APPARATUS AND METHOD FOR ROTATIONAL IMBALANCE REDUCTION

FIELD OF THE INVENTION

The present invention relates to an apparatus and method for reducing rotational imbalance of a machine. In particular, it relates to an apparatus and method for reducing rotational imbalance of a machine by active control.

BACKGROUND OF THE INVENTION

Rotational imbalance exists in machines having rotational parts, such as a spindle motor or a hard disc drive (HDD), during its rotational motion. This imbalance is generally due to the non-alignment of the geometry axis and the inertia axis of the rotational part of the machine. This rotational imbalance is undesirable in a number of applications, because it may cause vibration of the machine hence affect the rotational accuracy of the machine. In a HDD, for example, rotational imbalance may cause track-following error during the data read/write process.

With the increased demand on high read/write speed and large storage capacity, HDDs are expected to have a higher standard of rotational accuracy. One solution is to increase the manufacturing accuracy of the HDDs. Various other technologies have also been developed in order to reduce the rotational imbalance by a "compensation" technique.

One compensation technique is to add a balancing weight onto the rotational part of a machine, for example a HDD so that the imbalance may be reduced or cancelled. One example of this technique is disclosed by Larry C. Anderson in "Applied Balancing Theory for Hard Disk Drives" (Lynchburg, VA: American Hofmann Corporation, 1996), which is illustrated in Fig. 10.

In Fig. 10, a rotational part of a machine, including a disc 1 is rotatable about its center of rotation O. HS denotes the initial imbalance mass of the rotational part of the machine. Two correction masses M1 and M2 are provided, which are of the same size and mass, and are movable along a circumference with a radius r. When the two correction masses are respectively moved to locations to balance the initial imbalance HS, the respective imbalance value U_1, U_2 and the initial imbalance of the disk U_0 satisfy the following equations:

$$U_1 = U_2 = U_{bl} = m \cdot r \quad (1)$$

$$U_{12} = U_{22} = U_{bl} \cdot \sin(\alpha/2) \quad (2)$$

$$U_{11} + U_{21} = U_{bl} \cdot 2\cos(\alpha/2) = U_0 \quad (3)$$

where U_0 denotes the initial imbalance of the rotational part of the machine induced by HS;

U_{11} and U_{21} are components of the respective imbalance value of the correction masses M1 and M2, which are parallel to the initial imbalance U_0;

U_{12} and U_{22} are components of the respective imbalance value of the correction masses M1 and M2, which are perpendicular to the initial imbalance U_0;

r is the radius of the rotational circumference of the two correction masses;

m is the mass of each of the two correction masses;

α is the included angle between the two correction masses with respect to the center of rotation O.

According to equations (1) – (3) above, in order to cancel the initial imbalance by the two correction masses, the following condition must be satisfied:

$$U_{11} + U_{21} = U_0$$

$$U_{12} = U_{22}$$

Accordingly, the included angle α should be:

$$\alpha = 2\arccos(U_0/(2U_{bl})) = 2\arccos(U_0/(2mr)) \quad (4)$$

According to the above illustration, to achieve the reduction or cancellation of the initial imbalance, the correction masses must be moved toward the balancing locations. In order to cancel the imbalance, each correction mass must have a mass of no less than half of U_0/r.

One attempt which implements the above balancing method is disclosed in US Patent No. 6,005,749 to Ikuta et al. In this patent, a rotation drive apparatus for optical disc drives comprises a balancing member rotatively disposed with respect to the rotating part of an optical disc drive. Driven by the vibration induced by the imbalance, the balancing member can be moved to the balanced locations by virtue of the "automatic balancing principle", at which the imbalance may be reduced or cancelled so that the balance is kept.

As disclosed, the rotation drive apparatus in the Ikuta patent in HDD applied to CD-ROM drive which typically has an imbalance of about 3 g.cm. In applications such as a HDD, the imbalance is typically below 0.2 g.cm and therefore, other factors such as the manufacturing errors in relevant parts and the friction between the balancing members and the disc drive become very significant. By contrast, Iketa's apparatus works on the basis that these factors are negligible, and therefore cannot be effectively used in HDDs to provide imbalance reduction.

SUMMARY OF THE INVENTION

It is therefore an object of the present invention to provide an apparatus and method for reducing a rotational imbalance of a machine, such as a disc spindle pack of a hard disc drive, in which the balancing mass can be moved to the balancing locations by a driving device to effectively reduce or minimize the initial imbalance of the machine or the disc spindle pack of a hard disc drive.

In accordance with a first aspect of the present invention, there is provided an apparatus for reducing rotational imbalance of a machine, the apparatus comprises a balancing plate, a balancing mass, a driving device and a testing device. The balancing plate is to attach to a rotational part of the machine, and has at least one circular race coupled thereto. The balancing mass is moveably disposed in the circular race. The testing device is provided for detecting the rotational imbalance of the machine, and determining an equilibrium position of the rotational imbalance. The driving device is disposed adjacent to the balancing plate for generating an external force to move the balancing mass along the circular race. When the balancing mass is moved toward the equilibrium location, the imbalance can be reduced.

In this context, the term "coupled thereto" denotes the relationship between the circular race and the balancing plate. In one situation, the at least one circular race is formed on the balancing plate, such as through a machining process. In another situation, the at least one circular race is formed separately first, and attached to the balancing plate. The term "coupled thereto" should be understood to include either the former or the latter situation.

In one embodiment, the balancing mass is made of magnetic material and the driving device comprises a plurality of electromagnets disposed along a circumference adjacent to the balancing plate. The electromagnets can be controlled to generate magnetic forces to move the balancing mass along the circular race.

In this context, the term "initial imbalance" refers to an imbalance of the machine without the apparatus of the present invention attached thereon, and the term "rotational imbalance" denotes an imbalance caused by the initial imbalance, the balancing plate of the present invention attached to the machine before the balancing process, as well as the external force generated by the driving device.

The balancing mass may include one or more rigid bodies made of magnetic material, such as steel. The rigid bodies may be rigid balls rotatable along the circular race with a revolving radius R1. In one embodiment, the balancing mass includes only one steel ball. The mass of the steel ball may be determined through a first value of dividing the initial imbalance by the revolving radius R1, and the mass of the steel ball is preferably equal to the first value. In another embodiment, the balancing mass comprises two steel balls both being movably disposed in the circular race. The two steel balls are preferably the same mass and dimension, and can revolve along the circular race with a revolving radius R2. The mass of the two steel balls may be determined through a second value of dividing the rotational imbalance by the revolving radius R2. The mass of each steel balls is preferably no less than half of the second value.

In another embodiment, the balancing plate comprises two circular races having different radius and with one circular race formed within the other one circular race. Each circular race has one steel ball movably disposed therein.

In the context, the term "equilibrium location" refers to a location or locations where the balancing mass are finally located upon completion of the balancing process, by which the rotational imbalance of the machine are reduced to a minimum possible level.

In accordance with a second aspect of the present invention, there is provided an apparatus for rotational imbalance reduction. The apparatus comprises a balancing plate for attaching to a rotational part of the machine, and a

control device for determining an equilibrium location on the balancing plate and applying a balancing force at the equilibrium location to reduce the centrifugal force induced by the rotational imbalance.

Preferably, the control device further comprises an electromagnetic device, a sensor and a processor. The electromagnetic device is disposed adjacent to the balancing plate for applying magnetic forces on the balancing plate along a plurality of predetermined radial directions. The sensor is provided for detecting a plurality of vibration signals of the machine caused by the rotational imbalance, each of the plurality of vibration signals corresponds to a magnetic force in one of the plurality of predetermined radial directions, the location of the initial imbalance and the balancing force applied on the machine. The processor is coupled to the sensor for receiving and comparing the corresponding plurality of vibration signals. The equilibrium location is determined by recording a rotational imbalance along a direction corresponding to a minimal vibration signal of the plurality of vibration signals; and said balancing magnetic force is applied at the equilibrium location to reduce the imbalance.

Preferably, the balancing plate further comprises at least one circular race formed thereon and the apparatus further comprises a balancing mass movably disposed in the circular race, wherein the balancing mass is movable by the electromagnetic device towards the equilibrium location to reduce the imbalance.

In accordance with a third aspect of the present invention, there is provided a method for reducing rotational imbalance of a machine. The method comprises attaching a balancing plate having a circular race formed thereon to a rotational part of the machine; providing a balancing mass which is movable in the circular race; determining an equilibrium location of the rotational imbalance; and applying a magnetic force on the balancing mass to move the balancing mass towards the equilibrium location to reduce the rotational imbalance.

Preferably, the determining of the equilibrium location further comprises locating the balancing mass at a first position of the circular race; detecting a first vibration signal induced by the initial imbalance, the magnetic force and the balancing mass at the first position; obtaining a first imbalance value according to the first vibration signal; moving the balancing mass to a second position in the circular race; detecting a second vibration signal induced by the initial imbalance , the magnetic force and the balancing mass at the second position; obtaining a second imbalance value according to the second vibration signal; and comparing the first imbalance value and the second imbalance value to determine a direction for the balancing mass to move toward to reduce the imbalance.

In one embodiment, when the balancing mass is located at the equilibrium location, the magnetic force is removed.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1A is a partial perspective view of an apparatus according to a first embodiment of the present invention;

Fig. 1B is a partial top view of Fig. 1A

Fig. 2A is a partial perspective view of an apparatus of Fig. 1A when attached to a rotational disc for imbalance reduction;

Fig. 2B is a partial top view of Fig. 2A

Figs. 3A – 3C are partially enlarged views of the apparatus of Fig. 1 showing possible movement of the balancing mass;

Fig. 4A is a flow chart showing a method of reducing a rotational imbalance according to the present invention;

Fig. 4B is a flow chart showing a method of determining the equilibrium location of a rotational imbalance according to the present invention;

Fig. 5A is a schematic diagram showing a mathematical model for calculation of the rotational imbalance;

Figs. 5B and 5C are partial top views showing the process of determining the equilibrium location of the imbalance according to one embodiment of the present invention;

Fig. 6 is a sample oscilloscope measurement result showing the influence of the magnetic force to the imbalance.

Fig. 7 is a partial perspective view of an apparatus according to a second embodiment of the present invention;

Fig. 8 is a partial perspective view of an apparatus according to a third embodiment of the present invention;

Fig. 9 is a partial perspective view of an apparatus according to a fourth embodiment of the present invention; and

Fig. 10 is a schematic diagram showing the theoretical model of the imbalance compensation principle.

DETAILED DESCRIPTION OF THE PREFERED EMBODIMENTS

Fig. 1A shows an apparatus 100 for rotational imbalance reduction according to a first embodiment of the present invention. Fig. 2A shows the apparatus of Fig. 1A when attached to a rotational part of a hard disc drive (HDD), such as a disc for imbalance reduction. As shown in Figs. 1A, 1B, 2A and 2B, an apparatus 100 for reducing a rotational imbalance of a HDD comprises a balancing plate 110, a driving device, a testing device and a controller 140. The balancing plate 110 may be attached concentrically to the rotational part of a HDD such as the hub or a disc spindle pack 10. The disc spindle pack 10 is rotatable with respect to its axis of rotation 14, and has an initial imbalance mass 12. When the disc spindle pack 10 rotates, the initial imbalance mass 12 generates an initial rotational imbalance U_0, which is to be reduced by the apparatus of the present invention.

The balancing plate 110 has an axis of rotation 114 which is substantially aligned with the axis of rotation 14 of the disc spindle pack 10. The balancing plate 110 has a circular race 120 such as a circular groove formed thereon. A balancing mass, including two steel balls 122 and 124, is disposed in the circular race 120. The two steel balls 122 and 124 are freely movable in the circular race 120. Two spacer balls 126 and 128 are also provided and disposed between the two steel balls 122 and 124. The two spacer balls 126 and 128 are made of non-magnetic material, such as ceramic. The two spacer balls 126 and 128 are provided to prevent the two steel balls 122 and 124 from being attached to each other, hence to enable the two steel balls to move independently. Other numbers of steel balls and/or spacer balls may be used depending on the configurations or properties of the HDD and the imbalance status thereof. These configurations or properties may include, for example, the physical dimension of the rotating part, the desired level of the imbalance after reduction.

In this embodiment, the driving device includes a set of thirty six electromagnets 201 to 236 (only a few of the electromagnets are numbered as

201, 202, 203, 204, 235 and 236 for illustration) evenly disposed along a circumference 250 adjacent to the circular race 120 of the balancing plate 110. The electromagnets 201 to 236 may be coupled together in any appropriate manner for ease of positional adjustment adjacent to the circular race 120. In this embodiment, the electromagnets are coupled to a support ring 290 to move together. The electromagnets 201 to 236 may be activated and deactivated individually or jointly. When activated, the selected electromagnets generate magnetic forces to control the movement of the steel balls 122 and 124. Alternatively, any other appropriate numbers of electromagnets may be used. For example, the driving device may include only one electromagnet disposed adjacent to the circular race 120 to control the movement of the steel balls 122 and 124.

The testing device also includes a sensor 130 for measuring the vibration caused by the initial imbalance U_0, the balancing plate 110, the magnetic forces, the two steel balls 122 and 124 as well as the two spacer balls 126 and 128. A controller 140 is coupled to the sensor 130 for receiving vibration signals. The controller 140 is also coupled to the electromagnets 201 to 236 to control the activation and deactivation of the electromagnets 201 to 236. The controller 140 may further include a feedback device 142, a processor 144, and a power source 146. The feedback device 142 may be coupled to the processor 144, the power source 146 and the electromagnets 201 – 236 for activating and deactivating the electromagnets.

As shown in Fig. 3A, when the first electromagnet 201 is activated and all of the other electromagnets 202 – 236 are deactivated, the magnetic force F_{201} generated by this electromagnet 201 attracts the steel ball 122 to act against a first corresponding position 301 on the circular race 120. At this moment, the steel ball 122 is stationary relative to the circular race 120. When the second electromagnet 202 is activated and the first electromagnet 201 and other electromagnets 203 – 236 are deactivated, the magnetic force F_{202} generated by the electromagnet 202 is applied to the steel ball 122 and in the meantime, the

force F_{201} is eliminated. As a result, the steel ball 122 is moved toward position 302 by the force F_{202}, as shown in Fig. 3B. If the electromagnet 236 is activated and all other electromagnets 201 – 235 are deactivated, the steel ball 122 is moved toward position 236 by the effect of the magnetic force F_{236}, as shown in Fig. 3C. The time intervals between the activation and deactivation of the electromagnets may be varied by the controller 140, so that the steel ball 122 can be moved at a predetermined speed.

The electromagnets 203, 204, or 236, 235 etc. may be activated and deactivated in the same way, so that to control the movement of the steel balls 122 or 124 in the circular race 120. By controlling the activation and deactivation of the electromagnets 201 to 236, the two steel balls 122 and 124 can be moved in the circular race 120 to predetermined locations. In one scenario, the movement speed of the steel balls 122 and 124 may be controlled such that it is equal to the rotation speed of the disc spindle pack 10, i.e. the steel balls 122 and 124 will be relatively stationary with respect to the disc spindle pack 10. In another scenario, the steel balls 122 and 124 can be moved at a speed V_{ref} (rpm) relative to the disc spindle pack 10, through which the equilibrium location may be determined, as illustrated below.

As described above under the "Background of the Invention", in order to reduce the rotational imbalance of a disc, a machine or an assembly, the balancing mass must be moved toward the equilibrium location. To achieve this goal, the equilibrium location must be determined based on the imbalance status induced by the initial imbalance 12, the balancing plate 110, the two steel balls 122 and 124 and the magnetic forces, as according to the method of the present invention.

Fig. 4A is a flow chart showing a method 410 for reducing a rotational imbalance of a machine according to one embodiment of the present invention. In a first block 412, a balancing plate having a circular race formed thereon is attached to a rotating part of the machine. In a next block 414, a balancing mass

is provided, which is movably disposed in the circular race. In block 416, the equilibrium location of the rotational imbalance of the disc is determined. In a further block 418, a magnetic force is applied on the balancing mass to move the balancing mass toward the equilibrium location to reduce the rotational imbalance. Optionally in an additional block 419, the magnetic force is removed when the balancing mass is located at the equilibrium location.

Fig. 4B is a flow chart showing the process 416 of the equilibrium location determination according to the present invention. In a first block 416a, the two steel balls 122 and 124 are located together, and moved simultaneously by the magnetic force in the circular race 120 for a full round. The time interval T of the full-round movement is

$$T = 60 / V_{ball} \text{ (seconds)} \quad (5)$$

Where V_{ball} denotes the rotational speed of the steel balls relative to the fixed part of the disc spindle pack in revolutions per minute (rpm).

In a second block 416b, vibration signals are measured by the sensor 130 when the two steel balls are at selected sampling locations. In a third block 416c, the imbalance values are calculated by the controller 140 based on the vibration signals measured, and a minimal imbalance value is obtained. In a fourth block 416d, the locations of the steel balls 122 and 124 relative to the circular race 120 are varied, and corresponding imbalance value are obtained. If the imbalance value decreases, the two steel balls 122 and 124 will be moved along the same direction or, if the imbalance value is increased, the two steel balls 122 and 124 will be moved along an opposite direction.

In a fifth block 416e, the two steel balls move to a location where a first minimal imbalance value is obtained, at which the imbalance is reduced to a corresponding first maximum level. At this instant the two steel balls contact to each otherat a contact point directly opposite to the initial imbalance mass.

In a sixth block 416f, the two steel balls 122 and 124 are separated with respect to the direct opposite location with an included angle, so that the imbalance can be further reduced beyond the first maximum level, until fully cancelled.

It should be appreciated that in the method illustrated above, in order to effectively reduce the rotational imbalance to a lowest possible level towards zero, the joint centrifugal force generated by the two steel balls (when contacting to each other) should reach a level sufficient to generate a first balancing moment which is equal to or is greater than the rotational imbalance. In the event that the first balancing moment is greater than the rotational imbalance (i.e. the rotational imbalance is over-compensated), the two steel balls 122 and 124 may be separated with an included angle, so that a second balancing moment can be obtained to eliminate the "over-compensation". To determine the initial imbalance value and the included angle of balance between the two steel balls 122 and 124, the following derivations are used, as illustrated together with the process of equilibrium location determination, and in conjunction with Figs. 5A and 5B.

In Fig. 5A,

U_0 denotes the initial imbalance induced by the initial imbalance mass HS of the disc spindle pack 10;

U_{MF} denotes the imbalance induced by the magnetic force when applied to each of the two steel balls 122 and 124, and

$$U_{MF} = F_{201}/(2\pi rn/60)^2; \quad (6)$$

where F_{201} denotes the magnetic force generated by the electromagnet (not shown), and applied to each steel balls 122 and 124, and n denotes the rotational speed of the disc spindle pack, in rpm ;

U_{bl} denotes the imbalance induced by each steel ball;

α_0 denotes the included angle between the two steel balls with respect to the axis of rotation 14;

β denotes an angle between the center line 123 of the two steel balls 122 and 124 and the radius 13 corresponding to the opposite direction of the initial imbalance mass HS;

β_0 denotes the angle between the radius 13 and a radius that the center line 123 is initially located;

$$\beta = 2\pi f t + \beta_0 \tag{7}$$

where $f = V_{rel} / 60$ and V_{rel} is the relative speed between the steel balls and the circular race 120

U' denotes the resultant imbalance induced by the two steel balls and the magnetic force, and

$$U' = 2(U_{bl} + U_{MF}) \cos(\alpha_0/2); \tag{8}$$

The imbalance I_m induced by the magnetic forces U_{MF}, two steel balls U_{bl} and the initial imbalance U_0 is:

$$I_m^2 = U_0^2 + U'^2 - 2U_0U' \cos\beta$$
$$= U_o^2 + 4(U_{bl} + U_{MF})^2 \cos^2(\alpha_0/2) - 4U_0(U_{bl} + U_{MF})\cos(\alpha_0/2)\cos(\beta) \tag{9}$$

When $\beta = 180°$, U' is at the HS location, and the overall imbalance value is the maximum with the magnetic forces applied to the steel balls;

$$I_{m_max} = 2\,(U_{bl} + U_{MF})\cos\,(\alpha_0/2) + U_0 \qquad (10)$$

when $\beta = 0°$, U' is located opposite to the HS, and the overall imbalance value is the minimum with the magnetic forces applied to the steel balls;

$$I_{m_min} = 2\,(U_{bl} + U_{MF})\,\cos\,(\alpha_0/2) - U_0 \qquad (11)$$

When the electromagnets are deactivated, the steel balls willbe stationary relative to the circular race, and the overall imbalance without the magnetic force is

$$I_{m_noMF} = |\,2U_{bl}\,\cos\,(a_0/2) - U_0\,| \qquad (12)$$

From the above formulae, the initial imbalance U_0, the steel ball-induced imbalance U_{bl}, the magnetic force-induced imbalance, and the final included angle α representing the equilibrium locations of the two steel balls can now be derived as follows: -

$$U_0 = \frac{(I_{m_\max} - I_{m_\min})}{2} \qquad (13)$$

$$U_{MF} = \frac{I_{m_\max} + I_{m_\min}}{4\cos(\alpha/2)} - U_{bl} \qquad (14)$$

$$\alpha = 2\arccos(\frac{U_0}{2U_{bl}}) \qquad (15)$$

Reference is now made to Fig. 5B. Before starting the imbalance reduction process, a first control scheme is set as follows: the rotation speed of the disc spindle pack is set to about 1000 rpm, and the electromagnets 201 to 236 are controllably activated / deactivated so as to rotate the two steel balls 122 and 124

in a speed of 3 rpm relative to the balancing plate 110. According to this control scheme, the steel balls will move relative to the balancing plate 110 under a period time of 20 seconds for one full round along the circular race 120. It should be appreciated that other appropriate speed conditions of both the disc and the steel balls may also be used.

During the period of the above 20 seconds, the two steel balls 122 and 124 can be moved to various sampling locations in the circular race 120. Vibration signals may be measured by the sensor 130 and each of the sampling measurement result may be recorded by the controller 140 for analysis.

Upon starting of the imbalance reduction process, the two steel balls 122 and 124 are moved together in the circular race 120 for a full round, and the vibration signals are measured in a predetermined sampling instance, such as every 0.5 second sampling rate to determine the imbalance value instance.

In view of possible noises included in the vibration signal detection which corresponds to an imbalance, a filtered imbalance imf(n) is introduced to represent the actual imbalance value. The filtered imbalance is a weighted moving average by taking the vibration measurement of both the present and the previous filtered value into consideration. In this invention, the filtered imbalance is represented as:

$$imf(n) = imm(n)*w + imf(n-1)*(1-w) \quad (16)$$

In the above equation, w represents the selected weight value. w*100% of measured imbalance value imm(n) when the two balls are located at the present position, and (1-w)*100% of the filtered imbalance value when the two balls are located at a previous position are used to represent the actual imbalance value.

At a next sampling instance, the following equation is used:

$$imf(n-1)|_{new} = imf(n)|_{old} \quad (17)$$

which denotes that the "present position" quoted with respect to equation (16) is now referred as "pervious position".

Based on the above equations (16) and (17), in a selected sampling instance k (location 262), the filtered imbalance value imf(k) is obtained and recorded. When the two steel balls move to a next sampling instance k+1, for instance at location 264, the imbalance value imf(k+1) is also obtained and recorded. Comparison of these measurements can then be made by the controller 140. A comparison result of imf(k+1) < imf(k) indicates that the two steel balls are moving toward a direction whereby the imbalance is reducing. On the contrary, if the imbalance value imf(k+1) at a next sampling instance (location 266) is greater than imf(k), it indicates that the two steel balls are moving toward a direction whereby the imbalance is increasing. As such, the moving direction can be determined for the two steel balls to move toward to reduce the imbalance.

When the two steel balls are moved to a location 268, the imbalance value obtained reaches a first minimal imbalance level, which indicates that the two steel balls are now located direct opposite to the initial imbalance mass HS. At this juncture, a first stage of the imbalance reduction is completed, and the resultant imbalance reaches the first minimum possible level when the two steel balls are located together.

In the above equation, 90% of the present measurement value and 10% of the measurement value at a neighboring location are used to represent the actual imbalance value.

In this embodiment, since there are thirty six evenly disposed electromagnets, the two steel balls will be moved along the circular race under the control of the electromagnets at every 10° interval. This movement interval may be varied according to the dimensions of the disc spindle pack 10, the balancing

plate 110 and the steel balls 122 and 124. In an alternative embodiment, two neighboring electromagnets are both activated to hold the balls at a position between the two neighboring electromagnets and therefore, the movement interval is 5° instead of 10°. In a further embodiment, seventy two electromagnets are used. Each of the electromagnets is independently activated and the movement interval of the balls is 5°.

In this embodiment, each of the two steel balls 122 and 124 has a mass greater than a value which is half of the initial imbalance U_0 divided by the radius of the rotational circumference of the two steel balls 122 and 124. According to the above analysis, when the two steel balls are moved together to a location direct opposite to the initial imbalance mass, the first minimum possible resultant imbalance is achieved, but there is still a remaining imbalance. This remaining imbalance exists due to the fact that when the two steel balls are located at about the direct opposite location of the HS, the balancing moment generated by the two steel balls exceeds the initial imbalance, hence the initial imbalance is "over compensated". To reduce this "over compensated" imbalance, the two steel balls 122 and 124 are separated and moved to their respective equilibrium locations 272 and 274 with the included angle α satisfying equation (15) above, as illustrated in Fig. 5C. To respectively move the two steel balls to the locations 272 and 274, a second control scheme is developed, which is similar to that used in the first stage.

Under the second control scheme, firstly, the two steel balls are separated with an included angle α of 10°. Imbalance value is then obtained through the vibration signals measured after the electromagnets are deactivated. Next, the included angle α is increased by 10°, and the corresponding imbalance value is obtained. If the imbalance is reduced, the two steel balls will be separated further, for example, with an included angle of 40°, 50° and 60°, etc. and the corresponding imbalance value can be obtained.

Comparing the corresponding imbalance value obtained, the included angle corresponding to a second minimum imbalance level can be obtained and hence the corresponding locations of the two steel balls is determined. These locations correspond to the equilibrium location at which the two steel balls are to be located, and the overall imbalance is further reduced to the second minimum level.

It should be appreciated that in this embodiment, since the balancing plate is also made of magnetic material, the magnetic forces will also be applied to the balancing plate, which in turn plays a role in the imbalance reduction.

In Fig. 6, a first curve 610 represents the values and variation of the included angel between the two steel balls. A second curve 620 represents the amplitude measured, which corresponds to the imbalance induced by the magnetic force as applied on the balancing plate. A third curve 630 represents the activation (state "1") and deactivation (state "0") of the electromagnets.

In this embodiment, the imbalance is eventually reduced or cancelled by the steel balls. As such, all the electromagnets are deactivated at the end of the balancing process.

Fig. 7 is a partial perspective view showing an apparatus 700 for rotational imbalance reduction according to a second embodiment of the present invention. In this embodiment, the apparatus comprises a balancing plate 710 for attaching to a rotational disc 70. The balancing plate 710 has formed thereon two circular races 720 and 730. The two circular races have the same diameters and are concentrically disposed with respect to each other within two respective planes. A first steel ball 722 is movably disposed in circular race 720. A second steel ball 732 is movably disposed in circular race 730.

Two corresponding sets of electromagnets 750 and 760 each having thirty six electromagnets disposed along a circumference adjacent to the respective

circular races 720 and 730. With one or more of the electromagnets 750 and 760 controllably activated and deactivated, the corresponding steel balls 722 and 732 will be moved along the circular race toward the equilibrium location, thereby reducing the imbalance. It should be appreciated that in this embodiment, since the two balancing balls are disposed in different circular races, the possibility of two balls being attached together is prevented and it is not necessary to have spacer balls between the steel balls.

Fig. 8 is a partial perspective view showing an apparatus for rotational imbalance reduction according to a third embodiment of the present invention. In this embodiment, the apparatus comprises a balancing plate 810 for attaching to a rotational disc 80. The balancing plate 810 has formed thereon two circular races 820 and 830, which are concentrically disposed and with one race 820 disposed inside the other race 830. Both races 820 and 830 are within the same plane.

Two corresponding sets of electromagnets 850 and 860 each having thirty six electromagnets are disposed along a circumference adjacent to the respective circular races 820 and 830. With one or more of the electromagnets 850 and 860 controllably activated and deactivated, the corresponding steel balls 822 and 832 will be moved along the circular race toward the equilibrium location, thereby reducing the imbalance. It should be appreciated that in this embodiment, since the two balancing balls are disposed in different circular races, the possibility of two balls being attached together is prevented and it is not necessary to have spacer balls between the steel balls.

It should also be appreciated that in this embodiment, since the two circular races are of different radius, the respective steel balls disposed therein may be selected with different mass, which are preferably reverse proportional to the respective rotation radius, so as to achieve effective imbalance reduction.

Fig. 9 is a partial perspective view showing an apparatus for rotational imbalance reduction according to a fourth embodiment of the present invention.

In this embodiment, the apparatus comprises a balancing plate 910 for attaching to a rotational disc 90. The balancing plate 910 is made of magnetic material and cylindrical, but has no races formed thereon. A set of thirty six electromagnets 900 is disposed along a circumference adjacent to the balancing plate 910. During the process of determining the equilibrium location, magnetic forces are applied to the balance plate and generate the balancing effect as discussed above. Upon completion of the determining process, instead of utilizing the balancing balls to generate necessary centrifugal forces to reduce the imbalance of the disc, the magnetic forces are continuously applied onto the equilibrium location so that imbalance reduction, minimization or cancellation can be achieved.

Those skilled in the art would appreciate that the present invention as illustrated according to the above embodiments should not be understood as applicable to hard disc drives only, but also generally applicable to other type of machines or assemblies having an initial rotational imbalance to be reduced or minimized.

Although embodiments of the present invention have been illustrated in conjunction with the accompanying drawings and described in the foregoing detailed description, it should be appreciated that the invention is not limited to the embodiments disclosed, and is capable of numerous rearrangements, modifications, alternatives and substitutions without departing from the spirit of the invention as set forth and recited by the following claims. For example, an apparatus for rotational imbalance reduction according to the present invention maybe modified to combine features disclosed in different embodiments. For example, the apparatus may have multiple sets of electromagnets disposed in multiple planes. Each plane may contain one set of circumferentially disposed electromagnets. Alternatively, each plane may contain two or more sets of electromagnets which are respectively disposed along concentric circumferences.

CLAIMS

1. An apparatus for reducing a rotational imbalance of a machine, the machine having an initial imbalance and an axis of rotation, the apparatus comprising:

a balancing plate for attaching to a rotational part of the machine, the balancing plate having at least one circular race coupled thereto;

a balancing mass movably disposed in the at least one circular race;

a driving device disposed adjacent to the balancing plate for controlling the movement of the balancing mass,

a testing device for determining an equilibrium position of the rotational imbalance;

wherein the balancing mass is movable by the driving device in the at least one circular race towards the equilibrium location to reduce the rotational imbalance.

2. The apparatus as recited in claim 1, further comprising two concentrically disposed circular races and the balancing mass further comprising at least two balancing members each being movably disposed in one respective circular race.

3. The apparatus as recited in claim 2, wherein the two circular races having different diameters and formed within a same plane.

4. The apparatus as recited in claim 2, wherein two circular races having a same diameter and formed within different planes parallel to each other.

5. The apparatus as recited in claim 1, wherein the balancing mass is made of magnetic material and the driving device further comprising at least one electromagnet for generating magnetic forces to control the movement of the balancing mass.

6. The apparatus as recited in claim 5, further comprising a set of electromagnets disposed along a circumference adjacent to the at least one circular race.

7. The apparatus as recited in claim 6, wherein the magnetic forces are along a direction perpendicular to the axis of rotation.

8. The apparatus as recited in claim 6, wherein the magnetic forces are along a direction parallel to the axis of rotation.

9. The apparatus as recited in claim 6, wherein the set of electromagnets comprises at least two independently activatable electromagnets.

10. The apparatus as recited in claim 6, wherein the set of electromagnets are coupled together for being simultaneously displaced.

11. The apparatus as recited in claim 1, wherein the testing device further comprises a sensor for detecting a vibration signal induced by the initial imbalance, the balancing plate and the balancing mass, and a processor for receiving the vibration signal to determine the imbalance;

12. The apparatus as recited in claim 11, further comprising a feedback device coupled to the processor and the driving device for activating and deactivating the driving device based on the imbalance determined by the processor.

13. The apparatus as recited in claim 3, wherein the balancing mass is made of magnetic material and the driving device further comprises two sets of electromagnets disposed adjacent to the respective circular races for generating magnetic forces to move the balancing mass.

14. The apparatus as recited in claim 4, wherein the balancing mass is made of magnetic material and the driving device further comprises two sets of electromagnets disposed adjacent to the respective circular races for generating magnetic forces to move the balancing mass.

15. An apparatus for reducing a rotational imbalance of a machine comprising:
a balancing plate for attaching to a rotational part of the machine;
a control device for determining an equilibrium location of an imbalance induced by the machine and the balancing plate, and applying a balancing force proximate to the equilibrium location to reduce the imbalance.

16. The apparatus as recited in claim 15, wherein the control device further comprising:
an electromagnetic device disposed adjacent to the balancing plate for applying magnetic forces on the balancing plate along a plurality of predetermined directions;
a sensor for detecting a plurality of vibration signals caused by the rotational imbalance and the magnetic forces, each of the plurality of vibration signals corresponds to a magnetic force in one of the plurality of predetermined directions;
a processor coupled to the sensor for comparing the corresponding plurality of vibration signals,
wherein the equilibrium location is determined by recording a balancing magnetic force along a direction corresponding to a minimal vibration signal of the plurality of vibration signals; and
wherein said balancing magnetic force is applied at the equilibrium location to reduce the imbalance.

17. The apparatus as recited in claim 16, wherein the balancing plate further comprises at least one circular race formed thereon and the apparatus further comprises a balancing mass movably disposed in the circular race,

wherein balancing mass is movable by the electromagnetic device towards the equilibrium location to reduce the imbalance.

18. The apparatus as recited in claim 17, wherein the electromagnetic device further comprises a plurality of electromagnets disposed along a circumference adjacent to the circular race to control the movement of the balancing mass.

19. The apparatus as recited in claim 18, wherein the plurality of electromagnets are independently activatable for generating corresponding electromagnetic forces at predetermined locations of the circular race.

20. The apparatus as recited in claim 19, further comprising a power source coupled to the processor and the plurality of electromagnets for controllably activating and deactivating the plurality of electromagnets.

21. A method for reducing a rotational imbalance of a machine, the method comprising:

attaching a balancing plate onto a rotational part of the machine, the balancing plate having a circular racecoupled thereto;

providing a balancing mass which is movable in the circular race;

determining an equilibrium location of the rotational imbalance; and

applying a magnetic force on the balancing mass to move the balancing mass towards the equilibrium location to reduce the rotational imbalance.

22. The method as recited in claim 21, wherein the determining of the equilibrium location further comprises

locating the balancing mass at a first position of the circular race;

detecting a first vibration signal induced by the initial imbalance and the balancing mass at the first position;

obtaining a first imbalance value according to the first vibration signal;

moving the balancing mass to a second position in the circular race;

detecting a second vibration signal induced by the initial imbalance and the balancing mass at the second position;

obtaining a second imbalance value according to the second vibration signal; and

comparing the first imbalance value and the second imbalance value to determine a direction for the balancing mass to move toward to reduce the imbalance.

23. The method as recited in claim 22, further comprising moving the balancing mass according to the direction determined towards the equilibrium location to reduce the imbalance.

24. The method as recited in claim 21, wherein the moving of the balancing mass is effected by applying a rotational magnetic force to the balancing mass.

25. The method as recited in claim 21, further comprising removing the magnetic force when the balancing mass is located at the equilibrium location.