Reducing Vibrations in a Data Storage Device

The present invention relates to the reduction of mechanical vibrations in a data storage device (recording and/or reproducing device) such a magnetic disk drive. For example, it is applicable to reducing vibrations in a hard disk drive (HDD), and particularly to the reduction of such vibrations in the suspension and arm which support a read/write head of such a data storage device.

In data storage devices such as hard disk drives, suspensions are used to support read/write (recording/reproduction) heads over the recording media.

The head suspension plays a vital role which affects Hard Disc Interface (HDI) reliability and tribological properties. The mechanical resonance of the head suspension, which mainly involves first and second torsion modes and a sway mode, contributes to off-track errors and limits servo bandwidth. In order to reduce the effects of suspension vibrations and improve the servo bandwidth, some efforts have been made to improve the dynamic characteristics of the head actuator assembly. One method is to use a dual-stage actuator, shown, for example, in U.S. Pat. 6,157,522. This can provide additional flexibility in controlling the motion of the head actuator to compensate for the positioning error caused by the residual vibration. In such a system, the Voice Coil Motor (VCM) is used as the primary source of actuation and this provides coarse positioning. A micro-actuator in the dual-stage actuation is then utilised to provide micro-level fine tuning for head positioning. The use of a dual-stage actuator can sometimes compensate for suspension and arm vibrations, but it cannot reduce their vibrations effectively.

Another alternative is to use a viscoelastic damper, shown, for example, in U.S. Pat. 4,760,478. The viscoelastic material is sandwiched between the constrain layer and the suspension. However, this mechanical passive

damper cannot be tuned to effectively suppress the vibration in the suspension structure.

Mechanical systems incorporating piezoelectric materials have proven successful in civil, aeronautic and space structure applications for vibration control. Descriptions of such systems can be found in scientific and patent literature. However, the existing techniques have not been applied to a recording/reproducing apparatus such as a hard disk drive. Furthermore, most control methodologies using piezoelectric materials aim to control simple bending motions or vibrations. For the head suspension structure, however, it is desirable to control torsion and sway as they limit servo bandwidth and contribute to off-track errors. In addition, the head suspension is of a flexible structure in order to maintain stable HDI properties so the use of any sensor and actuator must not change this performance. Although conventional electrical resistance gauges are capable of measuring structural vibrations, see, for example, U.S. Pat. 5,862,015, the cost and effort involved to fit a resistance strain gauge to the surface of a structure, especially a flexible structure is high. In addition, the sensitivity of a resistance strain gauge is sometimes lower than that of the sensor proposed by the present invention..

The organic polymer, polyvinylidene fluoride (PVDF), exhibits a marked piezoelectric effect. In recent years, PVDF has been processed into thin films which are flexible and lightweight, and can be easily made in various sizes. It is thus suitable as a sensor and actuator for application in hard disk drives (HDD), especially small HDDs. The introduction of an active vibration control of the head suspension using a PVDF sensor and actuator is discussed in an article entitled "Active Actuation and Control of a Miniaturized Suspension Structure in Hard-Disk Drives Using A Polyvinylidene-Fluoride Actuator and Sensor" by Peng Gao et al (Measurement Science and Technology, Volume 11, No. 2,2000, p. 89-94). However, this control system requires complex

amplifiers and associated sensing and control electronics. It aims to control bending of the suspension in the vertical direction. In addition, stability problems are a drawback to the adoption of such a system. Passive piezoelectric damping can provide additional structural stability, however, this has some limitations such as either a small frequency bandwidth or limited effectiveness.

It is an object of the present invention to provide a new and useful method and apparatus for suppressing mechanical vibrations which at least mitigates the disadvantages of the systems described above.

According to a first aspect of the present invention, there is provided a method of reducing mechanical vibrations of a portion of a data storage device, the method comprising:

converting the vibrations of the portion of the data storage device into electrical signals,

feeding at least a component of the electrical signals into a dissipation circuit which dissipates the signals, and

feeding at least a component of the electrical signals into a control circuit which controls a mechanical actuator acting on the portion of the data storage device, the control circuit controlling the actuator using the electrical signals to control the movement of the portion of the data storage device to reduce the vibrations.

In certain embodiments of the first aspect of the invention the portion of the data storage device is the recording medium (disk) itself or a cover of the disk.

However, more preferably, the portion of the data storage device is the arm and/or suspension of an arm-suspension which supports a read/write head of the data storage device. Typically a data storage device having an arm-

suspension includes a mechanical actuator, such as a voice coil motor, for moving the read/write head of the data storage device over and parallel to the surface of a data storage medium to position it to read data from a selected portion of the data storage medium. In this case, the control circuit generates an adjustment signal which is fed to the actuator for reducing the mechanical vibrations of the arm-suspension. This concept provides a second, independent aspect of the invention.

Accordingly, a second aspect of the invention provides a method of reducing mechanical vibrations of an arm-suspension supporting a read/write head of a data storage device, the data storage device having a mechanical actuator for actuating the arm-suspension to position the read/write head in relation to a data storage medium, the method comprising:

converting the vibrations of the arm-suspension of the data storage device into electrical signals, and

feeding at least a component of the electrical signals into a control circuit which generates an adjustment signal and transmits the adjustment signal to the mechanical actuator, the actuator actuating the arm-suspension based on the adjustment signal to reduce the vibrations.

Thus, the second aspect of the invention permits control of lateral vibrations (i.e. parallel to the surface of the data storage medium). Since in a disk drive any vibration in the lateral direction limits the improvement of the servo-bandwidth and contributes to off-track errors, the invention makes it possible to improve the servo bandwidth of the head-actuator assembly including the suspension and the carriage arm.

Note that the sensed vibrations may be in either, or both, of the arm and the suspension.

In a third aspect the invention provides a data storage device comprising:

a data storage medium;

a read/write head for transferring data to/from the data storage medium;

one or more sensors located on a portion of the data storage device and for converting the vibrations of the portion of the data storage device into electrical signals,

a dissipation circuit arranged to receive at least a component of the electrical signals and dissipate the signals, and

a control circuit which is arranged to receive at least a component of the electrical signals and to control a mechanical actuator acting on the portion of the data storage device,

the control circuit being arranged to control the actuator based on the electrical signals to control the movement of the portion of the data storage device to reduce the vibrations.

Optionally, the passive damping performed by the dissipation circuit and the active damping performed by the control circuit may be based on signals generated by respective sets of one or more of the sensors. Alternatively, the outputs of the sensor(s) may be transmitted to both the dissipation circuit and the control circuit.

In a fourth aspect the invention provides a data storage device comprising:

a data storage medium;

an arm-suspension supporting a read/write head;

a mechanical actuator for actuating the arm-suspension to position the read/write head in relation to the data storage medium;

one or more sensors located on the arm-suspension and for converting vibrations of the data storage device into electrical signals; and

a control circuit which is arranged to receive at least a component of the electrical signals, to generate an adjustment signal, and to transmit the adjustment signal to the mechanical actuator,

the actuator being arranged to actuate the arm-suspension based on the electrical signals to reduce the vibrations.

The vibrations are suitably sensed by at least one polyvinylidene fluoride (PVDF) sensor which produces the electrical signals. In this regard, distributed PVDF sensors can sense complex mechanical vibration in the suspension. In the second aspect of the invention, the output signal of the PVDF sensors is fed into the Voice Coil Motor to (VCM) to damp suspension/arm vibrations, together with digital servo control signal for moving the head to the selected portion of the data storage medium. Also, the distributed PVDF sensors can transform vibration energy into electrical energy which is then dissipated through the external circuit that includes either a resistor or resistors, resistors/inductors or resistors/inductors/capacitors. The addition of controllers can decrease peak vibration amplitudes of the head suspension and improve its robustness.

According to a further aspect the present invention proposes a (miniature) suspension for a data storage device which comprises a silicon substrate, and a deposited vibration sensor for use as described above.

Some advantages of using a PVDF thin-film as a suspension vibration sensor are that it has a high sensitivity to strain, is very light in weight and offers great flexibility, and more importantly it has little or no effect on the properties of host structures. It can measure not only the bending motion but also the torsion and sway motions in the suspension structure. The use of a PVDF thin

film in the sensor of the present invention makes it possible to provide a strain sensor system that is easier, faster and less expensive as a means for measuring vibrations in the head suspension.

The present invention makes it possible that feedback control can be simple, and insensitive to mechanical variations.

Preferably, the configuration and parameters of the electronic components can be (or have been) changed and optimized to suppress the unwanted vibrations.

The present invention may be employed such that the PVDF based control method does not sacrifice the performance of the host structure.

The PVDF described in the present control system may be replaced by piezoelectric ceramics sensors, such as PZT, preferably a thin PZT bar or a plate.

Embodiments of the invention will now be particularly described with reference to the drawings in which :

Figure 1 is a perspective view of a head suspension having vibration modes which can be damped using the present invention,

Figure 2a is the suspension in Figure 1 moving in a cantilever vibration mode,

Figure 2b is the suspension in Figure 1 moving in a first torsion vibration mode,

Figure 2c is the suspension of Figure 1 moving in a second torsion vibration mode,

Figure 2d is the suspension of Figure 1 in a sway vibration mode,

Figure 3 is a plan view of a head suspension including the PVDF sensors in one position on the suspension,

Figure 4 is a plan view of a head suspension including a sensor in another position on the suspension,

Figure 5 is a sectional view of the head suspension integrated with a PVDF sensor,

Figure 6 is a sectional view of a smart silicon suspension structure,

Figure 7 is a block diagram of an active-passive damping system in accordance with the present invention with a piezoelectric layer which is formed from the output of the PVDF measuring signal to the input of the VCM,

Figure 8 is a block diagram of the active-passive damping system of a head suspension, and

Figure 9 is a second embodiment of the active-passive damping system of a head suspension.

Referring to the drawings, since it is likely that any occurrence of head slap or head-disc separation will cause damage, the shock load at which the head begins to move away from the disk is of particular interest. The critical situation for disk-head separation occurs when the deflection of the load beam at the tip due to the inertial force equals the static deflection. In other words, the cantilever action of a suspension appears in a shock-induced vibration process, whose dynamic characteristic should be dominated by the first resonance frequency of suspension. Thus, in order to effectively control a shock-induced vibration process, it is necessary to reduce the peak amplitude in this mode. It is known that the mechanical resonance in the suspension is the important factor affecting the accuracy of positioning and also in limiting servo bandwidth. Most commercially available suspensions have the first and

second torsion resonance in the range of 2-3 kHz and 5-8 Hz . Also, these suspensions exhibit a sway resonance between 8-13 kHz with a higher peak magnitude. The torsion and sway resonance contribute off-track errors and limit servo bandwidth.

Referring to Figure 1, a conventional head suspension 1 is shown. This includes a mounting region 2, a spring region 3, a relatively rigid region 4 and a flexure 5. The mounting region 2 has an aperture 6 to permit the suspension 1 to be mounted on an arm, which is itself on the shaft of a VCM (not shown). The flexure 5 supports a head slider (not shown) which flies on an air bearing created by a spinning magnetic disk (not shown), Figure 2a shows a cantilever vibration mode of the suspension 1, Figure 2b the first torsion vibration mode of the suspension 1 and Figure 2c shows the second torsion vibration mode of the suspension 1. In both the first and second torsion vibration modes the load beam of the head suspension 1 twists or rotates about a central longitudinally orientated material axis. Figure 2d shows the suspension 1 in the sway mode where the load beam bends about an axis that is perpendicular to the base of the load beam. Usually, the sway vibration mode exhibits a slight twisting motion as well.

With PVDF as the vibration sensor of the suspension, the location and orientation of the bonding on the suspension surface are chosen to maximize the sensitivity of the sensor. The position at which the PVDF thin-film is located on the suspension can be determined in accordance with the specific types of vibration modes which it is desired to monitor. Different resonance modes strain different sections of the head suspension. It is desirable to locate the PVDF sensor at a location with relatively high strain. Differing designs of the suspension assembly will have different locations at which the strain distribution is high. For any given design of suspension these locations can be determined for a given resonance mode by a finite element analysis. The finite element analysis can also indicate how the strain energy distribution

varies by orientation. The principal axes in the PVDF may be selected in accordance with an optimized orientation, so that not only bending motion but also torsion and sway motions can be measured effectively.

In Figure 3, a head suspension 1 is shown including a pair of spaced PVDF sensors 7 and 8 mounted on the spring region 3 of the suspension 1. The sensors 7 and 8 are in the form of thin-films which are bonded to the suspension 1 and with this orientation are capable of sensing the cantilever vibration mode of the suspension 1 effectively. They can also be used to sense either the first and second torsion vibration modes or the sway vibration mode.

In Figure 4, a head suspension 1 is shown having a pair of thin film PVDF sensors 9 and 10 are bonded to the relatively rigid region 4 and with an orientation such that they can sense both the torsion vibration mode and the sway vibration mode effectively.

Referring to Figure 5, the vibration sensor can either be a single patch PVDF thin-film 20 bonded to the suspension 1 by an adhesive layer 21 as shown in Figure 5(a) or a pair of PVDF thin films 22 and 23 which are each bonded with an adhesive layer 24 and 25 respectively on the opposite sides of the suspension 1 with different polarization directions as shown in Figure 5(b). The thin adhesive layer can be either conductive or non-conductive, depending on whether or not direct electrical connection between the PVDF sensor and the suspension is desired. A flexible and patterned cable including all leading wires of the sensors are preferable to reduce their effects on the dynamic behavior of the suspension structure.

Stainless steel is used for all present commercial head suspensions. However, as the suspension becomes thinner, steel tends to warp and buckle. A material that appears to show the most promise for future suspension designs is silicon. In this regard, it is possible to use MEMS techniques to

directly deposit piezoelectric materials onto a silicon suspension substrate and thereby to form a smart head suspension structure.

FIG 6 is an illustration of a sectional view of a smart silicon suspension structure showing the suspension 30 surmounted by a lower electrode 31, a piezo material (e.g. PZT or PVDF) layer 32 surmounting the electrode 31 and above the layer 32 an upper electrode 33.

FIG.7 is an illustration of a block diagram of the control system of the arm-suspension-slider assembly, incorporating the active-passive damping system described here which employs the output of the PVDF measurement signal to the input of the VCM. Thus, this control system constitutes a high performance vibration controller that uses a combination of an active feedback control and a passive energy dissipation element to suppress suspension vibrations at different frequencies.

In FIG. 7, the arm/suspension/slider assembly is indicated generally as 41. Any error in the position of the head is sensed, as is conventional, as a position error signal (PES). This is fed back to a conventional head positioning controller 40. At the same time the PVDF sensors (not shown) incorporated in the arm/suspension/slider assembly 41 sense any mechanical vibrations and output an electrical signal representative of the vibrations. This signal is into the active-passive control circuit 42. The active-passive control circuit 42 splits the signal from the PVDF sensors into a passive part which is dissipated as heat energy and into an active part. The active part is combined with the signal output by the conventional head-positioning controller 40, and input to the conventional VCM driver 44, which controls the conventional VCM 45. The contribution of the active-passive hybrid control circuit acts to reduce, or even eliminate, the vibrations in the arm/suspension/slider. Thus, the present invention is proposing an additional active-passive control loop, consisting of the known VCM driver 44, the known VCM 45, the

arm/suspension/slider assembly 41 itself and the novel active-passive hybrid control circuit.

Figure 8 is one embodiment of a schematic form of the active-passive damping system shown in Figure 7.

The PVDF sensor 20 when used in the passive mode in effect equates to a capacitor. The control circuit 42 includes a passive and active analog circuit 51 and 52 connected in series with the PVDF sensor 20, the location and orientation of the sensor 20 in this case being as shown in FIG. 4. The passive analog circuit 51 may include an inductor (not shown) for frequency control, connected in series with a dissipation element resistor (not shown). It may also include a plurality of energy dissipation resistor elements, and/or a plurality of frequency tuning inductor elements which can be connected in series or parallel with the dissipation element resistor(s). Such a configuration can be used to reduce the multi-mode vibration by transforming mechanical energy into electrical energy, and then dissipating it through resistors. The optimization of circuit configuration and of the parameters of the electronic components is not a part of the present invention, but will be clear to a skilled reader.

It is known that the design of an active controller alone to effectively suppress multi-mode vibrations is not a trivial task. Moreover, the stability of the system has to be considered. The passive controller described herein aims to enhance the stability and robustness of the system and increase the damping of vibrations. The present active-passive control circuit helps to suppress both the first and second torsion vibration modes and the sway vibration mode, which limit servo bandwidth and contribute off-track errors. Usually, an active controller can suppress some vibration modes more effectively than the other modes. Optionally, by tuning its frequency-selective components, the

passive controller can provide damping of the vibrations for which the active controller is not on its own sufficiently effective.

In addition, because the active-passive control circuit performs some passive control, its active control can be performed by a simple control algorithm, which reduces the complexity and potential instability of the active control system.

FIG. 9 is a second embodiment of the active-passive damping system of a head suspension. The passive control circuit 51 is connected to the PVDF sensors 20, whose location and orientation are as shown in FIG. 3, and the active control circuit 52 is connected to the PVDF sensors 20, whose location and orientation are as shown in FIG.4. The passive controller 51 can dissipate vibration energy, suppress the bending motion of a head suspension, and enhance the damping on the torsion and sway motions, which are simultaneously suppressed by the active controller.

The present invention thus makes it possible to suppress the vibration in HDDs, especially first and second torsion vibration modes and sway vibration mode, which contribute to off-track errors and limit servo bandwidth.

The present invention thus also makes it possible to reduce possible damage to both the surface of the disk and the read/write head caused by the CSS process.

The present invention also makes it possible to alleviate the shock or track-seeking operation induced vibrations in the suspension.

The present invention also makes it possible to develop a MEMS-based smart and miniature suspension structure for near future data storage devices.

Although the present invention aims to suppress the vibration of a head suspension, the configuration and control strategy may also be applied in the

reduction of vibration in the carriage arm of HDDs, including the voice coil motor and its supporting pivot assembly. In this regard, the PVDF or PZT sensor may be bonded on the high strain zone of the carriage arm, and the same control strategy as described above may be adopted to reduce the vibration of the carriage arm.

Although the invention has been described above in relation to reducing the vibrations of a suspension, another application of the invention is reducing in the vibration of the disk cover caused by internal excitation forces. Still, another application of the invention is the reduction of the vibration of a rotating disk itself. In these two applications, the PVDF or PZT sensor may be attached to the cover or disk of the device respectively, and the passive control method as described above may be adopted to reduce the vibrations.

Claims

1. A method of reducing mechanical vibrations of a portion of a data storage device, the method comprising:

converting the vibrations of the portion of the data storage device into electrical signals,

feeding at least a component of the electrical signals into a dissipation circuit which dissipates the signals, and

feeding at least a component of the electrical signals into a control circuit which controls a mechanical actuator acting on the portion of the data storage device, the control circuit controlling the actuator using the electrical signals to control the movement of the portion of the data storage device to reduce the vibrations.

2. A method according to claim 1 in which the portion of the data storage device is an arm-suspension which supports a read/write head of the data storage device, the mechanical actuator being arranged to further actuate the arm-suspension to move the read/write head of the data storage device parallel to the surface of a data storage medium to position the read/write head for transferring data to/from a selected portion of the data storage medium.

3. A method of reducing mechanical vibrations of an arm-suspension supporting a read/write head of a data storage device, the data storage device having a mechanical actuator for actuating the arm-suspension to selectively position the read/write head in relation to a data storage medium for transferring data read/write data to/from a selected portion of the data storage medium, the method comprising:

converting the vibrations of the arm-suspension of the data storage device into electrical signals, and

feeding at least a component of the electrical signals into a control circuit which generates an adjustment signal and transmits the adjustment signal to the mechanical actuator, the actuator actuating the arm-suspension based on the adjustment signal to reduce the vibrations.

4. A method according to claim 2 or claim 3 in which the vibrations are vibrations of the suspension.

5. A method according to claim 2 or claim 3 in which the vibrations are vibrations of the arm.

6. A method according to any of claims 3 to 5 further comprising feeding at least a component of the electrical signals into a dissipation circuit which dissipates the signals.

7. A method according to claim 1, claim 2 or claim 6 in which the dissipation circuit contains one or more resistive elements which dissipate the signals as heat energy.

8. A method according to claim 1, claim 2 or claim 6 in which the dissipation circuit contains one or more inductive elements for modifying the frequency-dependent performance of the dissipation circuit.

9. A method according to claim 2 or claim 3 in which the actuator is a voice coil motor.

10. A method according to any preceding claim in which the vibrations are sensed by a sensor comprising a piezoelectric material which produces the electrical signals.

11. A method according to claim 10 in which the piezoelectric material is either polyvinylidene fluoride (PVDF) or $Pb(Ti,Zr)O_3$ (PZT).

12. A data storage device comprising:

a data storage medium;

a read/write head for transferring data to/from the medium;

one or more sensors located on a portion of the data storage device and for converting the vibrations of the portion of the data storage device into electrical signals,

a dissipation circuit arranged to receive at least a component of the electrical signals and dissipate the signals, and

a control circuit which is arranged to receive at least a component of the electrical signals and to control a mechanical actuator acting on the portion of the data storage device,

the control circuit being arranged to control the actuator based on the electrical signals to control the movement of the portion of the data storage device to reduce the vibrations.

13. A data storage device according to claim 12 in which the portion of the data storage device is an arm-suspension which supports the read/write head, the mechanical actuator being arranged to further actuate the arm-suspension to move the read/write head of the data storage device parallel to the surface of the data storage medium to position the read/write head for transferring data to/from a selected portion of the data storage medium.

14. A data storage device comprising:

a data storage medium;

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an arm-suspension supporting a read/write head;

a mechanical actuator for actuating the arm-suspension to position the read/write head in relation to the data storage medium for transferring data read/write data to/from a selected portion of the data storage medium;

one or more sensors located on the arm-suspension and for converting vibrations of the data storage device into electrical signals; and

a control circuit which is arranged to receive at least a component of the electrical signals, to generate an adjustment signal, and to transmit the adjustment signal to the mechanical actuator,

the actuator being arranged to actuate the arm-suspension based on the electrical signals to reduce the vibrations.

15. A data storage device according to claim 14 in which at least one of the sensors is sensitive to vibrations of the suspension.

16. A data storage device according to claim 14 in which at least one of the sensors is sensitive to vibrations of the arm.

17. A data storage device according to any of claims 14 to 15 further including a dissipation circuit arranged to receive and to dissipate at least a component of the electrical signals.

18. A data storage device according to claim 12 or claim 17 in which the dissipation circuit contains one or more resistive elements for dissipating the signals as heat energy.

19. A data storage device according to claim 12, claim 17 or claim 18 in which the dissipation circuit contains one or more inductive elements for modifying the frequency-dependent performance of the dissipation circuit.

20. A data storage device according to claim 13 or 14, in which the actuator is a voice coil motor for controlling the movement of the portion of suspension.

21. A data storage device according to any of claims 12 to 20 in which the sensors comprise a piezoelectric material which produces the electrical signals.

22. A data storage device according to claim 21 in which the piezoelectric material is either polyvinylidene fluoride (PVDF) or $Pb(Ti,Zr)O_3$ (PZT) .

23. A data storage device according to claim 13 or claim 14 in which the suspension includes a member formed of silicon.

24. A data storage device according to claim 12 in which the portion of the data storage device is the data storage medium.

25. A data storage device according to claim 24 in which the sensor(s) are attached to the data storage medium.

26. A data storage device according to claim 12 in which the data storage medium is a disk, and the portion of the data storage device is a cover the disk.

27. A data storage device according to claim 26 in which the sensor(s) are incorporated in the cover.

28. A data storage device according to any of claims 12 to 27 which is a hard disk drive.