VERTICAL-PLANE PENDULUM ABSORBERS FOR MINIMIZING HELICOPTER VIBRATORY LOADS

Kenneth B. Amer
Manager, Technical Department

James R. Neff
Chief, Dynamics Analysis

Hughes Helicopters
Culver City, California

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

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

<table>
<thead>
<tr>
<th>Vertical Shear Load Path</th>
<th>In-Plane Shear Load Path</th>
</tr>
</thead>
<tbody>
<tr>
<td>4/rev Hub vertical force</td>
<td></td>
</tr>
<tr>
<td>5/rev Hub moment</td>
<td>5/rev Hub horizontal force</td>
</tr>
</tbody>
</table>

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**

<table>
<thead>
<tr>
<th>Flapwise</th>
<th>Chordwise (Cyclic Mode)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.72</td>
<td>5.14</td>
</tr>
<tr>
<td>4.87</td>
<td></td>
</tr>
</tbody>
</table>

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)**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>130</td>
<td>.86</td>
<td>.112</td>
<td>10</td>
<td>.35</td>
<td></td>
</tr>
<tr>
<td>.0012</td>
<td>.00265</td>
<td>.0106</td>
<td>.00193</td>
<td>.0077</td>
<td></td>
</tr>
<tr>
<td>.16</td>
<td>.23</td>
<td>1.19</td>
<td>.019</td>
<td>.27</td>
<td></td>
</tr>
</tbody>
</table>

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

Thus blade vertical bending at a frequency of 4/rev and blade chordwise bending at frequencies of 3/rev and 5/rev can be ignored and the primary sources of 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 of 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 2 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 mass (vibration absorber) is chosen to be equal to the frequency of the disturbing force. Thus, for the 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 accomplish this, it was decided to use the concept of a tuned centrifugal pendulum discussed on page 2 of Reference 2. This concept has been used for many years to minimize the torsional vibrations of piston engines. Thus, the final configuration evolved consisted of two pendulums mounted at the 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 shear force and blade motion which were to be minimized 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 pendulum is directed such as to cancel most of the transverse shear due to blade modal response. The net 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 did not show these methods to be sufficiently effective. Hub-mounted vertical plane pendulums were flown and proved to be effective, but considerations of drag and weight were unfavorable for this configuration. 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.
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)

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Root Shear Reduction</th>
<th>Cockpit Vibration, amp. in/sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>UnDamped Blade</td>
<td>3/Rev 85%</td>
<td>5/Rev 85%</td>
</tr>
<tr>
<td>Damped Blade</td>
<td>91</td>
<td>42</td>
</tr>
<tr>
<td></td>
<td>23</td>
<td>6</td>
</tr>
</tbody>
</table>

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.
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


Acknowledgment

The contribution of R. A. Wagner and other Hughes personnel to the development of the vertical-plane pendulum absorbers is hereby acknowledged.