotor system. So, KARI defined the rotor diameter for this KURS for unmanned helicopter. The rotor sizing was defined based on optimal disk loading and thrust coefficient over solidity considering the existing R-Max rotor. The rotor rpm (830rpm) was fixed since the same engine and platform was applied to this new rotor system. KARI determined to rotor diameter and chord length in considering analysis of existing unmanned helicopter trends and performance prediction by FLIGHTLAB. Other design parameters like twist, anhedral angle and airfoil distribution was same with the KARI's existing advanced blade planform. The information of the newly designed rotor is in th following table 2 and Fig 8. The performance prediction was peformed by using FLIGHTLAB. The predicted results was compared to that of R-Max original rotor capability. Based on this analysis, the new designed rotor has a better performance rather than the existing R-Max rotor.

Table 2. Rotor Sizing Results of new rotor system

Parameters	Unit	Value
Rotor Diameter	mm	2600
Rotor Chord Length	mm	82.7
Blade Linear Twist	degree	-12
Anhedral Angle	degree	25

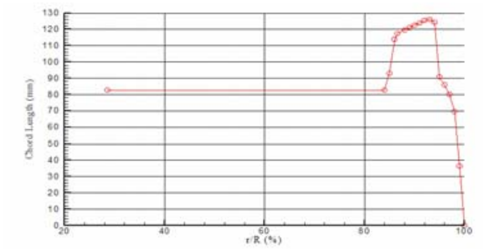


Fig. 8. The distribution of chord length of KURS blade

Basic Structural Design

The existing MHHS was chosen for the basic platform for a new KURS rotor system since this hub system has enough structural strength to sustain mach scale test and to have strong strength to be applied to a real helicopter. So, the sizing was determined to be applied to KURS rotor system. The new designed hub system for KURS was shown in Fig 9.

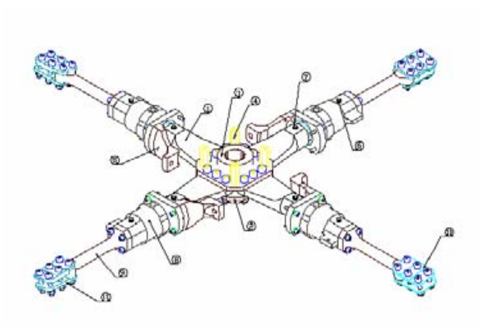


Fig. 9. KURS hub for ground test

The sectional design was conducted to sustain rotor loads in flight. The CORDAS developed at KARI in 1998 was applied to calculated sectional properties. This CORDAS stands for COmposite Rotor blade Design, and Analysis Software [5]. The major material was unidirectional glass fiber and carbon fabric materials manufactured by Hankook Fiber in Korea. The skin was composed of 2 plies glass fabric. Core of spar and nose weight of blade was filled with Rohacell foam 71WF and 110WF. The trailing edge core was filled with the conventional blue foam to keep blade shape. The typical section of KURS blade was shown in Fig 10.

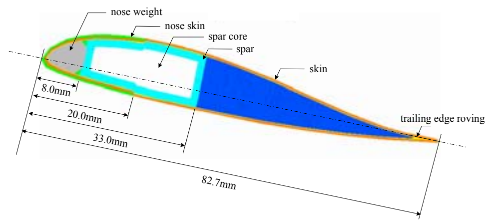


Fig. 10. The typical section of KURS Blade

Structural Analysis

The structural analysis was done on the major part of hub system by using Nastran. The applied load was calculated by CAMRAD II which was commercially developed by Johnson Aeronautics. The structural analysis of the blade was done analytically being based on Euler beam theory. The flexure and blade has enough strength to sustain flight load of KURS heliocpter. The typical result was shown on Fig 11 and 12.

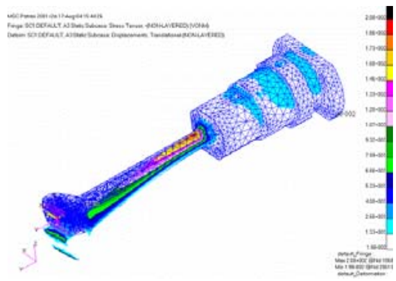


Fig. 11. Nastran analysis result at hover condition

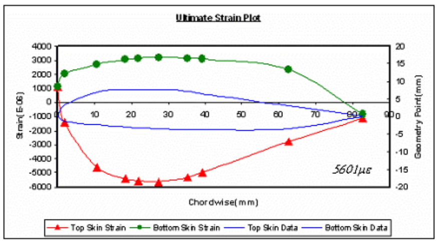


Fig. 12. typical strain results based on Euler beam theory

Dynamic Stability Analysis

The dynamic stability analysis of the newly designed KURS rotor system was conducted by using CAMRAD II. The frequencies were calculated and the basic damping values were also calculated The frequency distribution according to rotor rotating speed was summarized at Table 2. The frequency has well distributed among N/rev of rotor operational speed. The in-plane damping has a positive which means stable in lead-lag direction. The fan-plot diagram was shown on the Fig 13. The calculated damping value was shown on the Fig 14.

Table 2. Calculated results of rotor frequencies

Rotating Speed (rpm/Ω)	Natural Frequency (Hz)				
	1st Lag	1st Flap	2nd Flap	1st Torsion	3rd Flap
0.2	8.371	5.685	27.934	62.998	72.984
0.4	9.103	7.572	30.583	62.723	75.739
0.6	8.795	11.151	34.560	62.947	80.095
0.8	9.667	13.885	39.469	63.452	85.774
1.0	10.532	16.727	44.853	64.433	92.593
1.2	11.479	19.633	50.683	65.222	99.795

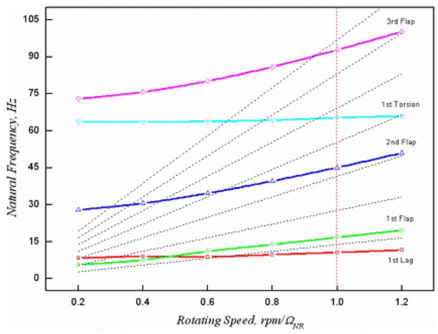
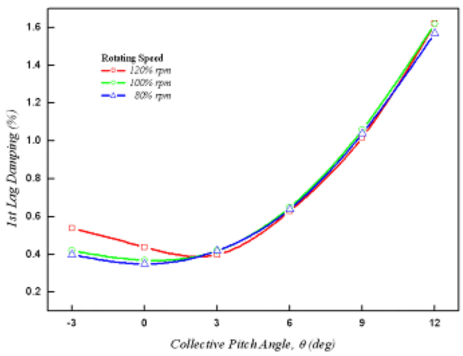
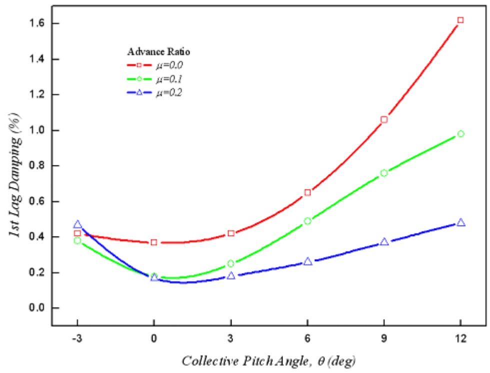


Fig. 13. Calculated frequency distribution for KURS rotor system.



(a) Hover Condition



(b) Forward Flight Condition

Fig. 14. Calculated damping of 1st lag mode for KURS rotor system.

Fuselage redesign

The research on the improvement of fuselage was conducted in parallel to rotor system improvement. The approaching methodology is the regressing-method which makes improvement of existing fuselage based on the analysis and is modified to make better lift to drag ratio(L/D). The global weight of the new fuselage is same to that of the existing R-Max fuselage cover. The CFD analysis was done by using FLUENT V6.2. The major changed part is the sharp edge parts and tailboom. The original sectional shape of the tailboom is the circle. In this research, the shape was changed into elliptic shape. The sharp edge parts were modified into smoothed shape. After CFD analysis, the wind tunnel test was conducted and verified. The pressure distribution of new developed cover was shown on the Fig 15.

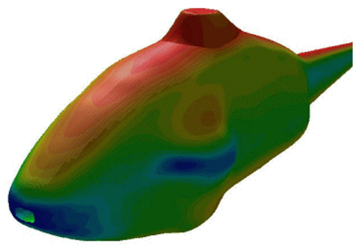


Fig. 15 The Cp contour of new fuselage cover

Ground Test

Hovering Test on the KARI GSRTS

The hover test was conducted on the KARI

GSRTS. The detailed capability of KARI GSRTS was described in the reference paper [2]. The thrust and torque were measured at 2-axis rotating balance installed on the rotor shaft. The thrust has enough capability for the KURS helicopter. The KURS rotor system installed on the KARI GSRTS was shown on the Fig 16. The test result of thrust and torque according to rotor rpm and collective pitch angle was shown on the Fig 17.

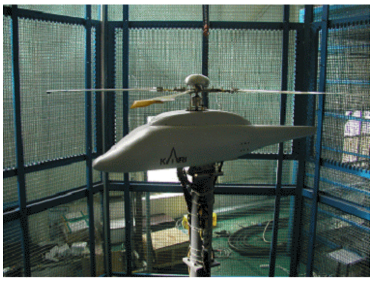
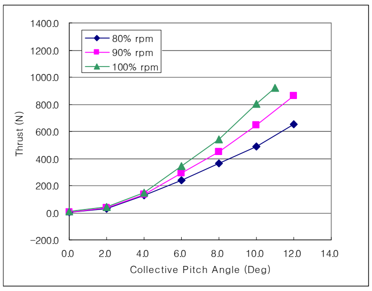
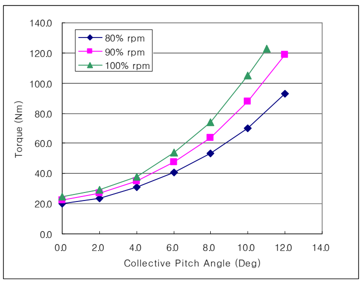


Fig. 16. Hover test installed on KARI GSRTS



(a) Thrust v.s. collective pitch angle



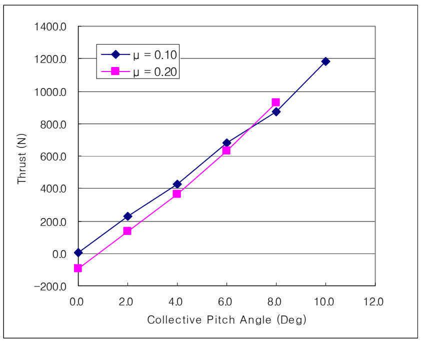
(b) Torque v.s. Collective pitch angle

Fig. 17. The hover test result of thrust(a) and torque (b) at collective pitch angle

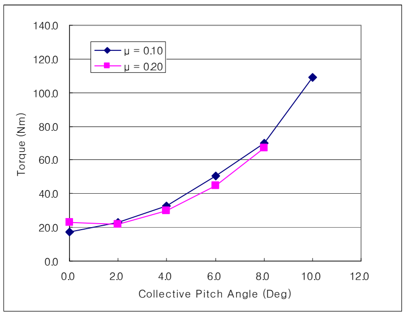
Forward Flight Test on the KARI LSWT

The forward flight test was conducted on the KARI LSWT. The detailed capability of KARI GSRTS was described in the reference paper [2]. The thrust and torque were measured at 2-axis rotating balance installed on the rotor shaft. The KURS rotor system installed on the KARI LSWT was shown on the Fig 18. The test result of thrust and torque according advance ratio and collective pitch angle was shown on the Fig 19.

Fig. 18. Forward flight test installed on KARI LSWT



(a) Thrust v.s. collective pitch angle



(b) Torque v.s. Collective pitch angle

Fig. 19. The wind tunnel test result of thrust(a) and torque (b) at collective pitch angle

Pre-flight Test

Tie-Down Test on the bench

The typical tie-down bench was developed for the KURS helicopter. This tie-down test was conducted before flight test. This test could show the stable thrust and torque level. The thrust and torque were measured the load and torque cell installed on the bench. The KURS helicopter installed on the tie-down test bench was shown on the Fig 20. The table 2 shows the sensor lists and their specifications.

This tie-down test was conducted on the KARI site located on the Daejeon. The thrust was measured at 4 vertical loadcells. The torque was measured at 2 horizontally installed loadcells. The capability of the yaw rate was measured on this bench. Pitch and roll moment was estimated by using vertical loadcell and center of gravity. The result of tie-down test was compared to that of analysis results calculated by using FLIGHTLAB. This result was shown on the Fig 21. It is shown that the results of tie-down test have the better Figure of merit rather than analysis results. The test results of hover on the GSRTS and tie-down test were compared on the Fig 22. It can be verified that the results of tie-down test have the better Figure of merit rather than that of hover test on GSRTS. It can be estimated that this better Figure of merit comes from the ground effect on the tie-down test rig. Finally, the results of KURS tie-down test was compared to that fo R-Max tie-down test. These comparisons were shown on the Fig 23. In the region of main operational range, The KURS helicopter shows better FM rather than R-Max about 5%~10%.

Fig. 20. KURS helicopter installed on the Tie-down test rig

Table 2. The sensor lists and specification of the tie-down test bench

Items	Specification	Remarks
Load cell (6ea)	-UMA K200 (DANA Loadcell) - Capacity : 200 kgf	- Signal Conditioner : SCC SG04 with LP01 Low Pass Filter (NI)
Heat Transfer (1ea)	- Thermocouple K Type	- Signal Conditioner : SCC TC01 (NI)
Optical Sensor (1ea)	- BF3RX (Autonics) - Photosensor with Fiber Optics Cable - Output : 1 Pulse/Rev.	
Accelerometer (1ea)	- 352B10 (PCB) Piezo Type Acc. with ICP - Output : 9.71 mV/g	- Signal Conditioner : 480E09 (PCB)
Rotoray Encoder (1ea)	- ENA-2048-3-2-5 (Autonics) - Use A,B Phase with Up-Down Counter - Output : 2048 Pulse/Rev. - Resolution : 0.176 Deg/Pulse	

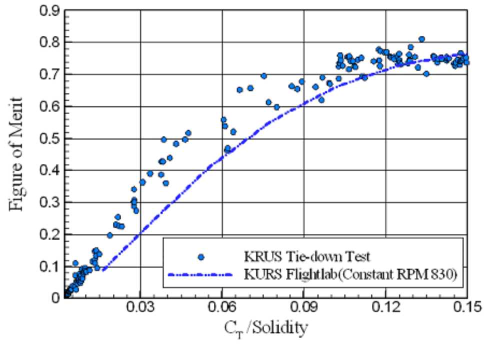


Fig. 21. Comparison of analysis and tie-down test result for KURS helicopter

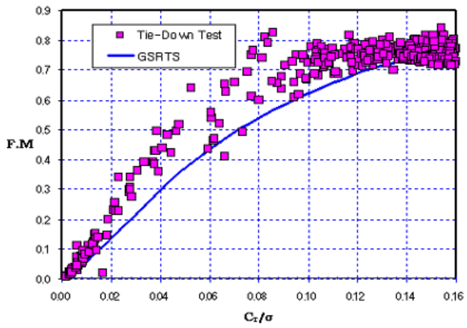


Fig. 22. Figure of merit Comparison of hover test on GSRTS and tie-down test of KURS helicopter

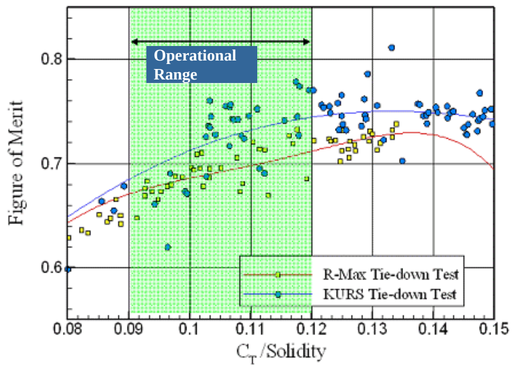


Fig. 23. Figure of merit comparison of the R-Max and KURS based on tie-down test.

Flight Test

KARI has its own flight test research center at Goheung area in Korea. Fig.24 shows the this flight center overview. The flight test at this flight test center was performed for the both original R-Max helicopter and KURS helicopter

Fig. 24. KARI's Flight Research Test at Goheung site

DAQ system in Flight Test

The DAQ system on the KURS is composed of three major parts. The general concept was shown on the Fig 25. The first part is the rotor rotating parts mounted on the rotor head. This part has a function of the measuring rotating data on the rotor such as blade strain, pitch angle, etc. Also, this rotating rotor part has a data transferring system onto the fuselage using Bluetooth module. This DAQ on the rotor has 32 channels which are composed of 20 chs for strain gauge, 6 chs for Hall effect sensors and 6 chs for others including voltage monitoring. The details of this system were shown on the Fig 26.

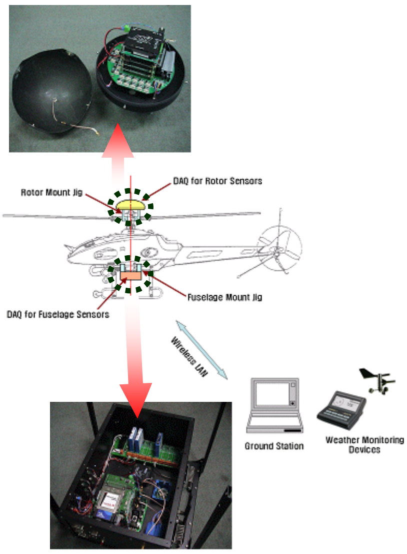


Fig. 25. The general DAQ system on the Flight Test Model

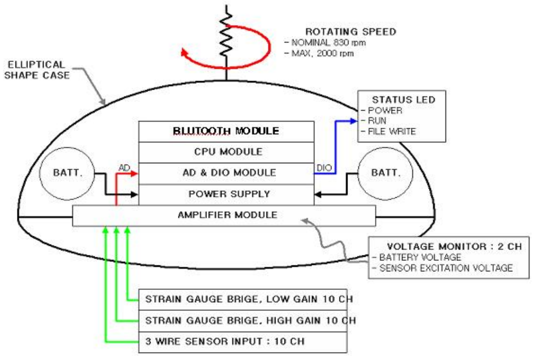


Fig. 26. The DAQ system on the rotating rotor

The second part is the fuselage parts mounted under the fuselage. This part has a function of the measuring data on the fuselage such as airframe strain, LVDT, gyro, potentiometer, etc. Also, the Bluetooth module receives the rotating data from rotor part or transferring data into the ground control station. This DAQ on the rotor has 32 channels which are composed of 11 chs for strain gauge, 11 chs for Gyro, accelerometers and Magnetic compass and 10 chs for others including LVDT, voltage monitoring, etc. The details of this system were shown on the Fig 27.

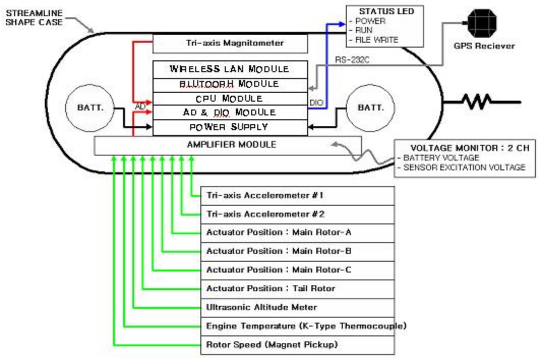


Fig. 27. The DAQ system under the fuselage

The third is the ground control station(GCS). This station shows all monitored and measured parameters on the computer screen. This station saves all data as a file. The LabVIEW was used for operation program and post processing program.

R-Max Original Flight Trial

The flight test of the original R-Max helicopter was shown on the Fig 28.

For the R-Max helicopter, the flight test was performed for the two-configuration. The one is the original R-Max and the other is the new fuselage cover to improve aerodynamic performance. The new cover R-Max has more efficient rather than the original cover R-Max. The Fig 29 shows that the R-Max with new cover has a better Figure of merit. That means the new fuselage cover has a better performance rather than the original cover

Fig. 28. The flight test of the R-Max helicopter

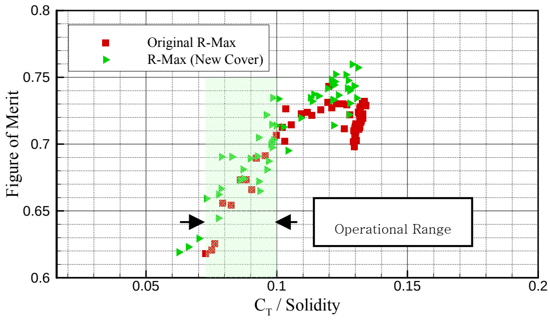


Fig. 29. Figure of merit comparison of original R-Max and R-Max with a new cover

KURS helicopter Flight Trial

The flight test of the KURS helicopter was shown on the Fig 30.

For the KURS helicopter, the flight test was performed for the two-configuration. The one is the KURS with the original R-Max cover and the other is the new fuselage cover to improve aerodynamic performance. The new cover KURS helicopter has more efficient rather than the original R-Max over. The Fig 31 shows that the KURS helicopter with new cover has a better Figure of merit. That means the new fuselage cover has a better performance rather than the original R-Max cover.

KURS helicopter has the best performance efficiency among three configurations. The results were shown on the Fig 32. The fuel rate of the KURS helicopter was reduced about 2.0%~3.0% rather than the original R-Max helicopter. The vibratory load level (Fz, thrust) of KURS helicopter is lower than that of original R-Max helicopter. The reason is 4-blades rotor system and lower vibration blade charateristics

Fig. 30. The flight test of the KURS helicopter

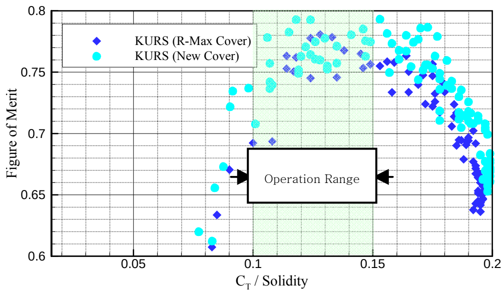


Fig. 31. Trend of design variables for robustness (Maximum Available Power)

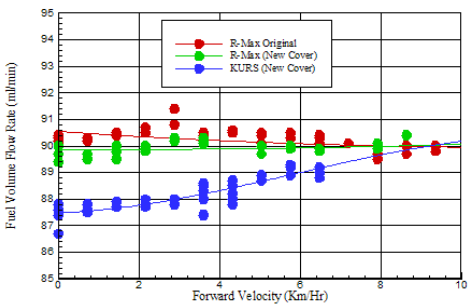


Fig. 32. Comparison of fuel flow rate among R-Max and KURS helicopter.

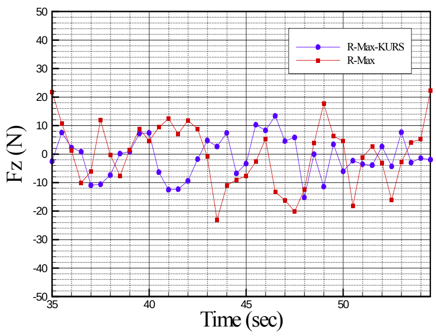


Fig. 33. Vibratory Load (Fz) of KURS vs. R-Max

Conclusions

KARI has developed new 4-blades advanced rotor system for 100kg-class MTOW unmanned helicopter.

The performance improvement of the new developed rotor system was verified by performing ground test and flight test

The figure of merit of KURS helicopter was increased about 5%~10% compared to the original R-Max helicopter.

The flow consumption rate of KURS helicopter was decreased about 3% compared to the original R-Max helicopter.

The vibration load level of KURS helicopter was decreased about 3% compared to the original R-Max helicopter.

This new designed airfoil and tip shape was used to increase performance and to reduce noise. From this research, KARI achieved increase of hover performance and reduction of vibration.

For the national development of unmanned helicopter in future, these technologies can be used and applicable in near future.

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