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DESIGN, FABRICATION AND TESTING OF THE COMPOSITE BEARINGLESS ROTOR SYSTEM FOR ROTARY-WING AIRCRAFT

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DESIGN, FABRICATION & TESTING OF THE COMPOSITE BEARINGLESS ROTOR SYSTEM FOR ROTARY-WING AIRCRAFT

by

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Abstract

Recently, small-medium class helicopters used primarily for army observation missions are required to have high maneuverability and good maintainability. High maneuverability is indispensable for NOE (Nap of the Earth) flight and easy maintenance is important for field use. For these requirements pursued was the new composite bearingless rotor system. There are two aims of this research. One is to increase control force by the bearingless rotor system to obtain high maneuverability. The other is to decrease the number of the parts and components of the rotor system by applying co-cured composite material manufacturing method.

This paper addresses the composite bearingless rotor system and its test results. Contents are (1) Research program and design concept of the rotor system having special emphasis on minimizing the coupling effect and reducing the damper size (2) Prototype 1 rotor system and results of the bench testing, the whirl tower testing, the airframe shake testing and the ground testing related to Prototype 1 (3) Prototype 2 rotor system on the Hughes 369J helicopter and results of the flight testing of Prototype 2.

It was concluded that the composite bearingless rotor system was applicable to the full-scale helicopter development to achieve high maneuverability and good maintainability.

1.Introduction

Most helicopters which have been currently used in Japan were manufactured in Japan by license production or imported from abroad. Therefore, little technical data of the helicopter, particularly as concerns the rotor system has been accumulated. However, Japan Defense Agency had conducted the in-house research on helicopter rotor blade aerodynamics. Recently the necessity of the helicopter having high maneuverability and good maintainability have been greatly increasing in the world. Based on this recognition, in order to improve the capability for design and evaluation of the rotor system and to prove the rotor system which possesses high maneuverability and good maintainability the research of the design, fabrication and testing of the composite bearingless rotor system were conducted in Japan Defense Agency in cooperation with Kawasaki Heavy Industries,LTD.

2 Research program

In Japan FY1983 it was initiated to study and manufacture the prototype of the key components of the composite bearingless rotor system as shown in Fig.1. From FY1986 to FY1987 the prototype of the rotor system (Prototype 1) was manufactured and subsequently the bench testings, the whirl tower testing, the airframe shake testing and the ground testing were conducted on Prototype 1. The bench testings included the static strength, fatigue and stiffness testings. The whirl tower testing was carried out to obtain the dynamic characteristics of the rotor system including the natural frequencies and the in-plane damping. The airframe shake testing was carried out to obtain the dynamic characteristics of the airframe without the rotor system of the Hughes 369J helicopter. Subsequently the rotor system was installed to this airframe for the ground testing. The ground testing was performed and the mechanical instability, called as ground resonance, was examined on the several conditions.

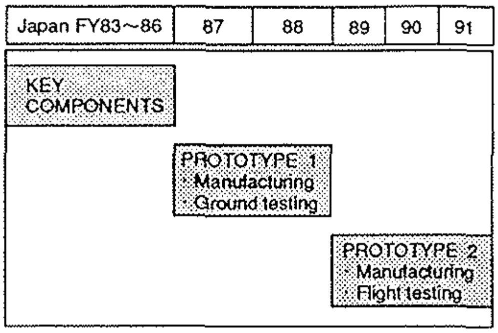


Fig.1 Research program

Based on these test results, the rotor system for the flight testing (Prototype 2) was fabricated from FY1989 to FY1990. The primary focus for the improvement of the rotor system was to reduce the size,which is smaller than that of Prototype 1. Especially, the size of the rotor hub system of Prototype 2 is smaller than that of Prototype 1. Prototype 2 was installed to the fully instrumented Hughes 369J helicopter. The flight testing was carried out from Jan.1991 to Oct.1991. The number of flight was 81 and the total flight hours were 69 hours. A survey of flight characteristics, flight load, air resonance stability and flight performance was successfully conducted.

3 Rotor system description

Two sets of the rotor system,Prototype 1 and Prototype 2, were fabricated based on the same design concept. Figure 2 shows Prototype 1 for the ground testing.

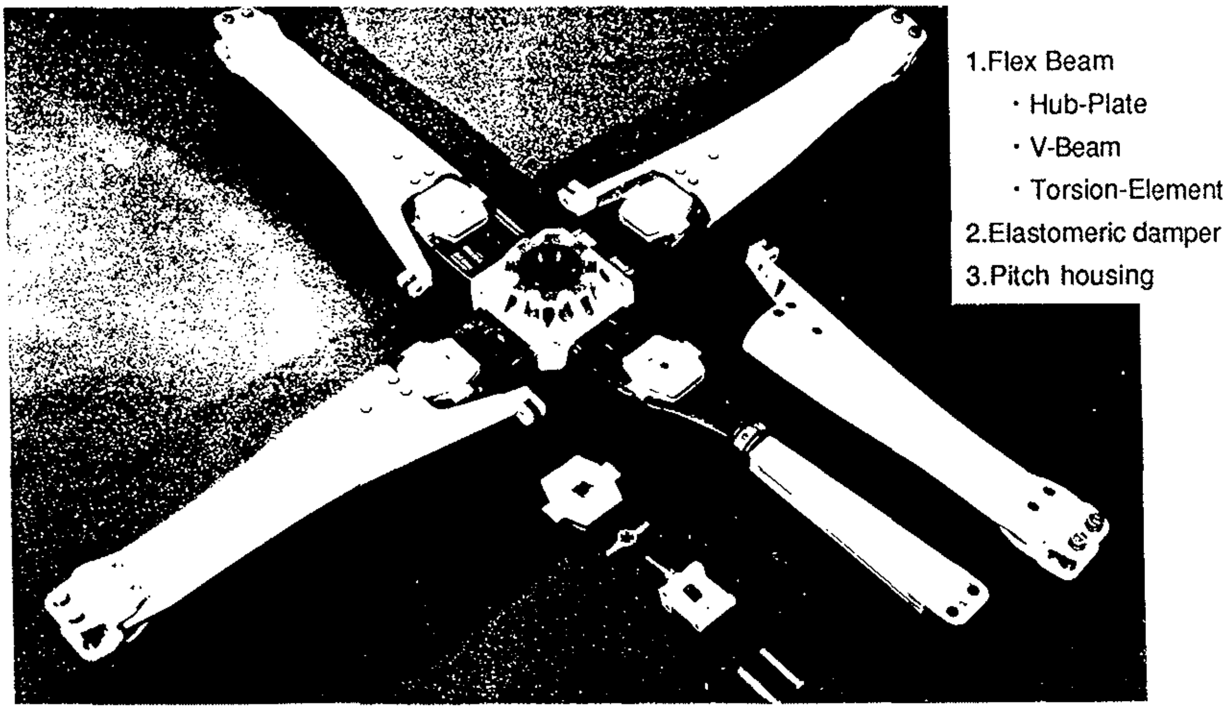


Fig.2 Prototype 1 (for the ground testing)

The rotor system consists of four composite rotor blades and a co-cured composite rotor hub system.The rotor hub system has sufficient hinge-offset to attain high maneuverability and its components are the flex beams, four elastomeric dampers, and four pitch housings.The flex beam is composed of Hub-Plate where flapping motion is allowed, V-Beam where lead-lag motion is allowed and Torsion-Element where feathering motion is allowed. As concerns the size of the rotor system, the diameter of the rotor hub system is about two meters and the blade span is about four meters.The composite materials used for the rotor system are CFRP and GFRP. The pitch housing is made of T300 carbon cloth-epoxy and the flex beam is made of uni-directional E-glass epoxy respectively. It was successfully achieved to reduce the number of total parts and components to around forty in order to accomplish good maintainability.

Pitch-flap-lag coupling of the bearingless rotor hub system was a critical issue.To prevent the instability caused by this coupling the deflection curve of the flex beam was carefully designed to reduce the coupling effect. This was the principal issue in the design concept. The point of effective hinge was defined as the intersection of the center line of the pitch housing and the rotor pitch axis for each direction. As shown in Fig.3 the spanwise positions of each effective hinge were separated enough to have no interferences between effective hinges. As a result obtaining decoupled effective hinges of the flex beam was successful.

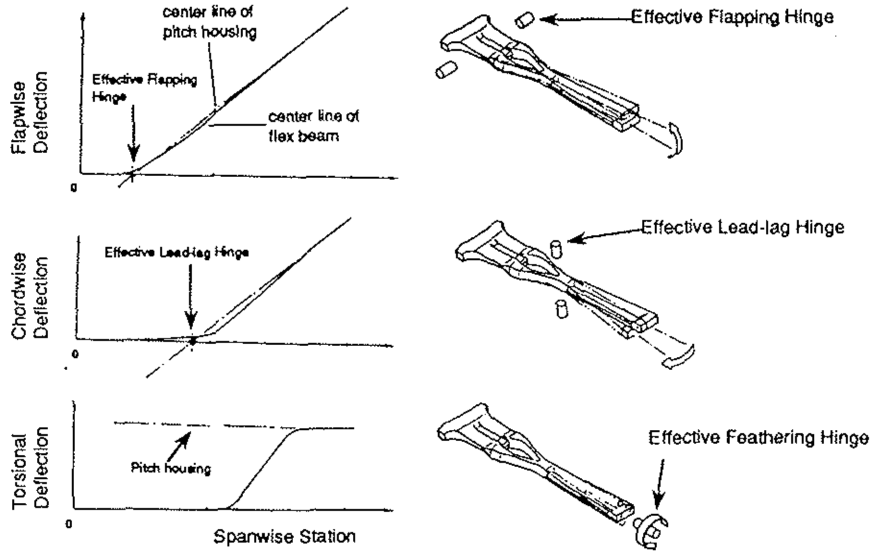


Fig.3 Decoupled effective hinges of the flex beam

Another important issue was to improve the efficiency of the lead-lag damper. In case of using the elastomeric (lead-lag) damper the in-plane damping moment is proportional to the product of the deflection of the lead-lag damper and the damper arm length as shown in Fig.4(1).
If S-deformation of the flex beam occurs, that means the offset, which is defined as the distance between the center line of the pitch housing and that of the flex beam, is large,

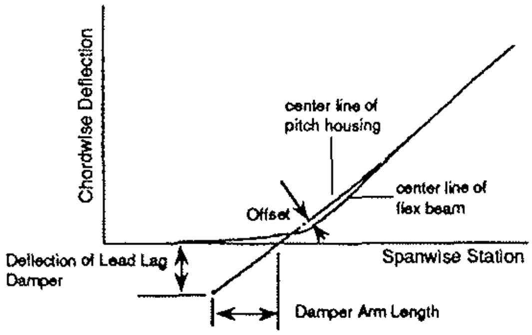


Fig.4(1) Efficiency of the lead-lag damper both the deflection of the lead-lag damper and the damper arm length become small and consequently the in-plane damping moment becomes small as shown in Fig.4(2). Therefore,it is necessary to design to make the offset small for obtaining large in-plane damping moment. So V-Beam structure was introduced.This was the second point of the design concept. As shown in Fig.4(3) V-Beam reacts as very stiff truss structure to the chordwise shear force and minimizes chordwise shear deflection, but is very flexible for the chordwise bending moment because of the small bending stiffness of each beam member. These two effects of V-Beam mentioned above decrease the chordwise bending moment of Torsion-Element. Therefore, no S-deformation of Torsion-Element occurs and the offset can be made small. As a result sufficient in-plane damping can be obtained.

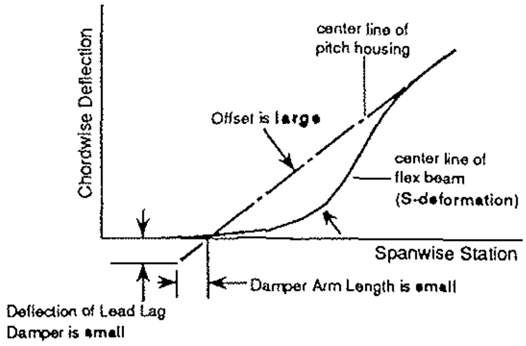


Fig.4(2) S-deformation of the flex beam

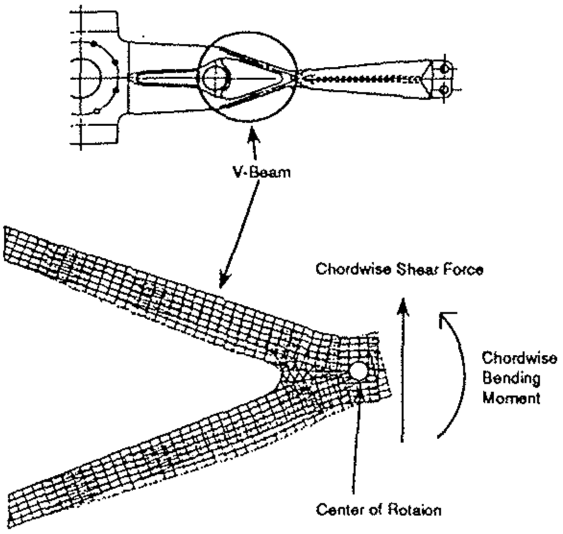


Fig.4(3) Effect of V-Beam

4 Ground testing

In FY1988, the ground testing of Prototype 1 was conducted. Ground testing consisted of the bench testing, the whirl tower testing, the airframe shake testing and the ground (rotating) testing on the Hughes 369J helicopter.

4.1 Bench testing(1) Static strength testing

The static strength testings of components of the rotor system were conducted for each flap, chord and torsional direction. As an example Figure 5 shows the testing of the flex beam to the flapwise bending moment. The flapwise bending moment was loaded by the two arms sited above and below the test specimen. The load condition considered was that forty knot wind blew to the rotor system without rotation on the ground . As shown in Fig.6 it was confirmed that the rotor system endured the ultimate-load and had sufficient static strength.

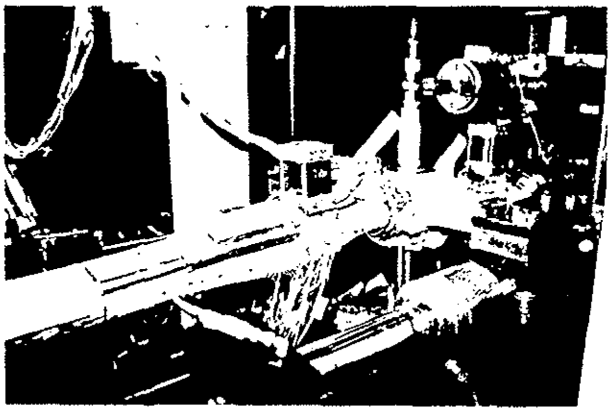


Fig.5 Bench testing(1) Static strength testing

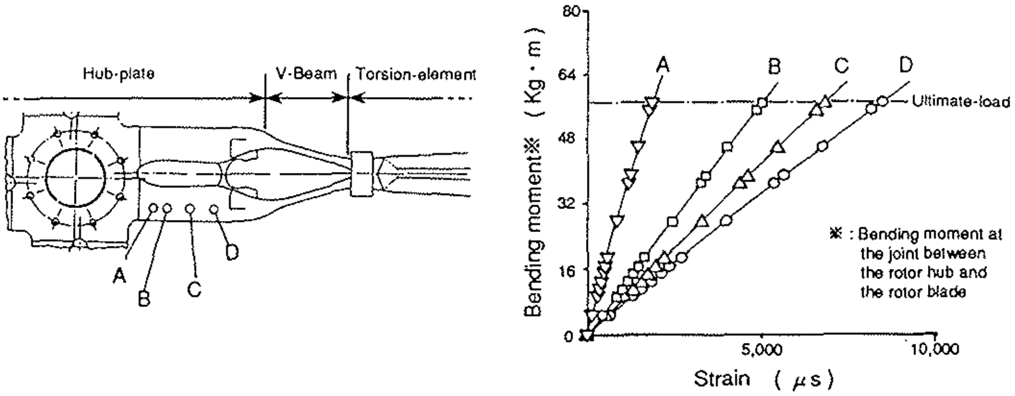


Fig.6 Test results - Static strength testing

4.2 Bench testing(2) Fatigue testing

The fatigue critical area of the flex beam are shown in Fig.7. The fatigue testing was carried out to obtain the S-N curves of the flex beam. As shown in Fig.8 flapwise and chordwise bending moments, spanwise axial force and the static mast torque were loaded simultaneously in the high cycle fatigue testing.

Part Name	Critical Area		Failure Mode
Hub-Plate	(1)	Flap Flex.	Fiber Break
	(2)	Transition	Shear
	(3)		Peal and Shear
	(4)	Flap Flex.	Transverse Break
	(5)	End of P.P.Tape	Shear
V-Beam	(6)	Apex Area	Bending
			Shear
Torsion-Element	(7)	Torsional Flex.	Shear
	(8)	End	Bending
			Shear

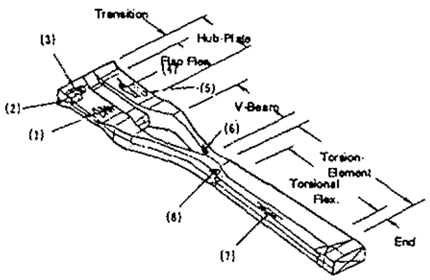


Fig.7 Fatigue critical area of the flex beam

And also the Ground-air-ground fatigue testing was conducted. Figure 9 shows the results of the S-N curves. These S-N curves were used for evaluation of the fatigue life of the rotor system with the load histgraph measured in the flight load survey of Prototype 2 on the Hughes 369J helicopter.

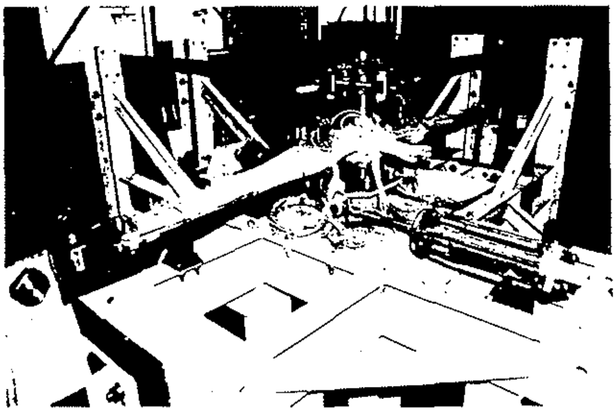


Fig.8 Bench testing(2) Fatigue testing

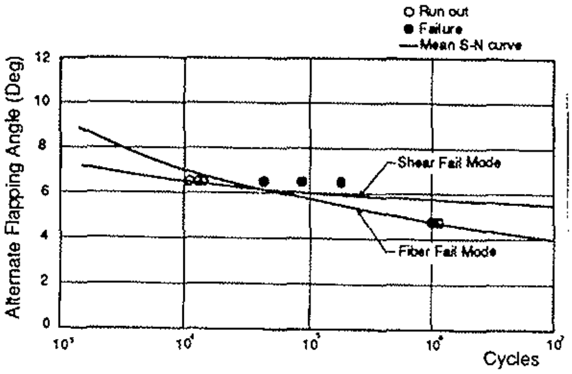


Fig.9 Test results - Fatigue testing

4.3 Whirl tower testing

In the whirl tower testing the dynamic characteristics of the rotor system including the natural frequencies and the in-plane damping, were examined. As shown in Fig.10 the rotor system was rotated on the whirl tower and its cyclic pitch was oscillated by the hydraulic actuator. The flapping and lead-lag motion were measured with strain gages attached to the rotor system and analyzed with the FFT analyzer when necessary.

Figure 11 shows the rotor system natural frequencies. In Fig.11 the areas which are shaded are resonant zones and the rotor system natural frequencies were designed not to pass through these areas. As shown in Fig.11 it was confirmed that the rotor system natural frequencies did not pass through these area. And they were consistent with the calculations of the rotor system natural frequencies.

Figure 12 shows the in-plane damping of the rotor system. The in-plane structural damping was evaluated in several conditions in which the parameter of the pitch link position was varied as shown in Fig.12(a). Subsequently the in-plane damping of Prototype 1 was measured in the whirl tower testing and it showed a good agreement with the analysis as shown in Fig.12(b).

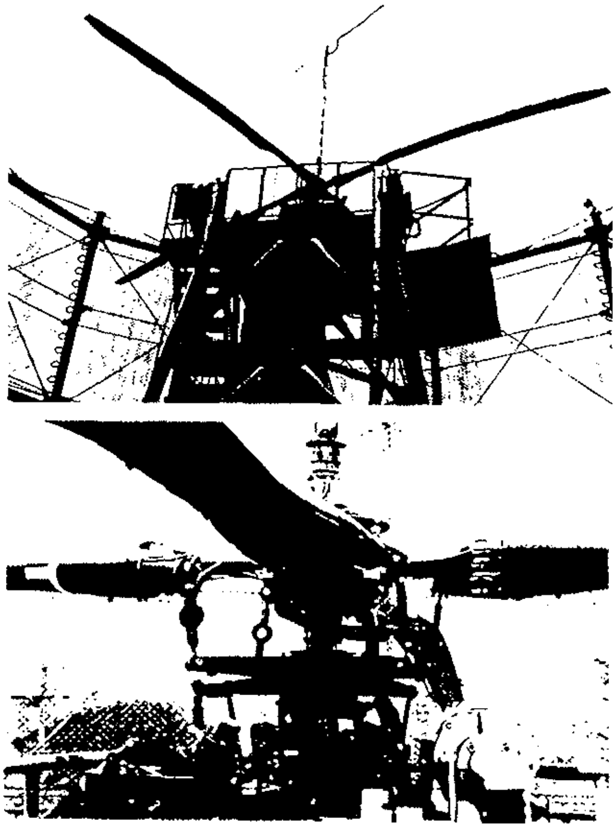


Fig.10 Whirl tower testing

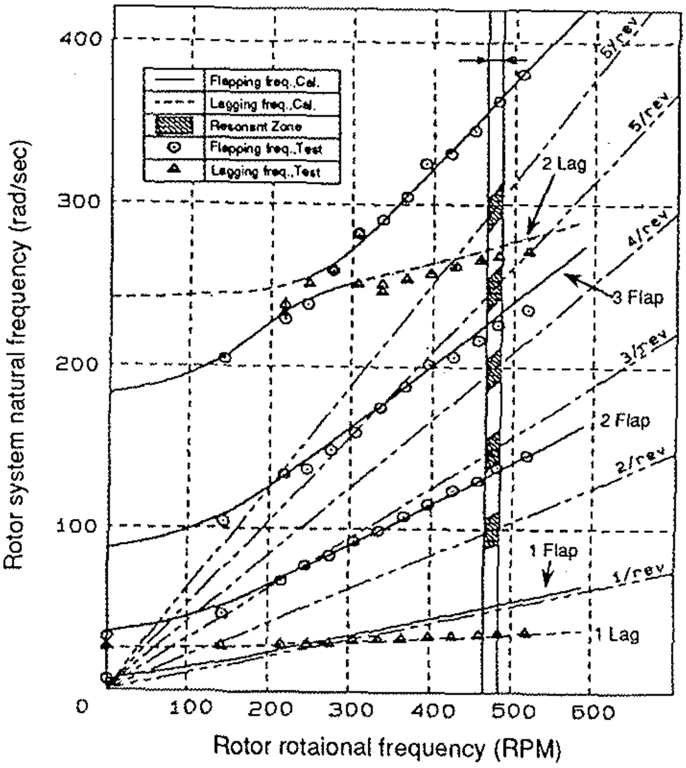
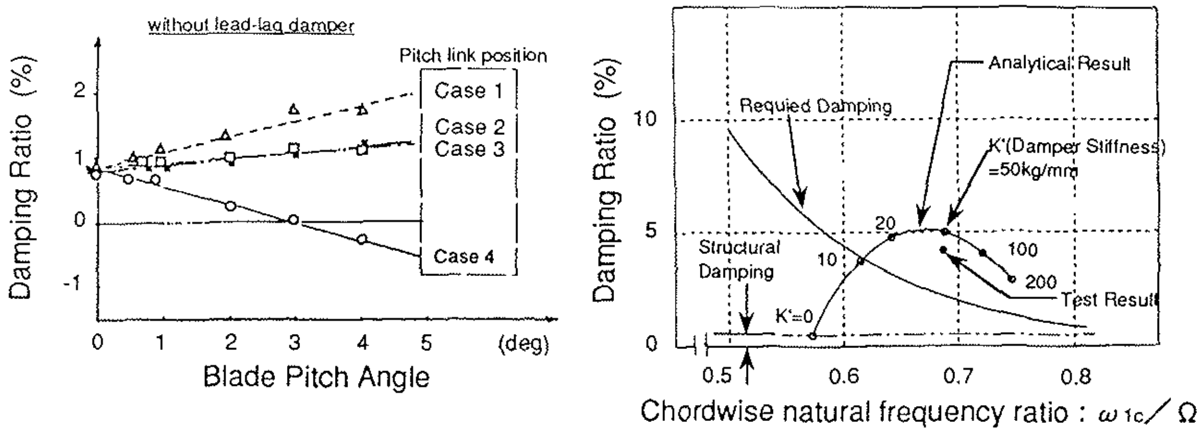


Fig.11 Frequency diagram of the rotor system



(a) In-plane structural damping (b) In-plane damping of Prototype 1

Fig.12 In-plane damping of the rotor system

4.4 Airframe shake testing

In the airframe shake testing the dynamic characteristics of the airframe including the natural frequencies and the dampings were examined. As shown in Fig.13 the airframe without the rotor system was set under the crane and shaken by the hydraulic actuators. The motion of the airframe was measured with G-sensors attached to the airframe. The airframe was the Hughes 369J helicopter on which the rotor system would be subsequently installed for the ground testing. In the airframe shake testing the parameters of the airborne ratio which was defined as lift-weight ratio and simulated by the crane, the airframe weight, the contact between the skid and the ground, the stiffness of the gear damper, which might affect dynamic characteristics of the airframe, were varied.

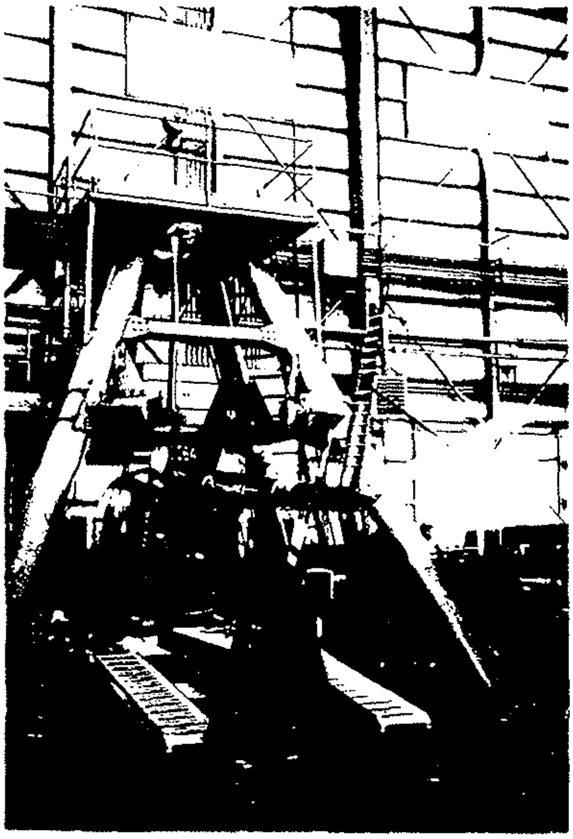


Fig.13 Airframe shake testing

4.5 Ground testing

As shown in Fig.14 the ground testing was performed on a Hughes 369J helicopter to evaluate the mechanical instability, so called ground resonance. In the ground testing the same parameters as those of the airframe shake testing were varied and the pilot oscillated the helicopter by the cyclic pitch control instead of the hydraulic actuators of the airframe shake testing. The motions of the rotor system and the airframe were measured with strain gages and G-sensors. As a result it was concluded that the rotor system had enough stability to avoid ground resonance. Also technical data which were necessary for verification of "Analytical computer program for ground resonance" were obtained.

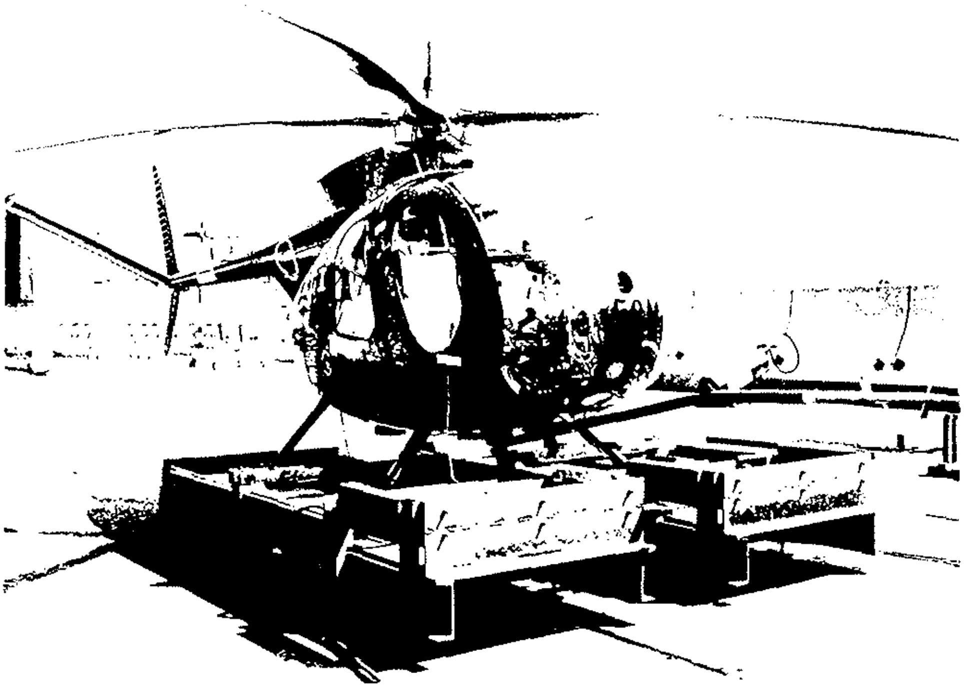


Fig.14 Ground testing

4.6 Analytical computer program for ground resonance

As shown in Fig.15 the input and output of "Analytical computer program for ground resonance" are as follows:

- program input are the dynamic characteristics of the rotor system which is obtained in the whirl tower testing, and the dynamic characteristics of the airframe which are measured in the airframe shake testing
- program output are the characteristic roots which are calculated by solving the characteristic equations of the helicopter motions

This analytical program was verified by comparing its output with results of the ground testing. In the verification importance was attached to the cyclic regressive mode of the rotor system. Figure 15 shows results of the verification. The program output were consistent with results of the ground testing and showed very good simulation of the area where the damping ratio decreased.

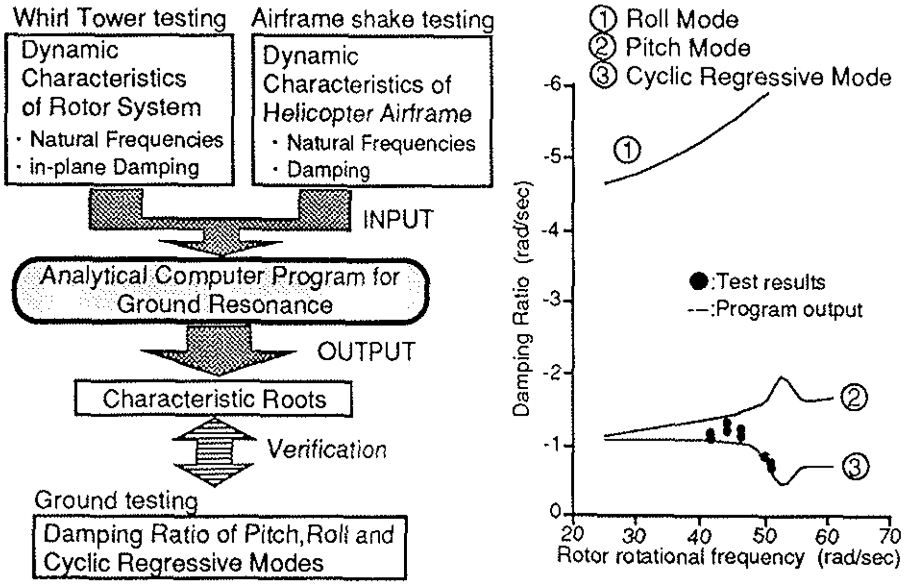
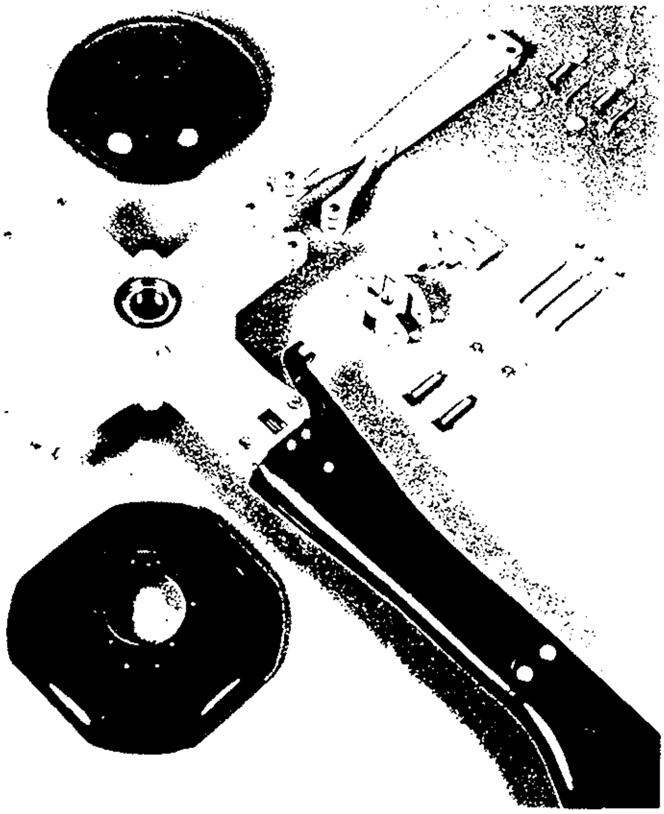


Fig.15 Analytical computer program for ground resonance

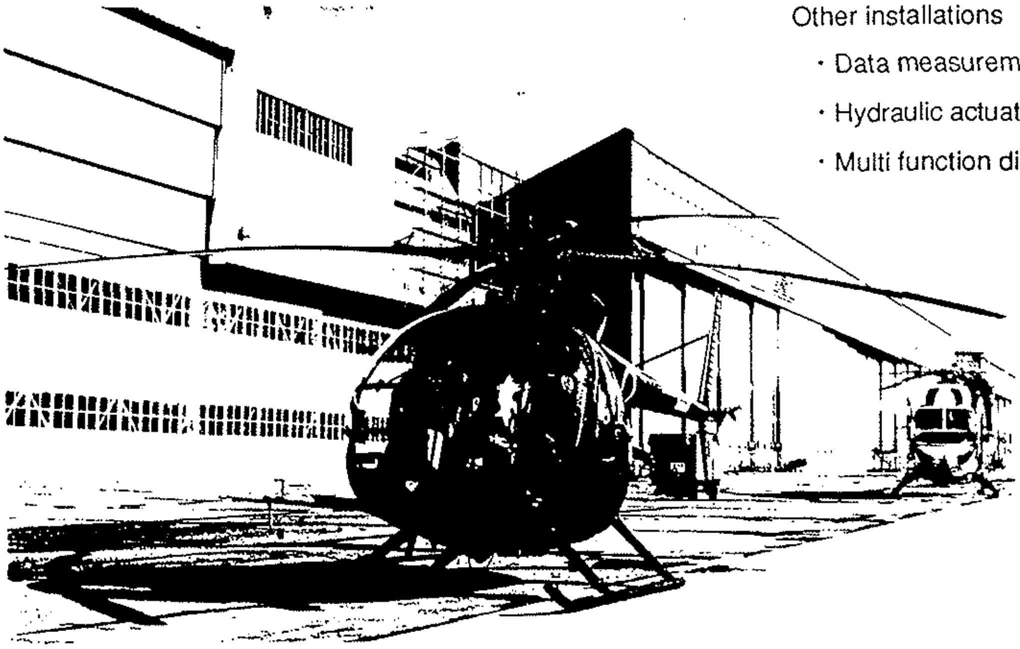
5 Flight testing

Figure 16 shows Prototype 2 for the flight testing. Improvements from the previous prototype are (1) adding the mechanism for the blade folding to the flex beam, (2) unifying the rotor blade and Torsion-Element, (3) reducing the size of the elastomeric damper and (4) installation of the fairing of the rotor hub. Prototype 2 was manufactured from FY1989 to FY1990 and installed to the Hughes 369J helicopter as shown in Fig.17. Other installations on the Hughes 369J helicopter were the data measurement system, the hydraulic actuators for flight control system and the multi function display as the pilot instrument. The flight characteristics, the flight load survey, the aerodynamic stability to air resonance and the flight performance were examined in the flight envelope shown in Fig.18. As shown in Fig.19 the flight testing was carried out from Jan.1991 to Oct.1991. The number of flight was 81 and the total flight hours were 69 hours.



1.Hub-Plate
2.Torsion-Element
3.Elastomeric damper
4.Rotor blade assembly
5.Fairing assembly

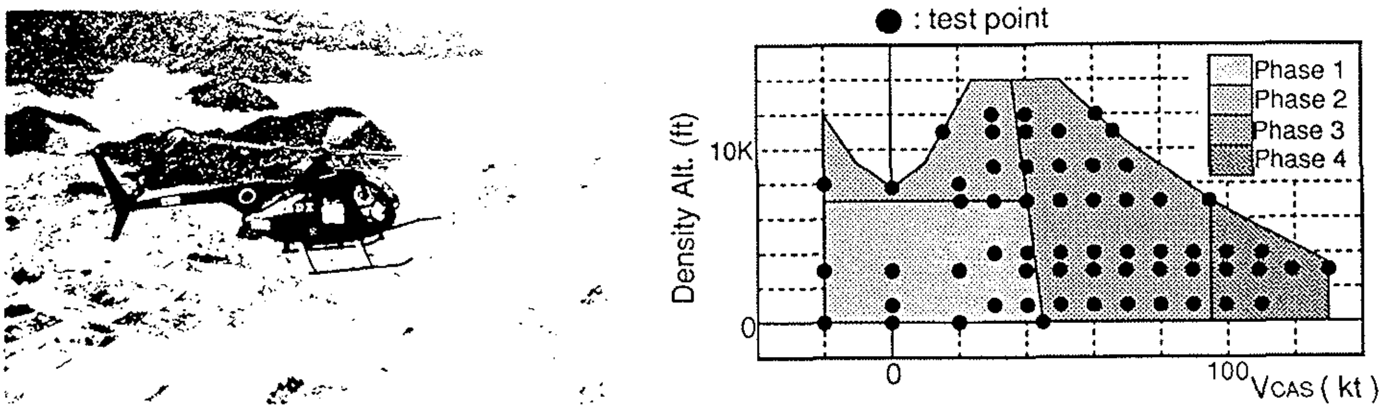
Fig.16 Prototype 2 (for the flight testing)



Other installations

- Data measurement system
- Hydraulic actuators for FCS
- Multi function display

Fig.17 Composite bearingless rotor system on the Hughes 369J helicopter



(a) Flight testing

(b) Flight envelope

Fig.18 Flight testing of the rotor system

5.1 Flight characteristics

In the flight characteristics testing the longitudinal and lateral maneuvering characteristics were evaluated mainly. The design criteria for the flight characteristics was based on ADS-33A which was specified by United States Army Aviation Systems Command. Figure 20 shows the test results of the pitch control power. The plus and minus normal load factors were developed by pull-up and push-over maneuver respectively. This testing was performed within the G-limitation of the Hughes 369J helicopter. The pull-up maneuver reached plus 2.5 G and the push-over maneuver minus 0.5 G. The test pilot told

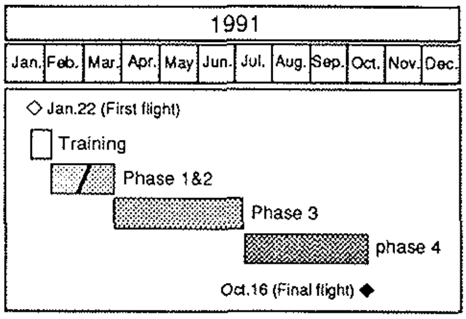


Fig.19 Flight testing schedule

that he could easily attain minus G in this helicopter in comparison with the conventional articulated rotor system helicopter.

Figure 21 shows the linearity of roll response and the rotor system had the good lateral controllability. Based on those test results the maximum steady state roll rate was calculated by multiplying control margin by steady state roll rate per unit lateral stick deflection. As a result the maximum steady state roll rate was more than fifty degrees per second and satisfied the design criteria.

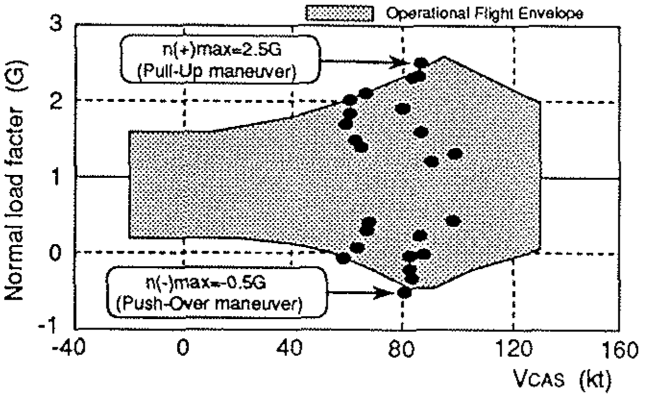


Fig.20 Flight characteristics - Pitch control power

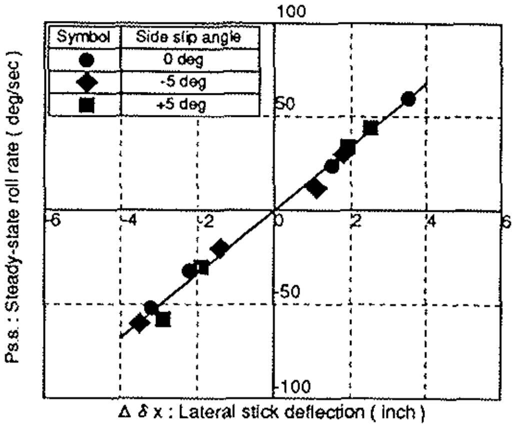


Fig.21 Flight characteristics - Linearity of roll response

5.2 Flight load survey

To obtain the flight load of the rotor system the stick and pedal reversal, autorotational landing and other testing were conducted based on the mission profile of the Hughes 369J helicopter. As shown in Fig.22 the load histgraph was calculated by means of Rain-flow method. The fatigue life of the rotor system was evaluated by applying Miner's law and satisfied the design criteria.

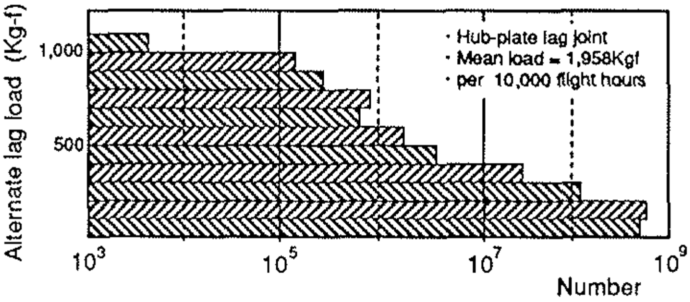


Fig.22 Flight load survey - Load histgraph

5.3 Air resonance stability

Figure 23 shows the damping ratio of the first in-plane mode which indicates the aerodynamic stability of air resonance. In Fig.23 analytical results were calculated by using "Analytical computer program for ground resonance". From these results it was confirmed that the rotor system had the sufficient air resonance stability and "Analytical computer program for ground resonance" was fully verified and an useful tool for the analysis of air resonance.

5.4 Flight performance

Level flights, climbs and autorotational descents were conducted in the survey of the flight performance. As an example of the results of those testing Figure 24 shows the required power curve as the level flight performance.

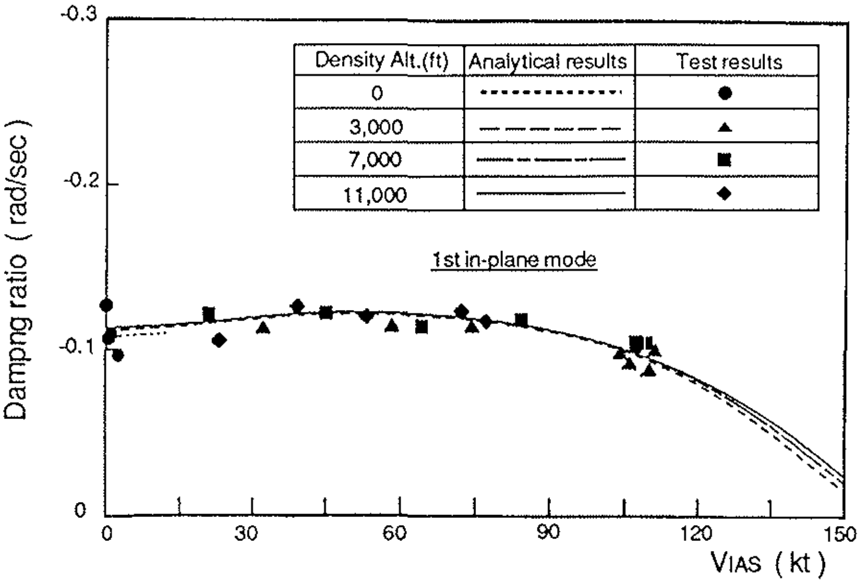


Fig.23 Air resonance stability

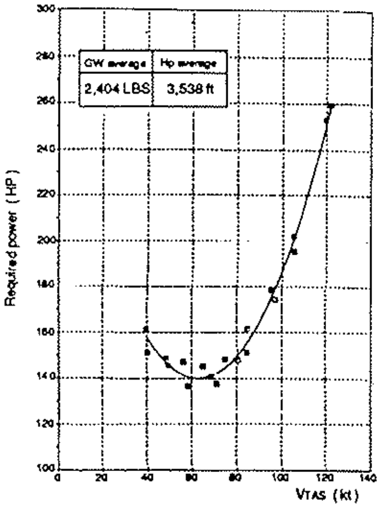


Fig.24 Level flight performance
(Required power curve)

6 conclusion

From the results of the flight testing it was concluded that the composite bearingless rotor system had sufficient control force,as shown by minus G maneuver capability and the high roll performance for high maneuverability in the NOE flight. Based on these results it was also concluded that the composite bearingless rotor system was applicable to the full-scale helicopter development to achieve high maneuverability and good maintainability.