THE DEVELOPMENT OF PROP-ROTOR SYSTEM FOR 52KG MTOW QUAD-TILT PROP(QTP) UAV

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Abstract

Electric Drone (UAV) was introduced to public people world widely. Especially the quadcopter which is one type of multi-copters was very popular in people who enjoy personal hobby and leisure. The market required to improve payload and forward flight speed. From this worldwide market trend, KARI had started to pay attention to electric drone (UAV) market such as the high-speed drone which has a capability of vertical take-off and landing (VTOL). Specially, the drone for observation and reconnaissance purpose gives an impressive attention to government officers, industry and military. For these purposes, KARI decided to develop 52kg MTOW Quad-Tilt Prop UAV (QTP UAV) based on KARI's existing tilt-rotor technologies. This paper introduces the development of 52kg MTOW QTP UAV and its Prop Rotor system. KARI had experienced rotor system development for over 20 years. KARI had developed the optimized propeller and hub system for this QTP UAV applying optimization of the hover performance and high forward flight speed performance. To develop this prop-rotor system, new propeller's aerodynamic design and structural design with carbon composite and titanium materials was conducted. For these 3 years development period, KARI had setup the development process of the prop-rotor system with high performance for QTP UAV based on helicopter rotor system's experience and optimization process. [1]

1. INSTRODUCTION

1.1. Background

Electric Drone (UAV) was introduced to public people world widely. Especially the quadcopter which is one type of multi-copters was very popular in people who enjoy personal hobby and leisure. The market required to improve payload and forward flight speed.

From this worldwide market trend, KARI had started to pay attention to electric drone (UAV) market such as the high-speed drone which has a capability of vertical take-off and landing (VTOL).

Specially, the drone for observation and reconnaissance purpose gives an impressive attention to government officers, industry and military. For these purposes, KARI decided to develop 52kg MTOW Quad-Tilt Prop UAV (QTP UAV) based on KARI's existing tilt-rotor technologies.

This QTP UAV program was launched on early January in 2016 and ended on the end of December in 2018 (36 months). This program was funded by KARI internal budget supported by NST(National Research Council of Science and Technology). The final goal of this program is to develop new high performance 52kg MTOW QTP UAV with electric motor and battery system, high performance carbon propeller and quad tilt prop-rotors. This paper focus on developing the prop-rotor system for QTP UAV. Figure 1 shows the 52kg MTOW Quad-Tilt Prop UAV (QTP UAV)

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At the initial stage, existing airfoils were surveyed as the primary candidate airfoils for prop-rotor within limited given time. Based on these airfoils, the thickness and curvature were fitted after considering trailing edge minimum thickness, root thickness and so on. To analyze airfoils, XFOIL tool was adapted to use viscous-panel method since this tool was effective in low Reynolds's environment including transient model. For optimized design & analysis, the ModelCenter was introduced which combined with CAMRAD II & STAR-CCM+ (CFD). After comparison of each existing propeller with optimized propeller, the final optimized propeller was selected. KARI in-house code (KSec2D) which is used for blade sectional analysis code was applied to do sectional structure design of this propeller. From this sectional structure design, the propeller's sectional properties were calculated. Finally, this propeller was fabricated. After checking the sectional properties and weight, the ground structural test of new fabricated carbon propeller was conducted and structural safety was verified based on static structural test.

At the next stage, ground propeller rotational test was conducted. The both of existing and new developed propellers were conducted and measured the thrust and torque to get figure of merit. After verification of this ground test, the flight test was conducted in the company's flight test site.

This paper introduces the development of 52kg MTOW QTP UAV and its Prop Rotor system. KARI had experienced rotor system development for over 20 years. KARI had developed the optimized propeller and hub system for this QTP UAV applying optimization of the hover performance and high forward flight speed performance. General development activities of prop-rotor system of QTP UAV will be described in this paper according to each development step. Figure 1 show the QTP UAV and Prop-rotor system

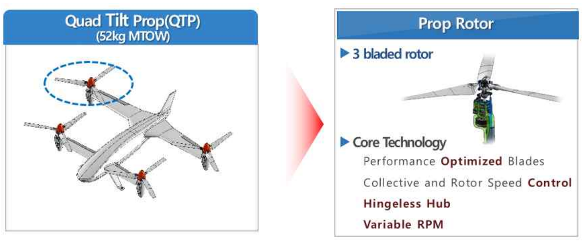

Figure 1 QTP UAV and Prop-Rotor System

1.2. Purpose

This study focused on design & analysis, fabrication and ground test to verify the hover performance characteristics of the QTP UAV. The well proven development process was applied in this prop-rotor system development. Aerodynamic design process will be introduced. Propeller's structural design will be described in detail based on the analysis of load and dynamic stability. Ground test such as static structural test and rotational test was conducted using specified test rig. Through these development process of new QTP UAV, KARI's existing development process and methodology had been verified at new UAV.

2. MAIN ACTIVITIES ON DEVEOPMENT OF QTP UAV'S PROP-ROTOR SYSTEM

2.1. Airfoils DB and Selection

For the selection of the airfoils, the existing airfoils were surveyed. As the first step, the operational flight condition was analyzed to identify the airfoil operational environment. It was found that the QTP UAV was operated in low Reynolds' No. environment. So, to build up the airfoils DB and to select appropriate airfoils to QTP prop-rotor system, XFOIL(viscous-panel method) and CFD (STAR-CCM+) tools were applied to analyze the existing airfoils. Based on these two tools, several candidate airfoil aerodynamic data base (lift and drag coefficients) were built up. For thin airfoils under Mach No. 0.4, the incompressible airfoil solver XFOIL was used. For thick airfoils, CFD was used.

After comparing the airfoil DB and hover performance, airfoils for QTP Prop-rotor were selected. Thickness to chord ratio(t/c) was distributed from 8% at tip to 25% at root area.

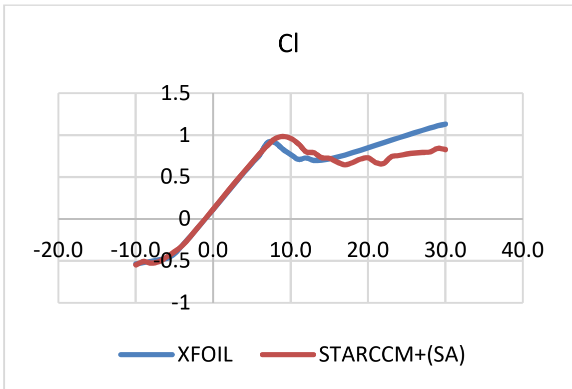

Figure 2 Airfoil DB Build-Up (ex : t/c 8%)

2.2. Propeller Design and Performance Analysis

The propeller planform optimized design was implemented by CAMRAD program as an analysis and ModelCenter as an optimized process integration. The CAMRAD program analyzed the

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hover and forward flight performance of QTP prop-rotor. The objective function of this optimized design process is multi-objective which maximize figure of merit at hover and propulsive efficiency at forward flight. The constraints are that pitch link forces are less than 2 times the baseline propeller of the other UAV(TR-60). Also, the power of optimized propeller is less than that of the existing baseline propeller. The representative analysis condition is defined as hover at ISA, sea level for hover mode and defined as forward flight speed 150km/h at ISA, 1km altitude. Table 1 shows the design variables for optimization of prop-rotor system. Figure 1 shows the optimized design and analysis process. Figure 4. shows the Process Integration on ModelCenter

Table 1. Design Variables

Variables	Range	Unit
Root Chord	0.08 ~ 0.1	m
Taper Ratio	0.5 ~ 1.0	-
Inboard Twist Slope	-60.0 ~ -30.0	deg./R
Outboard Twist Slope	-30.0 ~ -10.0	deg./R
Twist Control Angle	2.0 ~ 10.0	deg.
Tip Station	0.85~0.97	R
Anhedral Angle	0.0 ~ 20.0	deg.
Main Lifting Airfoil1	0.3~0.6	r/R
Main Lifting Airfoil2	0.7~0.9	r/R

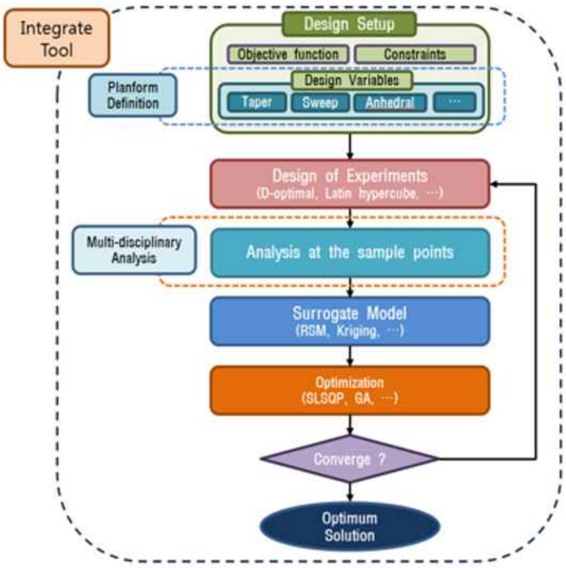

Figure 3 The Optimized Design and Analysis Process

After optimization process, optimized design variables are defined as table 2. Figure 5 shows the planform derived through the final optimized design. This propeller has a sweep back angle as 6.56 deg., anhedral angle as 8.82deg. and taper ratio as 0.5.

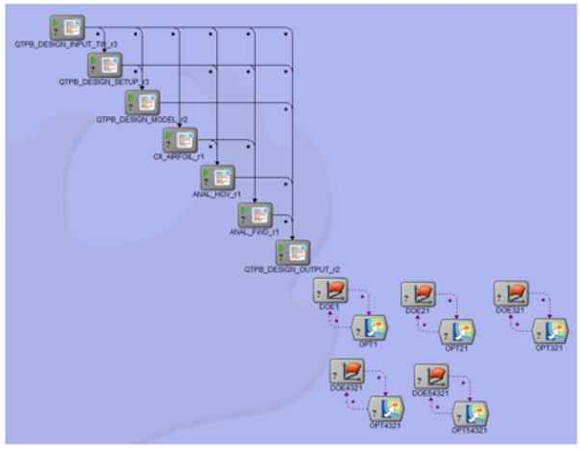

Figure 4 Process Integration on ModelCenter

Table 2. Optimized Design Results

Variables	Baseline	Optimized
Root Chord	0.0825	0.0847
Taper Ratio	0.6	0.504
Inboard Twist Slope	-45	-47.8
Outboard Twist Slope	-16	-16.3
Twist Control Angle	4	2.4
Tip Station	-	0.851
Anhedral Angle	0	8.82
Sweep Angle	0.0	6.56
Main Lifting Airfoil1	0.5	0.30
Main Lifting Airfoil2	0.75	0.73

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Analysis result shows the figure of merit of optimized propeller was increased as 0.83%~1.13% compared to baseline propeller. This result was shown at Figure 6. Analysis result shows the propulsive power efficiency of optimized propeller was increased as 8.07%~9.08% compared to baseline propeller. This result was shown at Figure 7. Main mission of the QTP UAV is the forward flight range. So, forward flight performance has more priority at weighting factor of design objective

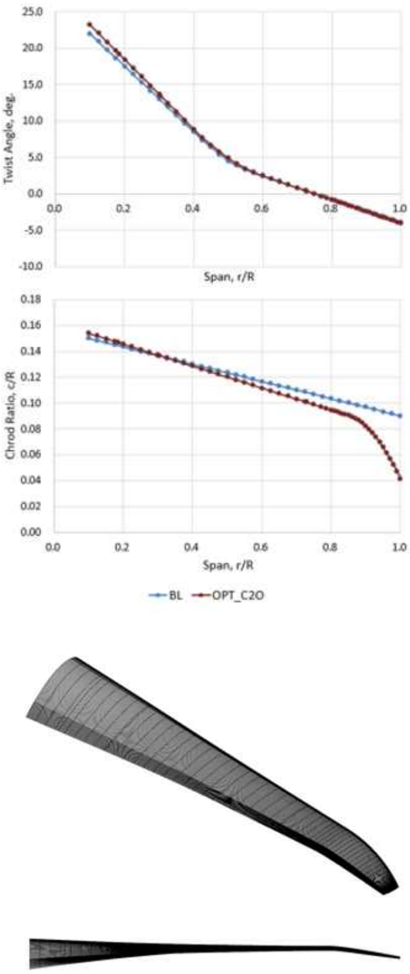

Figure 5. Optimized design shape of QTP Propeller

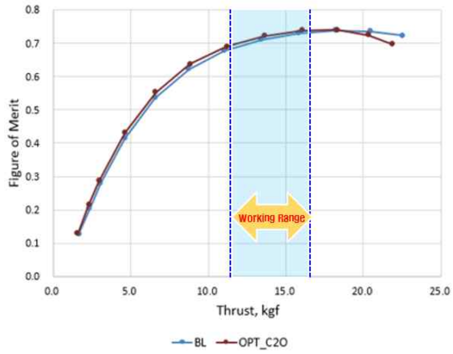

Figure 6. Hover Performance of QTP Propeller

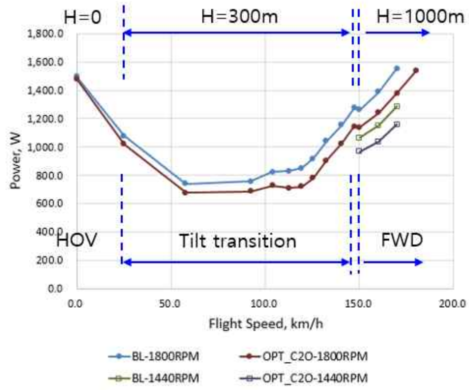

Figure 7. Forward Flight Performance of QTP Propeller

2.3. Structural Design & Analysis

2.3.1 Requirement Criteria Selection for Section Design

For the section design of the propeller, the criteria for strength and stiffness must be determined. The requirements of propeller are weight, stiffness and strength. So, these requirements are considered. Also, the structural material is considered in the design. Carbon composite materials are major materials. Hard foam was used for core material and tungsten strip was applied at leading edge to match chordwise balance.

The position of the sectional analysis was selected by increasing the propeller center direction from the 0% position to the 100% position in 2.5~10% increments in the direction of the propeller end (Figure 8). Propeller shape information was acquired through the 3D scan of the propeller, and the two - dimensional cross - sectional shape for each position was extracted using this information. The section analysis was performed using KSec2D [3] which is a two-dimensional finite element section analysis program

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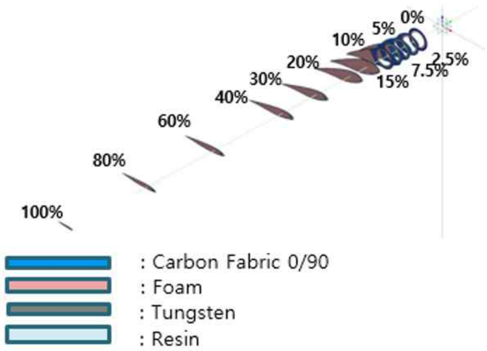

Figure 8. Propeller Analysis Section

2.3.2 Carbon Propeller Section Design and Analysis

For the section design of the propeller, orthogonal carbon fiber (Carbon Fabric) was used. Considering the centrifugal force and lift level generated during propeller operation, we applied tension/bending/torsion direction reinforcement structures such as spar. The inner shape was formed by hard foam and the composite carbon fiber was laminated on the C type spar internal of section. Tungsten strip was located in leading edge area to adjust chordwise center of gravity. Figure 8 shows typical section of QTP propeller at 30% station.

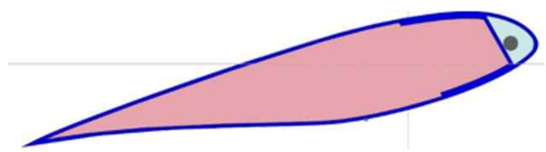

Figure 9. 30% Section Shape

Sectional analysis of each laminated pattern was performed on carbon propeller shapes. The following figures 10 and 11 show the results of the carbon QTP propeller cross section analysis and the results of the existing propeller cross section analysis for the bending stiffness.

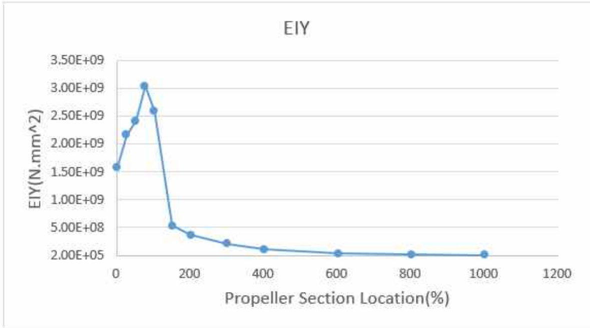

Figure 10. Sectional Analysis Results QTP Propeller–Flapwise Stiffness(EIY)

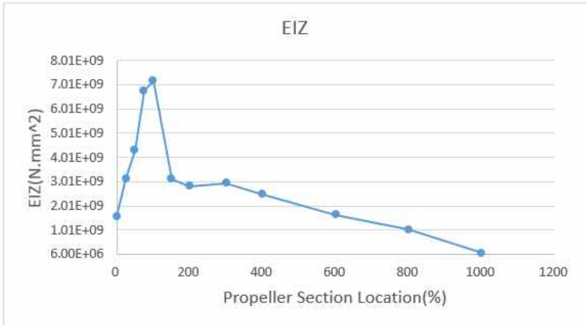

Figure 11. Sectional Analysis Results QTP Propeller–Lagwise Stiffness(EIZ)

2.3.3 Hub System Design and Analysis

Hub System was designed as a rigid hingeless hub system with three propellers. Control system has collective pitch control using simple sliding block without conventional swashplate. Hub pitch case are connected to propeller root with one pin mechanism. The detail structural analysis was conducted and verified for safety. Figure 12 shows the hub system and control system concept.

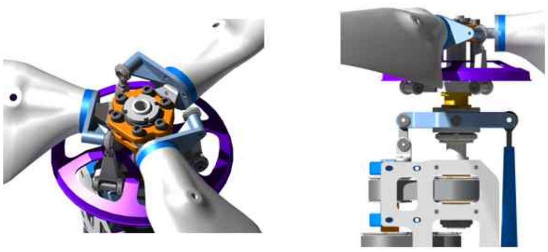

Figure 12. Hub and Pitch Control Concept

2.4. Dynamic & Load Analysis

2.4.1 Dynamic Analysis

For the propeller model with cross-sectional design, non-rotational and rotational natural frequency and mode shapes of the propeller were analyzed using the CAMRAD II. The sectional properties obtained in KSEC-2D was exchanged into input file of CAMRAD II. In order to analyze the change of the natural frequency according to the rotation speed of the propeller, the dynamic analysis was performed while increasing the rotation speed of the propeller up to 2,100 rpm. As shown in Figure 12, as the rotational speed of the propeller increases, it is confirmed that the natural frequencies of all the modes are increased by the influence of the centrifugal force. It is confirmed that the dynamic instability due to the resonance does not occur because it is sufficiently separated from the natural frequency of the airframe.

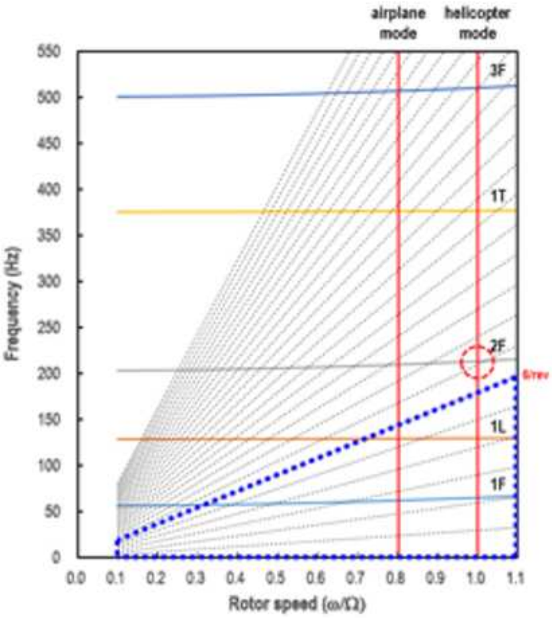

Figure 13. Sectional Analysis Results QTP Propeller–Lagwise Stiffness(EIZ)

2.4.2 Load & Structural Analysis

CAMRAD II [3], a comprehensive helicopter analysis program, was used to investigate the centrifugal force and bending moment distribution on the cross section according to the operating conditions of the propeller. As shown in Figure.14, the propeller analysis model consists of 23 aerodynamic panels in the radial direction to calculate the aerodynamic force according to the propeller rotating speed and angle of attack, and 8 structural elements were applied to account for elastic deformation. Figure. 15 shows the pitch link forces according to load case. As shown in Figure 16, the structural margin of the carbon fiber used for the skin was found to be at least 3.3 and structurally safe.

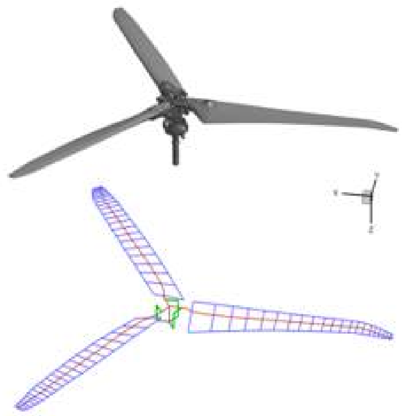

Figure 14. CAMRADII analysis model

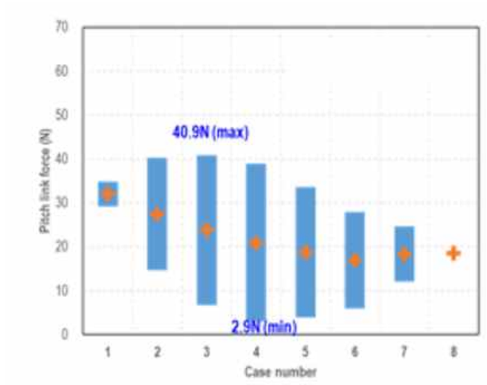

Figure 15. Pithc Link force distributions at Load case

Section	Applied Force			
	Fx(N)	My(N.m)	Mz(N.m)	M.S
2.5	1.08E+03	-3.47E+01	1.87E+01	19.20271
5	1.05E+03	-3.32E+01	1.66E+01	22.50299
7.5	1.01E+03	-3.09E+01	1.36E+01	27.6926
10	9.71E+02	-2.95E+01	1.26E+01	24.24095
15	8.99E+02	-2.65E+01	8.87E+00	3.755932
20	8.43E+02	-2.19E+01	-3.80E+00	3.492402
30	7.63E+02	-1.70E+01	-6.79E+00	3.379882
40	6.69E+02	-1.30E+01	-4.10E+00	3.823768
60	4.42E+02	-6.27E+00	-1.11E+00	5.587028
80	1.82E+02	-1.91E+00	5.98E-01	12.61016

Figure 16.: Finite element analysis results (peak stress) Fabrication

Propeller fabrication was carried out by applying the proposed composite laminate shape through the section design. The hot press method was used as a propeller manufacturing method considering that the lamination pattern and the inner shape are simple. In order to construct the internal shape, a hard foam was processed, a composite material

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was laminated on a hot press mold, and high temperature / high pressure was applied to produce a composite material propeller. Figure 17 shows the configuration check of fabricated propeller. Figure 18 shows the fabricated propeller

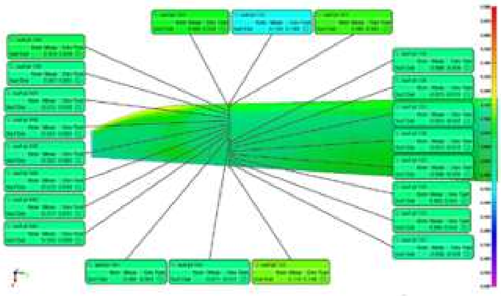

Figure 17: T check the Propeller Configuration

Figure 18. Propeller Fabrication

2.5. Test and Result

2.5.1 Ground Test

LabVIEW and DAQ devices of National Instruments (NI) were used to control the BLDC motor and collect test data such as thrust, power(torque) and rotating speed from load cell, torque meter and photo sensor. The following program for test was based on LabVIEW, made for generating PWM (Pulse Width Modulation) signal, and sends it through NI DAQ to electrical speed controller (ESC) to control the rotating speed of the BLDC motor. This program also has a function to collect and save the measured aerodynamic performance (thrust, power) and rotating speed of motor as a text file. Figure 19. shows the Ground Test

Figure 19. Ground Test

2.5.2 Flight Test

Flight tests were performed to demonstrate flight performance of KARI QTP. The flight test was conducted at KARI Goheung Aviation Test Center. The flight test was conducted successfully.

QTP UAV achieved the original target of forward flight speed and tilting system. Figure 20 shows the flight test and demonstration

Figure 20. Flight Test

2.5.3 Test Result

Ground tests were performed to demonstrate final performance of KARI QTP. The ground test result showed the comparison of existing propeller and new designed propeller for QTP. Figure 21 shows the the mechanical power comparison of baseline propeller and optimized propeller. Figure 22 shows the the figure of merit comparison of baseline propeller and optimized propeller.

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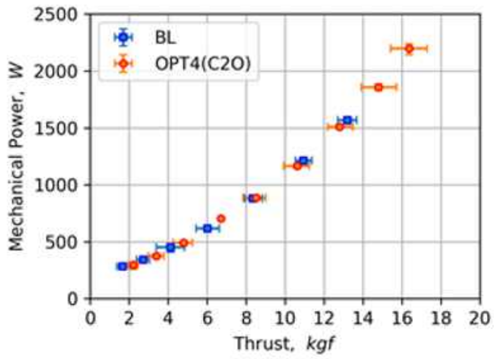

Figure 21. Mechanical Power vs Thrust Comparison

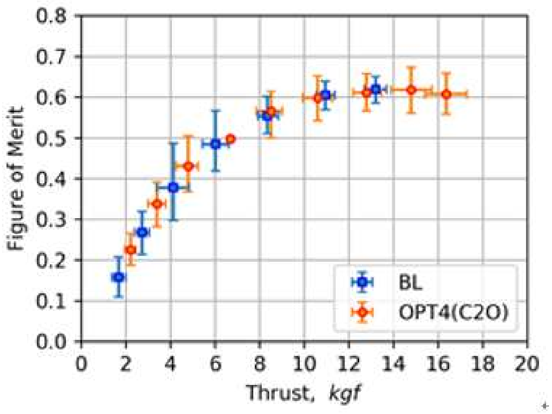

Figure 22. Figure of Merit vs Thrust

3. CONCLUSION

This paper describes the general overview of new Quad Tilt Prop development for 52kg Gross Weight UAV. Based on the design process of helicopter rotor blade, KARI conducted the prop-rotor system. All tools and facilities related to develop helicopter rotor blade were applied in this program. This paper shows the main research activities such as aerodynamic design and analysis, structural design and analysis, fabrication and investigation, ground and flight test. Finally, The The Development of Prop-Rotor System for 52kg MTOW was successfully conducted.

Acknowledgement

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References

[1] Drela, M., QProp Propeller/Windmill Analysis and Design, Ver. 1.22, Massachusetts Institute of Technology, Cambridge, MA, http://web.mit.edu/drela/Public/web/qprop, 2011

[2] Johnson, W., CAMRAD II, Comprehensive Analytical Model of Rotorcraft Aerodynamics and Dynamics, Release 4.9, 2012

[3] Park, I. J., Jung, S. N., Cho, J. Y., and Kim, D. H., "A Study on Calculation of Cross-Section Properties for Composite Rotor Blades Using Finite Element Method," Journal of the Korean Society for Aeronautical and Space Sciences, Vol. 37, No. 5, 2009, pp. 442~449.

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