Finite Element Analysis of Disk-Spindle Vibration in Hard Disk Drives

Thitima JINTANAWAN and Jakrapan LOENGNALUEMITRACHAI
Department of Mechanical Engineering, Chulalongkorn University,
Phayathai Road, Pathumwan, Bangkok 10330 Thailand
Phone 66(0)2218-6610      Fax 66(0)2252-2889      E-mail: thitima.j@chula.ac.th

Abstract
This paper aims at development of a finite element model (FEM) predicting natural vibration of a disk-spindle system for hard disk drives (HDD). The disk-spindle system consists of multiple and flexible disks clamped to a spindle hub which spins at constant speed. The top end of the hub is press-fit onto a flexible shaft, which is mounted on the spindle housing through radial and thrust hydrodynamic bearings (HDBs). In the FEM, the disks are modelled with shell elements, the hub and shaft are modelled with 3-D solid elements, and HDBs are modelled with linear spring and damper elements. To validate the FEM, natural frequencies predicted by the FEM are compared with the existing experimental results. Both results match very well; the discrepancy of the predicted frequencies and the experimental frequencies is less than 1%. Moreover effect of variation in parameters such as number of the disks, thickness of the disks, and clamp position of the disks on the natural frequencies is investigated using FEM.

Keywords: Vibration, Finite element, Disk-spindle, Hard disk drive.

1. Introduction
Mathematical models were developed to predict vibration of a disk-spindle system for hard disk drives (HDD) [1, 2, 3, and 4]. These models successfully explain the vibration phenomena in HDD as follows. The vibration modes of the disk-spindle system can be divided into: unbalanced (0,1) modes, balanced (0,1) modes, axisymmetric or (0,0) modes, and (0,2) disk modes [1, 2]. For the unbalanced (0,1) modes, all disks have in-phase, one-nodal-diametral vibration, resulting in the unbalanced moment transmitted to the spindle hub. Consequently, the hub undergoes a steady precession. For the balanced (0,1) modes, the disks have out-of-phase, one-nodal-diametral vibration balancing the moment. Hence the hub has no steady precession. The axisymmetric or (0,0) modes are umbrella-like mode shapes. Similar to the (0,1) modes, they can be grouped as unbalanced and balanced (0,0) modes. For the unbalanced (0,0) modes, all the disks have in-phase axisymmetric vibration, resulting in the axial vibration of the spindle. The balanced (0,0) modes exhibit the out-of phase axisymmetric vibration of the disks. In this case, the axial force is balanced out and the spindle hub has no axial vibration. For the (0,2) disk modes, each disk exhibits independent two-nodal-diametral vibration decoupling from the spindle hub motion. Among these vibration modes, the unbalanced (0,1) modes are the most critical for HDD vibration, because they contribute to Track Mis-Registration (TMR) of HDD.

The existing mathematical models of the disk-spindle system are limited by the assumptions that the spindle hub is rigid, and the disk/hub and shaft/hub interfaces are modelled as clamped boundary conditions. For vibration analysis of HDD, finite element method (FEM) is widely used to analyze the vibration of the flexible arms of head drives [5, 6, and 7]. With a limitation of the mathematical models, FEM can be used to model the complicated parts in the disk-spindle system such as flexibility of the spindle hub and imperfect boundary conditions at interfaces.

This paper aims at development of a FEM predicting the natural vibration of a disk-spindle system for HDD. Moreover, effects of variation in parameters such as number of the disks, thickness of the disk, and clamp position of the disks on the natural frequencies are investigated through the FEM. As a feasibility study, the FEM is developed to predict natural frequencies and mode shapes of the spindle system at stationary. With the results from finite element analysis (FEA), natural frequencies of the rotating spindle system can be further analyzed through the classical theory of a rotating plate [8].

2. Model Description of a Disk-Spindle System

2.1 Physical Model
Figure 1 shows a physical model of the disk-spindle system for HDD. The system consists of multiple and identical disks clamped to a spindle hub, which spins at constant speed. The top end of the hub is press-fit onto a flexible and rotating shaft, which is mounted on the spindle housing through the radial and thrust hydrodynamic bearings (HDBs).

A coupled motion of this system is characterized by: 1) the transverse deflection of the disks, 2) the spindle whirling due to the restoring and damping forces of the radial bearings, 3) the spindle precession or rocking, and 4) the axial vibration of the hub due to the restoring and damping forces of the thrust bearings.

---

1 The first and second indices in the parenthesis denote the number of nodal circles and nodal diameters of the disks, respectively.
2.2 Finite Element Model

The standard HDB spindle with four disks for the desktop drives is used for the vibration analysis. Figure 2 shows the FEM of this disk-spindle system. The model consists of the rotating components such as four identical disks, spindle hub, shaft, and HDBs. The disks are modelled with shell elements, the hub and shaft are modelled with 3-D solid elements, and the radial HDBs are modelled with linear spring and damper elements along the radial direction (xz-plane in Fig. 2). Material properties of each component used in the FEM are listed in Table 1.

![Figure 1 Physical model of a disk-spindle system in HDD](image1)

![Figure 2 FEM of a disk-spindle system](image2)

### Table 1 Material properties of the disk-spindle system

<table>
<thead>
<tr>
<th>Parts</th>
<th>Material</th>
<th>Young Modulus (GPa)</th>
<th>Density (Kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Disks</td>
<td>Aluminium</td>
<td>69</td>
<td>2700</td>
</tr>
<tr>
<td>Hub</td>
<td>Aluminium</td>
<td>69</td>
<td>2700</td>
</tr>
<tr>
<td>Shaft</td>
<td>Steel</td>
<td>200</td>
<td>7800</td>
</tr>
</tbody>
</table>

The radial HDBs are the spiral-grooved bearings. They provide the in-line and cross-coupling restoring and damping forces given by:

\[
\begin{pmatrix}
F_x \\
F_z
\end{pmatrix} = \begin{pmatrix}
k_1 & k_2 \\
-k_2 & k_1
\end{pmatrix} \begin{pmatrix}
x \\
z
\end{pmatrix} + \begin{pmatrix}
c_1 & c_2 \\
-c_2 & c_1
\end{pmatrix} \begin{pmatrix}
x \\
z
\end{pmatrix},
\]

(1)

where \(F_x\) and \(F_z\) are the bearing forces in x and z directions, \(k_1\), \(k_2\), \(c_1\), and \(c_2\), are the in-line and cross-coupling coefficients of stiffness and damping, respectively. Table 2 lists these bearing coefficients for the studied drive. The coefficients of stiffness \(k_1\) and \(k_2\) are proportional to the spin speed (\(\omega_3\)) as shown in Table 2. As a first investigation, we consider the case when \(\omega_3 = 0\), or the spindle is stationary. Hence the radial bearings provide only the damping forces whereas the restoring forces are zero.

<table>
<thead>
<tr>
<th></th>
<th>(k_1) (N/m)</th>
<th>(k_2) (N/m)</th>
<th>(c_1) (Ns/m)</th>
<th>(c_2) (Ns/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper</td>
<td>1.94e4 (\omega_3)</td>
<td>2.72e4 (\omega_3)</td>
<td>5.19e4</td>
<td>0</td>
</tr>
<tr>
<td>Lower</td>
<td>1.73e4 (\omega_3)</td>
<td>2.19e4 (\omega_3)</td>
<td>4.16e4</td>
<td>0</td>
</tr>
</tbody>
</table>

![Table 2 stiffness and damping coefficients of the radial HDBs](image3)

In the FEM, the disks of 0.8 mm thickness are clamped to the hub at nodes along the disk inner perimeter. The inner radius of the disk (or the clamping radius) is 13 mm. In addition, the shaft/hub interface or the press-fit end is modelled as clamped boundary conditions.

3. FEM Prediction of Natural Frequencies and Mode Shapes

Natural frequencies and mode shapes of the constructed FEM are determined using the commercial finite element program. Figures 3-(a) and 3-(b) show the vibration modes for the four-disk-spindle system. Fig. 3-(a) illustrates the unbalanced (0,1) modes where all disks have in-phase vibration with one-nodal diameter. The in-phase disk vibration results in an unbalanced moment to the spindle hub. Therefore the hub exhibits a steady precession or rocking (as seen from the right of Fig. 3-(a)). For the balanced (0,1) modes in Fig. 3-(b), the disks have out-of-phase vibration with one-nodal diameter. As a result, the moment is balanced out and the spindle hub has no motion. With the developed FEM, the unbalanced (0,0) modes cannot be observed, because the thrust bearing is not included in this model. The improved FEM, by including the model of the thrust bearing, will be able to predict the unbalanced (0,0) modes. Also
the FEA result for the four-disk-spindle system does not clearly show the balanced (0,0) modes and the (0,2) disk modes. However, there exists a vibration mode from the FEA (not shown here) that couples between the balanced (0,0) and (0,2) modes. This is probably because these two modes occur at about the same frequency for the studied system. Therefore, the motion of these two modes is coupled. The (0,2) disk mode can be observed for the spindle system with one disk as shown in Fig. 3-(c).

![Mode shapes of the disk-spindle systems from FEA](image)

Table 3 Comparison of the system natural frequencies from the FEA and from the experimental result [4]

<table>
<thead>
<tr>
<th>Vibration modes</th>
<th>Frequency from FEA (Hz)</th>
<th>Frequency from experiment (Hz)</th>
<th>% difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unbalanced (0,1)</td>
<td>374</td>
<td>370</td>
<td>1%</td>
</tr>
<tr>
<td>Balanced (0,1)</td>
<td>589</td>
<td>590</td>
<td>0.2%</td>
</tr>
<tr>
<td>(0,2)</td>
<td>Not found</td>
<td>700</td>
<td>-</td>
</tr>
</tbody>
</table>

4.1 Number and Thickness of Disks

Number of the disks in a disk stack and thickness of the disk indicate the flexibility of the system, and thus affect the system natural frequencies. Table 4 shows the natural frequencies of the balanced and unbalanced (0,1) modes when there exists either one disk or four disks in the disk stack. With more disks in the disk stack, the whole system is more flexible. Consequently, the natural frequencies of the unbalanced (0,1) modes of the four-disk system are lower. For the one-disk system, the rocking moment is not balanced out. Therefore the balanced (0,1) modes do not occur in this case.

Table 4 Natural frequencies for the one-disk system and four-disk system

<table>
<thead>
<tr>
<th>Vibration Modes</th>
<th>Frequency (Hz) [1-disk system]</th>
<th>Frequency (Hz) [4-disk system]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unbalanced (0,1)</td>
<td>494</td>
<td>374</td>
</tr>
<tr>
<td>Balanced (0,1)</td>
<td>Not occur</td>
<td>589</td>
</tr>
</tbody>
</table>

Table 5 shows the natural frequencies of the balanced and unbalanced (0,1) modes when thickness of the disks is either 0.8 or 1.27 mm. The disks with 0.8 mm or 1.27 mm thickness are standard in HDD. For the 0.8 mm disk thickness, the system natural frequencies are lower. This is natural, because the thinner disks result in the more flexible system.

Table 5 Natural frequencies of the system when the disk thickness is 0.8, and 1.27 mm
4.2 Location of Clamp Boundary at Disk/Hub Interface

For the disk drive assembly, the disks are mounted on the spindle hub using the clamp fastened with screws on the top of the hub (see Fig. 1). The spacers placing between the disks have the inner and outer radius of 12.5 and 15 mm. In the FEM, the disk/hub interface is modeled as clamped boundary conditions for simplicity. The radial position of the clamp boundary cannot be exactly defined. Due to the assembly, it might be varied from 12.5 to 15 mm as shown in Fig. 4. Effect of variation in the radial position of the clamp boundary on the system natural frequencies is then investigated.

Table 6 compares the natural frequencies of the balanced and unbalanced (0,1) modes predicted by the FEM, when the radial position of the clamp boundary is 12.5, 13, and 13.5 mm. If the radial position is decreased, the natural frequencies of the unbalanced and balanced (0,1) modes are reduced. This results from an increase in the disk flexibility due to a larger disk surface to vibrate.

<table>
<thead>
<tr>
<th>Vibration Modes</th>
<th>Frequency [12.5 mm radial clamp position]</th>
<th>Frequency [13 mm radial clamp position]</th>
<th>Frequency [13.5 mm radial clamp position]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unbalanced (0,1)</td>
<td>368 Hz</td>
<td>374 Hz</td>
<td>377 Hz</td>
</tr>
<tr>
<td>Balanced (0,1)</td>
<td>563 Hz</td>
<td>589 Hz</td>
<td>607 Hz</td>
</tr>
</tbody>
</table>

Table 6 Natural frequencies of the system when the radial clamp position is 12.5, 13, and 13.5 mm

In general, the variation in disk parameters (as investigated in subsection 4.1 and 4.2) significantly changes the frequency of the balanced (0,1) modes but slightly changes the frequency of the unbalanced (0,1) modes. This is because the balanced (0,1) modes are mainly affected by the disk flexibility whereas the unbalanced (0,1) modes are instead mainly affected by the spindle-bearing flexibility.

5. Conclusions

The FEM accurately predicts the natural frequencies of the disk-spindle system in HDD. The discrepancy of the natural frequencies from FEA and those from the experimental result is less than 1%. The parametric study using FEM shows that an increase in number of the disks, a decrease in disk thickness, or a decrease in the radial clamp position of the disks can decrease the natural frequencies of the system.

6. Acknowledgement

This research is supported by the New Researcher/Lecturer Endowment Fund, Chulalongkorn University.

References