High Frequency Radial Mode Vibration in Hard Disk Drive

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In this paper, a 3.5-in computer hard disk drive consisting of a rotating-shaft fluid dynamic bearing spindle motor and 4-disk spinning at 15 000 rpm under external linear vibration is analyzed by commercial finite element analysis software. Predicted frequency response functions of the head-disk off-track motion per unit input acceleration are compared to measured hard disk drive position-error signals on a shaker table. Both theoretical and experimental results show a huge disk pack radial motion near 1600 Hz under linear in-plane vibration. The mode shape analysis indicates that the large radial motion without noticeable disk bending is mainly due to the bending of the motor bracket and shaft. The characteristics of the high frequency radial mode are discussed with the variation of fluid dynamic bearing parameters with the verification of experimental results.

Index Terms—**Fluid dynamic bearings, frequency response function, hard disk drives, spindle motors, vibration.**

I. Introduction

FLUID DYNAMIC BEARING (FDB) spindle motors have been introduced into computer hard disk drives (HDD) for more than 10 years, and most HDDs shipping today are using so-called "rotating-shaft" FDB for economic reasons. However, it is known that rotating-shaft FDB is sensitive to external vibrations due to its weak structural rigidity—the top of the rotating-shaft is press fitted into a motor hub and another end of the shaft is free.

Besides the half frequency whirl and classic natural frequencies of rotating disks, the lowest resonance of the HDD spindle-disk pack system are the (0,1) unbalanced modes (so-called rocking, gyro or pitch modes) and (0,0) unbalanced modes (so-called axial modes). The characteristics of these modes have been discussed both theoretically and experimentally [1]–[4]. Many researchers have reported the effects of the flexibility of stationary parts, such as the HDD base or motor stator, on the natural frequencies of the HDD spindle-disk pack system [5]–[15]. Now, HDD design engineers are able to attenuate these modes effectively by either a robust mechanical design or an advanced servo algorithm.

As HDD capacity demand grows rapidly, data track widths keep shrinking, and HDDs also pack more disks into the same space. Dynamic characteristics of the HDD spindle-disk pack system with natural frequencies higher than (0,1) and (0,0) unbalanced modes have received lots of attention, especially under external vibration. Not only are HDD design engineers still unable to develop effective and economic methods to attenuate these high frequency spindle-disk pack system modes, but the HDD servo system is typically designed to amplify disturbances at these high frequency ranges. Several authors have demonstrated that HDDs have huge frequency response function (FRF) amplitudes at high frequency range under external linear vibration, such as the second and the third pair of (0,1) unbalanced modes in [7]–[9] and the translational mode in [10].

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All researchers who have published theoretical papers developed their own numerical methods to predict natural frequencies and FRFs of the HDD because the commercial finite element (FEM) software was not able to solve the rotating FDB system with large asymmetric damping until two years ago. We also found that there are no HDD position-error signals (PES) FRFs available. All published measured FRFs are at the HDD component level, with external vibrations excited by different methods, such as on a shaker table [1], [4], [14], by an impact hammer [7], [8], [12], [15], and by motor coil electromagnetic force [6], [16]. In addition, there are no experimental studies that compare variable FDB parameters with their impact on the high frequency modes.

In this paper, commercial FEM software is used to analyze an HDD under external linear vibration so the flexibility of all HDD components is considered. Predicted FRFs of the head-disk off-track motion per unit input acceleration are compared to HDD PES measurement data on a shaker table. In addition, the characteristics of the high frequency modes under external linear vibration are discussed with the variation of key FDB parameters with the verification of experimental results.

II. Finite Element Analysis

The FEM model of a 3.5-in HDD, consisting of a base, cover, disk pack on a FDB spindle motor, and actuator, is prepared by commercial FEM software. The rotating and stationary portions of the FDB are connected by elements consisting of FDB stiffness and damping coefficients at a specific rotating speed and temperature, for example at 15 000 rpm and 30 C. The air bearing surfaces of recording heads are connected to corresponding disk surfaces by elements consisting of air bearing stiffness and damping coefficients. The boundary condition of the HDD is fixed on the bottom of the base where screws are usually mounted. Full harmonic analysis is performed with a unit input linear acceleration on the HDD from 10 to 3000 Hz either along the HDD's longer axis (X direction), shorter axis (Y direction), or axial axis (Z direction).

In a full HDD FEM model, 3-axis FRFs of each point on disks or heads can be calculated, but only the relative displacements between the data point on the disk and the sensor element on the head in the off-track radial direction are of interest. The HDD

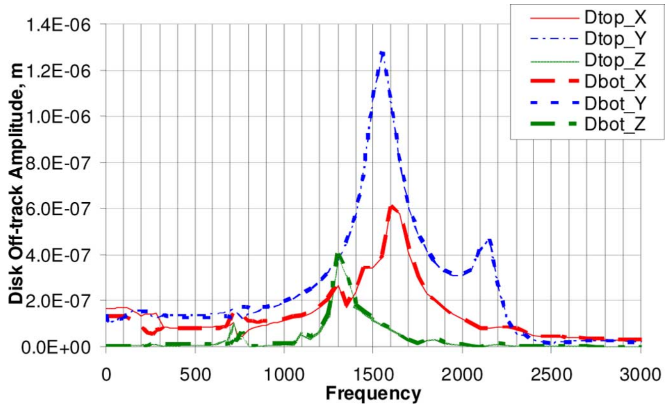

Fig. 1. FEM predicted disk off-track motion FRFs at the outer diameter of the top and bottom disks under linear vibrations, 30 C.

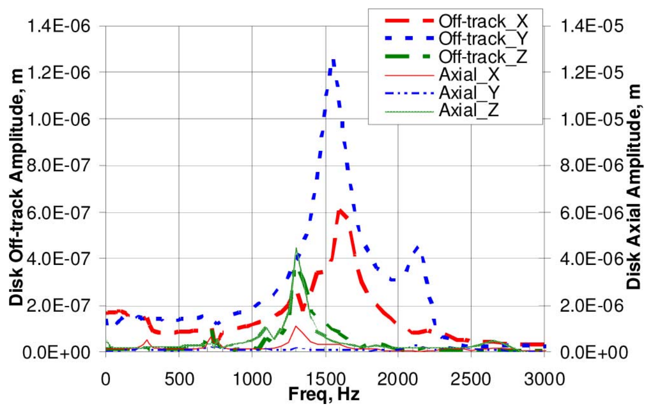

Fig. 2. Comparison of FEM predicted disk axial and off-track motion FRFs at the outer diameter of the top disk under linear vibrations, 30 C.

PES can be predicted by the head-disk relative off-track displacement mentioned above and an error reject function, which is provided by servo design engineers.

Fig. 1 shows disk off-track motion FRFs, which are disk displacements in the off-track radial direction divided by input accelerations, at the outer diameter of the top and bottom disks under linear vibrations in the X, Y, and Z directions, respectively. Fig. 2 compares disk axial and off-track motion FRFs at the outer diameter of the top disk under linear vibrations. Fig. 3 displays the corresponding mode shapes of all major modes related to the spindle disk-pack.

In the current HDD platform, the biggest disk off-track motion amplitudes are the modes near 1586 and 1611 Hz when the HDD is under linear vibrations in the X or Y direction. Mode shape animation clearly demonstrates that both the motor bracket and the shaft bend, and all disks vibrate together with large radial motion but without noticeable disk bending or motor tilting. In addition, this high frequency "radial mode" is not always excited by vibrations in the axial direction. Fig. 2 also demonstrates that disk axial displacement is very small at radial mode under vibrations in the X or Y direction. Therefore, track-mis-registration induced by disk axial displacement, such as in head rolling, pitching and suspension deformation [17], at the radial mode under in-plane vibration is very small. Based on the characteristics we observed from Figs. 1–3, the radial

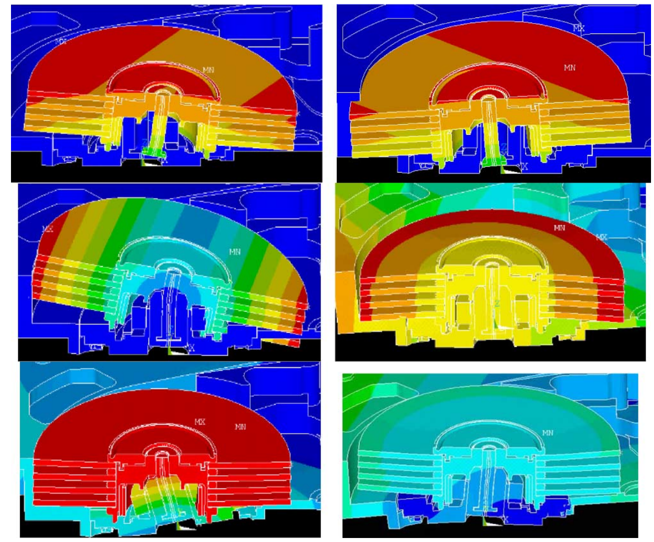

Fig. 3. Mode shapes of spindle-disk pack related modes, (a) upper left, conical half frequency whirl 117 Hz, (b) upper right, translational half frequency whirl 138 Hz (c) middle left, forward (0,1) unbalanced mode 764 Hz, (d) middle right, (0,0) unbalanced mode 1305 Hz, (e) lower left, radial mode 1586 Hz, (f) lower right, disk-based coupled mode 2140 Hz.

mode is more like the translation mode reported in [10] than the second or the third pair of (0,1) unbalanced modes reported in [7]–[9] in which disks bend a lot. The different of the mode shape from different papers is mainly caused by different HDD platforms, such as the difference of diameter and thickness of disks, rotating speed and base design.

The (0,0) unbalanced mode near 1305 Hz generates large off-track and axial motion amplitudes when the HDD is under vibrations in the Z direction. In-plane excitation may also excite this mode, such as the FRF resulting from vibration in the X direction shown in Figs. 1 and 2. The FRF amplitudes of backward and forward (0,1) unbalanced modes near 274 and 764 Hz and the conical half-frequency whirl near 117 Hz are minimized by a well designed spindle system. However, in Fig. 1 the off-track motion differences between the top and bottom disks at these modes are still noticeable due to angular motion of the spindle-disk pack. The highly damped translational half-frequency whirl shown in the mode shape animation, Fig. 3, cannot be identified in Figs. 1 and 2.

If computer memory is limited, the head stack assembly can be removed from the FEM model. The head-disk relative off-track displacements under vibration can be calculated by disk displacement in the off-track direction and head motion induced by disk axial displacement [17]. Only the arm and suspension coupled modes will be neglected and the characteristics of radial mode are still contained in the simplified FEM model.

III. Experimental Results

Based on mode shape animation of FEM results, the radial mode is highly affected by HDD structural rigidity. Therefore, PES of a functional HDD on a shaker table is measured instead of disk pack component level measurements, which often require modification of the HDD structure in order to gain access to the surface or edge of spinning disks.

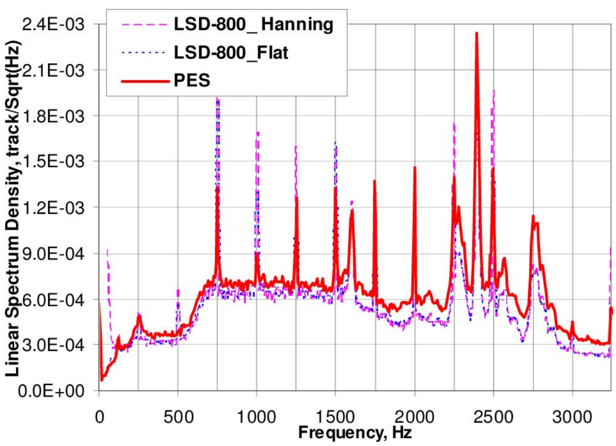

Fig. 4. Averaged linear spectrum density of top head PES at the outer diameter measured by HDD and spectrum analyzer (Hanning and Flat windows) from analog signals at no vibration.

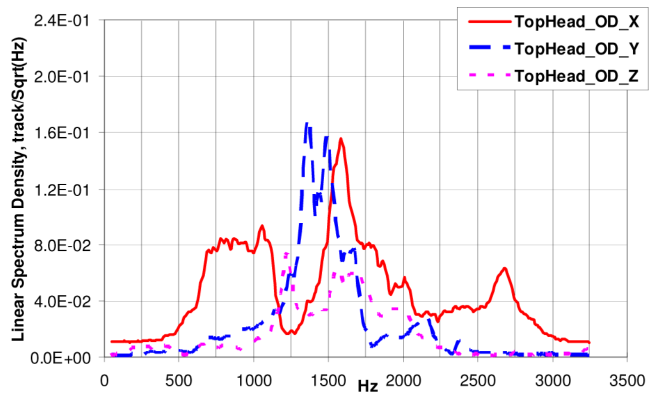

Fig. 5. Averaged linear spectrum density of top head PES at the outer diameter measured by spectrum analyzer from analog signals under vibration in the X, Y, and Z directions.

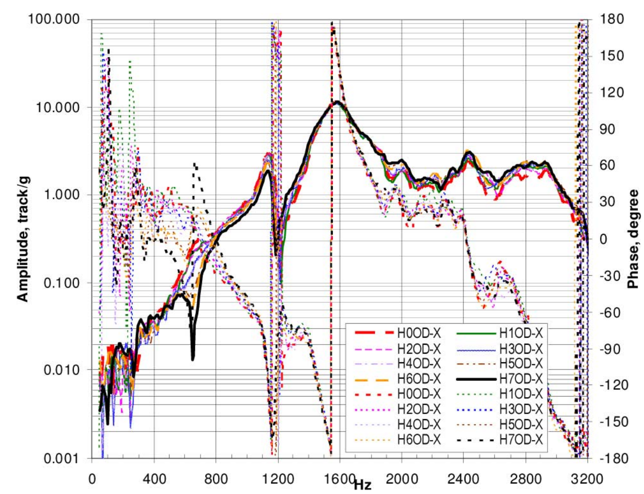

Fig. 6. Amplitudes and phases of analog PES FRFs of all heads at the outer diameter, vibration in the X (longer) direction, ~30C.

The HDD is mounted from the bottom of the base on a fixture on a shaker table. Fixtures are designed in different ways so that even if the shaker is shaking only in one direction, the HDD can be excited in the X, Y, and Z directions, respectively. A thermocouple is mounted on the bottom of the HDD where the thrust plate of the spindle motor is located to monitor the FDB temperature during the tests.

In order to average real time FRFs of PES under shaker excitation, analog PES signals are taken by a spectrum analyzer from the card of the functional HDD with special wiring. The HDD is under random vibration from 50 to 3250 Hz in the specific direction. For each test, the FRFs of the analog PES were averaged 200 times.

Fig. 4 compares the averaged top head track following PES at the outer diameter measured by an HDD PES and analog PES signals measured by a spectrum analyzer with two fast-furious-transform analysis windows when the HDD is under no vibration. Both analog PES signals agree well with HDD PES signals. When there is no vibration, amplitudes of HDD track following PES mainly result from flow-induced vibration, and the radial mode is not likely to be excited, and therefore we do not observe it in Fig. 4. Most of the sharp peaks in Fig. 4 are repeatable run outs and other peaks above 2000 Hz are arm, actuator, or classic rotating disk modes.

Fig. 5 displays the averaged top head PES at the outer diameter measured by a spectrum analyzer from analog signals when the HDD is under vibration in the X, Y, and Z directions, respectively. The amplitudes of analog PES under vibration in Fig. 5 are about 100 times larger than analog PES under no vibration in Fig. 4. Therefore, the contribution of flow-induced vibration on PES can be neglected when the HDD is under vibration.

Fig. 6 displays amplitudes and phases of analog PES FRFs of all heads at the outer diameter when the HDD is under vibration in the X direction at room temperature. Fig. 7 shows the comparison of analog PES FRFs of 4 heads at outer and inner diameters when the HDD is under vibration in the X direction at room temperature. The biggest amplitude of analog PES is near 1550 Hz, where all heads have about the same level of amplitudes and phases at both the outer and inner diameters. The analog PES results indicate all disks vibrate together with a large radial motion but without noticeable disk bending or motor tilting, just like the FEM mode shape demonstrated.

Figs. 8 and 9 display amplitudes and phases of analog PES FRFs of all heads at the outer diameter when the HDD is under vibration in the Y and Z directions at room temperature, respectively. As FEM predicted, the radial mode peak frequency when the HDD is under vibration in the X direction is slightly different from when the HDD is under vibration in the Y direction. However, the radial mode peak frequency is also observed under axial vibration. This is probably due to imperfect fixture design, which results in residual vibration in the X or Y direction when the HDD is under axial vibration.

Other spindle-disk pack related modes, such as the forward and backward (0,1) unbalanced modes and (0,0) unbalanced mode, can be identified by cross examining Figs. 6–9. The (0,0) unbalanced mode is near 1250 Hz and the forward (0,1) unbalanced mode is near 750 Hz. Both frequencies agree well with FEM predicted results.

Fig. 10 shows a comparison of top head PES FRFs at the outer diameter predicted by FEM and measured by analog PES under vibration in the X, Y, and Z directions. The agreement between FEM analysis and PES measurement is very good in

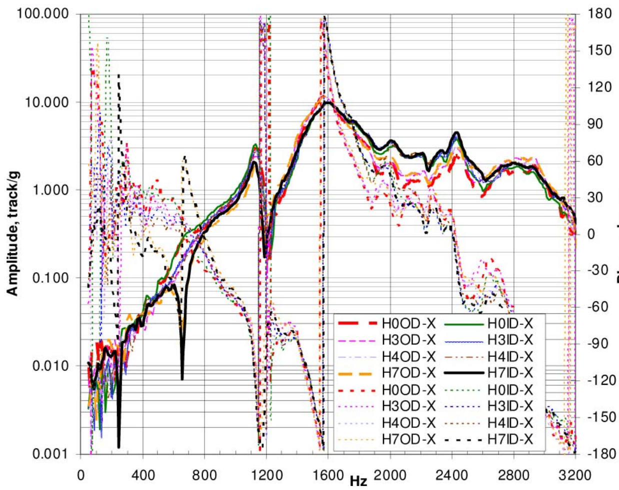

Fig. 7. Comparison of analog PES FRFs at the outer and inner diameters, vibration in the X direction, ∼30C.

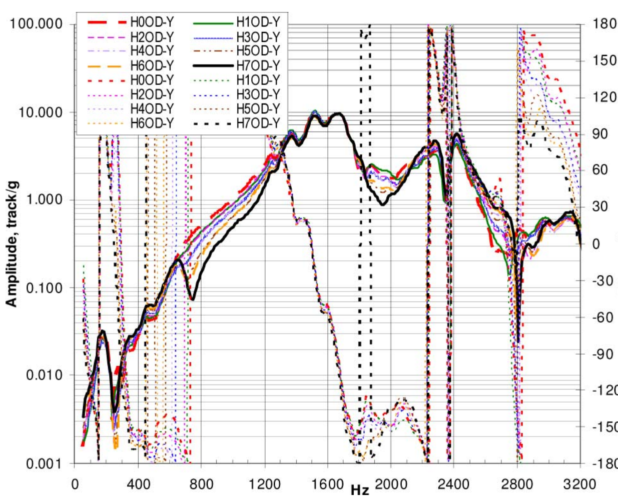

Fig. 8. Amplitudes and phases of analog PES FRFs of all heads at the outer diameter, vibration in the Y (short) direction, ∼30C.

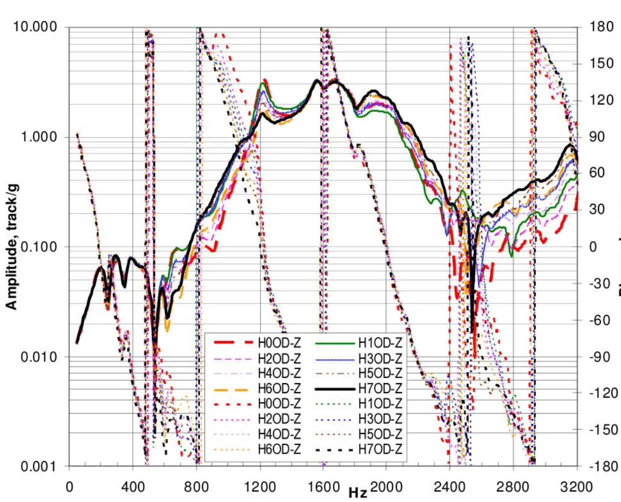

Fig. 9. Amplitudes and phases of analog PES FRFs of all heads at the outer diameter, vibration in the Z (axial) direction, ∼30C.

radial mode peak frequency and amplitude. The predicted PES is calculated based on head-disk relative off-track displacements

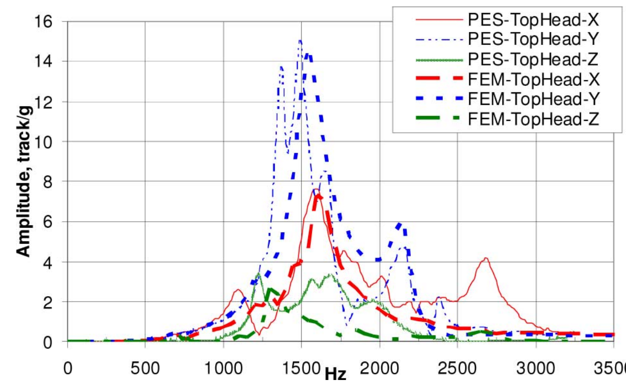

Fig. 10. Comparisons of top head PES FRFs at the outer diameter predicted by FEM and measured by analog PES under vibration in the X, Y, and Z directions, 30 C.

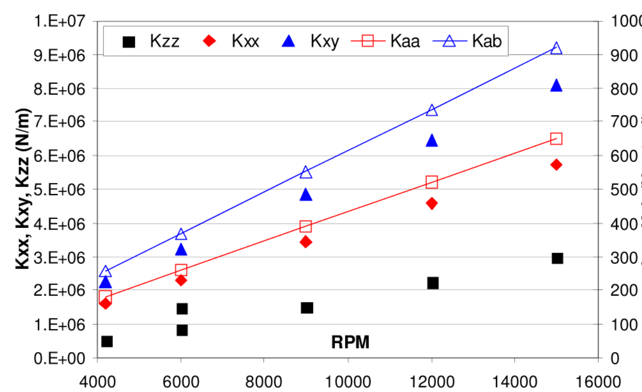

Fig. 11. Effect of rotating speeds on FDB stiffness coefficients, at 30 C.

resulting from FEM analysis and a measured error reject function of the test HDD.

IV. Radial Mode Amplitude Reduction

Based on mode shape animation of FEM results, the most effective way to reduce radial mode amplitude is to increase HDD structural rigidity, such as replacing the rotating-shaft FDB with a tied-shaft FDB or substituting the base with a higher stiffness material. However, either option increases HDD material cost dramatically. The current study will focus on the effect of the FDB properties on the radial mode.

Two simple ways to demonstrate the change of FDB dynamic characteristics without making FDB design changes are changing the rotating speed and lubricant temperature or viscosity. FDB stiffness coefficients are almost linearly proportional to rotating speed, as seen in Fig. 11, where Kaa and Kab are journal bearing angular stiffness coefficients, but the FDB damping coefficients are nearly constant across varying speeds. Figs. 12 and 13 display the effect of rotating speed on FEM predicted top disk FRFs at the outer diameter in off-track motion and axial motion, respectively, when the HDD is under vibration in the X direction. Both frequency and amplitude of the radial mode are not affected by the FDB journal bearing stiffness coefficients. Both frequency and amplitude of the axial mode are not affected by the FDB thrust bearing stiffness coefficients, either. However, at the frequency range lower than the half frequency whirl (117 Hz), both FRF amplitudes

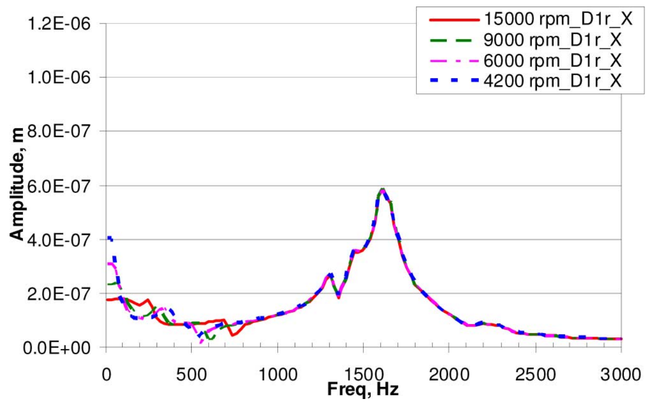

Fig. 12. FEM predicted top disk off-track motion FRFs at the outer diameter at different rotating speeds when the HDD is under vibration in the X direction, 30 C.

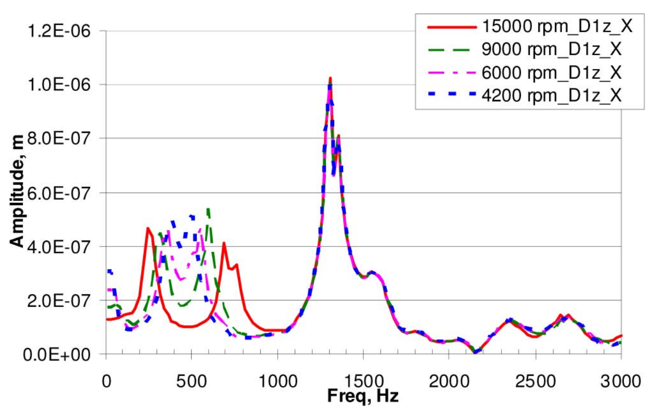

Fig. 13. FEM predicted top disk axial motion FRFs at the outer diameter at different rotating speeds when the HDD is under vibration in the X direction, 30 C.

of off-track and axial disk motion increase as rotating speed decreases, which results in decreased of FDB stiffness. In addition, as rotating speed increases, the backward (0,1) unbalanced mode frequency decreases, and forward (0,1) unbalanced mode frequency increases consistent with other publications.

Figs. 14 and 15 display the effect of FDB lubricant temperature on FEM predicted top disk FRFs at the outer diameter in off-track motion and axial motion, respectively, when the HDD is under vibration in the X direction. Both the FDB stiffness coefficient (K) and the damping coefficient multiplied by excitation frequency (ωC) are linearly proportional to lubricant viscosity as shown in Fig. 16. Increasing lubricant temperature, which results in lower lubricant viscosity and lower FDB stiffness and damping, reduces the FRF amplitudes of both the radial mode and axial mode, but the frequencies of these two modes remain almost unchanged. Combined with the results from Figs. 12 and 13, we conclude that the natural frequencies of both the radial and axial modes are mainly determined by HDD structure design, and reducing FDB damping reduces the FRF amplitudes of both the radial and axial modes. From FDB design point of view, lower FDB damping can be achieved by changing groove pattern. However, reducing FDB damping has a negative impact on FRF amplitudes of half frequency whirl and the (0,1) unbalanced mode.

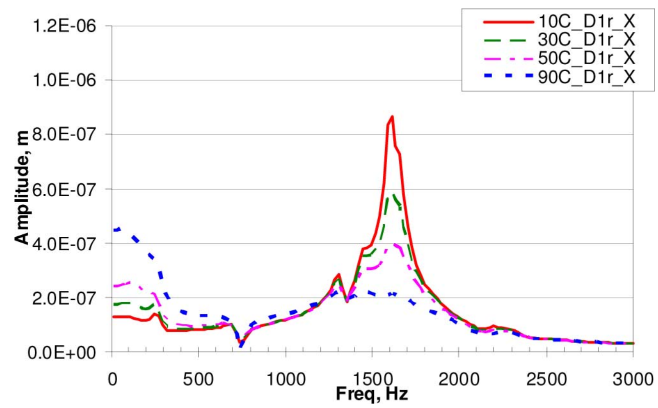

Fig. 14. Effect of lubricant temperature on FEM predicted top disk off-track motion FRFs at the outer diameter when the HDD is under vibration in the X direction.

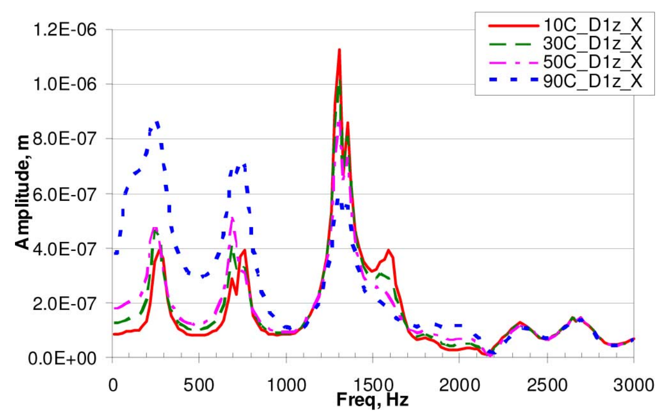

Fig. 15. Effect of lubricant temperature on FEM predicted top disk axial motion FRFs at the outer diameter when the HDD is under vibration in the X direction.

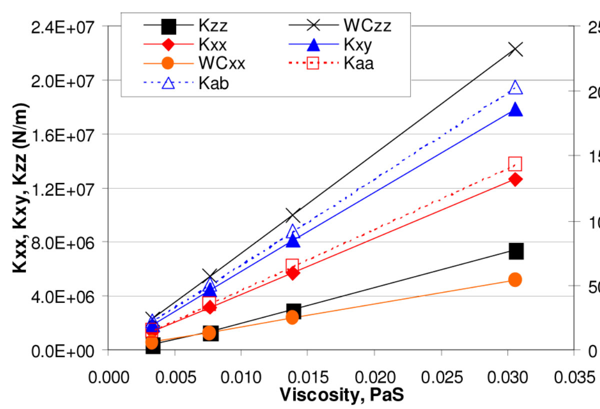

Fig. 16. Effect of lubricant temperature on FDB stiffness and damping coefficients, at 15 000 rpm.

In order to verify the effect of temperature on the radial mode FRF amplitudes, HDDs at different temperatures are mounted on a shaker table under vibration in the X direction. Fig. 17 displays measured analog PES FRFs of the top heads at the outer diameter. The amplitudes of the radial mode follow the trend of FEM predictions, where HDDs with higher temperatures have lower radial mode amplitudes. However, the absolute radial mode amplitude reduction is not as big as the FEM estimate, and the radial mode peak frequency increases slightly

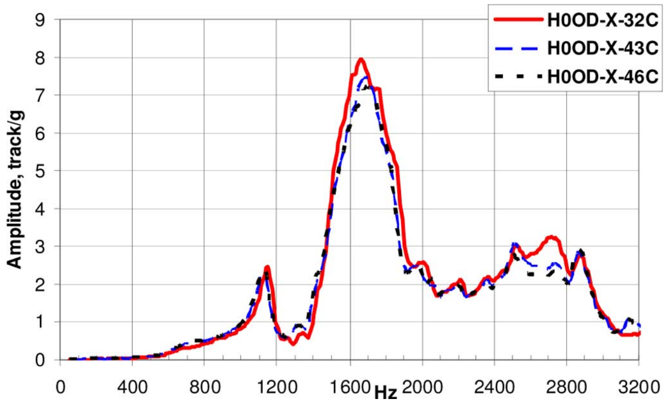

Fig. 17. Effect of temperature on measured analog PES FRFs of the top heads at outer diameter when the HDD is under vibration in X direction.

when temperature increases. This is because other parameters, such as material damping and bonding of motor sleeve and base, in HDDs are also affected by temperature change, but they are not included in the FEM results shown in Figs. 14 and 15.

The explanation of an increasing in the radial mode FRF amplitude due to a higher FDB damping is analogous to the increasing of the axial mode FRF amplitude resulting from a higher FDB damping, which has been reported in [4]. A two-degree-of-freedom (2-DOF) mass-spring system can be used to demonstrate the fact. When the 2-DOF system is excited at one of the system's natural frequencies, increasing the stiffness of the second spring increases the vibration amplitude of the second mass. When the stiffness of the second spring becomes larger, the second mass tends to follow the motion of the first mass, which is resonating at its natural frequency. In our HDD disk-pack system, the stationary parts are analogous to the first mass, the base bending stiffness to the first spring, all rotating parts to the second mass, and FDB stiffness and damping to the second spring. At the system's natural frequency, the radial mode frequency ω, the spring constant of the FDB is determined by FDB damping because the value of ω C at the radial mode frequency is much bigger than K. Therefore, a higher FDB damping increases the radial mode FRF amplitude of the rotating disks.

V. Conclusion

A 3.5-in computer hard disk drive consisting of a rotating-shaft fluid dynamic bearing spindle motor and 4 disks spinning at 15 000 rpm under external linear vibration was analyzed by commercial finite element analysis software. Predicted frequency response functions of the head-disk off-track motion per unit input acceleration are compared to measured hard disk drive analog position-error signals on a shaker table. Both theoretical and experimental results show a "radial mode" with huge disk pack radial motion near 1600 Hz under linear in-plane vibration. The radial mode peak frequency and amplitude predicted by finite element analysis and measured by analog position-error signal measurement agree very well. The finite element mode shape analysis demonstrates that the large radial motion without noticeable disk bending is mainly due to the bending of the motor bracket and shaft, which indicates that a stiffer base or a tied-shaft FDB is the most effective way to reduce radial mode amplitudes. The fluid dynamic bearing stiffness has negligible effect on the radial mode peak frequency and amplitude. However, both theoretical and experimental results show that a lower fluid dynamic bearing damping decreases the radial mode peak amplitude.

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