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AN OPERATIONAL TEST AND DYNAMIC BALANCING SENSITIVE STUDY OF THE ROTOR BLADE ON THE WHIRL TOWER

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Abstract

In this paper, the background of whirl tower establishment in KARI was introduced and the operational test result of this KARI whirl tower was explained. The blade dynamic balancing test for Korean Utility Helicopter (KUH) on the whirl tower was presented. The whirl tower was built for rotor whirl test and dynamic balancing test for KUH which has been developed in 2012. In this operational test, the sensor measuring system of whirl tower was verified and was investigated using some trial test. The rotation signal channels were tested by using strain gauge on the rotor blade and load cell on the pitch link. The potentiometer of main rotor damper was checked. Finally, 3-axis load cell was calibrated and checked by rotational test with main rotor blade. Through this dynamic balancing test, the blade tracking information and pitch link pitching moment are need to be measured. For blade track information measurement, the optical tracker was installed to get blade tip track. For pitch link pitching moment measurement, the load cell was installed at the pitch link. To satisfy the requirement of dynamic balancing, there are three methods which are pitch link adjustment, blade tab bending and dynamic weight moment. For low pitch region, pitch link and trim tab were used to satisfy low pitch requirement. For high pitch region, dynamic weight of blade tip and trim tab were used to satisfy high pitch requirement. Through this study, it was found that it can be finished so faster to satisfy this dynamic balancing requirement. The dynamic balancing for KUH main rotor blade was conducted by using this sensitive test result. For future production phase, it can be used continuously and effectively to speed up this dynamic balancing test

1. INTRODUCTION

The whirl tower for rotor develepment test and dynamic balancing of rotor blade has been required in Korea for developing Korean Utility Helicopter(KUH) in 2006 . Korea Aerospace Research Institute(KARI) was chosen as a development leading agency of KUH rotor blade. So,KARI has started to establish the Korean own whirl tower in Korea. KARI had chosen ZFL in Germany as a main equipment supplier and domestic construction company as a foundation and control building and others in 2007. KARI had started to establish February in 2007 and finished May in 2009. It almost took 27 months. In 2009, From 2009, KARI has conducted so many tests such as inital calibration and operational test, rotor performance test, rotor dynamic stability test, damper characteristic identification test, pre-flight endureance test(50hrs test), blade dynamic balancing test, rotor vibration reduction test. In this paper, the calibration and inital operational test was introduced and the sensitive stidy result of dynamic balancing test was described.

First, the calibration and initial operational test was conducted. The calibration result was described . The 3-axis load balance on the rotor shaft was calibrated. The torque value was calibrated by a supplier. The thrust and bending moment was calibrated on the whirl tower by using standard load cell and calirbration rig. The pitch link load of KUH rotor head was calibrated. The potentiomenter and strain gauges on the lead-lag damper was calibrated to measure the lead-lag displacement and load of main rotr damper. Finally, the strain gauges on the main rotor blade was calibrated to measure exactly flap and lag moment on the blade. The strain gauge signal on the main rotor blade was used to predict blade bending load and to predict a rotating natural frequency of main rotor blade. KUH has four blades rotor system. The unique color of each blade was given. The colors are yellow, blue, black and red. Normally, the yellow blade is used as a reference blade. The strain gauges were attached on yellow and black blade. Black blade has a role of spare sensor blade if there was a gauge failure on the yellow blade. After calibration, the gain for each sensor was calculated and used to predict physical meaning from the signal.

Second, the sensitive study on main rotor blade dynamic balancing of KUH helicopter on the whirl tower was descrbed. For reducing helicopter rotor vibration, the dynamic balancing of main rotor blade should be conducted before flying. If there is no dynamic balancing Most of dynamic balancing test are conducted on the whirl tower. The purpose of the dynamic balancing is to make the blades similar considering their flight behavior, in order to reduce the vibration as much as possible due to the manufacturing dispersion. This dispersion can cause the origins which are aerodynamic origin, center of gravity, geometric configureuration different from each blade. To minimize these differences of each blade, dynamic balancing can be conducted based on two criteria which are the lift for each pitch angle and the pitch moment for each pitch angle. The dynamic balancing consists of adjusting these two parameters for each blade in order to have the lowest scattering between the blades on the rotor and thus the most similar dynamic behavior [1]. Generally, there are two parameters to be adjusted in the dynamic balancing. There is track and pitch link load (or pitching moment). That means that these parameters are to be measured. So, the sensors to measure these parameters are needed to be installed. For track information measurement, the optical tracker was installed around the whirl tower. This tracker can measure the each blade track at blade tip area. For pitch link load (or pitching moment), the loadcell was installed on the pitch link. In this study, there are three means of conducting to meet these parameters. The first is pitch link length adjustment. The second is to bend blade tab. The third is tip weight movement along blade chord. As there are 4 parameters to adjust which are track at low pitch, pitching moment at low pitch, track slope versus pitch angle ratio and pitching moment slope versus pitch angle ratio. But there are only three means to be adjusted. So, the dynamic balancing is some kinds of compromise between these four parameters. This compromise requires tolerance on the parameters. These tolerances will be described next chapter. Korea Aerospace Research Institute (KARI) had built the Whirl Tower Test Facility (WTTF) to do dynamic balancing test for Surion (KUH) Helicopter. The general view of KARI WTTF was shown at Figure 1 [2]. KARI WTTF was built for whirl test and dynamic balancing test at Goheung Aviation Test Center Site. This WTTF has been used for Surion Helicopter which is the Korean Utility Helicopter (KUH) and is under development, 8000kg MTOW class through Korean Helicopter Program. In this paper, the sensitivity study of dynamic balancing test of KUH main rotor blade was presented and the result was shown. Through this dynamic balancing test, the blade tracking information and pitch link pitching moment are need to be measured. For blade track information measurement, the optical tracker was installed to get blade tip track. For pitch link pitching moment measurement, the loadcell was installed at the pitch link. To satisfy the requirement of dynamic balancing, there are three methods which are pitch link adjustment, blade tab bending and dynamic weight moment. In this sensitivity study, blade pitch link sensitivity study of track and pitching moment has been done before dynamic balancing test.

Figure 1 KARI Whirl Tower Test Facility (WTTF)

2. KARI WTTF

2.1. Generals

KARI WTTF was built for whirl test which is one of the core qualification tests for KUH helicopter development. It was also built for dynamic balancing test of helicopter main rotor blade. Major parts of KARI WTTF were purchased from ZFL in 2009 which is a German company. KARI WTTF is a multi-purpose whirl tower. It can be used for development test and production test (dynamic balancing test). For production test, the universal hub will be used. Through changing the blade adapter, all kinds of blades can be tested for dynamic balancing. At the moment, this universal hub can’t be used since there is no master blade. But, in near future, this universal hub will be used on dynamic balancing for KUH main rotor blades only if there should be a well defined master blade. These two configurations were shown in Figure 2 [3].

Figure 2 KARI Multi-Purpose whirl Tower

2.2. Specifications

KARI WTTF has 2.2MW continuous power motor. The maximum power for 1 minute is about 2.75MW. This drive motor is AC type. To control this drive motor, the frequency inverter system was installed. To achieve rotor rotational speed, this drive motor directly can be controlled by using this inverter system. There are several pitch ranges to be applied. In present configuration, KUH pitch angle ranges was set and fixed by hardware limit switch. KARI WTTF has -6.5degree~+6.5degree collective pitch angle range and -5.0degree~+5.0degree cyclic pitch angle range. The height of rotor rotation surface is about 9.65m from the ground. The other more detailed specifications are described in the Table 1. The 3-axis load balance was installed on the whirl tower. This load balance was installed between rotor shaft and drive motor shaft. This load balance can measure thrust, torque and bending moment. These values can be used to predict rotor power, thrust and bending moment of rotor system. The detailed specification of 3-axis load balance was described in Table 2.

Table 1 Specification of WTTF.

Items		Value	Unit
Height of Rotation Surface		9.65	m
Drive Motor	Max. Power	2,750	kW
Control System	Max. Torque	77,800	Nm
	Collective Pitch Angle	-6.5 ~ +6.5	Deg.
	Cyclic Pitch Angle	-5.0 ~ +5.0	Deg.
	Setting point	1	rpm
	Fluctuation	± 2	rpm
DAQ System	Resolution	16	bit
	Sampling Rate	1.0	kHz
	Number of Channel	110	EA
Excitati-on System	Test Condition	60	Hz
		±0.5 (Pitch angle)	Deg.

Table 2 Specification of 3-axis load balance

Parameter	Value (limit)	Accuracy
Thrust	133,440 (N)	0.5%
Torque	135,575 (N-m)	0.5%
Bending Moment	122,018 (N-m)	0.5%

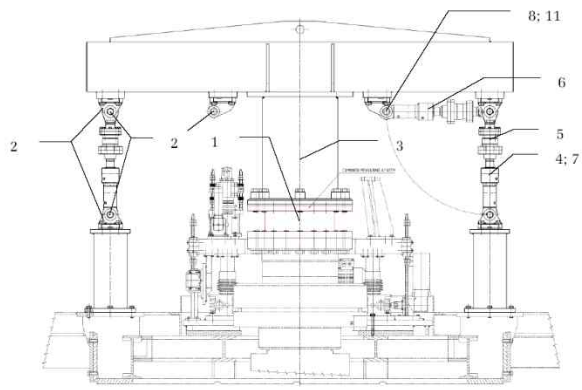
3. OPERATIONAL TEST OF KARI WTTF

3.1. WTTF Calibration

KARI WTTF has 3-axis load balance sensor on the rotor shaft (in rotating frame) for measuring rotor thrust, torque and bending moment. There is also pitch link load to measure pitch load transferred from rotor blade. For dynamic stability and load survey, strain gauges are attached on the main rotor blade. So, the calibration was required to predict exact load on the blade such as flapping moment, lead-lag moment and torsion moment. The damper load is also important to predict damper characteristics and operational flight time. All sensors required to be conducted a development test and dynamic balancing test was calibrated and verified.

3.2. 3-axis load balance

The 3-axis load balance is a key sensor in the whirl tower. This sensor measure rotor thrust and torque. From these measured value, the performance of new rotor system can be predicted by calculating figure of merit. Also, these values are used to run whirl tower safely to prevent overload condition such as over torque or over thrust. So, it is required to calibrate to get exact thrust and torque value. For bending moment, this value must be used as a monitoring of maximum KUH main rotor mast bending moment. For calibration, 2 standard load cell was used which were U3 type (100kN) manufacture by HBM. For thrust, 2 load cells get same direction load. For bending moment, 2 load cells get opposite direction load. Figure 3 and 4 show the 3-axis load balance calibrating device. Figure 5 shows some calibration result of thrust component in 3-axis load balance. The obtained gain value of thrust and bending are -1.101701 and -0.946624.



1 : 3-axis load balance
2 : Trestle Fixing Points
3 : Clamping Collar
4 : Hydraulic Cylinders
5 : Standard Load Cell
6 : Inoperative position of the hydraulic cylinders
7 : Operative position of the hydraulic cylinders
8 : Spring cotter of the center near bold
9 : Plug and socket of the load cell sensor
10 : Connecting of the hydraulic system
11 : Bold of the trestle

Figure 3 3-axis load balance Calibrating Device

Figure 4 3-axis load balance Calibration of WTTF

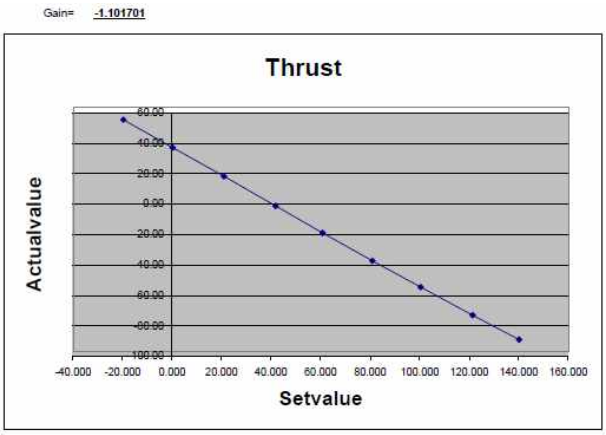


Figure 5 Calibration result of 3-axis load balance (thrust)

3.3. Lead-lag damper

The lead-lag damper of KUH rotor head on the whirl tower is one of important component which indicates lead-lag axial load and displacement. These strain gauges on the lead-lag damper can measure axial load. The potentiometer on the lead-lag damper can measure the displacement Figure 5 shows the potentiometer of lead-lag damper. Figure 6 shows the calibration result of potentiometer. The gain of this test is 0.0165 mm/(mV/V). This value is used to predict damper movement displacement using output voltage. The maximum length of this potentiometer is 100mm. Figure 7 shows calibration test of the strain gauges on the damper by using MTS UTM system. Figure 8 shows the calibration result of strain gauges. The gain of this test is 38,634N/mV. This value is used to predict damper axial load using output voltage. The maximum allowed load is 50,000N.

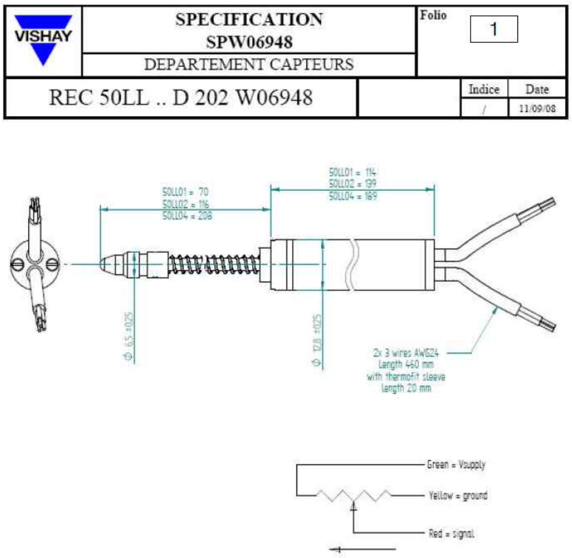


Figure 5 Potentiometer on the lead-lag damper

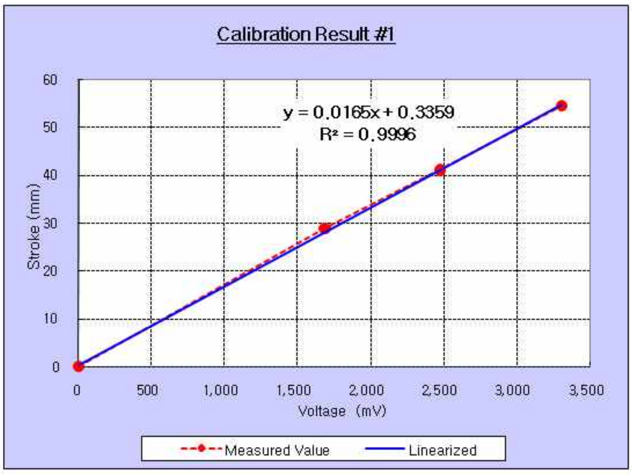


Figure 6 Calibration result of potentiometer on the lead-lag damper

Figure 7 Damper Calibration for Rotor Hub System

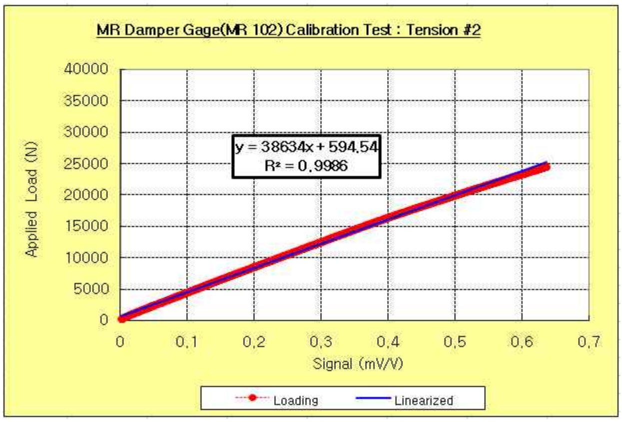


Figure 8 Damper Calibration for Rotor Hub System

3.4. Strain gauges on the Blade

The strain gauges on the rotor blade are used to predict rotor blade bending moment. To predict exactly load, the calibration was required. 8 stations on the blade are defined. The strain gauges are attached to comprise full bridge circuit. Figure 9 shows the strain gauges location on the main rotor blade. Figure 10 shows the actual calibrating method near the whirl tower. Figure 11 show some representative result value of flap bending moment calibration. At blade station 450 (BSTA 450), the gain value can be seen as a $1.873x10^{-6}$ strain per unit kg test load.

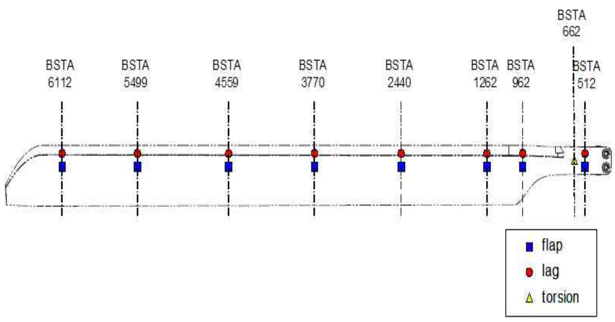


Figure 9 Strain Gauges Location on the Main Rotor Blade

Figure 10 Load Calibration of Main Rotor Blade

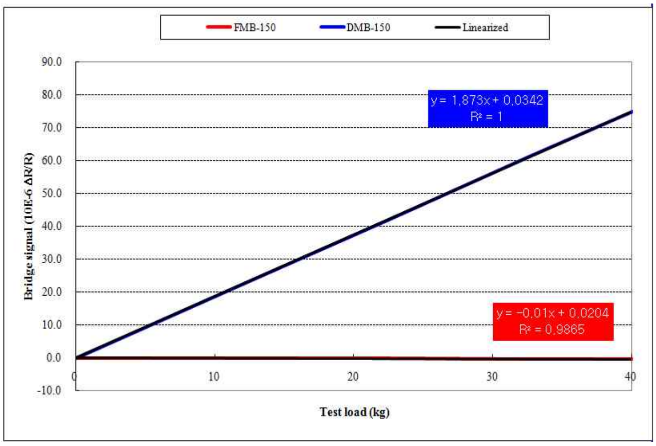


Figure 11 Load Calibration of Main Rotor Blade

3.5. Pitch load

The pitch link of KUH rotor system on the whirl tower is one of important component which indicates pitch link axial load (blade pitching moment). To measure this axial load, the load cell (HBM U3 type, 5kN) is installed on the pitch link. The load cell on the pitch link can measure blade pitching moment. So, the load cell is required to be calibrated. Figure 12 shows the load cell of pitch link. Figure 13 shows the calibration result of load cell. The gain of yellow blade pitch link is -2503.5-49N/(mV/V).

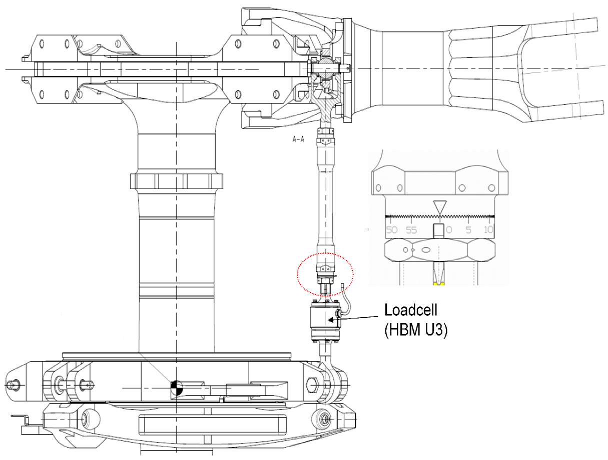


Figure 12 Load Calibration of Pitch Link

Amp. Channel	Code ID	Load Comp.	Calibration			
			input	coeffi.	Output	
			(mV/V)	Unit/(mV/V)	Value	Unit
CH. 49	Red	Axial	1.0	-2500.7502	-2,500.8	N
CH. 50	Yellow	Axial	1.0	-2503.5049	-2,503.5	N
CH. 51	Black	Axial	1.0	-2495.8693	-2,495.9	N

Figure 13 Calibration Result of Pitch Link

4. A SENSITIVE STUDY OF ROTOR BLADE

4.1. Generals

KARI WTTF has some device and sensor system to do dynamic balancing test for main rotor blade. The whirl tower must have a capability of measuring vibration and rotor blade track. KARI WTTF has an optical blade tracker (IAC OBT). This tracker can measure track of each blade. So, the track information can be gathered. IAC-1044 device is installed under the drive motor. This device can send sensor information such as vibration and rotor blade track. The PC-GBS software can analyze this data into physical value such as vibration and track information. The load cell on the pitch link can measure pitching moment of blade. The accelerometers on the rotor system can measure vibration. This sensor can show 1/rev vibration level. Before dynamic balancing, the 1/rev vibration reduction is required to do accurate dynamic balancing by adding mass into hub sleeve. Figure 14 shows the dynamic balancing devices on the KARI WTTF

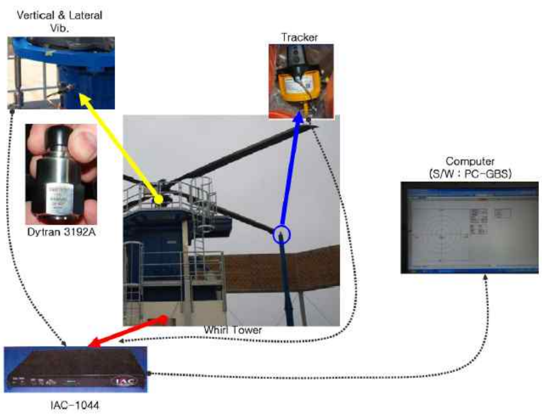


Figure 14 D**dynamic Balancing Devices on the KARI WTTF**

4.2. Pitch Link Length Adjustment

At the low pitch condition, the pitch link adjustment is the first step to satisfy track and pitching moment. In actual phenomena, the blades are influenced each other if there is track change at one of the blades. But in this study, it is not easy to make clear these influence. So, it is focused that the only adjustment of the one blade pitch link can affect its tract change. In this study, there will be some effects of wind condition. The results does not show these wind effect. The primary parameter for this adjustment is track. The pitching moment is secondary. The sensitive study results of the pitch link length adjustment are shown to Figure 15 and 16. It could be found that the average track variation per one notch click was a 1.3mm in viewpoint of track variation from Figure 16. Generally, it can be said that 1.5mm~2.0mm value can be used as a reference value to move pitch link length. It could be found that the average pitching link load variation per one notch click was a 1.4N~1.5N in viewpoint of pitch link load from Table 2 and Figure 16. Generally, it can be said that 0.26~0.27Nm value can be used as a reference value to move pitch link length at low pitch and high pitch condition.

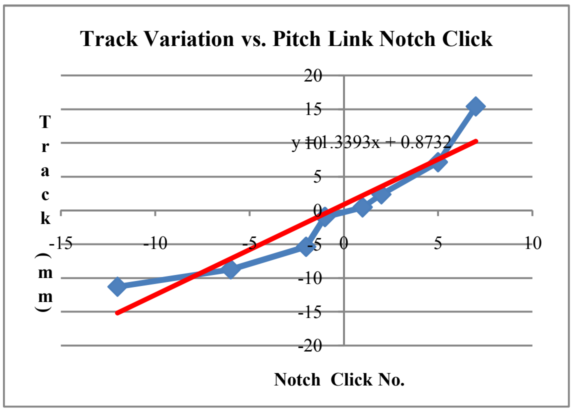


Figure 15 Track Variation vs Pitch Link Adjustment

Table 2 Requirements of Dynamic Balancing

Notch Click	Pitch Link Force (N)							
	Low Pitch (-5.0deg. at Sleeve)				High Pitch (+3.0deg. at Sleeve)			
	Red	Yel	Blk	Blu	Red	Yel	Blk	Blu
-20	406	352	337	366	-	-	-	-
-10	397	363	350	376	-799	-801	-814	-781
10	365	361	350	374	-829	-802	-814	-782
20	350	364	352	376	-845	-803	-815	-784
Slope	**-1.442**				**-1.504**			
Offset	**379.5**				**-814.2**			

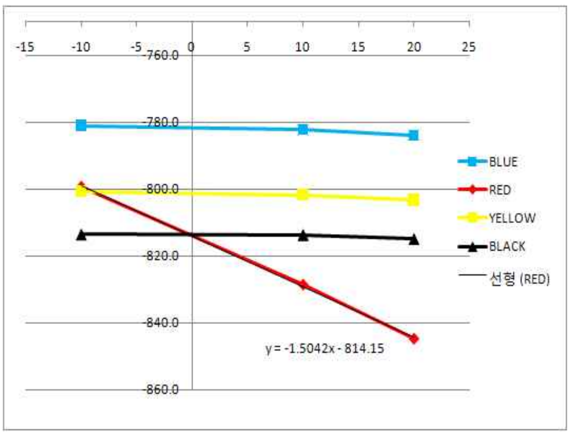


Figure. 16 Pitching Moment Variation versus Pitch Link Length adjustment (Red Pitch Link Adjustment)

4.3. Blade Trim Tab Adjustment

At the low pitch condition, the trim tab adjustment is the second step to satisfy track and pitching moment. In actual phenomena, the blades are influenced each other after trim tab bending. But in this study, it is not easy to make clear these influence. So, it is focused that the only adjustment of the one blade trim tab can affect its tract change. In this study, there will be some effects of wind condition. The results does not show these wind effect. Figure 17 shows trim tabs on the main rotor blade.

The sensitive study results of the trim tab local adjustment are shown to Figure 18 (a) and (b) in view point of track. It could be found that the average track variation per two tab bending down of 1.0degree was about 1.0mm at low pitch condition and 1.7mm at high pitch condition form Figure 18 (a). It could be found that the average track variation per two tab bending up of 1.0degree was about 1.0mm at low pitch condition and 0.7mm at high pitch condition. Generally, it can be said that 1.0mm value per 1.0 degree of 2 tab bending can be used as a reference value to bend blade trim tab. It can also be found that the average track variation per all six tabs bending down of 1.0degree was about 2.0mm at low pitch condition and 3.3mm at high pitch condition form Figure 19. So, this value can be used as a reference value. Figure 20 show the slope of a linear curve fitting for test results has a value for above mention reference value.

For viewpoint of pitching moment, it could be found that the average pitching moment variation per 1.0 degree of 6 tabs bending was a 10.0Nm at the low pitch condition. It could also be found that the average pitching moment variation per 1.0 degree of 6 tabs bending was a 13.0Nm at the high pitch condition. Figure 21 shows that the slope of a linear curve fitting has been used as a reference value to do dynamic balancing test.

At low pitch condition, it is required to optimize and iterate the pitch link length adjustment and trim tab bending together to meet low pitch dynamic balancing requirement. Generally 5~10 times iterative process was required to get some conclusions at low pitch condition. After finishing this low pitch dynamic balancing, next step is to satisfy high pitch dynamic balancing requirement. The only way to adjust track and moment at high pitch range is to use dynamic tip weight. So, it is required to identify the trend of track and moment change from the dynamic tip weight movement. The effect of blade tip weight adjustment was described in the next chapter.

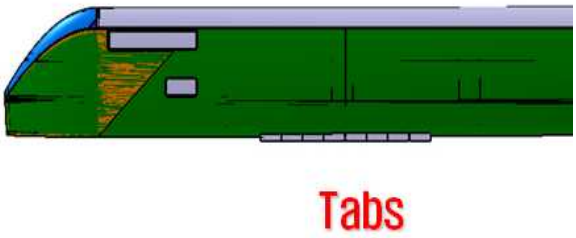


Figure 17 Trim Tab on the main rotor blade

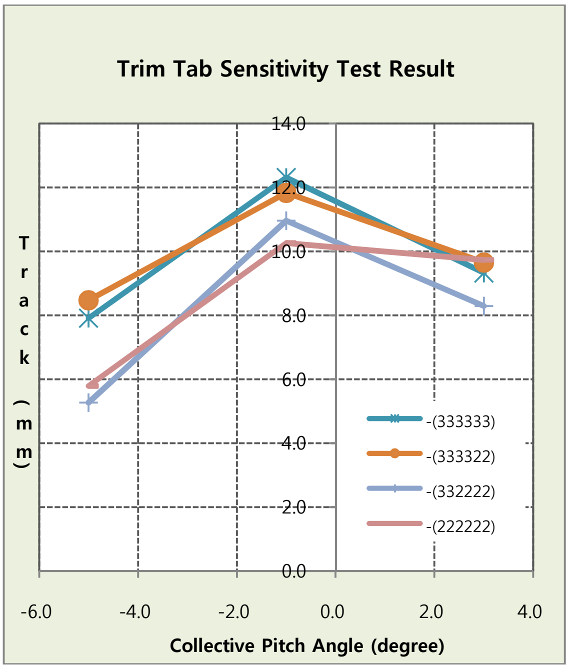


Figure 18 (a) Track Variation versus Trim Tab adjustment (local tab bending down)

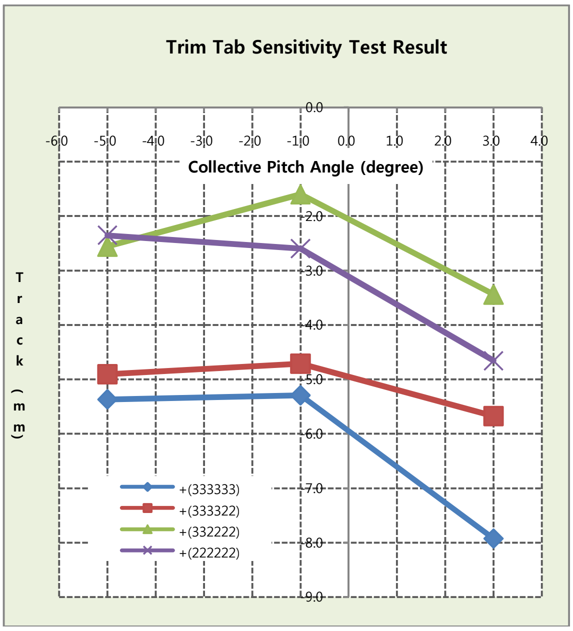


Figure 18 (b) Track Variation versus Trim Tab adjustment (Local tab bending up)

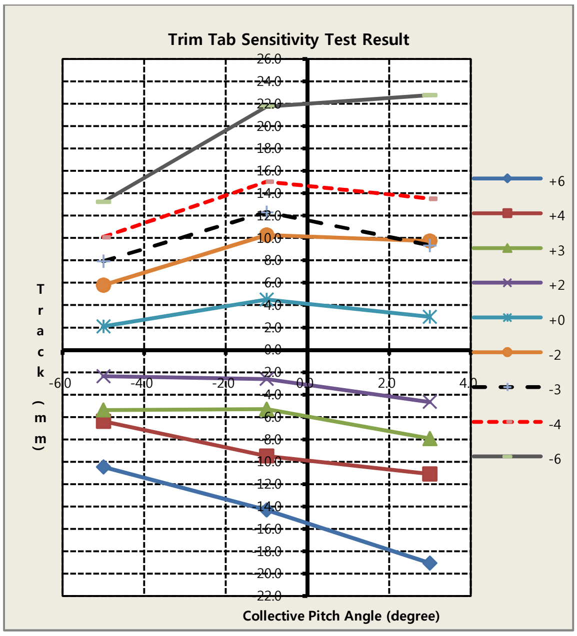


Figure 19 Track Variation versus Trim Tab adjustment (All tab bending)

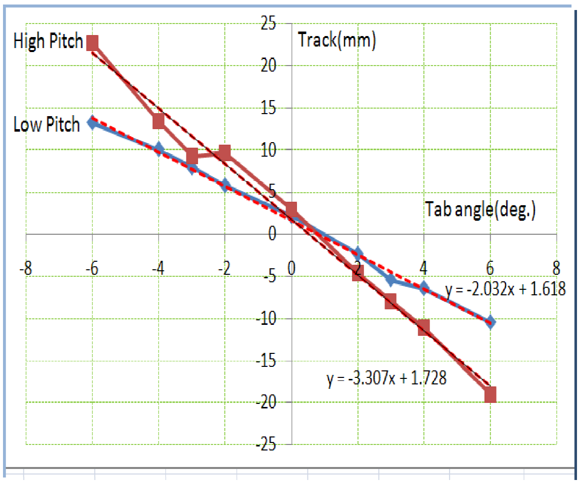


Figure 20 Track Curve Fitting versus Trim Tab adjustment

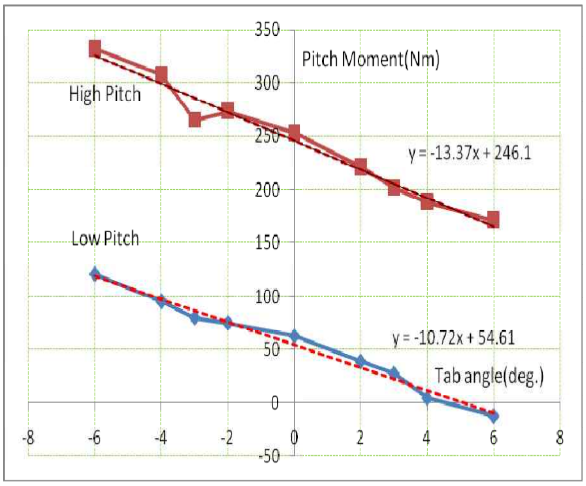


Figure 21 Pitching Moment Curve Fitting versus Trim Tab adjustment

4.4. Blade Tip Weight Movement

The tip weight movement of blade can change of the slope of pitching moment and track variation. Figure 22 shows tip weight configuration of main rotor blade. The sensitive study results of the dynamic tip weight movement length adjustment are shown to Figure 23 and 24. It could be found that the average track variation per 100g movement to blade leading edge (L.E.) was a -7.6mm from Figure. 23. Generally, it can be said that -8.0mm value can be used as a reference value to move track down from the dynamic tip weight movement. It could also be found that the average track variation per 100g movement to blade trailing edge (T.E.) was a +7.9mm from Figure. 24. Generally, it can be said that +8.0mm value can be used as a reference value to move track up from the dynamic tip weight movement.

From the several test and analysis, it was found that the pitching moment variation could be estimated from this track variation amount similar to trim tab bending sensitive study results. It means that the average pitching moment variation per 100g movement to blade trailing edge (T.E.) was a -32Nm. It means that the average pitching moment variation per 100g movement to blade leading edge (L.E.) was a +32Nm.

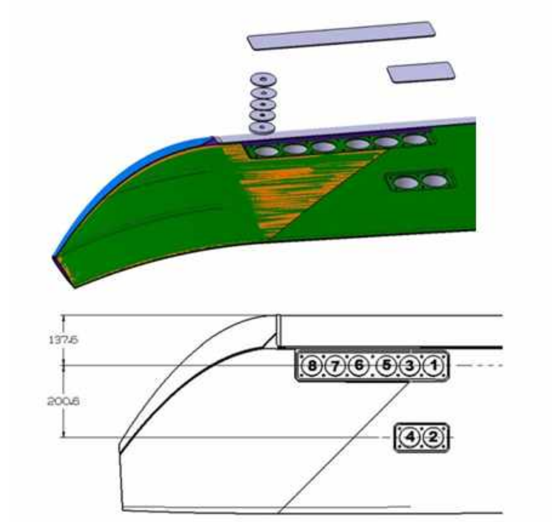


Figure 22 Tip Weight Configuration of main rotor blade

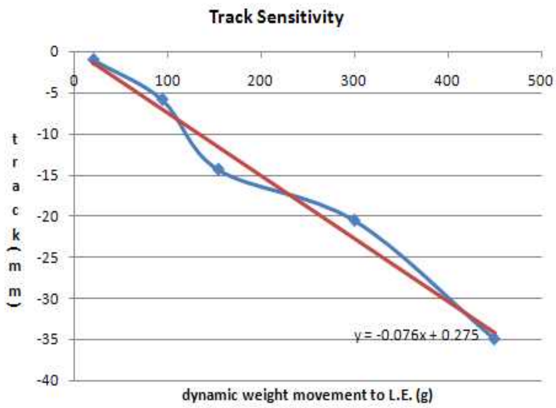


Figure 23 Track variation versus dynamic weight movement to leading edge

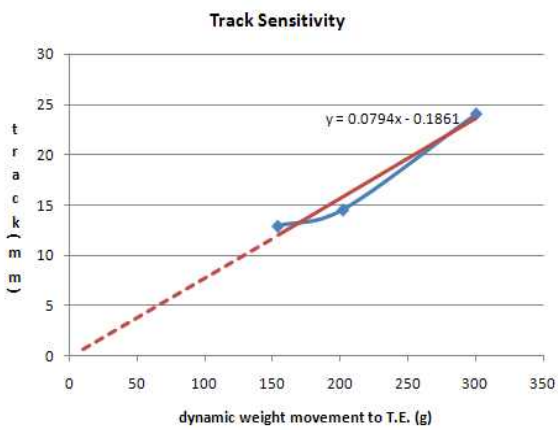


Figure 24 Track variation versus dynamic weight movement to trailing edge

4.5. Summary

After finishing this sensitive study of KUH main rotor blade dynamic balancing, it can be finished easily to satisfy the dynamic balancing requirement. First time, it took 2 weeks to reach the final result of dynamic balancing. But after this sensitive study, it took 3~5days to finish dynamic balancing. The final results of KUH main rotor dynamic balancing was shown in Figure 25 and 26. The outside lines are boundary of requirements. It can be easily found that all blades are in this requirement. The sensitive study results of the dynamic tip weight movement [6].

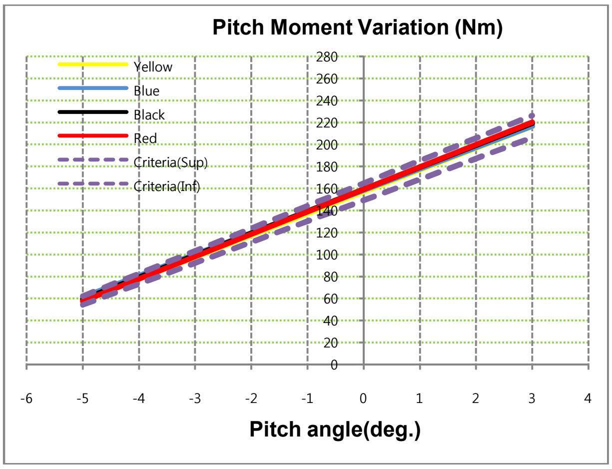


Figure 25 Pitch moment variation versus pitch angle

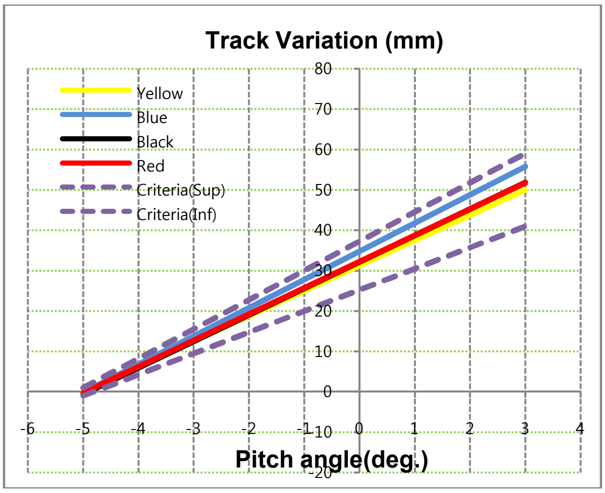


Figure 26 Track variation versus pitch angle

5. CONCLUSION

In this calibration and operational test, the system can be identified and verified which can lead the next test step such as performance test, dynamic stability test and pre-endurance test of KUH main rotor blade. The successful operational test had been done in appropriate time.

In this sensitivity study, blade pitch link sensitivity study of track and pitching moment has been done at first. As a result of this pitch link sensitivity study, it was found that 1.5mm~2.0 mm track information can be changed according to 1 notch (or click) adjustment of pitch link length. For pitching moment, it was found that 0.26Nm can be changed per 1 notch at low pitch (-5.0degree) and 0.27Nm can be changed per 1 notch at high pitch (+3.0degree). Next, the blade dynamic weight movement sensitivity study at high pitch condition has been done as the second study. As a result of this study, it was found that +7.9mm track information can be changed according to 100g dynamic weight movement in the direction of the blade trailing edge and -7.6mm track information in the direction of the blade leading edge. For pitching moment, it was found that 32Nm pitching moment can be changed according to 100g dynamic weight movement at high pitch. Finally, the blade tab bending sensitivity study at low and high pitch cases has been done. As a result of this study, it was found that -2.0mm track change can be done according to 1.0degree tab bending down of all 6 tabs at low pitch and -3.3mm track change at high pitch. For pitching moment, it was found that -10Nm pitching moment change can be done according to 1.0degree tab bending down of all 6 tabs at low pitch and -13Nm pitching moment change at high pitch. In this study, all each sensitive value for each adjustment parameters was investigated and these values can be used as a reference data to satisfy blade dynamic balancing requirement for KUH.

6. ACKNOWLEDGEMENT

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