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DUAL COIL ROTARY ACTUATOR

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates generally to computer hard disk drives and, more particularly, to improvements to the rotary actuator of hard disk drives for better dynamic performance.

2. Description of Related Art

Moving magnetic storage devices, especially magnetic disk drives, are the memory devices of choice. This is due to their expanded non-volatile memory storage capability combined with a relatively low cost.

Magnetic disk drives are information storage devices which utilize at least one rotatable magnetic media disk having concentric data tracks defined for storing data, a magnetic recording head or transducer for reading data from and/or writing data to the various data tracks, a slider for supporting the transducer in proximity to the data tracks typically in a flying mode above the storage media, a suspension assembly for resiliently supporting the slider and the transducer over the

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data tracks, and a positioning actuator coupled to the transducer/slider/suspension combination for moving the transducer across the media to the desired data track and maintaining the transducer over the data track center line during a read or a write operation. The transducer is attached to or is formed integrally with the slider which supports the transducer above the data surface of the storage disk by a cushion of air, referred to as an air-bearing, generated by the rotating disk.

Alternatively, the transducer may operate in contact with the surface of the disk. Thus the suspension provides desired slider loading and dimensional stability between the slider and an actuator positioner arm which couples the transducer/slider/suspension assembly to the actuator. The actuator positions the transducer over the correct track according to the data desired on a read operation or to the correct track for placement of the data during a write operation. The actuator is controlled to position the transducer over the desired data track by shifting the combination assembly across the surface of the disk in a direction generally transverse to the data tracks. The actuator may include a single positioner arm extending from a pivot point, or alternatively, a plurality of positioner arms arranged in a comb-like fashion extending from

a pivot point. A rotary voice coil motor (VCM) is attached to the rear portion of the actuator assembly to power movement of the actuator over the disks.

The VCM located at the rear portion of the actuator assembly is comprised of a top plate spaced above a bottom plate with a magnet or pair of magnets therebetween. The VCM further includes an electrically conductive coil disposed within the rearward extension of the actuator assembly and between the top and bottom plates, while overlying the magnet in a plane parallel to the magnet. In operation, current passes through the coil and interacts with the magnetic field of the magnet so as to rotate the actuator assembly around its pivot and thus positioning the transducer as desired.

The magnetic media disk or disks in the disk drive are mounted to a spindle. The spindle is attached to a spindle motor which rotates the spindle and the disks to provide read/write access to the various portions on the concentric tracks on the disks.

During operation of the disk drive, the actuator, driven by the VCM, is positioned radially over the disk surface under the control of a positioning servo system. The servo system is designed to accurately position the read/write transducer over a

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selected data track on the disk in as short a time as possible (seek operation) and to maintain the read/write transducer position over the data track as accurately as possible (track operation). As data storage density of disk drives is increased, the radial density of data tracks on the disk is increased. The ability of the servo system to accurately track on the resulting narrower data tracks becomes a limitation on the disk drive performance.

Actuator assemblies have resonant frequencies that can adversely affect the performance of the servo system. The resonances having the lowest frequencies severely limit the bandwidth of the servo system resulting in poor high frequency response and degraded disk drive performance.

SUMMARY OF THE INVENTION

It is an object of the present invention to ameliorate one or more disadvantages of the prior art.

According to one aspect of the present invention there is provided a magnetic storage system, comprising: a disk with a concentric data surface of data tracks; a spindle shaft supporting said disk, said spindle shaft for rotating said disk about an axis generally perpendicular to the disk; a slider maintained in operative relationship with the data surface when the disk is rotating; a transducer attached to the slider for reading data from and writing data to the data surface; an electronic module for processing data read from and written to the data surface; a first and second current supply for providing electrical power; and an actuator for moving the slider generally radially relative to the disk to allow the transducer to access the data tracks, the actuator further comprising a body defining the actuator pivot point; a first coil support arm extending from the body; a second coil support arm extending from the body, said first and second coil support arms forming an angular sector therebetween; an outer actuator coil connected to the first current supply and affixed to the first and second coil support arms in the angular sector between said first and second coil support arms; and an inner actuator coil connected to the second current supply and affixed to the outer actuator coil, said inner actuator coil lying inside and in the same plane as said outer actuator coil.

According to another aspect of the present invention there is provided a magnetic storage system, comprising: a disk with a concentric data surface of data tracks; a spindle shaft supporting said disk, said spindle shaft for rotating said disk about an axis generally perpendicular to the disk; a slider maintained in operative relationship with the data surface when the disk is rotating; a transducer attached to the slider for reading data from and

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writing data to the data surface; an electronics module for processing data read from and written to the data surface; a first and second current supply for providing electrical power; and an actuator for moving the slider generally radially relative to the disk to allow the transducer to access the data tracks, the actuator further comprising a body defining the actuator pivot point; a first coil support arm having a proximal end extending from the body to a distal end; a second coil support arm having a proximal end extending from the body to a distal end, said first and second coil support arms forming an angular sector therebetween; a front actuator coil connected to the first current supply and affixed to the first and second coil support arms in the angular sector between the proximal ends of said first and second coil support arms; and, a back actuator coil connected to the second current supply and affixed to the first and second coil support arms in the angular sector between the distal ends of said first and second coil support arms, said back actuator coil lying in the same plane as said front actuator coil.

According to still another aspect of the present invention there is provided a method of operating an actuator having concentric dual coils to move a transducer to a data track on a disk surface, which comprises the steps of: a) supplying an outer current and inner current having the same clockwise or counterclockwise sense to the outer coil and to the inner coil of the actuator respectively, to rapidly move the transducer to the proximity of the data track; and b) supplying the inner current having one sense to the inner coil and supplying the outer current having the opposite sense to the outer coil to accurately position the transducer over the data track and to maintain the position of the transducer over the data track.

According to still another aspect of the present invention there is provided a method of operating an actuator having front-and-rear dual coils to move a transducer to a

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data track on a disk surface, which comprises the steps of: supplying a front current and rear current having the same clockwise or counterclockwise sense to the front coil and to the back coil of the actuator respectively to rapidly move the transducer to the proximity of the data track; and supplying the front current having one sense to the front coil and supplying the rear current having the opposite sense to the rear coil to accurately position the transducer over the data track and to maintain the position of the transducer over the data track.

In accordance with the principles of the present invention, there is disclosed an actuator assembly for magnetic storage disk drives comprising dual actuator coils disposed within the rearward extensions of the actuator assembly. In one embodiment of the present invention, an outer coil and a concentric inner coil fixed to the rearward extensions of the actuator assembly lie in the plane in which the actuator is free to rotate when mounted in a disk drive. Both the outer coil and the inner coil are disposed between the magnetic poles of a voice coil motor

(VCM) magnet. The outer coil and the inner coil are electrically connected to a first current supply and a second current supply, respectively, where the current magnitude and sense of current flow of each current supply is individually controlled by the disk Drive controller electronics. During settling and tracking operations of the disk Drive, the current flow in the inner coil has the opposite sense (clockwise or counterclockwise) to the current flow in the outer coil, resulting in a net force on the actuator to position the slider/transducer on the desired data track with improved accuracy. The improved accuracy is obtained by adjusting the relative current flow in each coil so as to suppress excitation of the principal in-plane bending (sway) mode of the actuator allowing the use of an increased servo bandwidth for settling and tracking operations. During seek operations of the disk drive, where maximum torque on the actuator is desirable to rapidly locate the slider/transducer over a new track, the coil currents in the outer coil and the inner coil are chosen to have the same sense so that the forces on the actuator from the two coils are additive.

One advantage of the present invention is that it provides an actuator assembly having improved performance and stability. An additional advantage of the present invention is that the

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existing VCM magnet and plates can be used, thereby providing a simple and cost effective solution.

The above, as well as additional objects, features, and advantages of the present invention will become apparent in the following detailed written description.

BRIEF DESCRIPTION OF THE DRAWINGS

For a fuller understanding of the nature and advantages of the present invention, as well as the preferred mode of use, reference should be made to the following detailed description read in conjunction with the accompanying drawings. In the following drawings, like reference numerals designate like or similar parts throughout the drawings.

Fig. **1** is a simplified drawing of a magnetic recording disk drive system;

Fig. **2** is a perspective view of a disk drive;

Fig. **3** is a perspective view of a rotary actuator according to the present invention;

Figs. **4a** and **4b** are plan views of an actuator including concentric dual coils of a first embodiment of the present invention; Fig. **4c** is a cross-section view of the VCM magnet showing the concentric dual coils in the VCM magnet gap;

Figs. **5a** and **5b** are plan views of an actuator including front-and-back dual coils of a second embodiment of the present invention;

Fig. **6a** is a plan view of an actuator including the concentric outer and inner dual coils of the present invention

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showing the mode shape (not to scale) of a principal in-plane bending (sway) mode resonance;

Fig. **6b** is a plan view of an actuator including the front-and-back dual coils of the present invention showing the mode shape (not to scale) of a principal in-plane bending mode (sway) mode resonance;

Fig. **7** is graph illustrating a transfer function obtained from a finite element simulation of the response of a concentric dual coil actuator to current in the outer coil only;

Fig. **8** is a graph illustrating a transfer function obtained from a finite element simulation of the response of a concentric dual coil actuator to current in the inner and outer coils;

Fig. **9** is a graph illustrating a transfer function obtained from a finite element simulation of the response of a front-and-back dual coil actuator to current in the front coil only;

Fig. **10** is a graph illustrating transfer function obtained from a finite element simulation of the response of a front-and-back dual coil actuator to current in the front and back coils;

Fig. **11** is a schematic block diagram of an experiment to measure the transfer function for a dual coil actuator of the present invention;

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Fig. **12** is the measured transfer function for the response of a front-and-back dual coil actuator to current in the back coil only;

Fig. **13** is the measured transfer function for the response of a front-and-back dual coil actuator to current in the front coil only; and

Fig. **14** is the measured transfer function for the response of a front-and-back dual coil actuator to current in the front and back coils.

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DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

This invention is described in a preferred embodiment in the following description with reference to the Figures. While this invention is described in terms of the best mode for achieving this invention's objectives, it will be appreciated by those skilled in the art that variations may be accomplished in view of these teachings without deviating from the spirit or scope of the invention.

Referring now to Fig. **1**, there is shown a disk drive **20** embodying the present invention. As shown in Fig. **1**, at least one rotatable magnetic disk **22** is supported on a spindle **26** and rotated by a disk drive motor **30**. The magnetic recording media on each disk is in the form of an annular pattern of concentric data tracks (not shown) on the disk **22**.

At least one slider **24** is positioned on the disk **22**, each slider **24** supporting one or more magnetic read/write heads **34**. As the disks rotate, the slider **24** is moved radially in and out over the disk surface **36** so that the heads **34** may access different portions of the disk where desired data is recorded. Each slider **24** is attached to a positioner arm **32** by means of a suspension **28**. The suspension **28** provides a slight spring force which biases the slider **24** against the disk surface **36**. Each

positioner arm **32** is attached to an actuator **42** means. The actuator means as shown in Fig. **1** may be a voice coil motor (VCM). The VCM comprises a coil movable within a fixed magnetic field, the direction and speed of the coil movements being controlled by the motor current signals supplied by the control unit **46**.

During operation of the disk storage system, the rotation of the disk **22** generates an air bearing between the slider **24** and the disk surface **36** which exerts an upward force or lift on the slider. The air bearing thus counter-balances the slight spring force of the suspension **28** and supports the slider **24** off and slightly above the disk surface by a small, substantially constant spacing during normal operation.

The various components of the disk storage system are controlled in operation by control signals generated by a control unit **46**, such as access control signals and internal clock signals. Typically, the control unit **46** comprises logic control circuits, storage chips and a microprocessor. The control unit **46** generates control signals to control various system operations such as drive motor control signals on line **38** and head position and seek control signals on line **44**. The control signals on line **44** provide the desired current profiles to optimally move and

position the slider **24** to the desired data track on the disk **22**. Read and write signals are communicated to and from the read/write heads **34** by means of a recording channel **40**.

The above description of a typical magnetic disk storage system, and the accompanying illustration of Fig. **1** are for representation purposes only. It should be apparent that disk storage systems may contain a large number of disks and actuators, and each actuator may support a number of sliders.

Fig. **2** shows a hard disk drive **50** using the dual coil actuator of the present invention. The lid **54** of the disk drive is shown exploded. In operation, the lid would be disposed on top of the housing **52**. The disk drive **50** comprises one or more magnetic disks **56**. The disks may be conventional particulate or thin film recording disks, which are capable of storing digital data in concentric tracks. In a preferred embodiment, both sides of the disks **56** are available for storage, and it will be recognized by one of ordinary skill in the art that the disk drive **50** may include any number of such disks **56**.

The disks **56** are mounted to a spindle **58**. The spindle **58** is attached to a spindle motor (not shown) which rotates the spindle **58** and the disks **56** to provide read/write access to the various portions of the concentric tracks on the disks 56.

An actuator assembly **76** includes a positioner arm **60**, and a suspension assembly **62**. The suspension assembly **62** includes a slider/transducer assembly **64** at its distal end. Although only one slider/transducer assembly **64** of the suspension assembly **62** is shown, it will be recognized that the disk drive **50** has one slider/transducer assembly **64** for each side of each disk **56** included in the disk drive **50**. The positioner arm **60** further comprises a pivot **72** around which the positioner arm **60** pivots.

The disk drive **50** further includes a read/write chip **80**. As is well known in the art, the read/write chip **80** cooperates with the slider transducer assembly **64** to read data from or write data to the disks **56**. A flexible printed circuit member or actuator flex cable **78** carries signals between the read/write chip **80** and a connector pin assembly (not shown) which interfaces with the external signal processing electronics.

The main function of the actuator assembly **76** is to move the positioner arm **60** around the pivot **72**. Part of the actuator assembly **76** is the voice coil motor (VCM) assembly **74** which comprises a VCM bottom plate, a magnet and a VCM top plate in combination with a dual actuator coil. Current passing through the actuator coil interacts with the magnetic field of the magnet to rotate the positioner arm **60** and suspension assembly **62** around

the pivot **72**, thus positioning the slider/transducer assembly **64** as desired.

Most disk drives **50** have a number of disks **56** mounted on the spindle **58** to form a disk stack **70**. The actuator assembly **76** comprises a plurality of positioner arms **60** fixed in a comb-like arrangement such that the inner arms **65** fit between the disks **56** forming disk stack **70** and the outer arms **66, 68** extend over the top surface of the top disk and the bottom surface of the bottom disk, respectively. The inner arms **65** each support two suspension assemblies **62** (upper and lower suspension assemblies) with attached slider/transducer assemblies **64**. The upper outer arm **66** supports one suspension assembly **62** with its slider/transducer assembly **64** to access data on the top surface of the top disk of disk stack **70**. The lower outer arm **68** supports one suspension assembly **62** with its slider/transducer assembly **64** to access data on the bottom surface of the bottom disk of disk stack **70**.

Fig. **3** is a perspective view of an actuator assembly **90** according to an embodiment of the present invention. The actuator assembly **90** comprises a body **92**, a lower outer arm **68**, an upper outer arm **66**, one or more inner arms **65**, actuator coil supporting arms **94, 96** and concentric dual actuator coils **98**

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fixed to the actuator coil supporting arms **94, 96**. The body **92** is supported by bearings (not shown) which allow the actuator assembly **90** to rotate about a vertical axis when the actuator assembly **90** is mounted in a disk Drive. The body **92** supports positioner arms **65, 66, 68** which in turn support the suspension assemblies (not shown) on which slider/transducer assemblies (not shown) are fixed. The actuator coil support arms **94, 96** support the actuator coils **98** which are part of the VCM assembly which works to position the actuator assembly radially with respect to the disk surfaces.

When installed in a disk drive, the actuator assembly **90** with suspension assemblies fixed on the positioner arms **65, 66, 68** is rotated by the VCM motor to position the slider/transducer assemblies at the desired disk radius to read or write data on a data track on the recording media coating the disk surface. The forces applied to the actuator assembly **90** by the VCM motor can excite mechanical resonances of the actuator assembly. Resonances of the actuator assembly **90** in the plane of the radial motion of the actuator assembly **90** are of particular concern since they directly affect the dynamic performance of the actuator in positioning the slider/transducer assemblies over the desired data track.

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Figs. **4a** and **4b** show plan views of a dual coil actuator assembly **100** according to a first embodiment of the present invention. The actuator assembly **100** comprises a body **92**, actuator coil support arms **94** and **96** fixed to the body and extending rearward from the body **92**, an outer actuator coil **102** located between and fixed to the actuator support arms **94** and **96**, and an inner actuator coil **104** located inside the outer actuator coil **102** in a generally concentric arrangement. The inner coil **104** is fixed to the outer coil **102** with both coils lying in the plane defined by the actuator support arms **94** and **96**. The outer coil **102** is formed of a number **n** turns of wire which go around the sides of the generally trapezoidal plan of the coil and have starting and ending locations (not shown) near to one another. The inner coil **104** is formed of a number **m** turns of wire which go around the sides of the generally trapezoidal plan of the coil and have starting and ending locations (not shown) near to one another. In the preferred embodiment of the present invention the number **n** of turns of the outer coil **102** are equal to the number **m** of turns of the inner coil **104**. Alternatively, the number of turns **n** and **m** may be chosen to be different. Electrical connections (not shown) to the ends of the outer coil **102** and to the ends of the inner coil **104** enable the coils to

carry currents thereby generating magnetic fields which interact with the magnetic field of the VCM magnet **106** shown in the cross-sectional view of Fig. **4c**.

Fig. **4c** shows a cross-sectional view of the VCM magnet **106**. The VCM magnet **106** is formed to have a first zone **107** and a second zone **108**, wherein the direction of the magnetic field in the first zone **107** is opposite in direction to the magnetic field in the second zone **108**.

Referring again to Fig. **4a**, the directions of current flow in the outer and inner coils **102** and **104** are shown for a seek operation of the disk drive where maximum torque on the actuator **100** is desired in order to position the slider/transducer assembly **64** on a new track as rapidly as possible. For the seek operation, the current flow is in the same direction, in either a clockwise or an counterclockwise sense, in both the outer coil **102** and the inner coil **104**. The magnetic fields generated by the currents in each coil interact with the magnetic field of the VCM magnet **106** to produce forces that add together to produce a large resultant torque on the actuator. In the seeking operational mode, the dynamic response of the dual coil actuator is similar to the response of a prior art single coil actuator.

Fig. **4b** shows the directions of current flow in the outer and inner coils **102** and **104** for settling and tracking operations of the disk drive where large torques are not needed but improved dynamic response of the actuator is needed to provide precise tracking performance. For the settling and tracking operations, the current flow in the outer coil **102** has the opposite sense to the current flow in the inner coil **104**. The excitation of the sway mode by forces generated from each coil due to interaction with the VCM magnet **106** tend to cancel. However, the net torque on the actuator is non-zero which drives the actuator for the settling and tracking mode of operation. In the settling and tracking mode of operation, the dynamic response of the actuator is improved over the single coil actuator response due to reduced excitation of a resonance of the principal in-plane bending mode (sway mode) of the actuator. By a suitable choice of the ratio, I_O/I_I, of the magnitude of the current I_O flowing in the outer coil **102** to the magnitude of the current I_I flowing in the inner coil **104**, the sway mode resonance may be completely suppressed for the best dynamic response of the actuator according to the present invention.

Figs. **5a** and **5b** show plan views of a dual coil actuator assembly **110** according to a second embodiment of the present

invention. The actuator assembly **110** comprises a body **92**, actuator coil support arms **94** and **96** fixed to the body and extending rearward from the body **92**, a back coil **112** located between and fixed to the actuator support arms **94** and **96** at the distal ends of the support arms, and a front coil **114** located between the actuator support arms **94** and **96** and disposed between the back coil **112** and the actuator body **92**. The front coil **114** is fixed to actuator support arms **94** and **96** and to the contiguous segment of the back coil **112**. Both coils lie in the plane defined by the actuator support arms **94** and **96**. The back coil **112** is formed of a number **n** turns of wire which go around the sides of the generally trapezoidal plan of the coil and have starting and ending locations (not shown) near to one another. The front coil **114** is formed of a number **m** turns of wire which go around the sides of the generally trapezoidal plan of the coil and have starting and ending locations (not shown) near to one another. In this embodiment of the present invention the number **n** of turns of the back coil **112** are equal to the number **m** of turns of the front coil **114**. Alternatively, the number of turns **n** and **m** may be chosen to be different. Electrical connections (not shown) to the ends of the back coil **112** and to the ends of the front coil **114** enable the coils to carry currents thereby

generating magnetic fields which interact with the magnetic field of the VCM magnet **106**.

Figs. **5a** and **5b** show the directions of current flow in the coils for seeking and settling/tracking operations, respectively. In the seeking operation shown in Fig. **5a**, the directions of current flow in the back coil **112** and the front coil **114** have the same sense, that is currents in both coils are either clockwise or counterclockwise depending on the direction of actuator rotation desired. The torques acting on the actuator due to the currents flowing in the coil segments parallel to the actuator support arms are additive resulting in the maximum net torque to rapidly position the slider/transducer on a new track. In the settling/tracking mode of operation shown in Fig. **5b**, the direction of current flow in the back coil **112** has the opposite sense to the direction of current flow in the front coil **114**. The excitation of the sway mode of the actuator by forces generated from each coil due to interaction with the magnetic field from the VCM magnet **106** tend to cancel. However, the net torque on the actuator is non-zero which drives the actuator in the settling and tracking mode of operation. In the settling and tracking mode of operation, the dynamic response of the actuator is improved over the single coil actuator response due to reduced

excitation of a resonance of the principal in-plane bending mode (sway mode) of the actuator. Complete suppression of the sway mode resonance is achieved by suitable adjustment of the ratio, I_B/I_F, of the magnitude of the current I_B flowing in the back coil **112** to the magnitude of the current I_F flowing in the front coil **114**.

Figs. **6a** and **6b** show the mode shape (not to scale) due to excitation of the sway mode obtained for the concentric dual coil actuator **100** and the front-and-back dual coil actuator **110**, respectively, by finite element simulation methods known to the art. In both Figs. **6a** and **6b**, the undistorted actuator **120** is shown with the distorted actuator **122** for the simulation of the excited sway mode superimposed. For the finite element simulations of both actuators **100** and **110**, the input force on the actuators was calculated for current flow in only one of the dual coils in each actuator in order to simulate the response of a single coil actuator as used in the prior art. The sway mode resonance excited in this way degrades the dynamic performance of the disk drive and should be suppressed to improve the settling and tracking operations of the disk drive.

Figs. **7** and **8** show the mechanical transfer functions obtained from finite element simulations of the response of the

concentric dual coil actuator **100** to actuator coil current generated forces. The transfer functions are graphs showing the vibration displacement amplitude and phase response at the slider/transducer as a function of frequency to VCM input forces applied to the actuator assembly in the plane of actuator rotation. Fig. **7** shows the transfer function obtained for coil current flowing only in the outer coil **102** to simulate single coil actuator conditions. The large amplitude peak **126** at approximately 3000 Hz corresponds to the sway mode resonance of the actuator shown in Fig. **6a**. Fig. **8** shows the transfer function obtained for current flow in both the outer coil **102** and the inner coil **104** with the direction of current flow in the inner coil **104** having the opposite sense (clockwise or counterclockwise) to the current flow in the outer coil **102**. The ratio I_O/I_I of the magnitudes of the currents in the two coils has been adjusted to minimize excitation of the sway mode resonance. Absence of the peak at 3000 Hz shows that the sway mode resonance is not excited in the dual coil actuator as used in settling and tracking operations according to the present invention.

Choice of the optimum current ratio I_O/I_I may be made by experimentation to obtain the best transfer function with dual

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coil operation or by the following process. A current having an amplitude I_1 is applied to the outer coil to measure the transfer function for the outer coil driving the actuator motion. The amplitude of the sway mode resonance peak, Q_O, is measured from the outer coil transfer function. The same current amplitude I_1 is applied to the inner coil to measure the transfer function for the inner coil driving the actuator motion. The amplitude of the sway mode resonance peak, Q_I, is measured from the inner coil transfer function. The optimum current amplitude ratio I_O/I_I to use for dual coil operation in order to eliminate the sway mode resonance peak from the transfer function for the dual coils driving the actuator motion is given by $I_O/I_I = Q_I/Q_O$.

Figs. **9** and **10** show the mechanical transfer functions obtained from finite element simulations of the response of the front-and-back dual coil actuator **110** to actuator coil current generated forces. Fig. **9** shows the transfer function obtained for coil current flowing only in the front coil **112** to simulate single coil actuator conditions. The large amplitude peak **128** at approximately 3600 Hz corresponds to the sway mode resonance of the actuator shown in Fig. **6b**. The resonance has a higher frequency than was obtained for the concentric dual coil actuator **100** because of the different coil structure, coil mass and mass

distribution. Fig. **10** shows the transfer function obtained for current flow in both the back coil **112** and the front coil **114** with the direction of current flow in the front coil **114** having the opposite sense (clockwise or counterclockwise) to the current flow in the back coil **112**. The ratio I_B/I_F of the magnitudes of the currents in the two coils has been adjusted to minimize excitation of the sway mode resonance. Absence of the peak at 3600 Hz shows that the sway mode resonance is not excited in the front-and-back dual coil actuator as used in settling/tracking operations according to the present invention.

Fig. **11** show the experimental setup **130** used to measure the transfer function for a front-and-back dual coil actuator **110** according to the present invention mounted in a magnetic disk drive **132**. A laser light beam from a laser doppler vibrometer (LDV) **140** reflected from a slider **134** mounted on the actuator **100** and supported over the surface of a rotating disk **136** by an air bearing is used to measure the mechanical transfer function for slider positional response to actuator coil current generated forces. Current is provided to the back coil **112** and the front coil **114** from separate channels of a current source **146** driven by a sine wave voltage from a signal analyzer **142**. The LDV **140**

output signal is recorded and analyzed in the signal analyzer **142** to obtain the mechanical transfer functions.

Figs. **12**, **13** and **14** show the transfer functions obtained for current supplied to the back coil **112**, to the front coil **114**, and to both back coil **112** and front coil **114**, respectively. The transfer function shown in Fig. **12** was obtained by driving the back coil **112** with a current having an amplitude I_1. The transfer function shown in Fig. **13** was obtained by driving the front coil **114** with a current having the same amplitude I_1. The peaks **150**, **152** at a frequency of approximately 2300 Hz observed in both transfer functions are due to excitation of the fundamental bending mode (sway mode)of the experimental actuator. The transfer function shown in Fig. **14** was obtained by driving the back coil **112** with a current having amplitude I_B and the front coil **114** with a current having amplitude I_F, where the current flows in the opposite sense (clockwise or counterclockwise) through the front coil **114** relative to the back coil **112**. The relative amplitudes of the currents in the two coils were adjusted to satisfy the condition $I_B/I_F = Q_F/Q_B$, where Q_B is the amplitude of resonance peak **150** due to driving the back coil **112**, and Q_F is the amplitude of resonance peak **152** due to driving the front coil **114** with the identical current amplitude.

The transfer function shown in Fig. **14** has no resonance peak at 2300 Hz experimentally confirming the results of the finite element simulations discussed above. The lower resonance frequency observed in the experimentally measured transfer functions was due to a different structure and mass of the actuator coils used in the experiments.

Suppression of the sway mode resonance during the settling and tracking operations of the disk drive allows a significantly higher servo bandwidth to be used in the disk drive since this resonance is the fundamental limitation to servo stability in the single coil actuators of the prior art. The finite element simulations shown in Figs. **8** and **10** for the actuator of the present invention indicate that the servo stability will now be limited by higher frequency modes **127**, and **129** respectively, having resonant frequencies in the range of 5000-6000 Hz. This increase in the limiting frequency by 1500-2500 Hz will result in an increase in allowable servo bandwidth which in turn allows a comparable increase in track density.

In order to obtain the benefits of improved dynamic response during settling and tracking operations by using the dual coil actuator of the present invention without sacrificing the high performance seek operations of the single coil actuator of the

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prior art, the following method of disk drive operation is contemplated. When a new data track is to be accessed, the controller sends a command to supply peak currents to both coils of the dual coil actuator with current flow in each coil having the same sense. At about half way to the target position of the new data track, the peak currents are switched to the opposite sense in both coils to decelerate the actuator according to the optimal control algorithm of the seeking mode. When the transducer is about 1 to 5 tracks away from the target data track (depending on disk drive operation and control algorithm) the controller is switched to the settling and tracking mode. In the settling and tracking mode, the current in one of the coils is switched to have the opposite sense to the current in the other coil, the coil being switched depending on the desired direction of motion of the transducer. When the currents in the two coils have the opposite sense and are in the appropriate ratio, the actuator sway mode is suppressed while there is still a net torque to drive the actuator during track following. In the track following mode the servo bandwidth is improved because of suppression of the sway mode resulting in increased track following accuracy. In this mode of operation, two coil current

power supplies are needed which are switchable by commands from the controller.

While the present invention has been particularly shown and described with reference to the preferred embodiments, it will be understood by those skilled in the art that various changes in form and detail may be made without departing from the spirit, scope and teaching of the invention. Accordingly, the disclosed invention is to be considered merely as illustrative and limited in scope only as specified in the appended claims.

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CLAIMS:

1. A magnetic storage system, comprising:

a disk with a concentric data surface of data tracks;

a spindle shaft supporting said disk, said spindle shaft for rotating said disk about an axis generally perpendicular to the disk;

a slider maintained in operative relationship with the data surface when the disk is rotating;

a transducer attached to the slider for reading data from and writing data to the data surface;

an electronic module for processing data read from and written to the data surface;

a first and second current supply for providing electrical power; and

an actuator for moving the slider generally radially relative to the disk to allow the transducer to access the data tracks, the actuator further comprising a body defining the actuator pivot point; a first coil support arm extending from the body; a second coil support arm extending from the body, said first and second coil support arms forming an angular sector therebetween; an outer actuator coil connected to the first current supply and affixed to the first and second coil support arms in the angular sector between said first and second coil support arms; and an inner actuator coil connected to the second current supply and affixed to the outer actuator coil, said inner actuator coil lying inside and in the same plane as said outer actuator coil.

2. The magnetic storage system as recited in claim 1, wherein a number of turns of wire forming the outer actuator coil is equal to the number of turns of wire forming the inner actuator coil.

3. A magnetic storage system, comprising:

a disk with a concentric data surface of data tracks;

a spindle shaft supporting said disk, said spindle shaft for rotating said disk about an axis generally perpendicular to the disk;

a slider maintained in operative relationship with the data surface when the disk is rotating;

a transducer attached to the slider for reading data from and writing data to the data surface;

an electronics module for processing data read from and written to the data surface;

a first and second current supply for providing electrical power; and

an actuator for moving the slider generally radially relative to the disk to allow the transducer to access the data tracks, the actuator further comprising a body defining the actuator pivot point; a first coil support arm having a proximal end extending from the body to a distal end; a second coil support arm having a proximal end extending from the body to a distal end, said first and second coil support arms forming an angular sector therebetween; a front actuator coil connected to the first current supply and affixed to the first and second coil support arms in the angular sector between the proximal ends of said first and second coil support arms; and, a back actuator coil connected to the second current supply and affixed to the first and second coil support arms in the angular sector

between the distal ends of said first and second coil support arms, said back actuator coil lying in the same plane as said front actuator coil.

4. The magnetic storage system as recited in claim 3, wherein a number of turns of wire forming the front actuator coil is equal to the number of turns of wire forming the back actuator coil.

5. A method of operating an actuator having concentric dual coils to move a transducer to a data track on a disk surface, which comprises the steps of:

a) supplying an outer current and inner current having the same clockwise or counterclockwise sense to the outer coil and to the inner coil of the actuator respectively, to rapidly move the transducer to the proximity of the data track; and

b) supplying the inner current having one sense to the inner coil and supplying the outer current having the opposite sense to the outer coil to accurately position the transducer over the data track and to maintain the position of the transducer over the data track.

6. A method of operating an actuator having front-and-rear dual coils to move a transducer to a data track on a disk surface, which comprises the steps of:

supplying a front current and rear current having the same clockwise or counterclockwise sense to the front coil and to the back coil of the actuator respectively to rapidly move the transducer to the proximity of the data track; and

supplying the front current having one sense to the front coil and supplying the rear current having the opposite sense to the rear coil to accurately position the transducer over the data track and to maintain the position of the transducer over the data track.