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THE TEST RESULTS OF AVR (ACTIVE VIBRATION REDUCTION) SYSTEM

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ABSTRACT

Recently, many attempts to reduce the helicopter vibrations using the active control technology have been carried out in the world. A new method of actuating the main gearbox has been considered and the way to apply it to helicopters lighter than the medium weight class has been studied. Because the main gearbox usually has a role of supporting the main flight loads, a lot of power is required to vibrate the main gearbox with a hydraulic. Also, because a helicopter has many natural vibration modes, many actuators are required to get enough of an effect of vibration reduction all over the fuselage. Consequently, many big actuators must be installed and hydraulic generator must be enlarged. As a result, it is very difficult to apply this method to small helicopters rather than large ones because of weight and cost penalty. Enough of an effect with minimum power has been studied, and a fair method has been acquired. In this method, the helicopter vibrations in longitudinal and lateral direction are treated separately, and hydraulic actuators are installed to excite the natural vibration modes in each direction. To reduce the required power, the strut support system of the main gearbox is optimized so that the helicopter has the minimum addition of response for the rotor hub vibratory forces and has the maximum response for the excitation forces generated by the hydraulic actuators.

First, this concept has been confirmed by the analysis using NASTRAN and a computer code, which is programmed by the finite element method in the time domain and includes the control algorithm. Next, a test using a small skeleton model was implemented. Then finally, tests using BK117 helicopter was conducted. In these tests, the effectiveness of the system in steady vibration environments was examined, and the transient response of the system was also examined. From the results, the response speed of the system has been rapid enough to follow the variation of the vibration environment encounters in the normal maneuvers. The hydraulic flow required by the actuators has been in the range of the original hydraulic power, and so no auxiliary generator was required. It has been shown from these analysis and tests that this system has strong potential to reduce the helicopter vibrations.

1. Introduction

Vibration is so important a design factor of helicopters that it sometimes dominates the evaluation of the helicopters. In spite of long time efforts, state of the art of helicopter vibration is far from the desirable level. Most helicopters developed so far have established their own specifications that deviate from the public specification, which has been only a target of effort, but not the requirement. In such a state of things, ADS-27(Reference 6) is worth evaluating as it reforms the old way of prescribing the helicopter vibration and searches the way of more realistic requirements. At the same time, it will bring the vibration specification back to the position of the requirement. The requirements of ADS-27 are as the same degree of strictness as that of MIL-H-8501A for the medium weight class helicopters, but it is not an easy work to conform the requirement certainly.

The active control technology is thought to have the potential to overcome this difficulty. For the progress of recent computer engineering, the active vibration control technology is now becoming to be applied to all fields of industry, and there are so many practical applications, such as active suspension of automobile, anti-vibration technique of ship engine, anti-seismic system of building, mount system of precision instruments, etc. In this field of technology, it is becomming not always to be said that aircraft is the spearhead. Application of this active vibration control technology may degrade the vibration of helicopters to the desired level. (Refer to Figure 1. This figure is quoted from Reference 4 and modified.)

From a different point of view, there is a vibration problem at the development stage of helicopters. The helicopter vibration problem relates to many factors, and the analysis have not yet reached to the satisfactory level, so analytical prediction of the vibration characteristic of the inexistent helicopter under development cannot be confidential. For this reason, violent vibrations have sometimes be experienced at the early stage of the flight tests and the tests could not be continued without major design modifications. (Refere to Figure 2) As a result, the development period was forced to be prolonged and weight/cost penalty had to be payed out. If an active vibration control equipment is installed from the biginning of the development, it is expected that such a bad vibration condition can be reduced to the level at which the flight test can be continued after some local vibration treatments because of its powerfull ability, and the prolongment of the development period and/or the weight/cost penalty caused by the fundamental redesignment are expected to be avoided.

2. Concept

First of all, the target of the system has been narrowed down to the helicopters lighter than the medium weight class, and the followings have been taken as the aim.

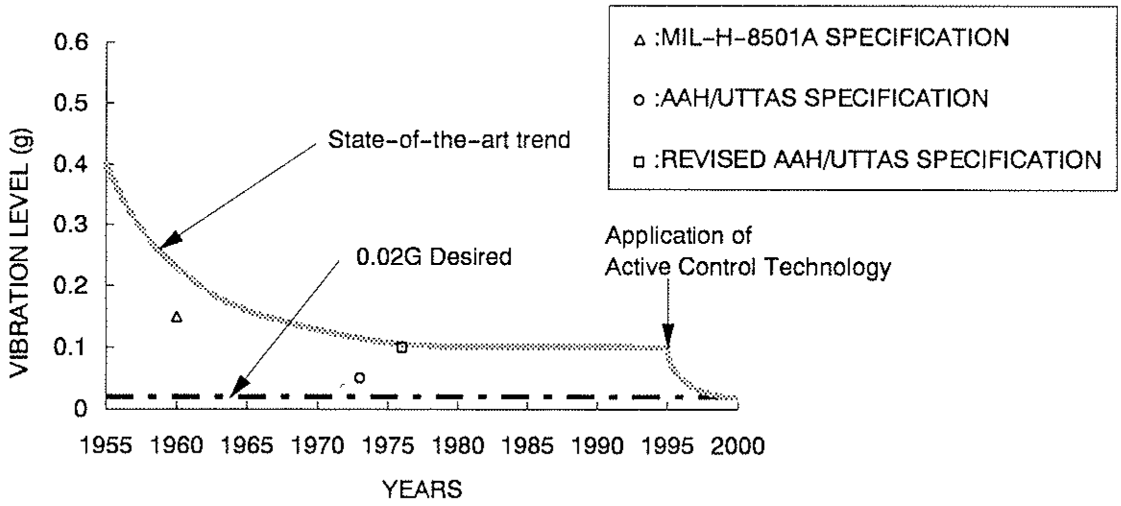


Figure 1 Trend of helicopter vibration levels since 1955

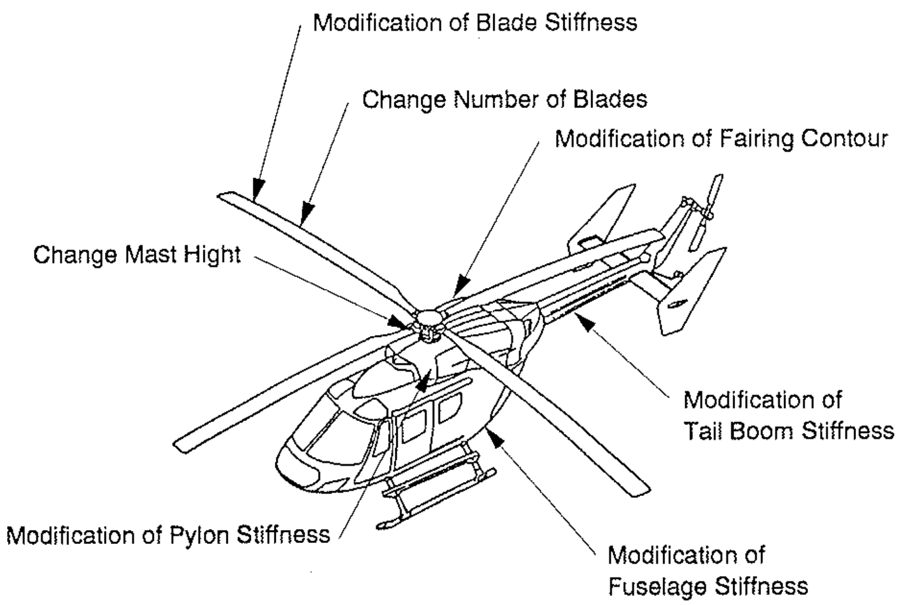


Figure 2 Examples of Aircraft Modification Caused by Vibration Problem
(Note; This is not for BK117 case, but general speaking)

1) Simple system construction
2) Minimum weight penalty
3) Minimum cost penalty

For helicopter engineers, vibration has been a matter of challenge for a long time, and so many methods have been invented. These ideas can be summarized in Table 1. In this table, direct type means that they are the methods to the main rotor, which is the source of vibration, and indirect type means the methods except to the rotor, those are to the fuselage or to the main gearbox mount system. In any case, many examples show that the attainable minimum vibration level by the passive provisions seems to have the limit around 0.1g. For the future trend of vibration specification stayed in introduction, or to avoid the risk in development stage, the active vibration control technologies are willing to be established. We have taken notice of the indirect active type because it does not affect the air worthiness under the consideration of reliability of the hydraulic actuator and the electronic equipment in the present situation.

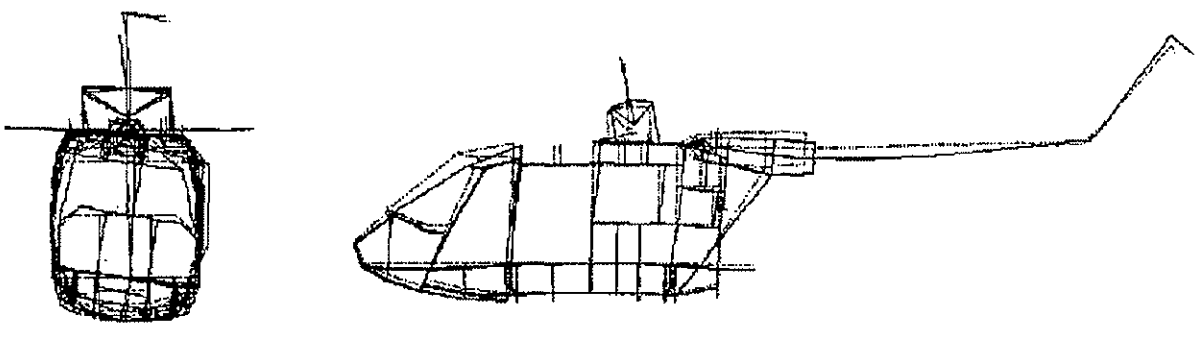
Table 1 Vibration Reduction Technologies

TYPE		ATTAINABLE G LEVEL	AERODYNAMIC PENALTY	WEIGHT PENALTY	REMARKS
DIRECT (ROTOR)	PASSIVE	0.1 ~ 0.15	LARGE	LARGE	Simple, Low Cost Can Follow Frequency Change
	ACTIVE	0.05	SMALL	SMALL	Complicated, High Cost, Can Follow Frequency Change, Needs Big Power Actuator
INDIRECT (FUSELAGE) (MGB MOUNT)	PASSIVE	0.1	NONE	LARGE	Simple, Cannot Follow Freq. Change, Mechanical Damping Degrades Its Performance
	ACTIVE	0.05	NONE	SMALL ~ LARGE	Complicated, Can Follow Frequency Change, Affect no Air worthiness

In the case of the indirect active type, it is expected to be most effective when the actuators are installed in the main gearbox mount area, which transfers the vibratory forces from the main rotor system to the fuselage. But, because this mount system supports all the flight loads, it is a fairly rigid structure in general, and it requires big power to deform this mount system. On the other hand, the indirect passive type requires no energy because it uses resonance of the pendulum. Nevertheless, the passive system has the problem of damping and the difficulty of frequency tuning. To solve these problems, even an idea to control the vibratory motion of the passive resonance weights by an active method can be found.

To reduce the vibration effectively by the active control technology, we have paid attention to the motion of the main gearbox in the vibration mode shape. The main gearbox and the main rotor system are heavy parts in the aircraft, and these parts have some displacements in many predominant vibration modes. It has been thought that these parts can be treated as the mass of dynamic absorber. If the spring stiffness of the mount system which supporting these parts is fairly tuned, they may act as a dynamic absorber, and the vibration of the fuselage may be reduced. But, the rotor system has a large damping caused by the aerodynamic forces, so enough effects cannot be expected if they are freed to be excited just passively. If active vibration forces are applied to these parts, not so much power should be required and very effective vibration reduction may be achieved. Such a concept of the vibration reduction system is called as AVR(Active Vibration Reduction) System.

Vibration frequencies of helicopters are very restricted to the multiple of the rotor rotating frequency, and the only target of the vibration reduction system is the blade passing frequency, practically. Also, helicopters have a longitudinally long figure in general, and the helicopters lighter than the medium weight class have relatively stiff structure than the large ones. For this reason, the predominant vibration modes can be restricted to only two modes, those are longitudinal bending mode and lateral bending mode. These two modes of BK117 helicopter are shown in Figure 3 as an example. Of course, there exit many other vibration modes in the helicopter vibration, but they can be treated as modes developed from the predominant vibration modes by local area vibrations. Consequently, most noxious vibrations must be removed if two vibration modes, longitudinal and lateral, near the blade passing frequency are treated as the subject of the vibration reduction countermeasure. In case that the main gearbox and the main rotor system are thought to be as the mass of dynamic absorber, it may be afraid that the vibration modes that this system can cope with are restricted. But, for the reason mentioned above, two modes are enough for the vibration reduction of the helicopters lighter than the medium weight class. Then this AVR concept is expected to have an enough vibration reduction effect.



Lateral Vibraion Mode　　　　Longitudinal Vibration Mode

Figure 3　Predominant Vibration Modes of BK117 Helicopter near Blade Passing Frequency

In order to materialize this AVR concept, the following things must be prepared.

1) Main gearbox mount system that can be excited in longitudinal and lateral direction and can be tuned to change the response of it
2) Typically, two actuators that can excite the main gearbox in longitudinal and lateral direction
3) Sensors that can pick up the longitudinal and the lateral vibrations
4) Control computer

5)Control law software

A typical example of the main gearbox mount arrangement that is one of the most suitable application of this AVR concept is shown in Figure 4. In this example, the main flight loads are supported by the struts positioned on the left and right side of the mast base. Spring elements are installed in two forward struts, and the longitudinal vibration characteristic can be tuned by changing these forward strut stiffness. Also, the lateral vibration characteristic can be tuned by changing the stiffness of these forward struts and also one strut that is equipped at the bottom of the main gearbox and spring element is installed in. Two hydraulic actuators are installed in each of two forward struts for excitation. When these two actuators are excited in the same phase, the main gearbox is excited in the longitudinal direction, and when excited in the opposite phase each other, the main gearbox is excited in the lateral direction. The spring stiffness of three struts is to be tuned to enlarge the vibration response of the fuselage when the actuators are excited at the blade passing frequency.

The spring elements have a possibility of excessively large deformation when extremely high loads such as limit loads are applied. In case the displacement of the main gearbox becomes large, the fatigue strength problem of the engine input shaft and the tail rotor output shaft or the coupling problem of the control system may come to an issue. To prevent these problems, stopper provisions are installed to the struts, so the loads are supported by the stoppers when the displacement of the spring elements exceeds some limit. For this, the spring stiffness of each strut can be decided independent of the static loads applied to them. In practice, the stopper contacts only in the extremely violent maneuver conditions that are requested to certificate the aircraft static strength, so it has no effects in normal flight conditions.

For the control law of AVR, the same frequency domain control law as that is shown in Reference 9 as a self tuning regulator can be applied. As for the AVR system, the variation of the transfer matrix caused by changing the operating condition is presumed to be smaller than the higher harmonic control, because the transfer matrix of AVR is concerned little with the rotor aerodynamics. So the necessity of the continuous identification of the transfer matrix must be low and the response problem due to the variation of the transfer matrix must not exist on AVR system.

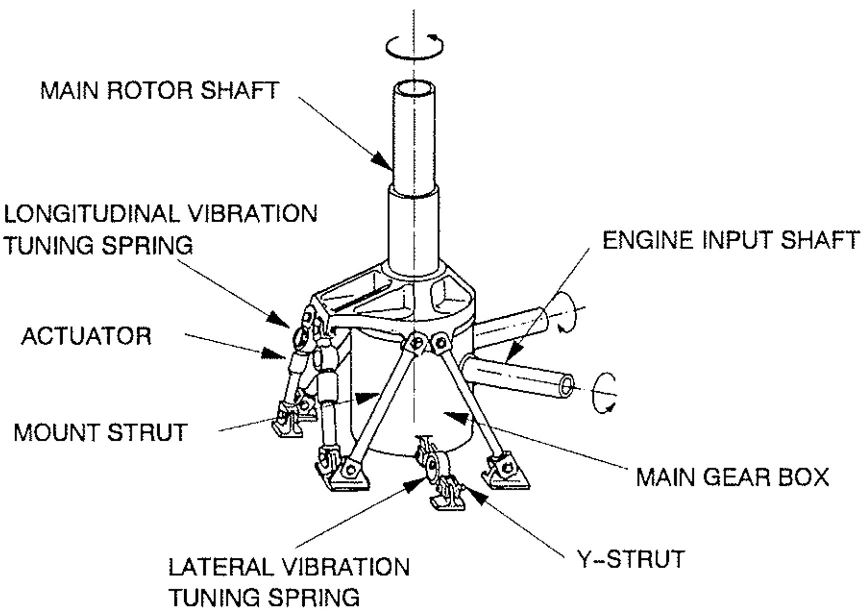


Figure 4 Typical AVR System Application

3. Analytical Study

To validate the concept of AVR mentioned above, analytical study was performed using NASTRAN. First, the vibratory forces acting in flight were applied on the rotor hub, and the vibration response of the fuselage was calculated. Then the excitation forces by AVR actuators were applied at both ends of the struts. At that time, the excitation forces were applied in the same phase or in the opposite phase, and the vibration responses of the fuselage were compared with the hub excitation case.

In this analysis, the optimum condition in which the response of the fuselage to the actuator excitation is enlarged was searched by changing the spring stiffness of three struts. The variation of the fuselage response when the spring stiffness of the tuning spring at the bottom of the main gearbox was changed is shown in Figure 5 and Figure 6. The model helicopter used in this analysis is in the class of 3500kg gross weight, and the blade passing frequency is about 25Hz. The vibration characteristic of the system is symbolized better by the magnitude of the vibration response at natural frequencies near 25Hz than just at 25Hz. What is shown in these figures is the variation of the magnitude of the vibration response at these natural frequencies near 25Hz. From these figures, the followings can be found: When two actuators are excited in the opposite phase each other , the response of the fuselage in Y-direction varies dramatically by changing the stiffness of Y-strut, and the maximum response is obtained near at the stiffness of 500kg/mm. On the other hand, the fuselage response by the hub excitation forces depends very little on the stiffness of Y-strut. In short, these figures show that it is possible to make the fuselage response from the actuators larger without making the response from the hub large.

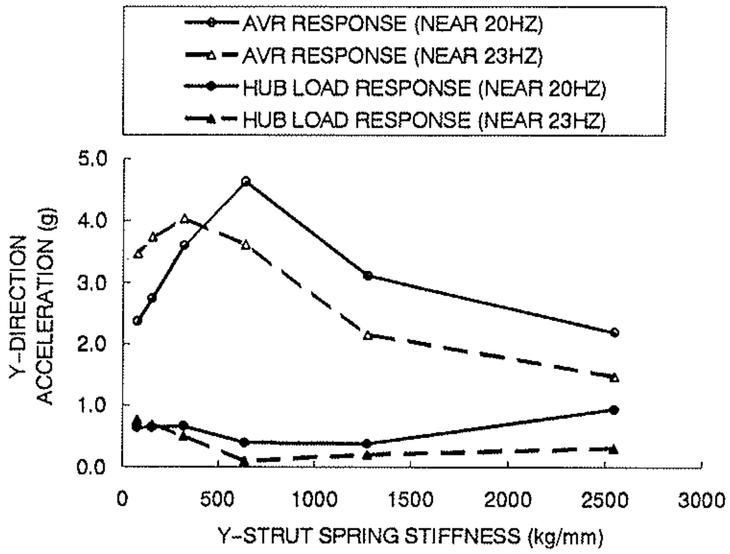


Figure 5 Y-Direction Response Variation by Y-Strut Stiffness

Figure 6 is for the longitudinal vibration. This figure shows that the longitudinal vibration characteristic does not change though the stiffness of Y-strut changes. Consequently, the lateral vibration characteristic can be tuned without changing the longitudinal vibration characteristic by adjusting the stiffness of Y-strut after adjusting the stiffness of forward two struts for the longitudinal vibration characteristic.

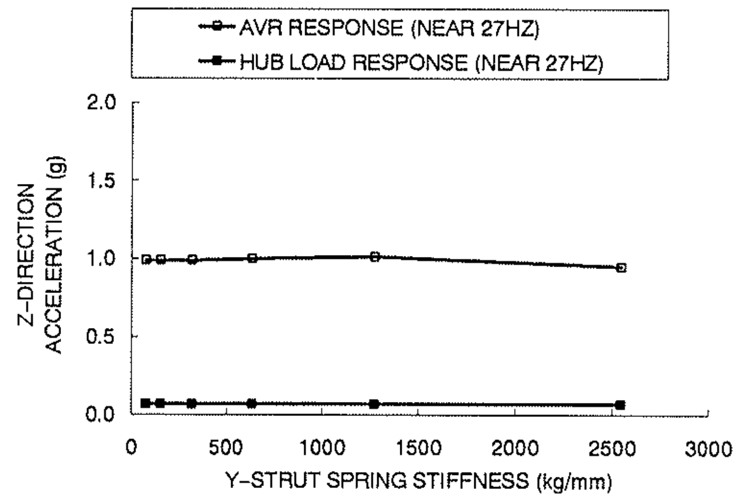


Figure 6 Z-Direction Response Variation by Y-Strut Stiffness

Also interestingly, it has been found from the analytical study that when the response to the hub is large, the response to AVR actuator is also large. It means that if the rotorcraft has a bad vibration characteristic, AVR system works effectively. Then, it is assured by analysis as mentioned in the introduction that AVR is very effective to avoid the vibration problem at the development stage of helicopters.

After the fuselage vibration characteristic has been calculated using NASTRAN, the new computer code of finite element method, with which numerical simulation in the time domain can be performed, was developed and an investigation including control law was carried out. As a result, it has been calculated that AVR system has a good vibration reduction ability as has been presumed in the concept.

4. Model Test

After the concept of AVR system mentioned above has been calculated, the system was constructed with real hardware and a model test was performed. Description of the test model is shown in Figure 7. The aircraft fuselage was simulated by a simple beam structure, and the mount system of the model simulated the BK117 construction shown in Figure 8 to cope with the following tests using real BK117 helicopter. Electric actuators were used to simulate the oscillatory hub load and as AVR actuators. AVR actuators were installed in two forward Z-struts of four Z-struts. Three axis accelerometers were located at seven places over the fuselage, and the most forward three were used for the control.

In this test, first, the vibration reduction ability of AVR system was surveyed in various hub excitation conditions, and it has been found that the expected result can be obtained with the real hardware.

Next, it was investigated if the control law can follow the variation of vibration conditions such as amplitude, direction, frequency, et al. while the control is operating. One example of the test results is shown in Figure 9. From this figure, it was found that about 0.25g vibratory acceleration in X and Y-direction was occurred without control (ⓐin the figure), but the vibration level was reduced to about 0.07g in both X and Y-direction by controlling (ⓑin the figure). In X-direction, the vibration level increased, but the amount of it was very little. After that, on/off operation of the hub excitation was repeated, but it has been found that the control law can operate stably in spite of such an abrupt change of the vibration condition. In this test condition, an increase of the vibration level has been

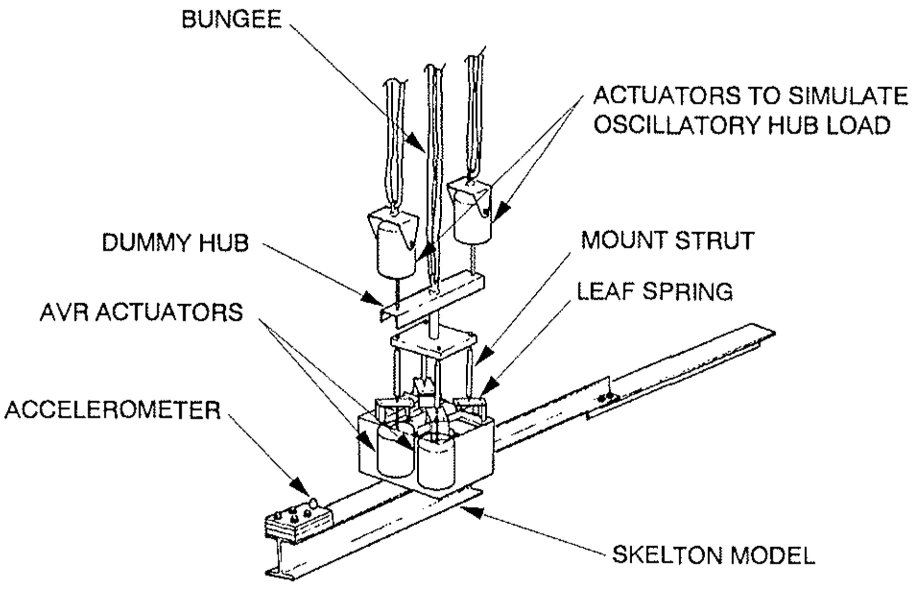


Figure 7 Description of Model Test

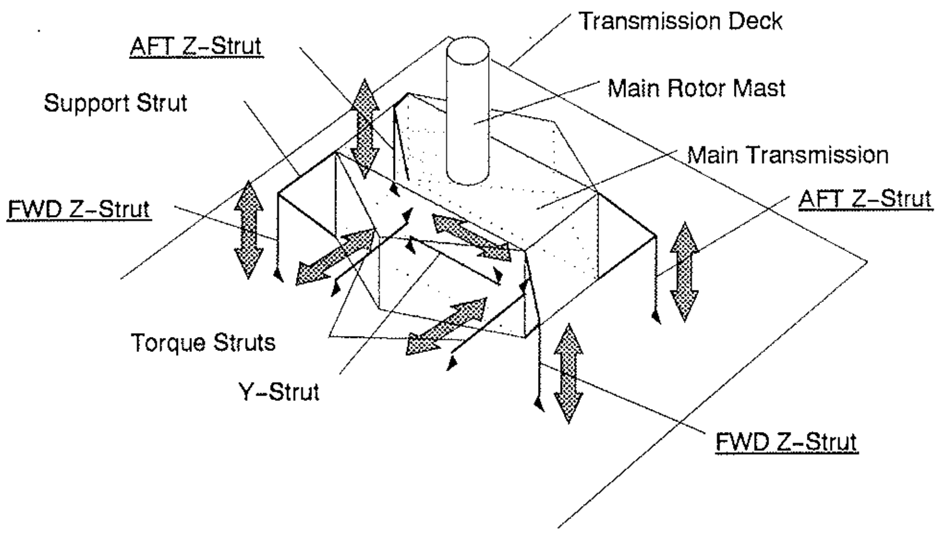


Figure 8 Description of BK117 Mount Strut System

observed at the moment when the hub excitation force had changed in step, but there must not be such an abrupt change of the excitation forces in the real flight conditions, so the transient increase of the vibration level was presumed to be little, but it must be confirmed in a flight test. The control law operated stably also for the variation of conditions other than above. However, when the control was attempt to operate at the natural frequency of the model fuselage, the humming of the vibration was observed. At the real helicopter structure, it is designed not to coincident the natural frequency of the fuselage and the blade passing frequency (that is the control frequency), and the structural damping is larger than the mode, this will not to be a problem, but it must be confirmed by the test using real helicopter.

5. Tests with Real Helicopter

In the model test mentioned above, two major problems of the response and the humming have been pointed out. Other than these problems, the real helicopter structure has much more complicated vibration modes than the model structure, and there are many none linear factors such as backlash in the structure, so the confirmation test using a real helicopter was required. Also, the effect of the frequency response characteristic of the hydraulic actuator must be confirmed and

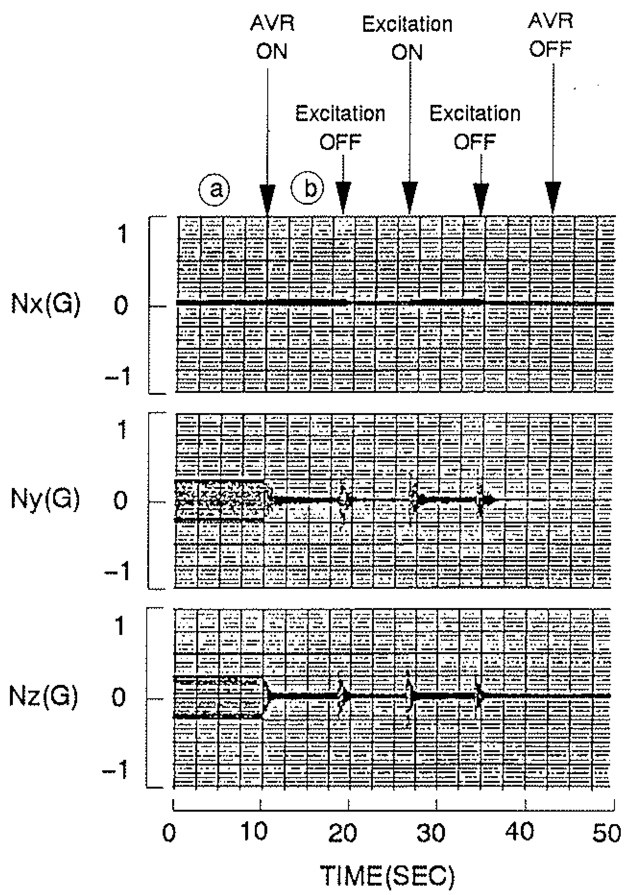


Figure 9 Model Test Results

the data acquisition for the quantitative investigation of the actuator required power was required.

For these reasons, a rig test using BK117 helicopter was performed. BK117 has the type of mount system shown in Figure 10, and the AVR actuators and the spring elements that are arranged parallel in the load path were installed in the afterward two Z-struts, and the spring elements only were installed in two forward Z-struts to reduce the stiffness. The reason the mount system optimum for AVR as shown in Figure 4 was not adopted but such a mount system was adopted is that the test was limited to the extent of arranging the existing BK117 helicopter. Also, the lateral vibration is predominant in the case of BK117, so it seemed to be ideal to install one of the AVR actuators in Y-strut, but the experimental hydraulic actuator was too big to install it in Y-strut. To install the actuator in such a way, a major modification of the aircraft structure was required, so such an arrangement could not be realistic at that time.

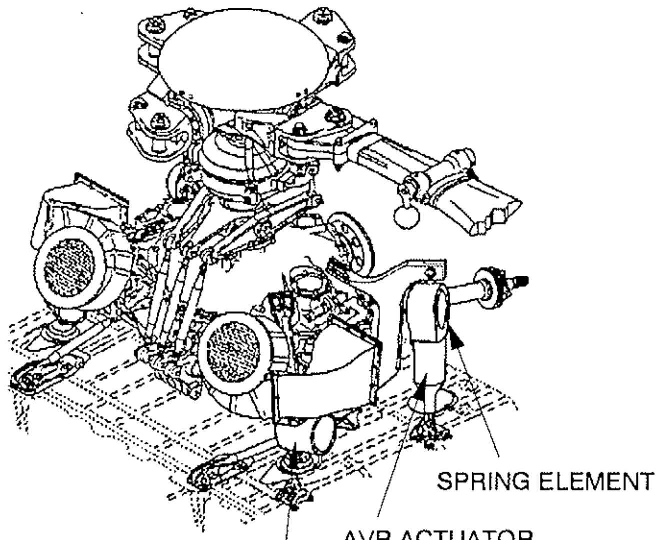


Figure 10 AVR System Installation

Accelerometers were attached all over the fuselage to measure the vibration response, and the signals measured at the pilot seat position in three directions were used for the control. The main rotor hub of the test vehicle was removed, and the dummy hub that has the same effective mass was installed. The vehicle was under slung at the dummy hub from the test rig, and the vibratory environment in flight condition was simulated by exciting the dummy hub by the hydraulic actuators. In this test equipment, the test vehicle can be excited both in pitch and roll direction by changing the position of the hydraulic actuators. The test set-up situation is shown in Figure 11 and Figure 12. The test system block diagram including both the AVR system and the measurement system is shown

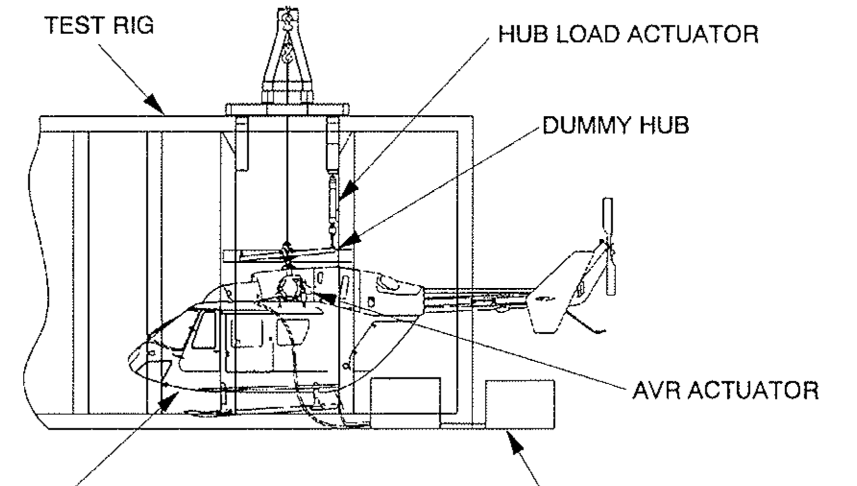


Figure 11 Rig Test Setup

in Figure 13.

First, to study the open-loop characteristic of the system, the following 2 items were tested.

■ In the control law algorithm, linearity from the control input (command signal of the control actuator) to the observational quantity (signals measured by the accelerometers) is assumed. To confirm this assumption, the acceleration response of the fuselage was measured while the magnitude of the control actuator excitation force was varied. At the early stage, real structure of helicopters was thought to have none linear factors, but as a result of the test, the system showed a good linearity, and so the control theory shown in Reference 9 has been proven to be applicable to AVR concept.

■ In flight condition, there may be some factors that affect the transfer characteristic of the system such as variation of weight and rotor speed. So, it was studied how much such factors change the transfer characteristic of the system. The result showed that the amount of changing was comparatively small, and the control kept stability without identifying the transfer characteristics continuously. As mentioned in the section of concept, the transfer characteristic of AVR is predominated by the fuselage characteristic and

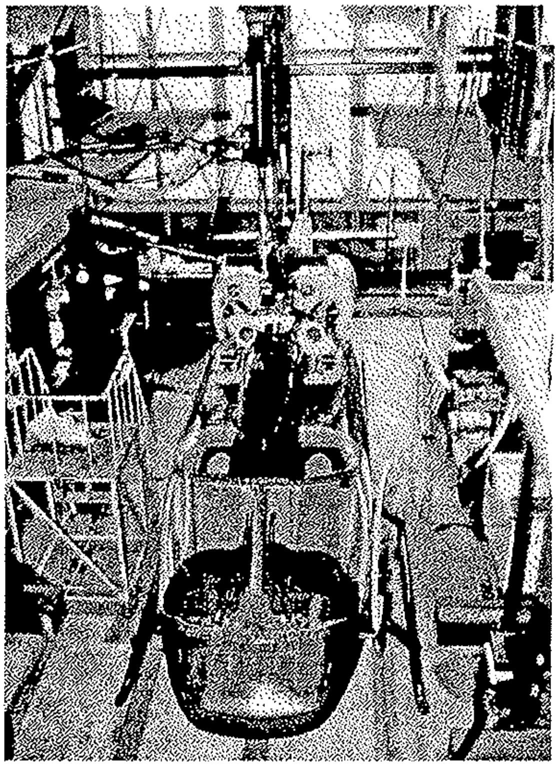


Figure 12 Description of Rig Test

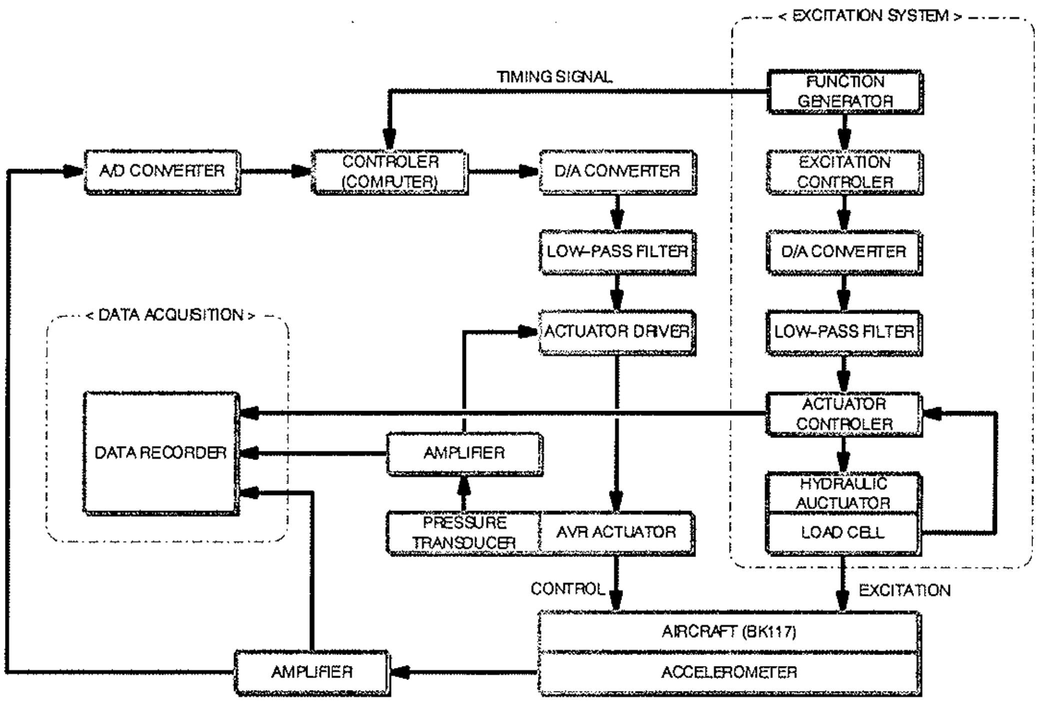


Figure 13 Block Diagram of Test System

the rotor characteristic has little influence on it. So, the test result means that the transfer characteristic on the AVR control is very stable and the response of the control is expected to be rapid enough.

Next, to study the closed-loop characteristics of the system, the following two items were tested.

■The steady vibration reduction effect all over the fuselage in steady hub excitation conditions was examined. Figure 14 and Figure 15 show the results when the hub was excited in pitch or roll direction. The vibration level was reduced almost all area of the fuselage except some places where the original vibration level was low. The test was conducted also at the condition where the control frequency was coincident with the natural frequency of the fuselage, but the humming phenomenon that was observed in the model test was not occurred.

■The variation of the fuselage vibration response while the control is operating was investigated when the excitation condition, such as excitation amplitude, frequency, and the gross weight of the helicopter was changed. This test item was performed to study the response of the control law for the variation of the vibration condition that may be encountered in flight. One example of the test results is shown in Figure 16. Same as the model test, transient vibration increase caused by the delay of the control law was observed, but the degree of increase was small. The response speed of the control for the variation of the vibration environment encounters in real operation has been presumed to be rapid enough.

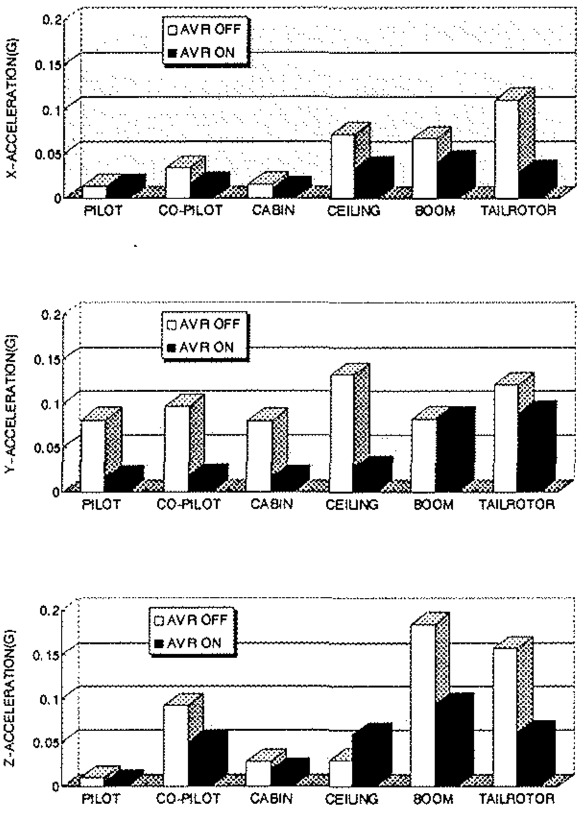


Figure 14 Rig Test Results (Roll Excitation)

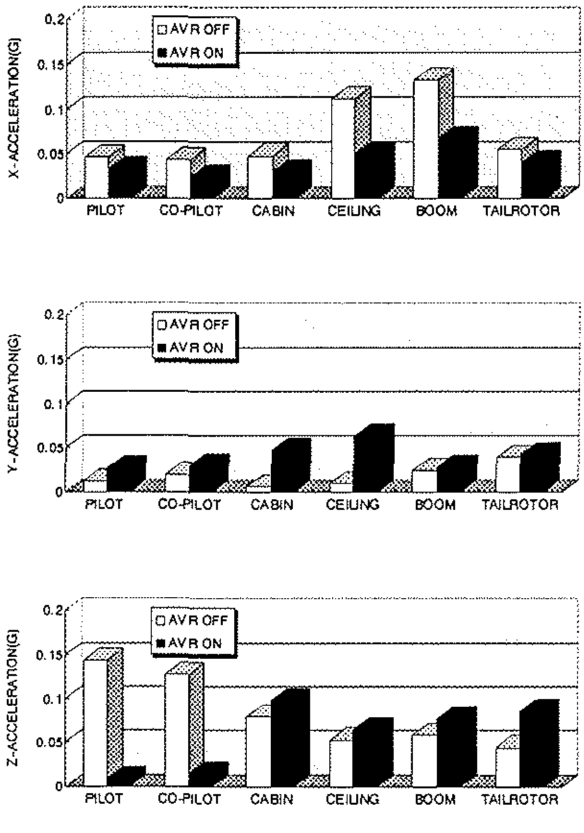


Figure 15 Rig Test Results (Pitch Excitation)

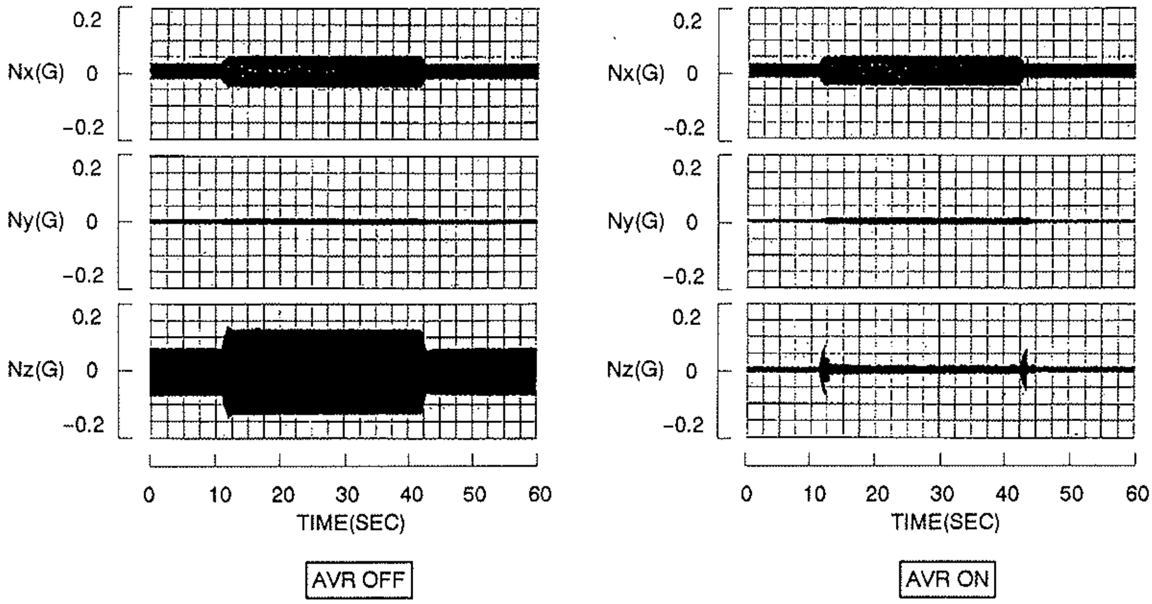


Figure 16 Rig Test Results (Control Response During Pitch Excitation)

Because good results have been obtained in the rig test and a fair prospect of practical use has been acquired, the flight test using BK117 helicopter was planned and carried out. Figure 17 shows the vibration reduction capacity of AVR system in steady flight conditions measured in the flight test. The vibration level of BK117 helicopter is already low enough for practical operation, so the rate of reduction of the vibration was not so high, but the achieved vibration level was satisfactory low, especially in Z-direction. On the contrary, X and Y-direction vibrations were reduced not so much.

For the case of BK117, vibration in steady flight conditions is good, but it is being desired to reduce the transient vibration especially in flare condition. However, the vibration level in flare could not be reduced to the level of satisfaction at the flight test.

Search for the source of this problem, the flight test measurements were analyzed, and it has been found that Y-direction vibration is predominant in flare flight condition. As the flight test results in steady flight conditions show, the actuator arrangement of the tested AVR system is not ideal for the Y-direction vibration reduction. More effect is

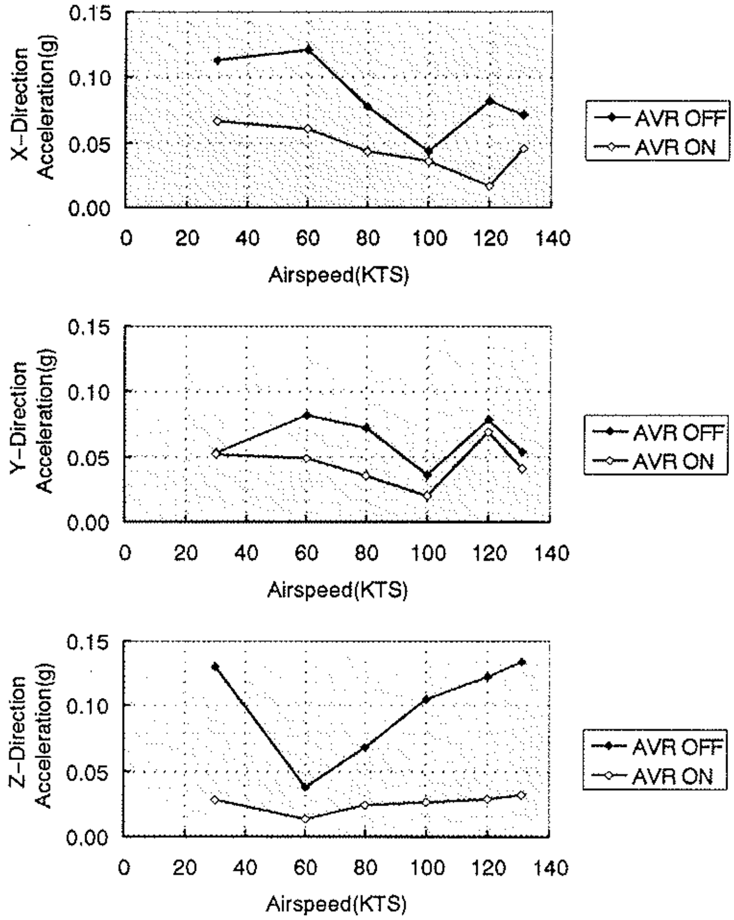


Figure 17 4/rev. Vibration Reduction Effect of AVR expected if the actuator is installed in Y-strut. But, the limitation of using the existing helicopter and actuators prevented it from being realized. Now, a new smaller actuator is being designed, and a flight test using this actuator in Y-strut is being planned to confirm the vibration reduction effect of this configuration.

Another reason for the inadequate vibration reduction effect in flare has been presumed that the control law, which operates in frequency domain, could not follow the variation of vibration in flare flight condition. Thereupon, the sensitivity of AVR system from the excitation force at the hub to the acceleration response at the observation point was analyzed. It has been found that the system has enough ability to follow the variation of vibration lower than about 0.4Hz. From the flight test, the predominant frequency component of the variation of vibration in flare flight condition was below 0.2Hz, and it has been confirmed that this is in the range of frequency that AVR system can follow.

By the way, for the optimum design at the present, the required oil flow rate is estimated at about 6l/min. and it is in the range of original oil generator of BK117, which has a capacity of excessive 6.7l/min. flow. As a result, the weight penalty of AVR system for the medium weight class helicopter of 3000 to 4000kg gross weight is estimated at about 0.5%. This is one of the most peculiar feature of AVR system comparing to other vibration reduction system.

6. Conclusion

From the results of the analytical simulation, the model test, and the test using the real helicopter, the effectiveness of AVR system as a vibration reduction system for helicopters lighter than the medium weight class has been confirmed, and it has come to the conclusion that it is applicable to real helicopter.

If the main gearbox mount system is arranged optimum for AVR system from the early stage of the development of the helicopter, effect of the system must be promoted much more.

7. References

1) Y. Niwa, et al., Active Vibration Reduction System for a Helicopter, paper presented at 31st Aircraft Symposium, Nov. 1993.
2) N. Katayama, et al., Ground Testing of Active Vibration Reduction System for Helicopters, paper presented at 31st Aircraft Symposium, Nov. 1993.
3) M. Aso, et al., Study of the Control Law for Active Vibration Reduction System of Helicopter, paper presented at 31st Aircraft Symposium, Nov. 1993.
4) E.R. Wood, R.W. Powers, J.H. Cline, and C.E. Hammond, On Developing and Flight Testing a Higher Harmonic Control System, paper presented at 39th Annual Forum of the American Helicopter Society, May, 1983.
5) S.T. Crews, Rotorcraft Vibration Criteria a New Perspective, paper presented at 43rd Annual Forum of the American Helicopter Society, May, 1987.
6) U.S. Army Aviation System Command, Requirements for Rotorcraft Vibration Specifications, Modeling and Testing, Aeronautical Design Standard(ADS)-27, Nov. 1986.
7) L.E. Smollen, P. Marshall, and R. Gabel, Active Vibration Isolation of Helicopter Rotors, paper presented at IAS 30th Annual Meeting, Jan. 1962.

8) D.L. Kidd, R.W. Balke, W.F. Wilson, and R.K. Wernicke, Recent Advances in Helicopter Vibration Control, paper presented at 26th Annual National Forum of the American Helicopter Society, June, 1970.
9) W. Johnson, Self-Tuning Regulators for Multicyclic Control of Helicopter Vibration, NASA Technical Paper 1996, Mar. 1982.