DESIGN AND TEST EVALUATION OF FBR BEARINGLESS MAIN ROTOR

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Abstract

A new main rotor system has been developed and flight test evaluated on a Bell Model 412 helicopter to assess its capability at Fuji Heavy Industries (FHI). The rotor system, designated the FBR (Fuji Bearingless Rotor), is an all composite, four-bladed, soft-inplane bearingless main rotor for 10,000 to 12,000 lbs. gross weight helicopters. Based on the advanced composite technology at FHI along with the extensive research on aerodynamics, noise, and vibration, the rotor system was planned and developed for new generation helicopters with challenging design objectives. Beginning by introducing brief descriptions of the FBR rotor system, overviews of aerodynamic/low noise and low vibration/dynamics design are presented. The flight test results with respect to performance, handling qualities, noise emission, and vibration levels are discussed. Overviews of structural features, strength substantiation, and ground test results are also presented. The rotor system has shown an improvement in high speed performance as expected, a significant reduction in noise emission and a remarkable reduction in vibration levels. What had not been expected in the design, remarkable reductions in hover noise and cabin noise were observed. In conclusion, it was confirmed that the design objectives have been achieved or in part surpassed and the FBR rotor system has demonstrated its capability.

List of Symbols and Abbreviations

AGL	above ground level
BVI	blade vortex interaction
C.G.	center of gravity
Clmax	airfoil section maximum lift coefficient
CFRP	carbon fiber reinforced plastic
dB	decibel
dBA	decibel (A-weighted)
EPNL	Effective Perceived Noise Level
FAR	Federal Aviation Regulations
FBR	Fuji Bearingless Rotor
FHI	Fuji Heavy Industries Ltd.
GFRP	glass fiber reinforced plastic
GW	gross weight
HSI	high speed impulsive
i	number of blades used as i/rev
ICAO	International Civil Aviation Organization
IFR	Instrument Flight Rules
JCAB	Japan Civil Aviation Bureau
JGSDF	Japan Ground Self Defense Force
KIAS	knots indicated airspeed
KTAS	knots true airspeed
LMS	least mean square
MCP	maximum continuous power
Mdd	airfoil section drag divergence Mach number
MITI	Ministry of International Trade and Industry
NC	numerical control
σ	density ratio
SHP	shaft horse power
SJAC	Society of Japanese Aerospace Companies, Inc.
SL	sea level
SPL	sound pressure level
STA	fuselage longitudinal station
STD	standard
VFR	Visual Flight Rules
V_H	maximum speed at MCP
V_{NE}	never exceed speed
XMSN	transmission

Introduction

The use of the helicopter is somewhat restricted considering its incomparable vertical flight and lift capability. What restrict the use, various factors are pointed out. Technologically speaking, the following three are important:

- High operating costs due to mechanical complexity, limited component and system equipment lives, and modest performance.
- Poor passenger comfort and limited

operational envelopes due to unpleasant noise and vibration.
- Insufficient compliance with environmental requirements due to noise emission.

To improve these shortcomings, FHI, among the major helicopter manufacturing companies in Japan and manufacturer of AH-1S attack helicopters and UH-1J multirole utility helicopters for the JGSDF (Japan Ground Self Defense Force) under Bell Helicopter license, started the development of a new rotor system as part of the company funded research. The major objectives were as follows:
- Develop the advanced rotor aerodynamic technology including airfoils and tip shape to improve rotor performance.
- Develop the advanced composite rotor technology including hub and blade to improve reliability and maintainability.
- Incorporate the structural dynamics optimization technique to reduce rotor vibrations without vibration absorbing devices.
- Establish the acoustic design methodology to reduce rotor noise emission.

On March 29, 1996, after a decade of strenuous research and development, the FBR rotor system installed on a Bell Model 412SP helicopter successfully made its first flight. During the five months of subsequent evaluation flight test, over fifty flights were conducted.

FBR Rotor System Descriptions

As outlined in Figure 1, the FBR main rotor system consists of the following:
- Two stacked GFRP flexbeams with the double-Y sectional shape to minimize the coupling of flap, lead-lag and pitch motions.
- Four CFRP low drag and high stiffness pitchsleeves to transmit the pitching control from pitch links.
- Four GFRP advanced airfoil rotor blades with the parabolic tip to realize high performance and low noise.
- Eight elastomeric lead-lag dampers with four elastomeric shear restraint pivots to prevent ground and air resonance.

FBR Design

To achieve the overall design objectives while reducing the weight, the design efforts were concentrated on aerodynamics, noise, vibrations and dynamics. This section presents an overview of the FBR design.

Aerodynamic and Low Noise Design

Our practical design goals were to improve the high speed performance and to reduce the noise level of the baseline Bell Model 412 helicopter with the minimum penalty on the

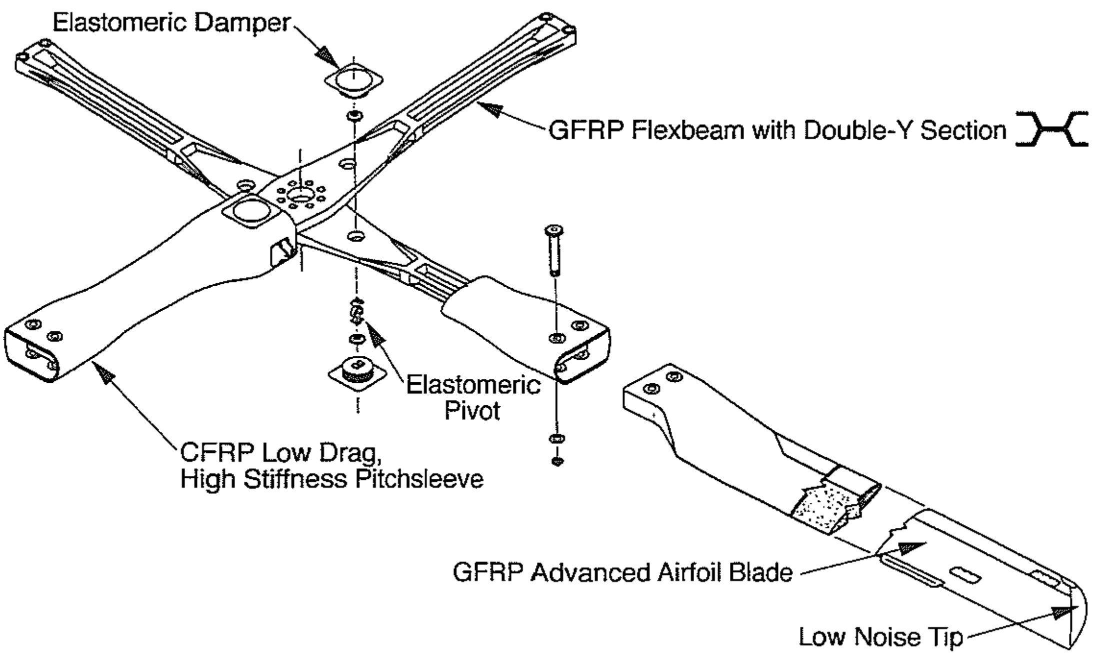


Figure 1 Outline of FBR Bearingless Main Rotor

hover performance. Under the design constraint of not changing the baseline rotor speed, the remaining design/sizing parameters were rotor radius, blade chord length including planform, blade twist, blade airfoils, blade tip shape, and pitchsleeve shape.

First of the design, blade chord length and rotor radius were optimized about high speed performance, hover performance, noise level and g capability. Tapered planform and high twist like the Model 412 are advantageous for hover performance but may lead to an increase in vibration levels at high speed flight. After careful deliberation, tapered planform was given up and a moderate twist of 12 degrees, slightly smaller than that of the baseline Model 412, was selected to reduce the developmental risk. As a result of this design compromise and to minimize the loss in hover performance, it was not realistic to reduce the rotor radius or the tip speed of the baseline Model 412.

With respect to the airfoils, high Clmax and high Mdd new generation U896H series (Reference 1) were selected for the outer portion of the blade to improve high speed performance and to reduce HSI (high speed impulsive) noise. High lift to drag ratio U926H series airfoils were newly designed for the mid to inner portion to regain the loss in hover performance due to the disadvantageous planform and twist. Figure 2 shows the Clmax versus Mdd of the airfoils as compared to other airfoils.

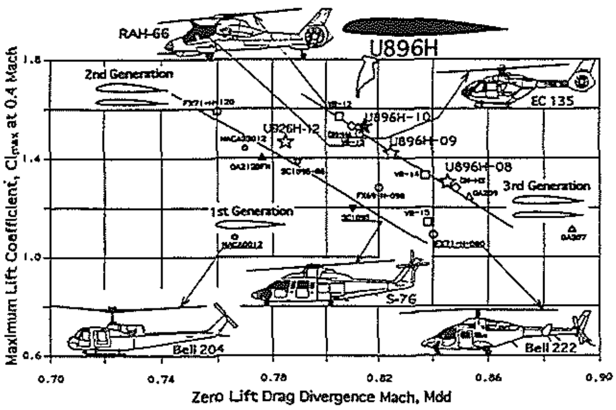


Figure 2 FHI Rotor Blade Airfoils

Last of the blade design, a parabolic planform with the straight trailing edge was selected for the blade tip shape based on the blade tip wind tunnel (Figure 3) results to reduce power required and HSI noise by weakening the shock around the tip at high speed flight.

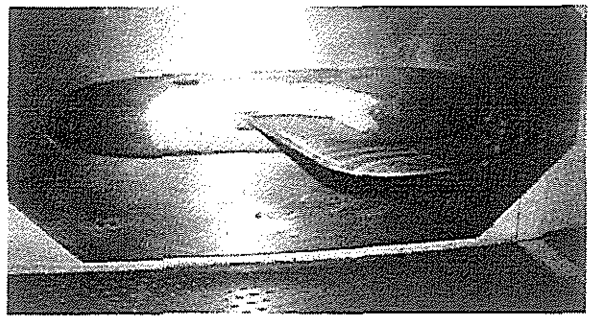


Figure 3 Rotor Blade Tip Wind Tunnel Test

Regarding the BVI (blade vortex interaction) noise, a small scale model rotor wind tunnel test (Figure 4) was conducted to validate the anhedral blade tip that sheds the tip vortex at a lower position, makes it pass farther beneath the succeeding blade than the tip without anhedral and moderates the interaction. A parabolic planform tip was also tested. The anhedral tip showed the effects of weakening the SPL (Sound Pressure Level) peak at approach condition while the parabolic tip showed little significant effects. A parabolic tip with the trailing edge sweep was also discussed in the design. The trailing edge of this type passes more downward at positive angles of attack and consequently sheds the tip vortex at a lower position than the tip with the straight trailing edge. However, again after careful deliberation, neither the anhedral nor the trailing edge sweep tip was selected for fear of excessive vibration levels or high control loads. What was not expected but found to have been referred to in References 2 through 4, the parabolic tip showed a small reduction in the power required in hover. This gave us additional grounds for selecting the tip.

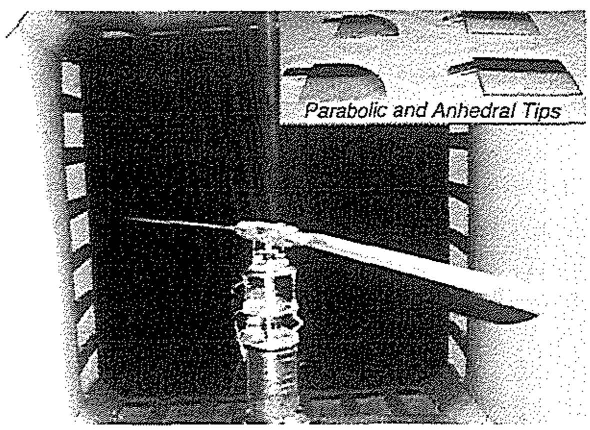


Figure 4 Low Noise Rotor Wind Tunnel Test

A hub-pylon rotating wind tunnel test (Figure 5) was conducted to obtain low drag pitchsleeve shapes. The hub of the Model 412 is very compact and among the lowest drag rotor hubs. A hub with the elliptic sectional shape pitchsleeve, much larger in radius and much thicker, showed comparable hub drag to that of the Model 412 with pendulum absorbers. Furthermore, top and bottom surfaces were flattened to make the pitchsleeve thinner and reduce the drag.

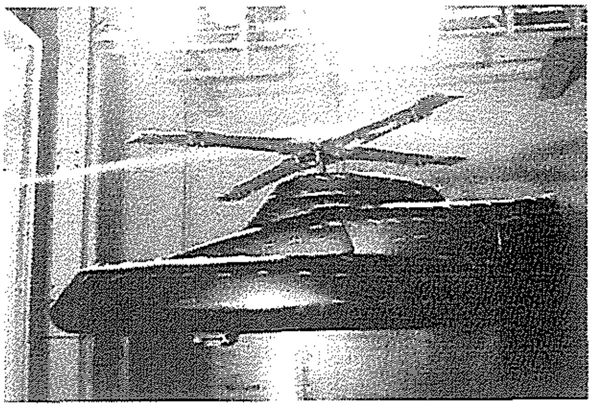


Figure 5 Hub-pylon Rotating Wind Tunnel Test (Concept Validation)

Table 1 shows the geometrical summary of the aerodynamic and low noise design. Due to the comparatively high tip speed of 780 ft. per second inherited from the baseline Model 412 and with the high Clmax airfoils of the FBR, the stall margin of the retreating blade is considerably large compared to the Mdd margin of the advancing blade. In other words, the FBR design can hardly be optimal at high speed flight, however in conclusion, four knots of the speed gain over the baseline Model 412 was predicted. The increase in the power required in hover was estimated to be no more than 2 percent without taking into account the power reduction effect of the parabolic tip.

Table 1 Design Summary

Rotor Radius	23 ft.
Blade Chord Length	13.5 ins. Constant
Blade Planform	Rectangular
Blade Twist	-12 deg. Linear (Hub Center to Tip)
Airfoils	U926H-12 (0 - 70 % radius) U896H-10 (85 % radius) U896H-08 (Tip)
Tip Shape (Planform)	Parabolic
Pitchsleeve Shape (Section)	Elliptic (Top and Bottom Flattened)

Low Vibration and Dynamics Design

An approach was employed that optimizes the mass and stiffness distribution of the blade to reduce the rotor vibrations by isolating the natural frequencies from the i/rev frequency and by counterbalancing the aerodynamic force with the inertial force. A research was performed to validate the concept under a SJAC (Society of Japanese Aerospace Companies) contract with funding by the MITI (Ministry of International Trade and Industry). In this research, a Froude scaled small model rotor wind tunnel test (Figure 6) was conducted. The optimized rotor showed a reduction of approximately 40 percent in vibration levels over the datum or not optimized rotor at the design speed. In the practical design, an optimization routine was coupled to the CAMRAD II comprehensive analysis code to automatically minimize rotor vibrations.

Figure 6 Low Vibration Rotor Wind Tunnel Test (Concept Validation)

After a careful design compromise between high controllability and mild gust response, a relatively small equivalent hinge offset of 3 percent rotor radius was selected. The natural frequency of rotor chord mode was tailored to have enough margin to operational rotor speed to help the damping of elastomeric dampers.

FBR Structural Features

To realize the unlimited life of the composite components, FHI's long and wide experience in the composite structures on fixed wing aircraft and unmanned helicopter rotor was made effective use of in manufacturing the major components of the composite rotor system shown in Figure 7. This section overviews the structural features of the FBR rotor system.

Flexbeams

The flexbeams are fabricated mainly of continuous bundles of filament wound S-glass belts that form the lugs for the blade retention at both ends of the flexbeam. The belts are cured for the smooth spanwise change in the sectional shape. Pieces of pre-cured S-glass fabric are added to achieve the tailored shape along the span.

Blades

The main structure of the blade consists of the following major components, fiberglass spar, channel, nose block, trailing edge, skin and Rohacell core. A unique feature of the spar is the root joints inserted to the bored holes at the root for cost reduction instead of the lugs wound around with unidirectional fiberglass. Finally nickel abrasion strip and tip cap are bonded.

Pitchsleeves

The pitchsleeves are fabricated primarily of pieces of carbon fiber filament wound over the mandrels using NC filament winder. Unidirectional tape is added to provide higher chordwise bending stiffness. Roughly trimmed pitch sleeves over the mandrels are then cured using bagging technique in the pressure plates to obtain better outer contours.

FBR Strength Substantiation

In general, the objective of the strength substantiation was to show compliance with the FAR part 29 (Reference 5) civil regulations. In practice, a building block approach was employed based on the procedures outlined in the AC: 20-107A advisory circular (Reference 6). The consistent results of the strength tests on the limited number of specimens, from coupons, elements to full-scale structures including

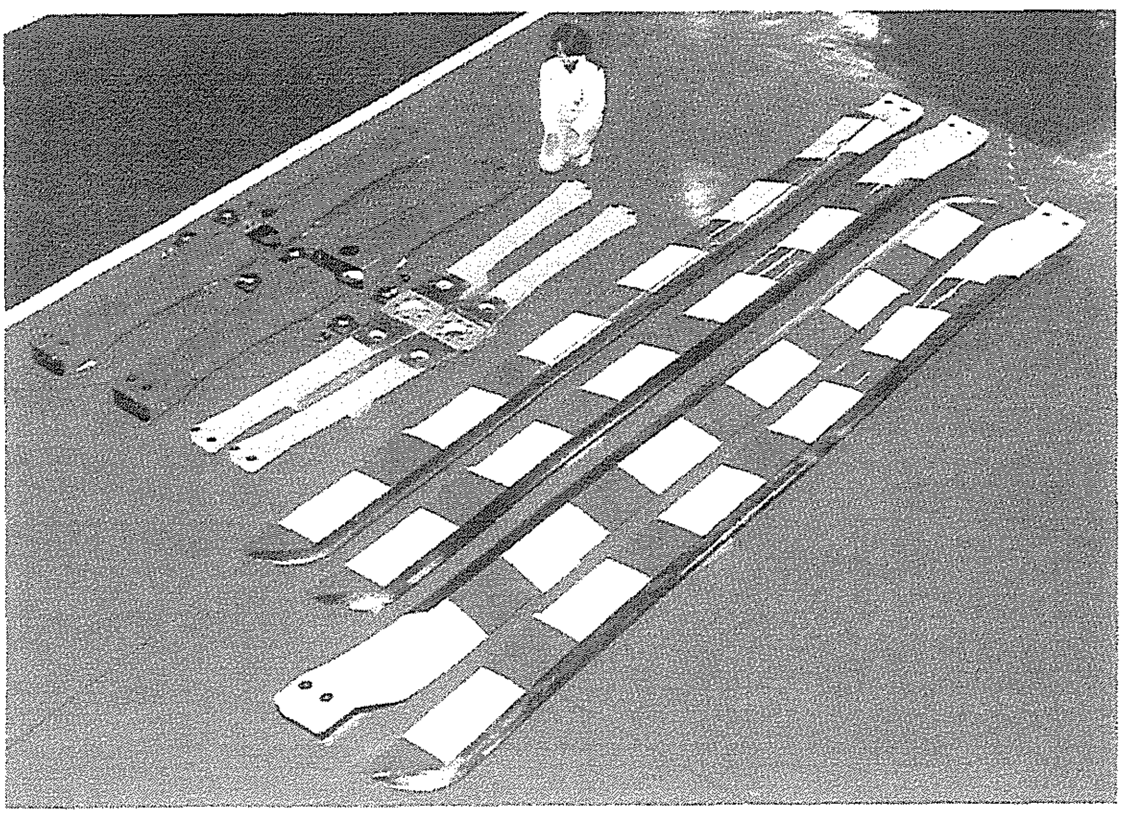


Figure 7 FBR Major Components

structural components, together with analyses validated by these test results were used to substantiate the FBR strength. The full-scale strength tests conducted include blade components static and fatigue, blade stiffness and vibration, flexbeam stiffness, hub assembly static and fatigue, and mast joint strain survey. Figure 8 outlines the hub assembly full-scale test.

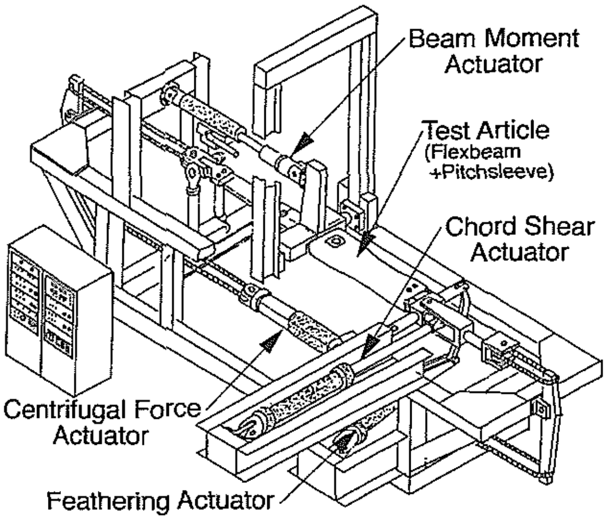


Figure 8 Hub Assembly Full-scale Test

FBR Evaluation Test

After almost three years of detailed design, fabrication and qualification tests, the FBR rotor system was assembled and installed on a Bell Model 412SP helicopter. The test vehicle was instrumented in terms of attitudes, rates, control positions, acceleration g's including vibrations, loads, angle of attack and angle of sideslip (Figure 9).

Ground Test

Prior to the first flight, a series of ground tests were conducted to identify critical vibration frequencies and modes. Starting from ground idle, the rotor speed was increased step by step and cyclic stick inputs were made to excite the roll, pitch and forward-aft modes of rotor, pylon and fuselage. The result was carefully checked and the next rotor speed increment was decided according to the damping criteria. The ground test results showed that the natural frequencies of all the rotor elastic modes avoided the resonant areas as predicted. The natural frequencies of second flap, third flap and third chord modes, in particular third chord mode had larger margins to the resonant areas than those of the Model 412, which indicated that the low vibration design was successful. The rotor system on the Model 412 airframe showed enough damping up to 104.5 percent or the maximum operational rotor speed of the Model 412 and demonstrated freedom from ground resonance instability.

Flight Test

After a month of ground tests, the FBR test vehicle first flew on March 29, 1996. First six weeks of low speed flight within airfield area achieved airspeeds of 60 knots forward, 20 knots sideward and rearward. Once the flight envelope above was established the aircraft cleared "out of the airfield" flight. Throughout the five months of evaluation flight test (Figure 10), cyclic stick inputs were made to excite the flapping, torsional and inplane modes as the flight envelope was expanded. The result was

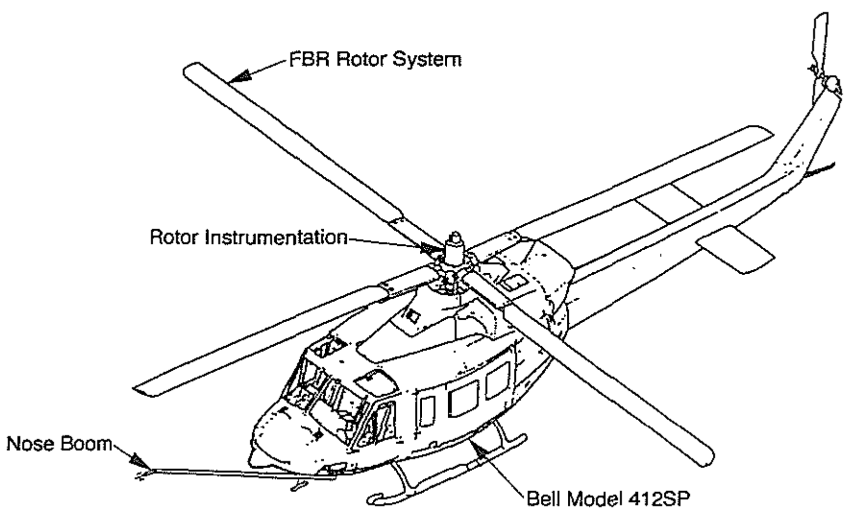
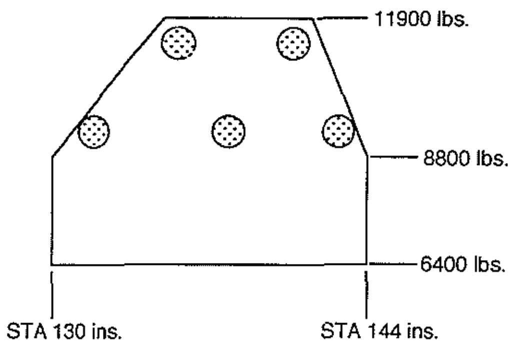
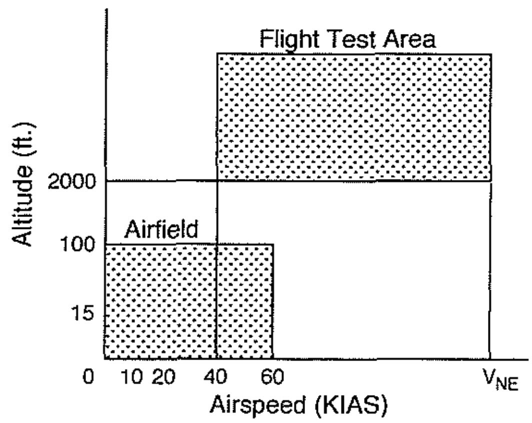


Figure 9 Flight Test Vehicle

Figure 10 FBR Flight Test



Gross Weight vs. C.G.



Altitude vs. Airspeed

Figure 11 Flight Envelopes Tested

carefully checked and in terms of airspeed the next increment was decided according to the damping criteria. Vibrations and loads were also monitored. On June 19, the aircraft reached 140 knots, the maximum allowable airspeed under the limited approval of the test flight by the JCAB (Japan Civil Aviation Bureau) or V_{NE} of the baseline Model 412. The flight envelopes tested in terms of the gross weight versus longitudinal center of gravity and the altitude versus airspeed are illustrated in Figure 11. The FBR showed enough damping up to 140 knots and demonstrated freedom from air resonance instability.

With respect to the performance testing, the procedure was based on the AC: 29-2A advisory circular (Reference 7) and the AMCP 706-204 (Reference 8) engineering design handbook on helicopter performance testing. Figure 12 shows the power required in level flight as compared to the baseline Bell Model 412 flight data at FHI. The FBR is approximately five knots faster than the Model 412, slightly faster than the predicted four knots gain. The increase in the power required in hover was no larger than 1 percent (Figure 13), smaller than the estimated increase of 2 percent.

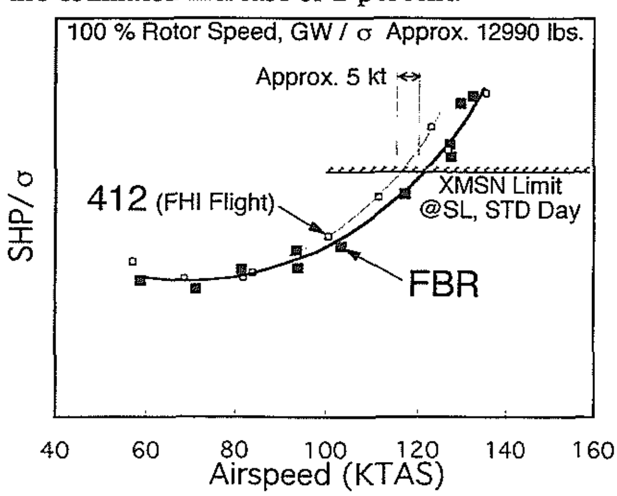


Figure 12 Level Flight Performance

Handling qualities testing was aimed primarily at the MIL-H-8501A (Reference 9) military specification whose requirements were more descriptive and detailed than those of the FAR part 29. Figure 14 shows the static longitudinal stability as compared to the Model 412 flight data at FHI. The FBR exhibited similar characteristics to the Model 412 as expected. Figure 15 illustrates the controllability in hover as compared to the MIL-H-8501A requirement. The spot check flight data of the Model 412 at FHI are also shown. The FBR exhibited slightly higher controllability in terms of control sensitivity and rate damping than that of the Model 412.

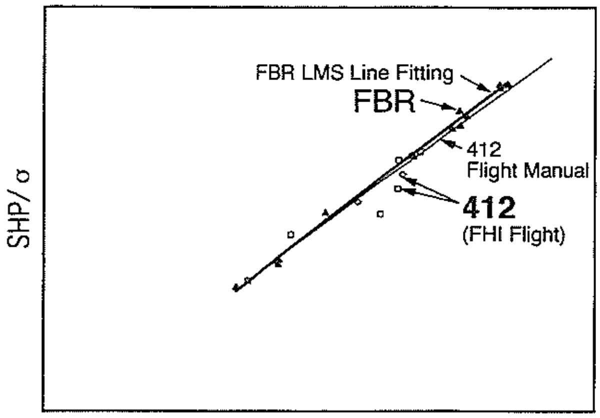


Figure 13 Hover Performance

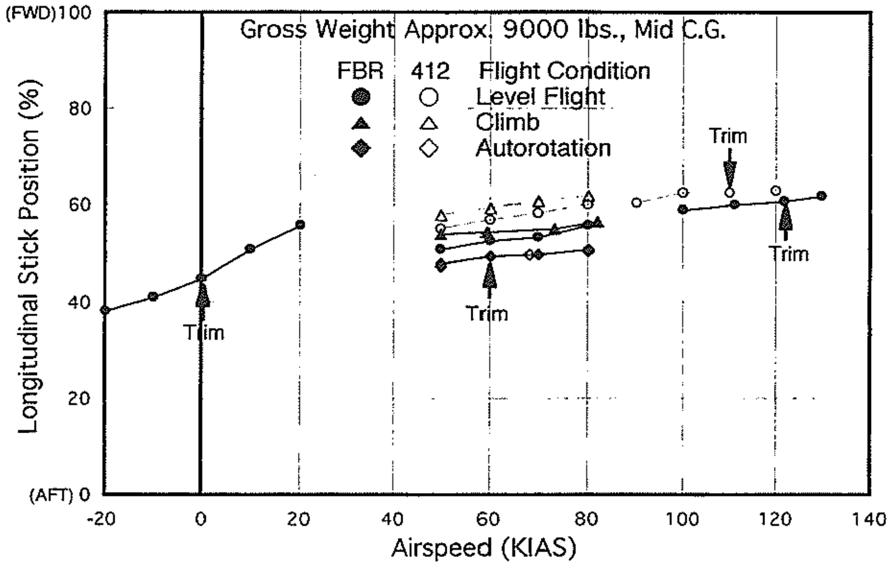


Figure 14 Static Longitudinal Stability

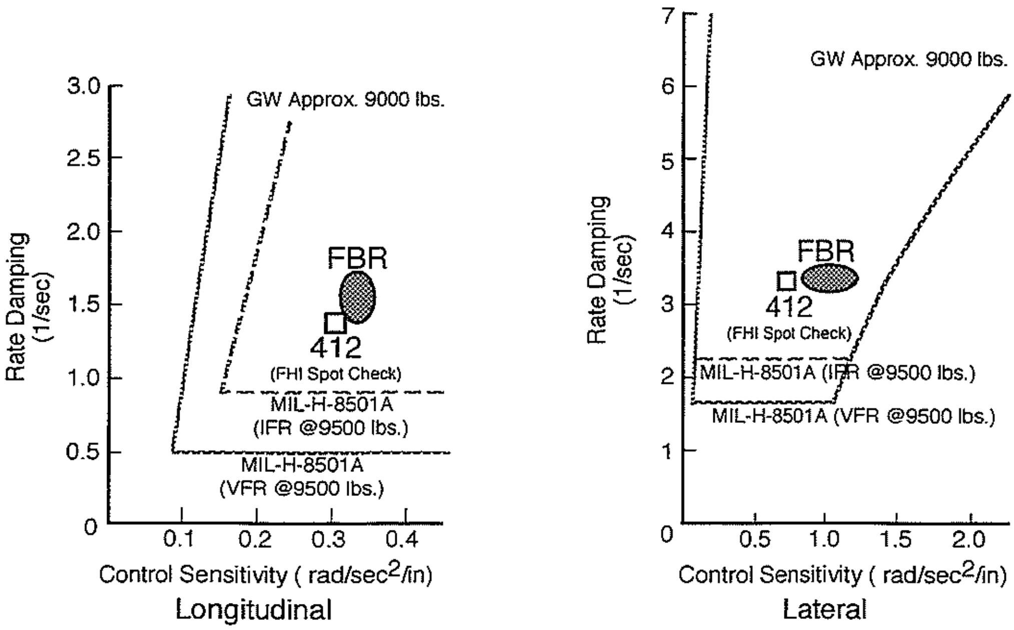


Figure 15 Controllability in Hover

Noise testing was conducted based on the ICAO Annex 16 procedure (Reference 10) except the limited number of flights. Figure 16 summarizes the ICAO EPNL as compared to the published Model 412 noise. The flyover noise level of the FBR is 1.5 EPNL(dB) lower than that of the Model 412. The reduction in the approach noise level is 0.7 EPNL(dB), small but larger than the measurement variance. The reduction in the takeoff noise level is not significant. Figure 17 shows the noise levels in 150 ft. above ground level (AGL) hover as compared to the Model 412 data at FHI. An unexpected reduction of approximately four dBA was found. Figure 18 summarizes the cabin noise at the midpoint of pilot's and copilot's ears as compared to the Model 412 flight data at FHI. Again a surprising reduction of 3.5 to 9.0 dBA was observed. The mechanism of the reductions in hover noise and cabin noise has not been explained yet. Further investigation has to be undergone.

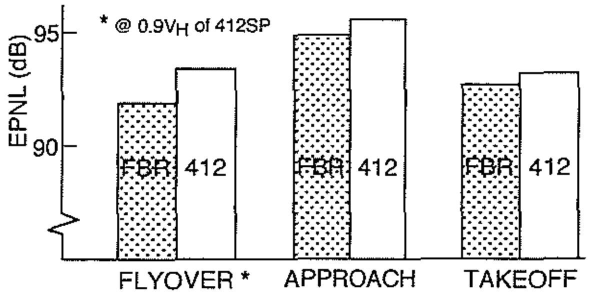


Figure 16 ICAO EPNL

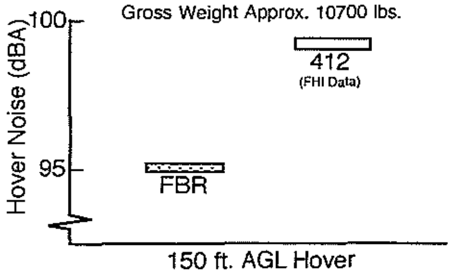


Figure 17 Hover Noise

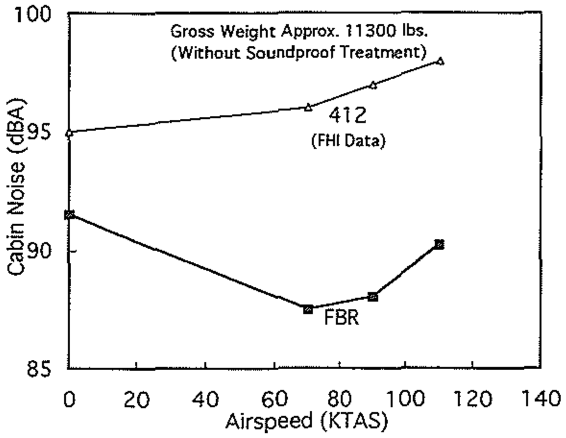


Figure 18 Cabin Noise

Figure 19 shows the vibration levels as compared to the Model 412. The FBR exhibited lower vibration levels without vibration absorbing devices than those of the Model 412 with pendulum absorbers. The reductions in vertical vibrations around the transverse region and lateral vibrations at high speed flight are remarkable, almost half the levels of the Model 412.

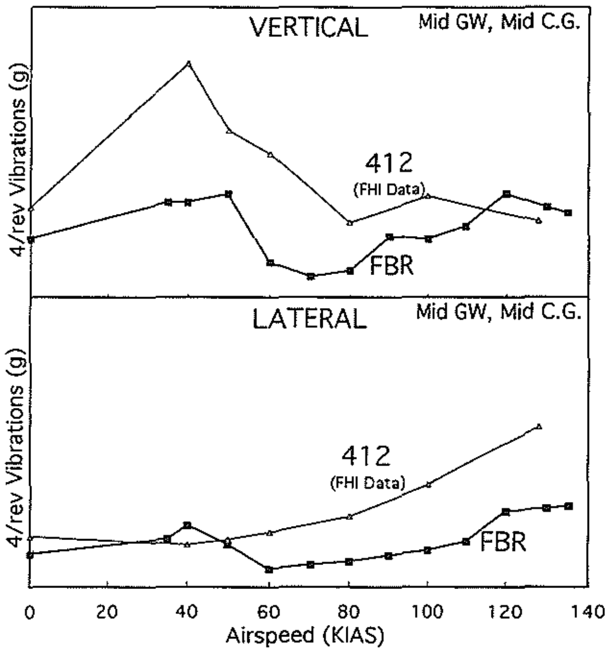


Figure 19 Vibration Levels at Pilot's Seat

Concluding Remarks

The evaluation flight test demonstrated the capability of the FBR rotor system, high speed, low noise emission, low vibration levels and good handling qualities. The rotor system achieved or in part surpassed the design objectives. These good characteristics were attained by the new generation airfoils, the extensive use of wind tunnels, the incorporation of the structural dynamics optimization technique and the wide experience in manufacturing various composite structures.

Acknowledgment

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