VERTICAL-PLANE PENDULUM ABSORBERS FOR MINIMIZING HELICOPTER VIBRATORY LOADS

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Abstract

This paper discusses the use of pendulum dynamic absorbers mounted on the blade root and operating in the vertical plane to minimize helicopter vibratory loads.

The paper describes qualitatively the concept of the dynamic absorbers and presents results of analytical studies showing the degree of reduction in vibratory loads attainable. Operational experience of vertical plane dynamic absorbers on the OH-6A helicopter is also discussed.

Introduction

In a helicopter it is important to maintain a low level of vibration for two reasons; first for the comfort of the crew and passengers, and secondly to minimize maintenance problems. During early flight tests of the OH-6A helicopter (see Figure 1) in 1963, a high level of 4/rev fuselage vibration was encountered primarily during approach to hover and during high speed flight.

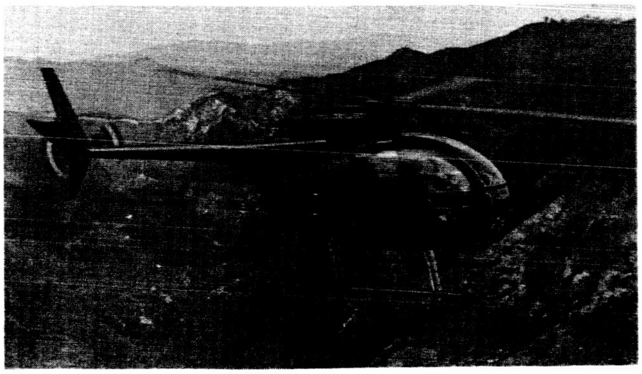

Figure 1. OH-6A Helicopter

Various analytical studies and experimental programs were conducted in an effort to alleviate this problem. The configuration finally adopted was vertical-plane pendulum absorbers mounted at the roots of the main rotor blades (see Figure 2). It is the purpose of this paper to describe the concept of the vertical-plane pendulum dynamic absorber and to present the results of analytical studies and flight tests showing the degree of reduction in vibratory loads attained.

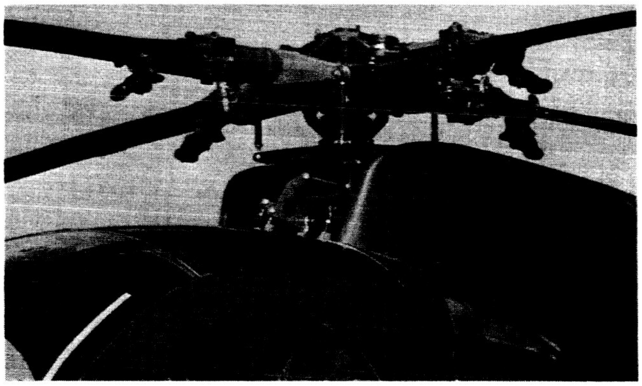

Figure 2. Pendulum Absorbers on OH-6A

Over 3 million flight hours of satisfactory experience have been obtained with the use of vertical-plane pendulum absorbers on the OH-6A helicopter and on its commercial counterpart, the Model 500 helicopter. This operational experience is also discussed in this paper.

Sources of Fuselage Vibration

The OH-6A helicopter has a 4-bladed main rotor. Table I summarizes the sources of 4/rev fuselage vibration from the main rotor. It can be seen from Table I that vertical shears at the blade root with frequencies of 3/rev, 4/rev, and 5/rev can induce 4/rev vibrations in the fuselage. The 3/rev and 5/rev blade root shears induce 4/rev fuselage vibrations by producing 4/rev hub moments. The 4/rev blade root shear produces a 4/rev hub vertical force. With regard to in-plane blade root shears, both the 3/rev and the 5/rev component of in-plane root shear produce a 4/rev hub horizontal force. A further discussion of the mechanism by which rotor blades induce vibration in the fuselage can be found in Chapter 12 of Reference 1, particularly the tables on pages 318 and 319.

Table I. Sources of 4/Rev Fuselage Vibration - 4-Bladed Rotor

Vertical Shear	Load Path	In-Plane Shear	Load Path
3/rev	Hub moment	3-rev	Hub horizontal force
4/rev	Hub vertical force	-	-
5/rev	Hub moment	5/rev	Hub horizontal force

Table I indicates that there are 5 possible sources of excessive fuselage 4/rev vibration in the OH-6A helicopter. The next step was to establish which of the 5 possible sources of vibration were the most important. Tables II and III provide an answer to this question.

Table II. OH-6A Main Rotor Blade Natural Frequencies (per rev) - 100% RPM - Pendulums Off

Flapwise	Chordwise (Cyclic Mode)
2.72	5.14
4.87	

In Table II are listed the main rotor blade flapwise and chordwise natural frequencies near the 3/rev through 5/rev frequency. It can be seen from Table II that the two frequencies most likely to cause a 4/rev vibration in the fuselage are the first and second mode flapwise bending frequencies which are very close to 3/rev and 5/rev. The blade chordwise natural frequency is also close to 5/rev (see Table II). However, Table III confirms that the blade flapwise first mode and second mode frequencies are the primary source of the vibration problem, in that the fuselage vibration is much more responsive to hub moments than it is to hub vertical or horizontal forces.

Table III. OH-6A Cockpit Response to Rotor Excitation, V = 100 Knots (No Pendulums Installed)

	4/Rev Vertical	4/Rev Pitching Moment	4/Rev Rolling Moment	4/Rev Longitudinal Shear	4/Rev Lateral Shear
Excitation Force, lt	130	*86	**112	10	35
Unit Response at Cockpit, in/sec/lb	.0012	.00265	.0106	.00193	.0077
Response at Cockpit, in/sec	.16	.23	1.19	.019	.27

* Blade vertical shear force causing pitching moment.
** Blade vertical shear force causing rolling moment.

Thus blade vertical bending at a frequency of 4/r and blade chordwise bending at frequencies of 3/r and 5/rev can be ignored and the primary sources vibration can be concluded to be blade flapwise bending at 3/rev and at 5/rev.

Concept of Vertical-Plane Dynamic Absorbers

Based on the above evaluation, it was concluded that it was necessary to reduce the level blade 3/rev and 5/rev flapwise bending. After investigating a number of possible approaches,* it was decided to pursue the concept of a dynamic vibration absorber which is discussed in Reference in the section starting on page 87.

The concept of a dynamic vibration absorber consists of adding a small mass to a large mass. The uncoupled natural frequency of the small mas (vibration absorber) is chosen to be equal to th frequency of the disturbing force. Thus, for th OH-6 vibration problem, it was concluded that it would be necessary to incorporate two dynamic vibration absorbers; one tuned at 3/rev and the other tuned at 5/rev. Furthermore, inasmuch as rotor speed can vary somewhat, it was necessary that the vibration absorbers maintain the proper frequency relative to rotor speed. In order to complish this, it was decided to use the concept a tuned centrifugal pendulum discussed on page 2 of Reference 2. This concept has been used for many years to minimize the torsional vibrations piston engines. Thus, the final configuration t evolved consisted of two pendulums mounted at th roots of the main rotor blades; one tuned to a natural frequency of 3/rev, the other tuned to a natural frequency of 5/rev. Inasmuch as the she force and blade motion which were to be minimize were in the vertical plane, the dynamic pendulum were oriented to oscillate in the vertical plane

Figure 3 shows schematically the pendulum motion relative to the blade deflection for the case of response to 3/rev excitation. It is evident that the centrifugal force from the pendulu is directed such as to cancel most of the transverse shear due to blade modal response. The ne result is a significant reduction in the 3/rev vertical shear force transmitted to the hub.

* Other approaches evaluated included providing control of blade first and second mode natural frequencies by means of anti-node weights and by use of preloaded internal cables. Flight tests not show these methods to be sufficiently effect Hub-mounted vertical plane pendulums were flown proved to be effective, but considerations of dr and weight were unfavorable for this configurati Fuselage-mounted non-rotating dampers were eliminated because of the difficulty of tuning to a sufficiently wide range of frequency. Fuselage-mounted centrifugal pendulum dampers were considered impractical from the standpoint of space requirements and mechanical complexity.

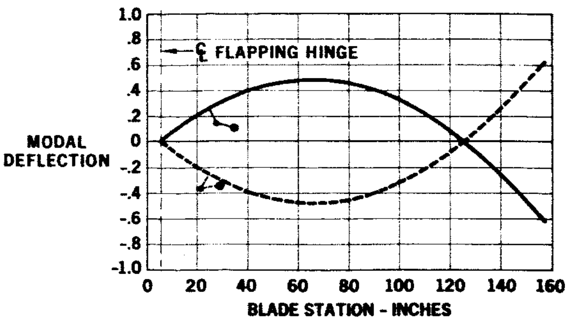

Figure 3. Pendulum Motion Schematic

Basic Physical Parameters

The pendulum configuration that was established, flight tested, and put into service has the following characteristics:

<u>3/rev pendulum</u>
weight: 1.8 lb
actual mass ratio: .048
modal mass ratio: .64

<u>5/rev pendulum</u>
weight: .7 lb
actual mass ratio: .019
modal mass ratio: .52

The pivot axis of both pendulums is located at 15% of the blade span from the center line of the rotor, and 29% of the chord from the leading edge. This location was chosen so that existing bolts in the blade root fitting could be used, thus preventing the introduction of stress concentration points into critical sections of the blade. Analysis indicates that a location further outboard would be more favorable, but this has not been confirmed by test, because of the structural considerations cited above.

Damping of the pendulums due to friction in the pivot bearings is estimated to be equivalent to 1% of the critical viscous damping ratio for the 3/rev pendulums at an amplitude of $\pm 16^{o}$. For the 5/rev pendulums at the same amplitude the damping ratio is 3% of critical.

The dampers are "bench" tuned, by means of shims, to the correct pendular frequency within 0.5% of the length of the 3/rev pendulums and to within 1% of the length of the 5/rev pendulums. The effect of mis-tuning has been investigated only to the extent of showing that $\pm$ one shim does not have a consistently observable effect on either qualitative or measured cockpit vibration.

Analytical Studies

Analytical studies were conducted to investigate the effectiveness of vertical plane pendulum absorbers in minimizing the blade vertical root shears and the fuselage vibration levels. The results of these analytical studies are presented in Table IV for the OH-6A at a forward speed of 100 knots. It can be seen from Table IV that the addition of the 3/rev pendulum dynamic absorber reduces the 3/rev vertical root shear by 75%. The addition of the 5/rev vertical dynamic absorber reduces the 5/rev vertical root shear by 85%. The net result is a 72% reduction in the vibration level in the crew compartment.

Table IV. Effect of Vertical-Plane Pendulum Absorbers on Root Shear and Cockpit Vibration - OH-6A

(Analytical Studies, 100 Knots)

Configuration	Root Shear 3/Rev	5/Rev	Cockpit Vibration, amp. in/sec
Undamped Blade	91	42	1.8
Damped Blade	23	6	.5

The analytical procedure used to achieve the results of Table IV is designated SADSAM. This analytical procedure is described in Reference 3 and was conducted in two steps. In the first step, SADSAM was used to calculate the blade root shears for a forward speed of 100 knots both without and with the pendulum absorbers. The analytical model of the blade used in this step was a ten station, fully coupled representation with aerodynamic excitation forces obtained from flight measured pressure distributions (Reference 4). In the second phase of the analysis, a 41 degree-of-freedom fuselage mathematical model, adjusted to agree with shake test results, was analyzed using SADSAM to obtain the effect of the resulting hub moments on the response in the crew compartment.

Flight Test Results

The favorable analytical results referred to above led to a decision to fabricate an experimental set of pendulum dynamic absorbers. These absorbers, similar to those shown in Figure 2, were installed on the flight test OH-6A helicopter. Tests were conducted measuring the vibration level in the crew compartment, both without and with the vertical-plane dynamic absorbers installed. The measured vibration levels at the pilot's seat are presented in Figure 4. It can be seen that the addition of the vertical-plane vibration absorbers reduces the vibration level at the pilot's seat approximately in half. The qualitative assessment by the pilot was also very favorable. Based on these results the decision was made to incorporate vertical-plane dynamic absorbers in the production OH-6A helicopter.

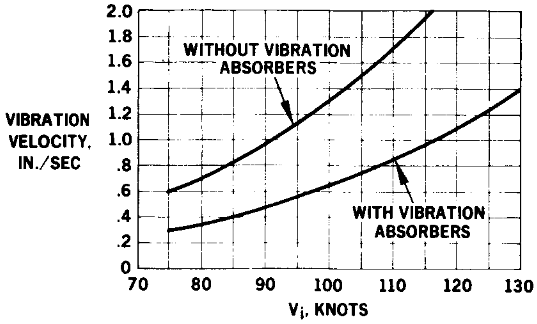

Figure 4. Measured Vibration Level of OH-6A Without and With Pendulum Absorbers

Operational Experience on OH-6A

The vertical plane pendulum absorbers were incorporated on all production OH-6A helicopters and on its commercial counterpart, the Model 500. Over 3,000,000 flight hours have been accumulated. Up to a service life of between 300 and 600 hours, the absorbers did a good job of controlling the vibration level of the helicopter. However, after approximately 300 to 600 hours of service, the bearings and shafts on which the absorbers are mounted exhibited excessive wear, resulting in increased vibration level in the helicopter. Replacement of the bearings and shafts generally returned the helicopter to an acceptable level of vibration. The premature wearing of the bearings and shafts was attributed to the high PV value.

Laboratory tests were conducted on various combinations of bearings and shaft types with the objective of selecting a combination that would have the desired service life of 1200 hours. It was also required that any new shaft and/or bearing materials be interchangeable with the initial production bearings and shafts. Thus no change in geometry was permitted.

The results of these laboratory tests showed that all combinations of shafts and bearings tests, with the exception of one, were inferior to the original configuration (which consisted of a bearing consisting of a stainless steel outer race with a bonded self-lubricating teflon liner, and a stainless steel shaft with an 8 RMS finish). The only improved configuration consisted of an Astro AM1282 bearing, which was specially made for the laboratory test operating on the original shaft. This Astro bearing is currently under consideration for retrofit.

Conclusions

This paper has demonstrated both analytically and by operational experience that the use of pendulum dynamic absorbers, mounted on the blade root and operating in the vertical plane, can successfully reduce helicopter vibratory loads. The specific application on an OH-6A helicopter was a 4-bladed rotor with the pendulums tuned to 3/rev and 5/rev. The pendulums reduced the vibration level in the cockpit to approximately one half of the level that existed prior to the installation of the pendulums.

References

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3. Peterson, L., "SADSAM User's Manual," The MacNeal-Schwendler Corp., 7442 N. Figueroa St., Los Angeles, CA, Report MSR-10, December 1970.

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Acknowledgment

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