# THE OVERVIEW OF KARI BEARINGLESS MAIN ROTOR HUB SYSTEM

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## ABSTRACT

The new composite bearingless main rotor hub system had been developed and tested on the whirl tower at Korea Aerospace Research Institute (hereinafter KARI). The purpose of this program is to prepare future helicopter development program and to study the advanced core technologies in helicopter composite rotor hub system. KARI bearingless main rotor hub system (hereinafter KARI BMR) is an all composite, four bladed, soft-in-plane, crucial cross attachment concept for a 7,000lb gross weight helicopters. The KARI BMR was developed for 7,000lb class but tested with BO-105 blades (5,000lbs class) on the whirl tower since the available blade is the only BO-105 blade in KARI. Based on the KARI experience on composite rotor system for research and development, KARI could start to launch the national research program on bearingless rotor hub system development. In Korea, there had been no research activities on full-scale bearingless rotor hub system until 2010. But through many experiences on the previous several rotor research projects, KARI could have confidence in the opportunity of the advanced rotor hub system research such as a full-scale composite bearingless rotor hub system. The KARI BMR has several core composite parts such as flexbeam, torque tube and damper system. The primary part is the flexbeam to give elastic hinges for flapping, lagging and feathering. The sectional shape and construction design of flexbeam are complicated to give these hinges as one part. The secondary part is the torque tube to give pitch change of blade with appropriate stiffness. The sectional shape and construction design of torque tube are also complicated to give appropriate lag stiffness and torsional stiffness with a low aerodynamic drag. The shear restrainer and damper system is other's parts. The overview program of KARI BMR was introduced in this paper. The general development procedure and activities were also described. The overview of design and analysis were explained generally. In consequence, the basic qualification tests such as sectional property test, structural test and whirl test were conducted and the brief results were described in this paper. Consequently, KARI BMR Program showed the improvement of weight advantages, aerodynamic drag reduction and the reduction of the total number of rotor hub parts. In conclusion, it was convinced that the development object have been achieved or the core technology of BMR have been achieved in KARI.

## 1. INTRODUCTION

The development of KARI bearingless main rotor hub system (KARI BMR) was initiated in 2010 to prepare future helicopter development program and to study the advanced core technologies in rotor hub system. In Korea, there had been no research activities on full-scale bearingless rotor hub system until 2010. From the experience of national helicopter development program, KARI could have confidence in the opportunity of the advanced rotor hub system research such as a full-scale composite bearingless rotor hub system. KARI had experience in some research activities on composite hingeless rotor system as a small-scale rotor model [1]. The rotor system of a helicopter has the important roles including the generation of thrust, moment and control forces in hover and forward flight. The rotor system is one of the key components of the helicopter since it has multi-roles as one component. For these complicated roles as one component, the mechanism of the rotor system is quite complicated and should be so strong to endure severe flight loads. These complexities cause the rotor system so heavy and weight penalties. This heaviness of the rotor system is not so useful to the helicopter performance and the operational cost in that these factors can increase rotor drag, decrease the payload and shorten the mean time between regular maintenance. To reduce the weight and complexity of the rotor system, composite materials have been used in rotor system since the early 1970's. In particular, the rotor blade has been designed with composite materials for so long time. After accumulating the experience of blade application, the various rotor hub systems, such as a hingeless and bearingless hub system, have been developed by applying composite materials into the key components of the new hub system such as flexure, flexbeam or torque tube, etc. At present, most of all rotor blades are made with composite materials. The advantages of composite materials application to the rotor system have been emphasized due to the dynamic characteristics improvement such as aeroelastic stability improvement and vibration reduction. The most of articulated hub systems were designed mainly with metallic materials. However, the technology progress of composite materials introduced other types of hub systems, such as the hingeless and bearingless which used somewhat simple mechanism and light materials. These rotor systems were developed to overcome the complexity and heaviness of the previous articulated rotor systems [2-3]. There had been so many studies to predict dynamic behaviour of rotor system. Hodges and Dowell [4], Rosen and Friedmann [5-6] applied moderate deflection beam model to predict dynamic characteristics and aeroelastic problem of rotor system. Also they studied that this moderate deflection beam model could be applicable to rotor system for more realistic and effective aeroelastic stability prediction [7-9]. There were also additional efforts to predict aeroelastic stability more accurately. Cho and Lee [10-11] studied that the aeroelastic stability boundary using large deflection beam model could be different from using moderate deflection beam model in high thrust condition. To predict more accurate aeroelastic stability prediction in combination with an experimental result, some experimental studies which could cover in hover and forward flight condition were required. For this work, Bousman studied an experimental investigation of the effects of aeroelastic couplings on aeromechanical stability of a hingeless rotor helicopter [12]. Weller also investigated relative aeromechanical stability characteristics for hingeless and bearingless rotor [13]. Gaonkar investigated an experimental and analytical investigation of isolated rotor flap-lag stability in forward flight [14]. The bearingless main rotor hub system has a few important composite parts. The primary part is the flexbeam to give elastic hinges for flapping, lagging and feathering. The sectional shape and construction design of flexbeam are complicated to give these hinges as one part. The secondary part is the torque tube to give pitch change of blade. The sectional shape and construction design of torque tube are also complicated to give appropriate lag stiffness and torsional stiffness with a low aerodynamic drag. The shear restrainer and damper system is other's parts. Figure 1 shows that the bearingless hub system has more simple mechanism rather than articulated or hingeless hub system. The composite bearingless rotor hub system has many advantages such as a simple structure, less number of parts, a light weight, low aerodynamic drag and a long fatigue life. These characteristics can give the helicopter operator a low operational cost, high payload and high controllability in manoeuvring flight [15-16]. As an example, EC 135 bearingless main rotor hub system shows 50 kg weight reduction and 40 % less parts count compared to the B0105 rotor [17]. The composite flexbeam and torque tube were required to develop in KARI to acquire core technology in Korea. So, KARI proposed to research and to develop Bearingless Main Rotor Hub System of 7,000lb class helicopter application. Figure 1 shows the several types of rotor system

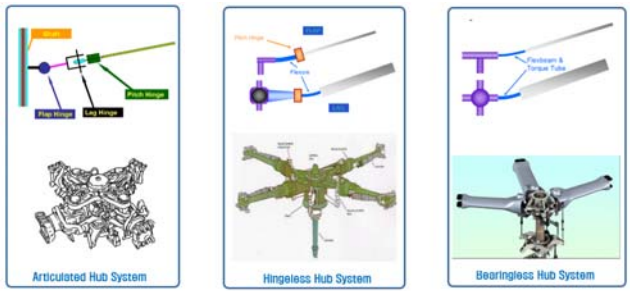
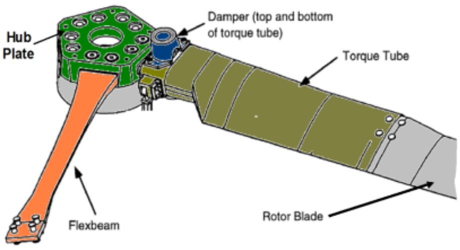


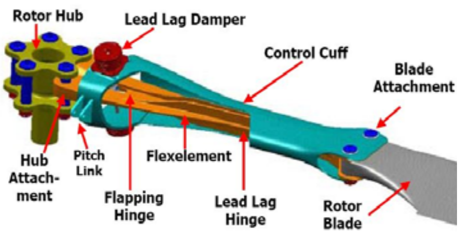
Figure 1 Several Types of Main Rotor Hub System

### 1.1. Background

KARI BMR program was launched 1st of July in 2010 and ended 30th of October in 2013(41 months). This program was funded by Government. The final goal of this program is to develop core technologies of composite bearingless main rotor hub system for 3,500lbs~7,000lbs class helicopter and to demonstrate technology achievement through functional test for validation, structural test for fatigue, whirl test for performance and stability. For development, KARI was chosen as the leading organization and 3 universities were joined to study more detailed analysis on specific subjects. The main activities of universities in this program were to study on accurate load prediction on bearingless rotor system, to study on aeroelastic stability prediction, to experience all required design processes for composite bearingless rotor hub development, to get manufacturing process and related technologies for complex composite rotor hub parts and to get required technologies in ground tests (structural test, whirl test). The main facilities in KARI such as whirl tower, fatigue test facility were used for this program. Most of the required infrastructures were used with a minimized modification. The same composite materials for bearingless hub system (flexbeam, torque tube) were used with those of the previous national program. The seven requirements such as number of parts reduction, weight saving, aerodynamic hub drag reduction, aeroelastic stability achievement, appropriate 1/rev vibration level, fatigue life over than 8,000hrs and structural strength (2.8g) were planned to evaluate this program. Figure 2 (a) shows basic components and mechanism of RAH-66 bearingless main rotor hub systems. Figure 2 (b) shows basic components and mechanism of advanced technology rotor (ATR) bearingless main rotor hub systems in Eurocopter. In this development program, KARI has the responsibility of whole BMR development program with domestic universities and companies. The three universities participated in detail analysis fields to support KARI analysis works. Seoul National University conducted detail load analysis using their own developed in-house code. Konkuk University conducted detail sectional analysis of BMR core parts using their own developed in-house code. KAIST conducted detail aeroelastic analysis using their own developed in-house code. KARI compared its own results with these universities results for validation and confirmation. Domestic Companies had a role in fabrication of BMR core parts such as flexbeam and torque tube. Also, it had a role in fabrication of metal parts of whirl tower installation and adaptation. KARI conducted major test and evaluation of developed KARI BMR such as structural substantiation test and whirl test. Figure 3 shows the program organization of KARI BMR development




a. RAH-66 (Boeing)




b. ATR (Eurocopter)

Figure 2 Representative Bearingless Main Rotor Hub System

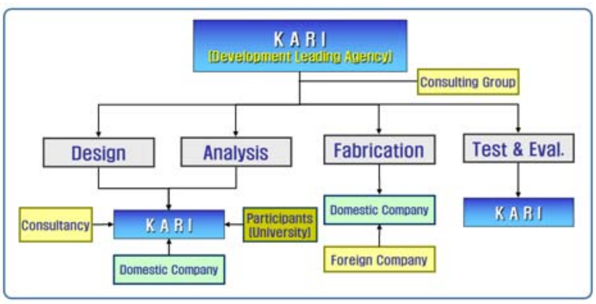



Figure 3 Organization of KARI BMR Development

### 1.2. Development Approach

At the 1st stage, 7,000lbs class main rotor hub system was designed and developed. For this work, the 7,000lbs class blade properties were used to analyse the performance, flight load, natural frequencies and fatigue life. Figure 4 shows the representative blade configuration for 7,000lbs class helicopter which had been studied at KARI in 1998. For whirl test, there was required to rotate to investigate 1/rev vibration, rotor stability and performance of BMR with 7,000lbs blades. But KARI had no available actual blades for whirl test. The only available real blades were BO-105 blades used at KARI whirl tower test facility (KARI WTTF) acceptance test 5 years ago. So, the reinforcement of BO-105 blades' roots were planned to do whirl test for improvement of lag stiffness. At the 2nd stage, reinforced BO-105 blades were investigated for whirl test. The whirl test of KARI BMR was conducted with the reinforced BO-105 blades. Figure 5 shows the top view of KARI BMR with two types of blades.

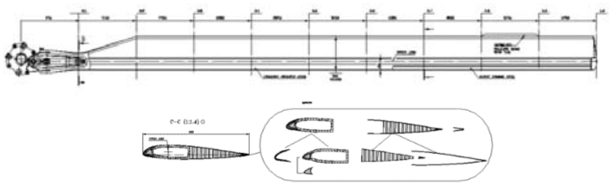


Figure 4 Representative Blade for 7,000lbs Class Helicopter

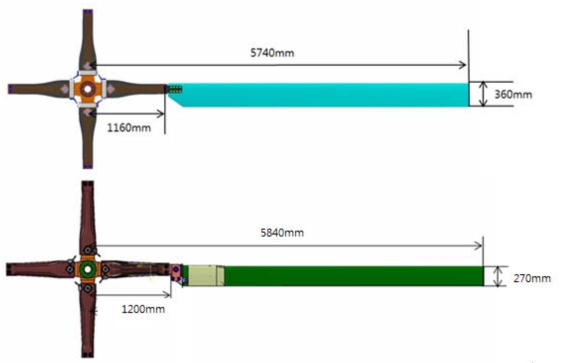



Figure 5 Top View of 7,000lbs Class Blades (Upper) and BO-105 blades (Lower) of KARI BMR

## 2. MAIN ACTIVITIES

### 2.1. General Hub Design

The design philosophy of KARI BMR is the simple mechanism, lower parts numbers, light-weight and long life bearingless hub system with same stability and performance characteristics in comparison with other hub system. To do this work, KARI reviewed several types of existing bearingless hub systems to get optimal design concept and conducted trade-off study to get idea. The crucial cross-strap mechanism was chosen as a basic concept since this system has more benefits in viewpoint of lower parts numbers and light-weights. The separation type of hub mechanism has each hub arm has its own torque tube and flexbeam. So, this design require more number of parts to assemble all parts into one system generally. The crucial cross-strap type of hub mechanism has the two flexbeams on the hub center for 4-blades rotor systems. Figure 6 shows the typical mechanism of bearingless main rotor hub system. KARI developed and improved the bearingless hub design based on the initial concept and mechanism. The final design of KARI BMR concept was frozen based on the requirements and constraints. Several hub design concepts were reviewed such as several types of the existing BMR flexbeam such as double C-channels, cross section, X-type sections, H-sections, Double H-types. During design stage, the crucial cross-strap mechanism was improved and grown up based on the detail analysis and manufacturing drawings for fabrications. Figure 7 shows the improvement of KARI BMR mechanism according to design phase.

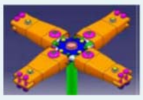
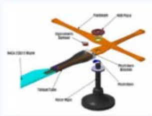
| Type | Parts No. & Weights | Configurations |
|---|---|---|
| Separation | Parts No. : 224 EA<br>Weights : 82.9kg |  |
| Crucial Cross-Strap | Parts No. : 184 EA<br>Weights : 81.5kg |  |

Figure 6 Typical Mechanism of Bearingless Main Rotor Hub System

| | OML-0 | OML-1 | OML-2 |
|---|---|---|---|
| Typical Configuration |  |  |  |
| Major Changes | ✓ PDR Configuration<br>✓ Rectangular Section (Torque Tube)<br>✓ Pitch Horn : L/E Attachment | ✓ Torque Tube Sectional Shape (Rectangular → Elliptic)<br>✓ Pitch Horn : T/E Attachment<br>✓ BO-105 Root Reinforcement | ✓ Torque Tube Sectional Shape (Tapered Elliptic)<br>✓ Blade Adapter<br>✓ Whirl Tower Amplifier Box<br>✓ BO-105 Root Reinforcement |

Figure 7 Design Improvement of KARI BMR

### 2.1.1. Flexbeam Design

The trade-off studies of cross sectional shape of flexbeam were conducted to identify the physical understanding and fabrication feasibility. KARI adopted double H-types as the cross sectional shape of flexbeam among the existing designs such as double C-channels, cross section, X-type sections, H-sections, double H-types. The double H-types has the advantages on the easily accessible design to satisfy required flap and lag stiffness with appropriate flexible torsional stiffness using simple composite materials. The other shapes had more complicated design characteristics to meet stiffness requirements, aeromechanical stability and fatigue life requirements. Figure 8 shows the several types of cross sectional shape of the existing flexbeam. Figure 9 shows the typical cross section of KARI BMR flexbeam. Figure 10 shows each modification of flexbeam design according to each design stage. OML-0 means preliminary design (PD) configuration. OML-1 means interim design configuration between PD and CD. OML-2 means critical design (CD) stage. During these design stage, the concept of crucial cross-strap has been improved to get enough structural strength and safety. The major material of flexbeam is unidirectional glass fiber (TVR 380 0300 M12) and the glass fabric is used to final treatment of flexbeam surface.

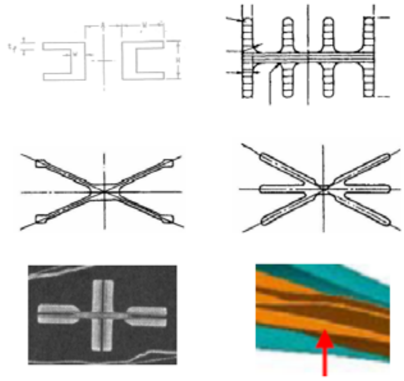


Figure 8 Typical Cross Sectional Shape of Flexbeam

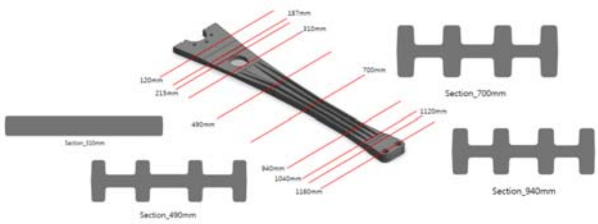


Figure 9 Typical Sectional Shape of KARI BMR Flexbeam

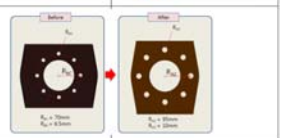
| | OML-0 | OML-1 | OML-2 |
|---|---|---|---|
| Typical Configuration |  |  |  |
| Major Changes | |  | |

Figure 10 Design Improvement of Flexbeam at Each Stage

### 2.1.2. Torque Tube Design

The cross section of the torque tube shape was chosen as the elliptic shape to reduce aerodynamic drag. The rotor hub system of helicopter is one of the main drag sources. So, the requirement of torque tube design is to give enough torsional stiffness to allow blade pitch change and to reduce aerodynamic hub drag. To do this work, the cross sectional shape of torque tube was chosen as an elliptic shape after the CFD calculation. To avoid interference between flexbeam and torque tube during blade pitch change, the kinematic analysis had been conducted. The trade-off studies of cross sectional shape of torque tubes were conducted to identify the physical understanding and fabrication feasibility. KARI adopted elliptic shape as the cross sectional shape of torque tube among the existing designs such as circular section, elliptic section and torque control rod. The elliptic shape is more popular concept and has the advantages on the easily accessible design to satisfy required torsional stiffness, lag stiffness and lower aerodynamic drag using simple composite materials. Figure 11 shows the kinematic study of KARI BMR. Figure 12 shows the typical cross section of KARI BMR torque tube. The major material of torque tube is unidirectional carbon fabrics (HPW 193/RS1222) and the unidirectional carbon fiber to increase lagwise stiffness of torque tube.

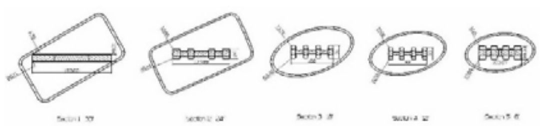


Figure 11 Kinematic Study of KARI BMR

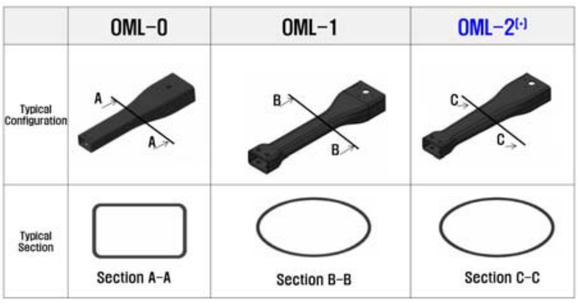



Figure 12 Typical Sectional Shape of KARI BMR Torque Tube

### 2.1.3. Shear Restrainer and Damper Design

The design concept of the shear restrainer and damper system was chosen using the existing proven technology. KARI studied the EC 135 and Bell 430 design concept. KARI chose the combined concept of these two system and modified to meet KARI BMR system. The domestic company could not make the shear restrainer and damper parts. So, KARI made contract with foreign company which had proven technology. The required damping amount and stiffness was predicted based on the 1st lag frequency and stability analysis to acquire aeroelastic stability. Figure 13 shows the shear restrainer and damper system of KARI BMR.

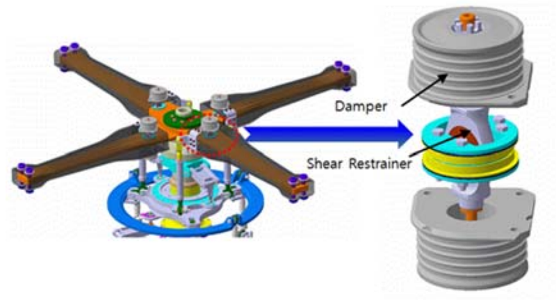



Figure 13 Shear Restrainer and Damper System of KARI BMR

### 2.1.4. KARI BMR Assembly

KARI had finalized all design issues in consideration of performance and interface requirements of on whirl tower. KARI had worked with domestic company to make fabrication drawings and checked all constraints and interfaces. KARI also considered interface with whirl tower for installation. Figure 14 shows the major interface information of KARI BMR. Figure 15 shows the typical cut-out view (upper) and assembly view (lower) of KARI BMR. For design. KARI provided the weight pocket in the attachment bolts to balance rotor hub mass imbalance.

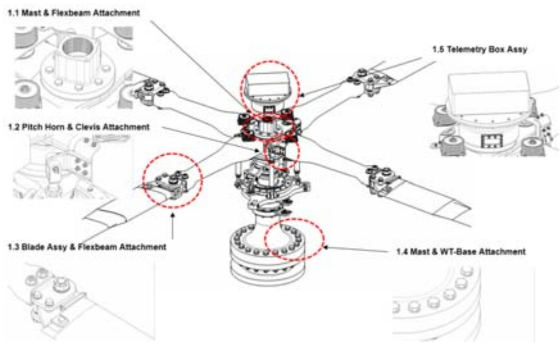



Figure 14 Major Interfaces of KARI BMR

## 2.2. Analysis

KARI conducted all required analysis to develop bearingless main rotor hub system. Some analysis such as stability analysis, load prediction, performance analysis were conducted using commercial software. Other analysis such as CFD, sectional analysis were conducted using in-house code. Figure 16 shows the all analysis tools used in KARI BMR development program.

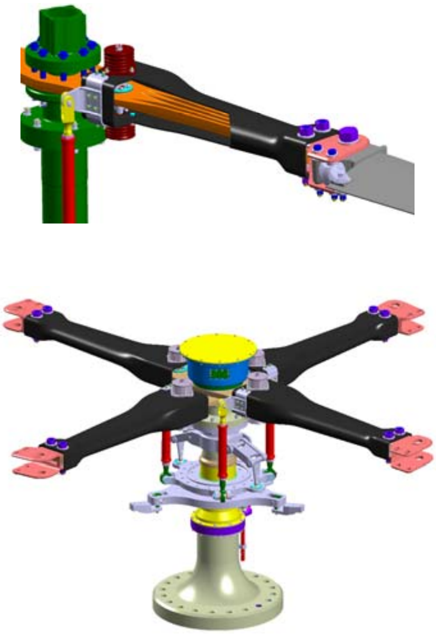


Figure 15 Typical Cut-out View (upper) and Assembly View (lower) of KARI BMR

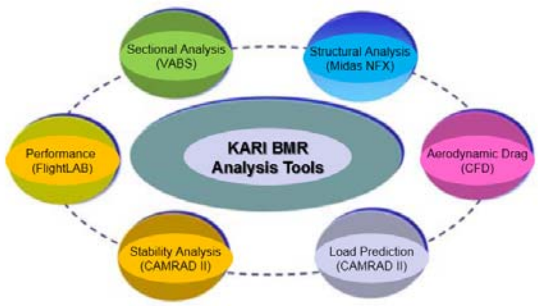



Figure 16 Analysis Tools of KARI BMR

### 2.2.1. Hub Drag Prediction

To optimize the torque tube configuration in conjunction with hub drag, kinematics and stiffness, KARI in-house CFD code was used to predict hub drag. Torque tube is the dominant part of total hub drag. So, the elliptic torque tube shape had achieved more effective aerodynamic hub drag reduction. CFD prediction showed the aerodynamic drag of KARI BMR was almost 19% of total aircraft drag. This predicted value was lower than the hub drag requirement, 23% of total aircraft drag.

### 2.2.2. Rotor Performance Prediction

The rotor performance prediction was conducted using FlightLAB. To predict required power and thrust at given collective pitch angle, KARI BMR and the baseline blade for 7,000lbs class helicopter was modelled in FlightLAB. The required collective pitch angle for 7,000lbs thrust was predicted as 6.6 degree. From this prediction result, the whirl tower test condition was established. Through rotor performance test on the whirl tower, the test and prediction result was compared together. Figure 17 shows the rotor performance prediction results using FlightLAB.

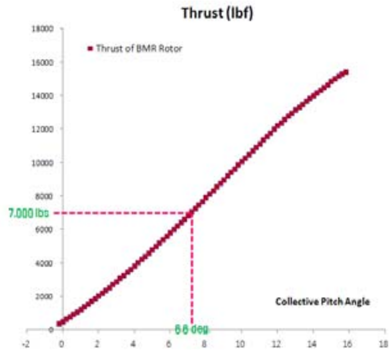



Figure 17 KARI BMR Rotor Performance Prediction Using FlightLAB.

### 2.2.3. BMR Sectional Analysis

The sectional analysis of KARI BMR was conducted using VABS and Konkuk university in-house code. The results were compared with each other. The calculated sectional properties were transferred into performance analysis tool (FlightLAB) and load and stability analysis tools (CAMRADII). This predicted sectional properties were compared with the result of sectional basic property test. Figure 18 shows the sectional properties of flexbeam.

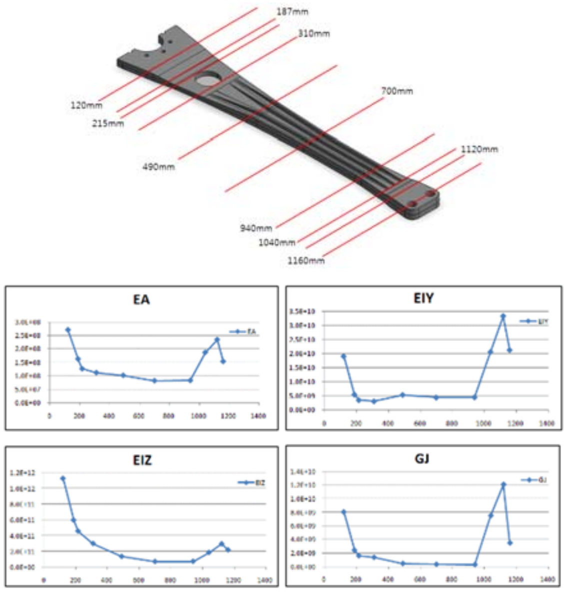



Figure 18 Sectional Properties of KARI BMR Flexbeam

### 2.2.4. Hub Load Prediction

The hub load prediction of KARI BMR was conducted using CAMRAD II. The isolated rotor model was built for whirl test. To ensure structural strength, +2.8g load factor was applied to get flight load. The forward flight speed was simulated up to 0.4 advanced ratio to define flight load. The sectional load of each parts of KARI BMR were predicted as 6-component loads. For CAMRAD II modelling, the flexbeam was modelled as 15 beam elements and the torque tube was modelled as 9 beam elements. These two parts were modelled into multiple load path mechanism. For the aerodynamic model, the second-order lifting line method was used for swept tips and yawed flow implement. For unsteady aerodynamic environment, the non-uniform inflow models were used. Total 21 aerodynamic elements were adopted in this analysis. Figure 19 shows the load prediction of KARI BMR using CAMRAD II

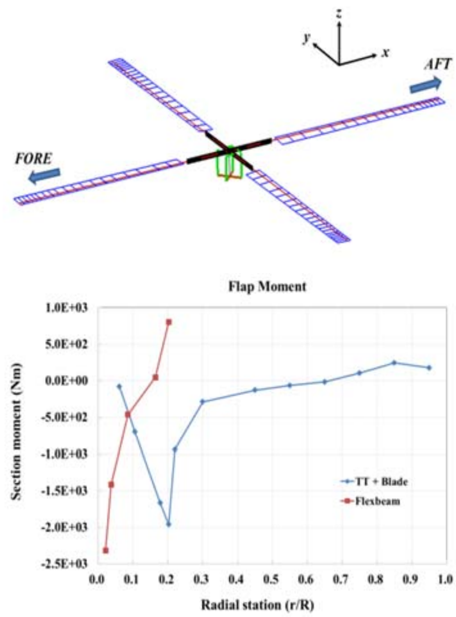



Figure 19 Load Prediction of KARI BMR Using CAMRADII

### 2.2.5. Structural Analysis

The structural analysis of KARI BMR was conducted using 2-D Euler beam theory and 3-D FE Analysis. In preliminary design stage, the simple and quick method based on 2-D Euler beam theory was adopted to acquire structural strength and safety in given load level. In critical design stage, the 3D FE analysis was conducted on separate part and on assembly components. The factor of safety (1.5) was applied into design limit load. The static analysis showed the there was no failure on structure of KARI BMR. The fatigue analysis showed that the predicted fatigue life on critical section (STA 700) of KARI BMR flexbeam is longer than requirement, 8,000hrs. Figure 20 shows the 3-D FEM Analysis results. The critical sectional of KARI BMR is near the shear restrainer (STA 320) and end of double H section (STA 1040). The margin of safety was about 0.82. Figure 21 shows the fatigue life analysis on critical section of flexbeam.

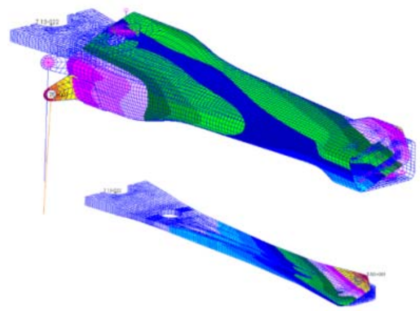


Figure 20 3-D FE Analysis of KARI BMR

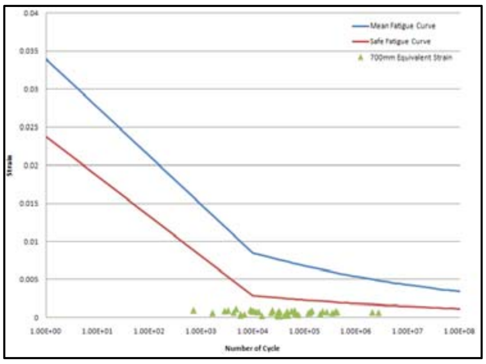



Figure 21 Fatigue Life Prediction of KARI BMR

### 2.2.6. Stability Analysis

The stability analysis of KARI BMR was conducted using CAMRAD II. The model of CAMRADII was used for load prediction. The isolated rotor model was built for whirl test. In stability analysis, the natural frequencies were avoided with n/rev frequencies and the 1$^{st}$ lag damping ratio was achieved over than the requirement, 2%. The 1$^{st}$ lag frequency was predicted as 0.69/rev. The analysis model was updated using sectional basic property test result.

### 2.3. BMR Fabrication

For fabrication, domestic company was chosen to build up the manufacturing process. The curing process was reviewed with manufacturer. KARI and domestic company designed the assembly process together. Specially, the flexbeam fabrication was so complicated due to its complex configuration such as double H shape. To define and setup its curing process, several prototypes of specimen were prepared and fabricated to finalize manufacturing process.

### 2.3.1. Flexbeam Fabrication

The flexbeam was assembled with 9 pre-formed separate parts into one parts using master moulds. This process was so complicated and the several trials were required to stabilize manufacturing process. Figure 22 shows the manufacturing process of KARI BMR flexbeam prototypes.

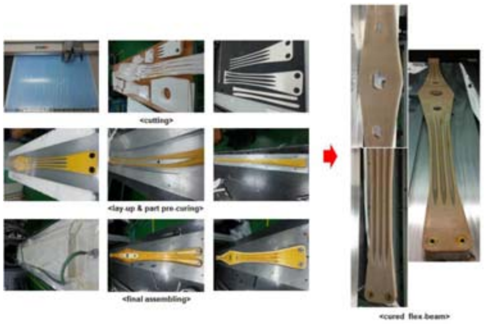


Figure 22 Manufacturing Process of KARI BMR Flexbeam

### 2.3.2. Torque Tube Fabrication

The torque tube was assembled in master moulds which comprised in upper and lower parts. The inner mandrel was used to wrap up the torque tube. Figure 23 shows the manufacturing process of KARI BMR torque tube prototypes.


Figure 23 Manufacturing Process of KARI BMR Torque Tube

## 2.4. BMR Prototype Inspection

### 2.4.1. Flexbeam Inspection

To inspect the fabricated flexbeam of KARI BMR, the profile templates were used to check major sectional dimension of flexbeam. The templates were machined with laser cutting to get accurate dimension. After inspection of profile dimension, the NDI (X-ray) inspection was conducted to investigate the foreign object, voids, delamination of layers. To do this, the pre-test was conducted to verify the exact angle and X-ray amount to get accurate quality. Figure 24 shows the X-ray inspection and profile inspection of flexbeam.

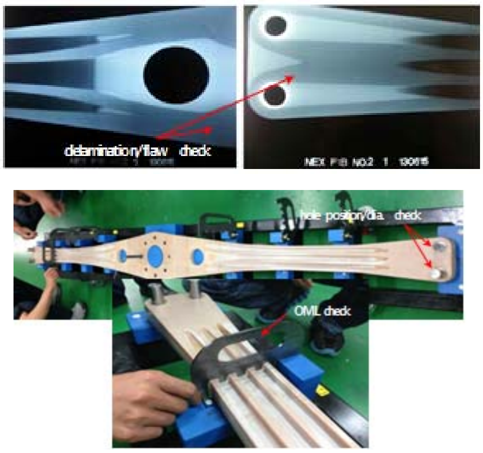



Figure 24 X-ray Inspection and Profile Inspection of KARI BMR Flexbeam

### 2.4.2. Torque Tube Inspection

To inspect the fabricated torque tube of KARI BMR, the profile templates were used to check major sectional dimension of torque tube. The templates were machined with laser cutting to get accurate dimension. After inspection of profile dimension, the NDI (X-ray) inspection was conducted to investigate the foreign object, voids, delamination of layers. To do this, the pre-test was conducted to verify the exact angle and X-ray amount to get accurate quality. Figure 25 shows the X-ray inspection and profile inspection of torque tube.

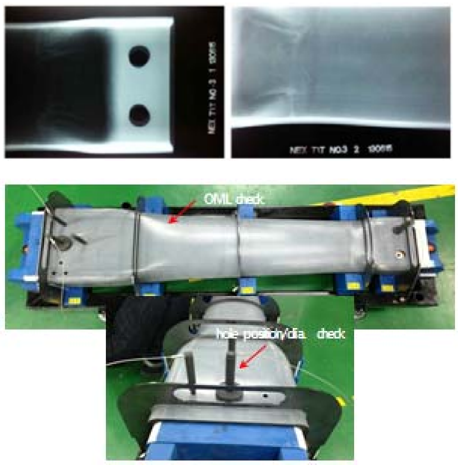



Figure 25 X-ray inspection and Profile Inspection of KARI BMR Torque Tube

### 2.5. BMR Assembly

All fabricated parts of KARI BMR and interface parts (Rotor control system and whirl tower adapter ring) were assembled into whirl tower together. As the 1st step, the KARI BMR rotor system was assemble on the ground rig. As the 2nd step, the KARI BMR rotor system was installed on the whirl tower. After installation of BMR on the whirl tower, the operating configuration was modified to do whirl test. Figure 26 shows the general view of KARI BMR on the whirl tower.

Figure 26 General View of KARI BMR on Ground Rig (upper) and the Whirl Tower (lower)

### 2.6. BMR Test and Evaluation

For test and evaluation of KARI BMR, the several tests were conducted. Material verification test was conducted first to verify the property and strength of materials to be used in KARI BMR. Basic sectional property test was conducted to get actual stiffness of flap, lag and torsional stiffness of KARI BMR flexbeam and torque tube. For structural test, the flexbeam and torque tube were separated into two test rigs. The four load actuators in flexbeam fatigue test were used for applying two centrifugal loads, one flapping moment and one lagging moment load. The four load actuators in torque tube fatigue test were used for applying one centrifugal load, one pitch rod load, one flapping moment and one lagging moment. Finally whirl test was conducted to demonstrate the global performance and stability of KARI BMR rotor system. With the reinforced BO-105 blades, the limitation of collective pitch angle was given into test condition for safe whirl test operation.

#### 2.6.1. Sectional Property Test

The sectional stiffnesses were measured to verify the analysis result and to compensate the actual value of sectional properties. The strain gauges were attached on the main sections of flexbeam and torque tube. The predicted value and measured value were matched well. Figure 27. shows typical flapwise stiffness results of flexbeam and general view of test.

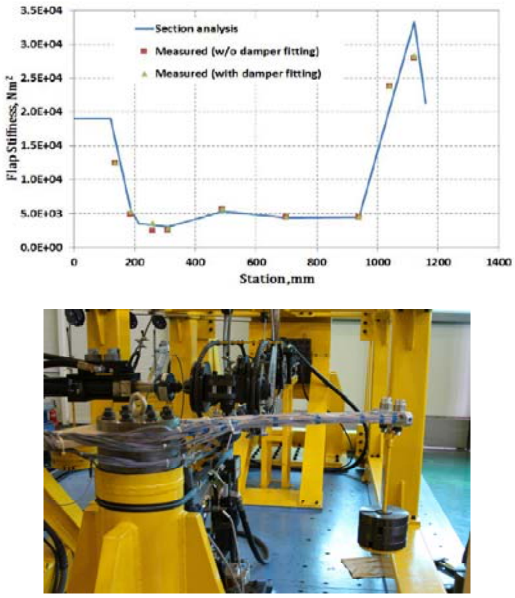



Figure 27 Sectional Property Test of Flexbeam

#### 2.6.2. Functional Test on the Ground

For confirmation of KARI BMR operation on the whirl tower in advance, the several functional tests were conducted on the ground test rig. The kinematic motion was checked with designed pitch angle and flap angle. Also, the deflection was checked briefly with given centrifugal force. Specially, the required pitch angle was investigated with shear restrainer and damper assembly. To measure deflection and angle, the dial gauge, potentiometer, inclinometer were used. The basic functional test on the ground was conducted successfully. Figure 28 shows the typical view of functional test on the ground.

#### 2.6.3. Structural Test

For technical demonstration of structural strength and fatigue life, the static and fatigue tests were conducted on flexbeam and torque tube. For static test, the final structural margin of safety of each parts was obtained with limit load and ultimate load. The final margin of safety of static test of flexbeam was 0.35. The final margin of safety of static test of torque tube was 4.04. For fatigue test, the two fatigue specimens were used and the final fatigue life of flexbeam was calculated 15,000hrs through fatigue test. The final fatigue life of flexbeam was calculated infinite through fatigue test. So, the torque tube has much margin of fatigue life. Figure 29 shows the fatigue test of flexbeam and torque tube.

Figure 28 Typical View of Functional Test of KARI BMR on the Ground

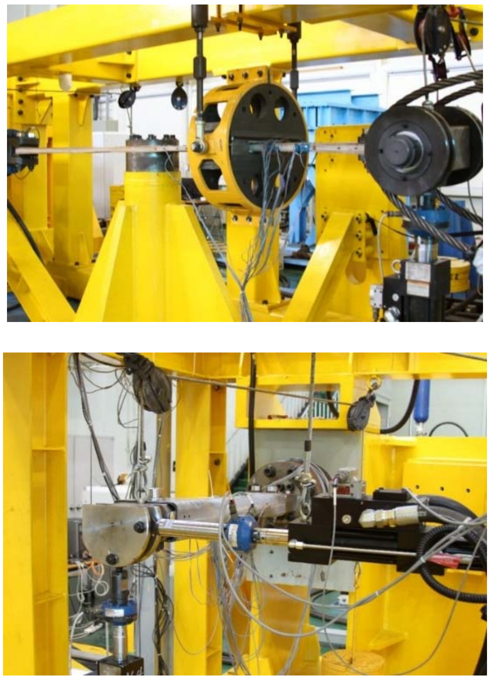
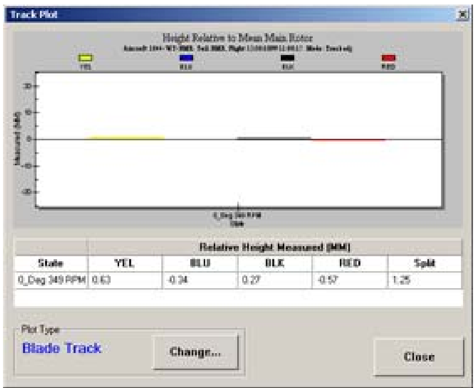


Figure 29 Fatigue Test of Flexbeam (upper) and Torque Tube (lower)

### 2.6.4. Whirl Test

As a final step of technology demonstration of KARI BMR rotor system, the whirl test with reinforced BO-105 blades was conducted. Before conducting whirl test, several activities such as strain gauges installation and calibration, LVDT installation, Amplifier installation, etc. were prepared in advance. For whirl test, KARI had experience in previous KHP program. So, most of test items are similar with the previous test. The manual rotation was conducted to check the interference with the existing whirl tower parts. The root of the BO-105 blades was reinforced with carbon materials for lag stiffness improvement since the original root BO-105 blade is soft relatively. Figure 30 shows general view of KARI BMR on the whirl tower. Before conducting whirl test, the rotor tracking and balancing were conducted using pitch link adjustment and tab bending to get required value. The final track with 7.0degree collective pitch angle was 1.25mm. The final 1/rev vibration level was achieved 0.05ips with mass added in weight balance pocket. Figure 31 shows the rotor tracking and balancing result of KARI BMR on the whirl tower. Figure 32 shows the rest results of KARI BMR rotor performance and natural frequency compared with the analysis results. The dynamic stability test was conducted within the limitation of safety. The measured 1st lag frequency was 0.75/rev with 345 rpm rotor speed.

Figure 30 General View of KARI BMR on the Whirl Tower



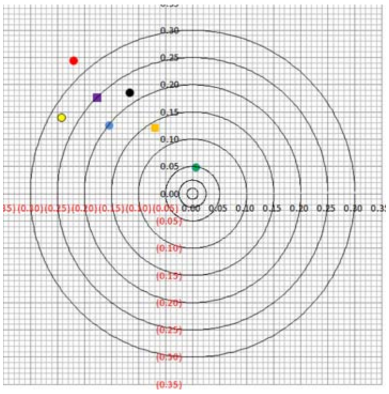


Figure 31 Rotor Tracking and Balancing of KARI BMR on the Whirl Tower

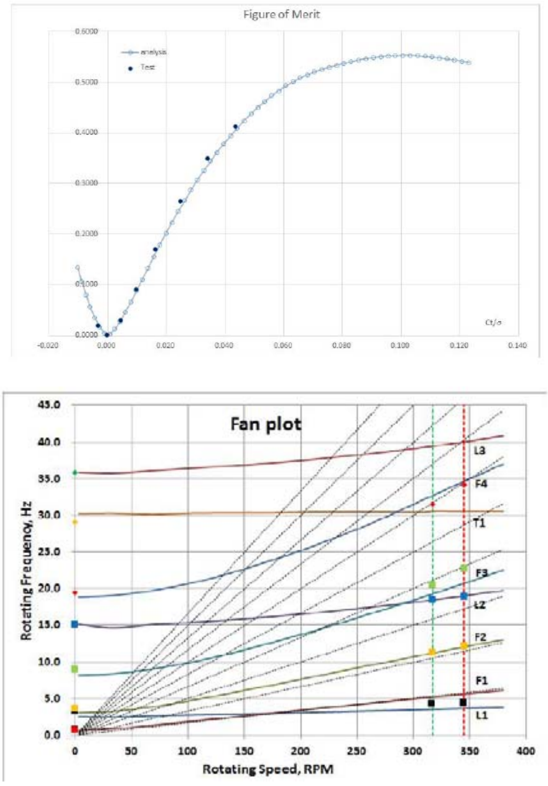



Figure 32 Typical Results of the Whirl Test for KARI BMR

## 3. CONCLUSION

This paper described the overview of Development of KARI Bearingless Main Rotor Hub System (KARI BMR). To finalize KARI BMR program, it took 41 months from the program launching to the whirl test. From this program, the core technologies of bearingless rotor hub system were achieved in KARI and in Korea. These technologies can be applied into Korea future rotor development program. Through this national program, the several core technologies were achieved as follows

- Composite design technology for advanced rotor system such as bearingless rotor hub system.
- Advanced analysis technology for complicated rotor system such as multiple load path rotor system.
- Whole experience of all required development activities through this program.
- Manufacturing technique for complex bearingless parts such as flexbeam and torque tube.
- Accurate prediction improvement through the correlation between analysis and test results.
- The requirements of this program such as lower parts numbers, light-weight hub system, low aerodynamic drag, and enough fatigue life were satisfied.

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