



A PASSIVE DAMPER FOR THE VIBRATION MODES OF THE HEAD ACTUATOR IN HARD DISK DRIVES

L. JIANG AND R. N. MILES

*Department of Mechanical Engineering, State University of New York,
Binghamton, NY13902-6000, U.S.A.*

(Received 7 October 1997, and in final form 27 August 1998)

As the track density of hard disk drives increases, further improvement in the performance of the read/write head positioning servo system is required. However, the servo performance is limited mainly by the inherent mechanical resonances of the head actuator. Passive damping has the potential to improve the head actuator dynamics. In this paper, a practical passive vibration damper is proposed that is very effective for damping the critical vibration modes of the head actuator. The experimental results from the application of this passive damper to two commercially available hard disk drives are presented. The measured data show that the tracking dynamics of the head actuator can be greatly improved by this passive damper. The vibration induced variation of the flying height is also significantly reduced.

© 1999 Academic Press

1. INTRODUCTION

A primary trend in hard disk drives is that the track density and storage capacity are increasing very rapidly. This is projected to place extreme requirements on the precision with which the head actuator rapidly moves the read/write heads across the disk surfaces and maintains them over the specific data tracks for reading and writing information. It is therefore required to improve further the read/write head positioning servo performance for future high track density hard disk drives.

Figure 1 shows the schematic of the head actuator in a hard disk drive. The head actuator consists of head/suspension/arm assemblies, actuator shaft, ball bearing assembly and voice coil motor. The position of the read/write heads is controlled by a positioning servo system.

It is well known that the head actuator is a flexible mechanical structure, and the tracking servo is a typical non-colocated positioning control system, which has potential instability problems [1]. It is also known that the positioning accuracy of the read/write heads strongly depends on the servo bandwidth [2]. However, the servo bandwidth is limited mainly by the inherent mechanical resonance of the head actuator. Also, further decrease of the data access time is hampered by

residual vibrations caused by the flexibility of the head actuator. As a result, the mechanical resonance of the head actuator is a predominant factor in limiting the servo performance. Considerable efforts have been made to design a control system that minimizes the effect of the vibrations on the operation of hard disk drives [3–10]. However, the control system cannot compensate for all the mechanical resonances. Therefore, improvement of the head actuator dynamics is needed for future high-performance hard disk drives.

The need for passive damping of the head actuator has been realized in the hard disk drive industry. The constrained layer damper applied on the suspensions was patented in 1988 [11], and thoroughly studied by Henze *et al.* [12]. It was shown that the constrained layer damper reduced the amplitude of the suspension bending and torsion modes, but it was not effective in reducing the amplitude of the suspension sway mode, which was caused by the in-plane deflection of the suspension and contributed to significant off-track error. The effectiveness of the constrained layer damper can be improved by putting it on the bending area of the suspension, which is the weakest part connecting the suspension and the arm [13]. However, the bending section of the suspension is a critical part since the bending stiffness should be consistently controlled in order to maintain the stability of the slider flying. It is not possible to sufficiently control the stiffness of a constrained layer damper. Also, the outgassing of the viscoelastic damping material often precludes its application in the clean disk enclosure. A rotary actuator vibration damper, which was installed inside the actuator ball bearing assembly, was proposed by Stricklin and Blanks [14]. This vibration damper behaves as a mass damper and reduces the amplitude of the actuator mode, which is caused by the radial flexibility of the actuator ball bearing. However, as an alternative, the actuator mode can be eliminated by suitably controlling the radial stiffness of the ball bearing [15].

It is a common feature of present hard disk drives that a strong system vibration mode exists between 3 and 4.5 kHz, which involves the coupled vibration of the head, suspension, arm and ball bearing assembly [15]. The system mode, which is generated by the distortion of the ball bearing, is particularly troublesome for the servo system since it is very sensitive to the assembly process and contributes to significant off-track error. As a result, this system mode should be eliminated for the robust position control of the read/write head. None of the existing dampers are effective in reducing the amplitude of this critical vibration mode. The main purpose of this paper is therefore to propose a practical passive damper that is very effective in damping the troublesome system mode while minimizing the impact on the overall design of hard disk drives.

In this paper, the motivation of the development of a passive damper is first described. The proposed passive damper is then documented. The experimental results from the application of this passive damper to two commercially available hard disk drives are presented. One is an IBM DPES-30540 hard drive with one disk and two heads. Another is a Seagate ST-3660A hard drive with two disks and four heads. The measured data shows that the tracking dynamics of the head actuator can be greatly improved by the passive damper. The vibration induced variation of the flying height is also significantly reduced. Finally, analysis of the

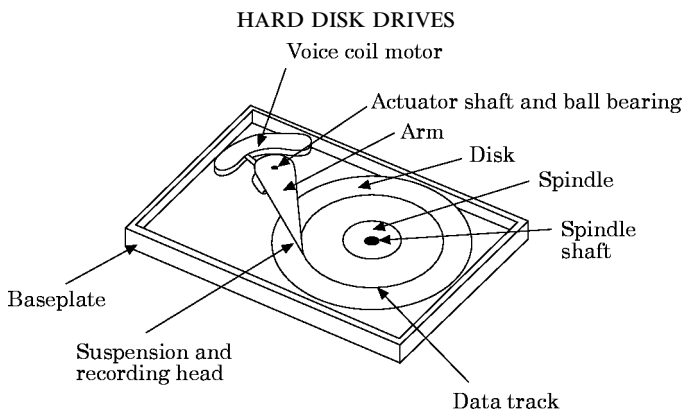


Figure 1. Schematic of the head actuator in a hard disk drive.

damping configuration will be given in order to provide a better understanding of this passive damper.

2. EFFECT OF THE COVER ON THE HEAD ACTUATOR

In conventional hard disk drives, the actuator shaft is mounted on the drive baseplate and supported by the cover through a screw. The installation of the cover was found to have significant effects on the head actuator dynamics. Figure 2 shows the effect of the cover on the head actuator dynamics. The cover applies a vertical force P_z and a lateral force P_y on the actuator shaft. The vertical force P_z is applied by the contact between the cover and the top surface of the actuator shaft. Since the contact surface is not perfectly flat, the contact pressure is not uniform. The non-uniform contact pressure will cause the local deformation of the ball bearing [16]. Also, the contact pressure reduces the runout of the ball bearing. As a result, the cover will reduce the amplitudes of the suspension torsion and sway modes. The lateral force P_y is applied due to the dimensional mismatch between the cover and the baseplate. The actuator shaft can be significantly deflected by the lateral force P_y . The deflection of the actuator shaft results in the distortion of the ball bearing, and hence generating the system mode, which involves a coupled vibration of the slider, suspension, arm and ball bearing assembly. The system mode is therefore particularly troublesome since it is very sensitive to the

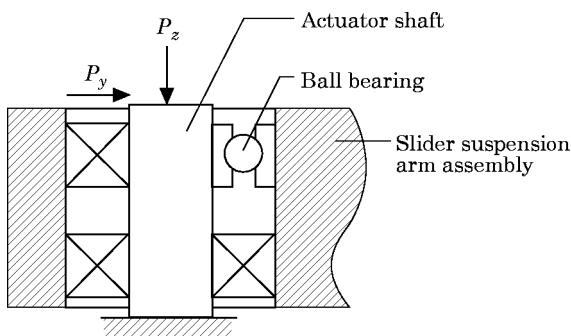


Figure 2. Effect of the cover on the head actuator dynamics.

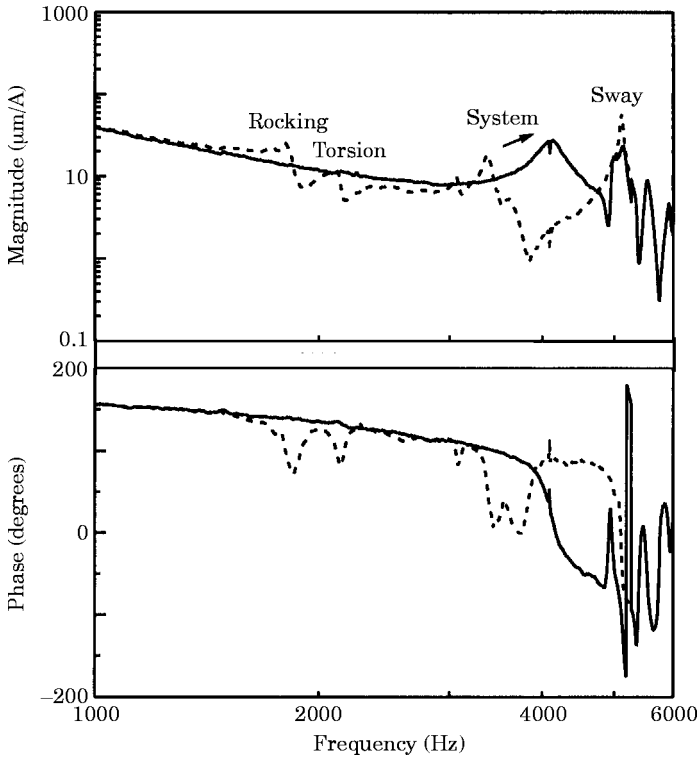


Figure 3. Effect of the cover on the head actuator dynamics for the IBM hard drive: —, with the cover; ----, without the cover.

assembly process. Finally, the cover increases the rigidity of the shaft so that the rocking motion of the actuator shaft is eliminated. In the following, the measured data obtained from both the Seagate drive and the IBM drive under the operating conditions with and without the cover will be presented. The effect of the cover on the head actuator dynamics discussed here will be observed.

Figure 3 shows the measured frequency responses of the radial slider displacement relative to the current input to the voice coil motor under the operating conditions with and without the cover for the IBM hard drive. It can be seen that the installation of the cover has great effects on the head actuator dynamics. Four major vibration modes exist (rocking, torsion, system and sway) that generate the radial slider motion under the operating condition without the cover. A detailed description of these modes can be found elsewhere [15]. As shown in Figure 3, the head actuator dynamics is greatly improved by the cover. Only the system mode and the sway mode generate radial slider motions under the actual operating condition with the cover installed. The resonant frequency of the system mode was found to vary from 3.3–4.1 kHz when the screw connecting the cover to the actuator shaft was tightened.

Figure 4 shows the measured frequency responses of the radial slider displacement relative to the current input to the voice coil motor under the operating conditions with and without the cover for the Seagate hard drive. As in the IBM hard drive, the cover has significant effects on the head actuator

dynamics. There are four major vibration modes (actuator, torsion, system and sway) that generate the radial slider vibration under the normal operation with the cover installed.

3. PROPOSED PASSIVE DAMPER

As discussed above, the cover has significant effects on the head actuator dynamics. In general, the head actuator dynamics is improved by the cover. However, the installation of the cover also has harmful effects on the head actuator dynamics. The most important modes for the servo system were found to involve translation of the actuator shaft. An effective way to damp those modes would be to place damping material such that it will be deformed by the relative motion of the top of the actuator shaft and the cover. In this section, a practical passive damper for effectively damping the critical vibration modes of the head actuator will be proposed. The basic idea is to incorporate passive damping into the entire head actuator system.

Figure 5 shows the section view of the head actuator assembly with the passive damper installed. The passive damper is installed outside the disk enclosure between the actuator shaft and the cover. As shown in Figure 5, the passive damper is composed of the support, viscoelastic damping layer and constraining layer. The support is fastened to the actuator shaft by the means of a screw-joint.

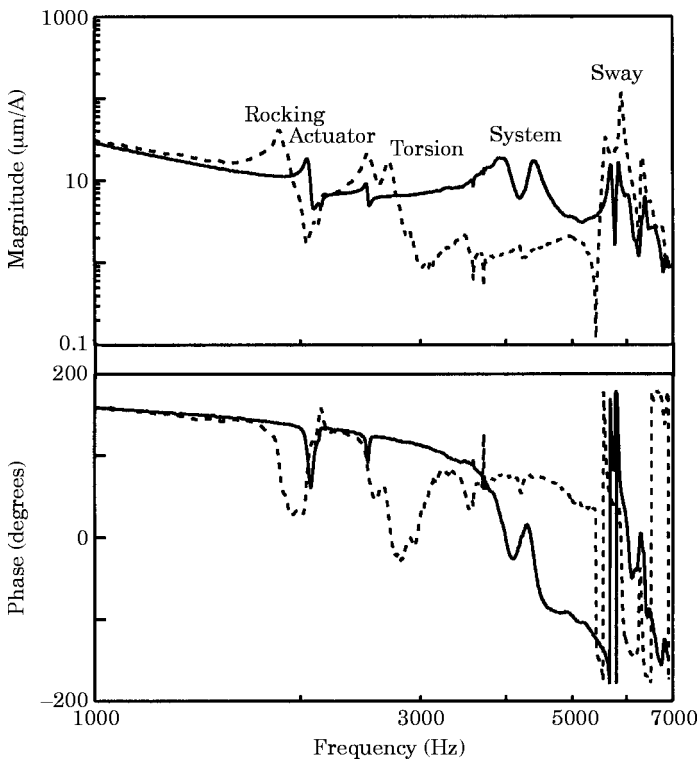


Figure 4. Effect of the cover on the head actuator dynamics for the Seagate hard drive. Key as for Figure 3.

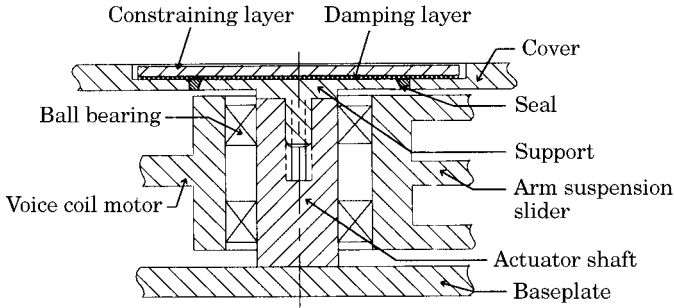


Figure 5. Section view of the head actuator with the passive damper installed.

One side of the damping layer is attached to the top surface of the support and the outer surface of the cover. The constraining layer is fixed to the other side of the damping layer. The disk enclosure is sealed by a ring, so that the damping material is located outside the disk enclosure.

Vibration of the head actuator results in cyclic strain induced into the damping material and hence the dissipation of the vibration energy. The damping layer may comprise any suitable viscoelastic damping material. The preferred damping material is a viscoelastic damping polymer provided in the form of a pressure sensitive adhesive tape with high loss factor. The constraining layer is shaped as a circle disc. Other shapes may also be used. The seal may be any suitable soft material, such as that used to seal the cover in present hard disk drives.

The damper results in significantly reduced preload on the actuator bearings during the assembly process. Also, the distortion of the ball bearing due to the dimensional mismatch between the cover and the baseplate is prevented. In conventional disk drives, a non-uniform preload is applied to the actuator shaft when the cover is installed. In the current configuration, the cover may be installed initially without making contact with the actuator shaft. With the cover in place, the damper is then installed in such a way that any residual preload due to dimensional mismatch must be transferred by shear in the viscoelastic damping material. Because viscoelastic materials are very flexible in response to static load, the loads transferred to the bearing are minimized. The distortion of the ball bearing is thus minimized because (1) the cover installation is independent of the actuator shaft, and (2) residual preloads induced during installation of the damper must be transferred through a very flexible viscoelastic material. The damper not only improves the working condition of the bearing assembly, but also reduces the resonances to the accepted level. The damper is very effective in reducing the amplitude of the system vibration mode and the actuator mode as shown in the next section.

Figure 6 shows another damping configuration for the head actuator. The damper is fixed to the actuator shaft by the screw. The damping layer is constrained between the outer surface of the cover and the constraining layer. The damping layer is also isolated from the disk enclosure by the seal. This damping configuration differs from the first damper in that a significant preload is applied on the actuator shaft by the screw.

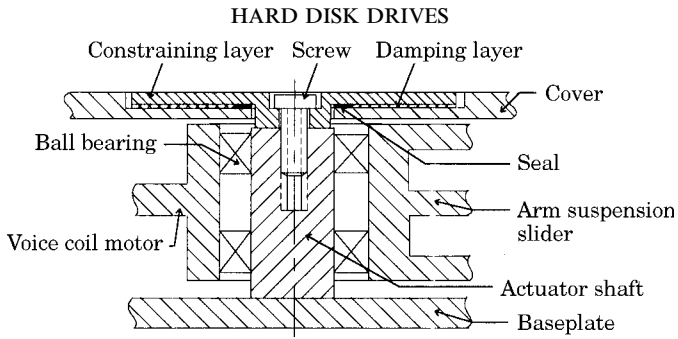


Figure 6. Section view of the head actuator with the second damping configuration.

In the following, the experimental results from the application of this passive damper to both the IBM hard drive and the Seagate hard drive will be presented. The damping material is a Roush Anatrol Inc. product, Anatrol 218, with a thickness of 0.015 in. Other damping material may also be used to achieve similar results.

4. IMPROVED TRACKING DYNAMICS OF THE HEAD ACTUATOR

Figure 7 shows the measured frequency responses of the radial slider displacement relative to the current input to the voice coil motor under the

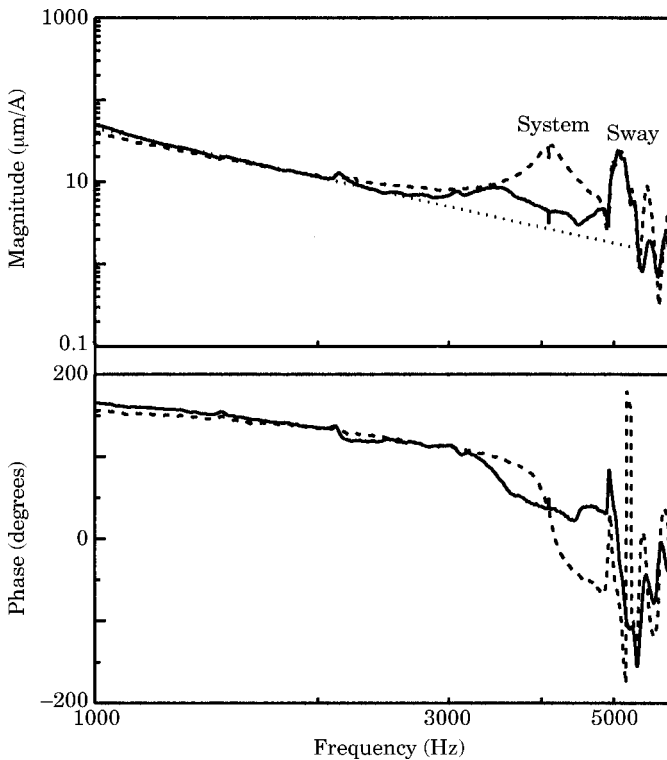


Figure 7. Improved tracking dynamics of the head actuator for the IBM hard drive: —, with the damper; ---, without the damper; ····, ideal rigid body response.

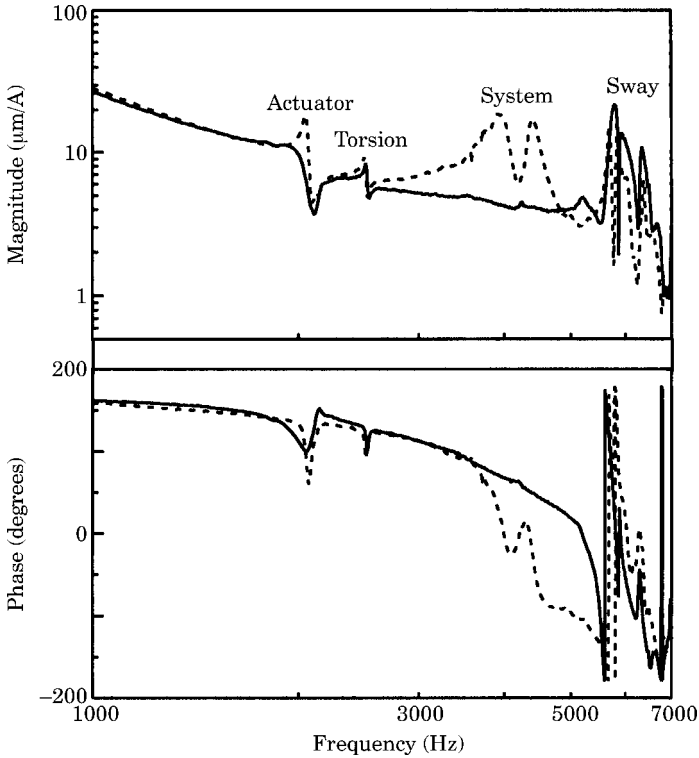


Figure 8. Improved tracking dynamics of the head actuator for the Seagate drive: —, with the damper; ---, without the damper.

operating conditions with and without the passive damper for the IBM hard drive. The ideal frequency response is also included for comparison. Since the ideal dynamics of the head actuator is that of a rigid body, the ideal frequency response is simply a straight line when plotted on a log-log scale. As shown in Figure 7, the predominant system mode is effectively damped by the passive damper. However, this passive damper is not effective for damping the sway mode.

Figure 8 shows the measured frequency responses of the radial slider displacement relative to the current input to the voice coil motor under the operating conditions with and without the passive damper for the Seagate hard drive. It is obvious that the actuator mode is effectively damped by the passive damper. The system mode is completely eliminated. As in the IBM hard drive, this passive damper is also not effective for damping the sway mode.

5. IMPROVED FLYING PERFORMANCE

The frequency response of the vertical slider displacement response relative to the current input to the voice coil motor was also measured under the operating conditions with and without the passive damper. The measured data shows that the vibration induced variation of the flying height can be significantly reduced by this proposed passive damper.

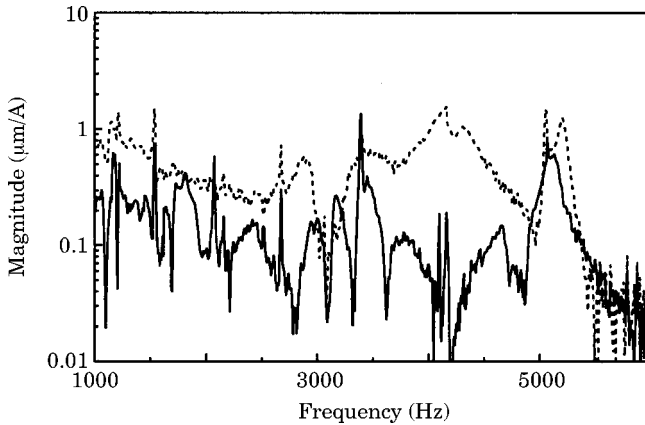


Figure 9. Comparison of the frequency response of the vertical slider displacement relative to the current input to the voice coil motor for the IBM hard drive. Key as for Figure 8.

Figure 9 shows a comparison of the frequency response of the vertical slider displacement under the operating conditions with and without the passive damper for the IBM hard drive. It can be seen that the vertical slider vibration is greatly reduced by the passive damper.

The comparison of the frequency response of the vertical slider displacement response for the Seagate hard drive is shown in Figure 10. For the Seagate hard drive, the suspension bending mode at 2.1 kHz is the primary source for the vertical slider vibration. The measured data show that the amplitude of the suspension bending mode is significantly reduced by the passive damper.

6. ANALYSIS OF THE DAMPING CONFIGURATION

In this section, an analysis of this proposed damping configuration for providing a better understanding of the damping mechanism and optimizing the damping treatment will be given.

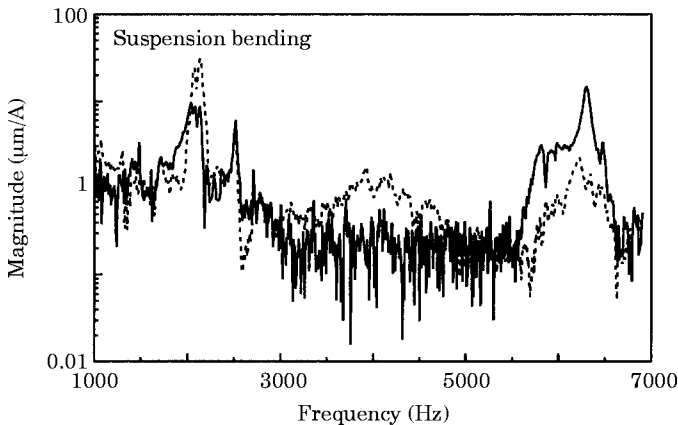


Figure 10. Comparison of the frequency response of the vertical slider displacement relative to the current input to the voice coil motor for the Seagate hard drive. Key as for Figure 8.

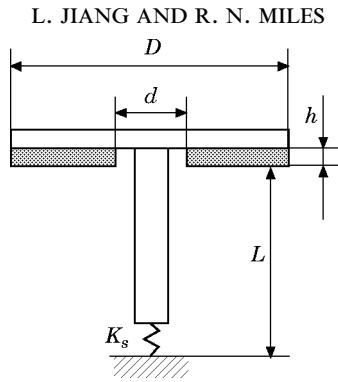


Figure 11. Analytical model of the proposed damping configuration.

Figure 11 shows an analytical model of the second damping configuration as shown in Figure 6. The torsional spring constant K_s simulates the rigidity of the actuator shaft, h is the thickness of the viscoelastic damping layer, d and D are the inner and outer diameter of the damping layer respectively and L is the length between the damping layer and the bottom of the actuator shaft.

The kinetic energy of the head actuator system is

$$T = \frac{1}{2}I(d\theta/dt)^2, \quad (1)$$

where I is the inertial moment of the head actuator, and θ is the rocking angle.

The potential energy due to the rocking of the actuator shaft is

$$V_1 = \frac{1}{2}K_s\theta^2. \quad (2)$$

The potential energy due to the viscoelastic damping layer is

$$V_2 = \frac{1}{2} \int \mathbf{G}^* \gamma^2 dv, \quad (3)$$

where \mathbf{G}^* is the complex modulus of the damping material, and γ is the shear strain. V_2 can be rewritten as

$$V_2 = \frac{1}{2}G^*h\pi \frac{(D^2 - d^2)}{4} \left(\frac{L\theta}{h}\right)^2 = \frac{G^*\pi(D^2 - d^2)}{8h} L^2\theta^2 = \frac{1}{2}\mathbf{K}_d^* L^2\theta^2, \quad (4)$$

where $\mathbf{K}_d^* = G^*\pi(D^2 - d^2)/4h = K_d(1 + i\beta)$ and β is the equivalent loss factor.

The total potential energy is then

$$V = V_1 + V_2 = \frac{1}{2}K_s\theta^2 + \frac{1}{2}\mathbf{K}_d^* L^2\theta^2. \quad (5)$$

According to Lagrange's equation, the governing equation of the system is

$$I d^2\theta/dt^2 + (K_s + \mathbf{K}_d^* L^2)\theta = 0. \quad (6)$$

The natural frequency of the system is

$$\omega_d^2 = (K_s + \mathbf{K}_d^* L^2)/I = \frac{K_s + K_d(1 + i\beta)L^2}{I} = \omega_0^2(1 + i\eta), \quad (7)$$

where η is the loss factor of the system,

$$\eta = K_d \beta L^2 / (K_s + K_d L^2). \quad (8)$$

From equation (8), it can be seen that in order to increase the damping of the system, the damper must contribute significantly to the total system stiffness.

7. CONCLUSIONS

A practical passive vibration damper has been developed that is very effective for damping the critical vibration modes of the head actuator. The experimental results from the application of the passive damper to both the IBM and Seagate hard drives are presented. It has been shown that this passive damper is very effective for damping both the actuator mode and the system mode of the head actuator. The tracking dynamics of the head actuator is therefore greatly improved. It is also shown that the vibration induced variation of the flying height can be significantly reduced by this passive damper. Another advantage of this proposed passive damper is that it is inexpensive to fabricate and very easy to incorporate into present hard disk drives.

ACKNOWLEDGMENT

This project was supported by the National Science Foundation of the U.S.A. under grant CMS-9523088.

REFERENCES

1. D. P. FAZZIO, M. A. MOSER, C. J. POLSON and J. N. SCHEFFEL 1993 *IBM Journal of Research and Development* **37**, 479–489. Head actuator dynamics of an IBM 5 1/4-inch disk drive.
2. L. S. FAN, H. H. OTTESEN, T. C. REILEY and R. W. WOOD 1995 *IEEE Transactions on Industrial Electronics* **42**, 222–233. Magnetic recording head positioning at very high track densities using a microactuator-based, two-stage servo system.
3. E. S. COOPER 1993 *Ph. D. Dissertation, Santa Clara University*. Minimum time control with minimum vibration and with power limiting, with application to the magnetic disk file.
4. R. HOROWITZ and J. MCCORMICK 1991 *IEEE Transactions on Magnetics* **27**, 4490–4495. A self-tuning control scheme for disk file servos.
5. T. H. LEE, T. S. LOW, A. AL-MAMUN and C. H. TAN 1995 *IEEE Transactions on Industrial Electronics* **42**, 248–256. Internal model control (IMC) approach for designing disk drive servo-controller.
6. M. LEWIS 1996 *U.S. Patent, No. 5,510,939*. Disk drive with adaptive positioning.
7. D. K. MIU and S. P. BHAT 1991 *ASME Advances in Information Storage Systems* **3**, 161–171. Residual vibrationless track accessing control for computer rigid disk drives using laplace transform technique.
8. S. WEERASOORIYA and T. PHAN 1995 *IEEE Transactions on Industrial Electronics* **42**, 240–247. Discrete-time LQG/LTR design and modeling of a disk drive actuator tracking servo system.
9. M. L. WORKMAN 1987 *Ph.D. Dissertation, Stanford University*. Adaptive proximate time-optimal servomechanisms.

10. T. YAMAGUCHI, K. SHISHIDA, H. HIRAI, K. TSUNETA and M. SATO 1992 *IEEE Transactions on Magnetics* **28**, 2910–2912. Improvement of servo robustness for digital sector servo system.
11. G. S. PAL and C. G. SNYDER 1988 *U.S. Patent No.* 4,760,478. Viscoelastically damped magnetic head suspension assembly.
12. D. HENZE, R. KARAM and A. JEANS 1990 *IEEE Transactions On Magnetics* **26**, 2439–2441. Effects of constrained layer damping on the dynamics of a type 4 in-line head suspension.
13. E. M. AUSTIN, J. C. GOODDING and W. A. DRISCOLL 1991. *Proceedings of Damping '91, Paper No. EDC*. Damping design for a disk drive head flexure.
14. J. D. STRICKLIN and J. B. BLANKS 1996 *U.S. Patent No.* 5,491,598. Rotary actuator vibration damper.
15. L. JIANG 1997 *Ph. D. Dissertation, State University of New York at Binghamton*. Improved servo performance of hard disk drives with a passive vibration damper.
16. T. A. HARRIS 1991 *Rolling Bearing Analysis*. New York: John Wiley; third Edition.