#### **GENERAL EXPLANATION OF HOW MAGNETIC BEARINGS WORK**

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Magnetic Bearings are devices used to support (levitate) objects using magnetic forces. Some magnetic bearings provide a full non-contact support of an object, whereas others provide only a partial support working together with more conventional mechanical bearings.

While a wide variety of magnetic bearings have been developed, only one type has been widely accepted in the industry so far - Active Magnetic Bearings (AMBs). This is because an active magnetic bearing can exert higher-density forces on surfaces of supported objects than any other type of magnetic bearing. They can also operate in a wide range of environments and their properties can be made highly configurable through software parameters. Ongoing dramatic improvements in Digital Signal Processors (DSP) – faster performance, integration of important peripheral features, and cost reductions – have further boosted commercial attractiveness of active magnetic bearings.

The basic operating principle of an active magnetic bearing is very simple. A ferrous object is known to be attracted to a permanent magnet or an electromagnet (an electrical coil wound around a ferrous core). For example, Figure 1 shows a ferrous object which will be attracted to an electromagnet located next to it whenever the coil is energized with a current. Note that the force between an electromagnet and a ferrous object is **always attractive** – it cannot be repulsive.



FIG. 1

The pulling force exerted by electromagnet on an object depends on two parameters:

- a.) Current *I* in the electromagnet, and
- b.) Distance or gap *g* between the object and the electromagnet.

If the current *I* does not change, the force  $F_{em}$  pulling the object towards the electromagnet will get stronger when the rotor gets closer to the electromagnet. Because of this, and because the gravity force  $F_{grav}$  effectively does not change with the rotor position, if you bring the rotor close enough to the electromagnet for the electromagnetic force  $F_{em}$  to overcome the gravity force  $F_{grav}$ , the rotor will jump to the electromagnet and stick to it. Alternatively, if you place the rotor too far from the electromagnet where the gravity force is larger than electromagnetic force, the rotor will fall on the floor.

This behavior is just opposite to what would happen if the rotor was suspended on a spring as shown in Fig. 2 - the force with which spring would pull the rotor up would get weaker when the rotor moves up and stronger when the rotor moves down. It is said that a spring suspension shown in Fig. 2 has a positive stiffness (defined as a rate at which spring force changes with the rotor displacement taken with a negative sign) whereas the electromagnet suspension shown in Fig. 1 has a negative stiffness. We know that an object can be suspended on a spring as shown in Fig. 1, but it is not possible to suspend an object using an electromagnet shown in Fig. 1 without it coming to a full contact with the electromagnet.



FIG. 2

## **Position Control in a Magnetic Bearing**

In order to achieve stable levitation of a rotor in an active magnetic bearing, the current in the electromagnet is continuously adjusted to keep the rotor in the desired position. This position is constantly measured using a position sensor, shown in Fig. 3, which passes information to a controller, which, in turn, adjusts the current (typically by applying some control voltage at the input of a power amplifier). The position sensor electronics, the controller and the power amplifier are all part of the Magnetic Bearing Controller (MBC).

An important advantage of the arrangement shown in Fig. 3 compared to Fig. 2 or any other type of magnetic bearing is that the current *I* can be adjusted so that the object deflection from the desired position would remain zero regardless of the value of the external force acting on the object (this can be done, however, only with static or slowly changing forces). In effect, this is equivalent to a spring as in Fig. 2 with an infinite positive stiffness.





The portion of an active magnetic bearing that is responsible for generating electromagnetic forces is called the electromagnetic actuator. Thus, the electromagnet shown in Fig. 3 is a simple form of an electromagnetic actuator. In addition to an electromagnetic actuator any magnetic bearing includes three other components shown in Fig. 3: position sensor, controller and power amplifier. There is one more component present in all active magnetic bearings, which is not shown in Fig. 3 – a backup bearing (also often referred to as 'touchdown bearing', 'auxiliary bearing', 'catcher bearing', or 'retainer bearing'). The purpose of this component is to support the rotor when the main part of active magnetic bearing is not activated, gets overloaded or malfunctions.

# **Bias Current (or Flux) Linearization**

Since the force between an electromagnet and a ferrous object is always an attractive one, the AMB shown in Fig. 3 can operate only if the external forces acting on the object (such as the gravity force  $F_{grav}$ ) are directed away from the electromagnet. If the external force can change sign, two electromagnets located on the opposite sides of the object along the force line must be used as shown in Fig. 4. For example, if the external force is applied in the positive Y direction, the bottom electromagnet in Fig. 4 can be energized to counteract that force and keep the object in place. Alternatively, if the external force is applied in the negative Y direction, the top electromagnet can be energized to counteract it.

In practical applications, the external force acting on an object (the rotor of a machine supported by a magnetic bearing) will vary with time or reverses sign. This makes the current control in of the electromagnetic much more difficult than when the external force is constant (such as the gravity force in Fig. 3). To understand these complications we need to look at how the force exerted by the electromagnet on the object depends on the current in the electromagnet. This dependence is quadratic in nature:  $F_{em} \sim I^2$ . Fig. 5 shows an example of  $F_{em}$  vs I curve. Note that the slope of this curve is not constant and changes with the current (force). Particularly important is that when we try to generate a small force close to zero, the force doesn't respond much to changes in the current. This makes choosing the right current to offset an external force and stably levitate an object at the desired position difficult.





FIG. 4



A common method used to avoid complications with non-linearity of the  $F_{em}$  vs *I* curve is to pre-energize both electromagnets Y+ and Y- in Fig. 4 with the same constant current  $I_0$  called bias current. If the object in Fig. 4 is centered between two identical electromagnets and both are energized with the same current, the net pull force on the object would be zero (the bottom electromagnet would pull the object down with exactly the same force as the top electromagnet would pull it up). Therefore, with bias current  $I_0$ alone there is no net electromagnetic force on a centered object.

In order to produce a net force, an additional current, called control current  $I_c$ , is injected into both electromagnets in such a way that if it adds to the bias current in one coil, it subtracts from it in another coil. For example in order to produce a force in the positive Y direction, the control current  $I_c$  has to be added to the bias current  $I_0$  in the top electromagnet and subtracted from it in the bottom electromagnet. Then the force produced by the top electromagnet would be

$$F_{+} \sim (I_{0} + I_{c})^{2} \tag{1}$$

and the force produced by the bottom electromagnet would be

$$F_{-} \sim (I_0 - I_c)^2.$$
 (2)

The net force exerted on the object would be

$$F = F_{+} - F_{-} \sim (I_{0} + I_{c})^{2} - (I_{0} - I_{c})^{2} = 2I_{0}I_{c}.$$
(3)

If the bias current  $I_0$  is kept constant and the object is kept at the center between two electromagnets, the electromagnetic force exerted on the object would be simply a linear function of the control current (Fig. 6). Reversing sign of the control current will reverse the sign of the force.





If two more electromagnets are added as shown in Fig. 7, the object position can be controlled along two axes - X and Y. The structure shown in Fig. 7 represents the typical basic radial active magnetic bearing design employed by most magnetic bearing companies (Calnetix utilizes a different approach as will be discussed later). The only difference is that in practical designs individual electromagnets are often linked together by a common ferrous path and there might be different poles arrangements.



FIG. 7

# **Heteropolar Magnetic Bearings**

In realistic turbomachinery application the object, a turbomachinery rotor, normally spins about its axis Z (directed out of page in Fig. 7) and this brings other complications. To discuss those complications we will focus only on the bias field for now (for simplicity) and redraw Fig. 7 using 'North' and 'South' designation for the electromagnet poles instead of arrows showing the field direction. (The convention is that the magnetic field is coming out of the 'North' Pole and returns into the 'South' pole).

Two symmetric patterns of the bias poles are possible as shown in Figs. 8a and 8b. In either case, a point on the object (rotor) will see changes of the bias magnetic field polarity when the rotor spins: NN-SS-NN-SS in case of Fig. 8a and N-S-N-S-N-S in case of Fig. 8b. A complication arises when the rotor material is not only magnetically permeable but also electrically conductive, and this is normally the case in practical rotating machines. This is because rotors spinning at high speeds experience high mechanical stresses and while there are some materials that are magnetically permeable but not electrically conductive, such as ferrites, they are not sufficiently strong mechanically. These considerations make magnetically-permeable ferrous steels a material of choice for the rotors, and they are electrically conductive.





When a rotor spins in a non-uniform magnetic field such as shown in Figs. 8a and 8b, each point of the rotor sees time-periodic magnetic field variations. In Fig. 8a the frequency of the main field harmonic will be 2f and in Fig. 8b it will be 4f, where f is the frequency of rotor rotation in revolutions per second. According to Faraday's law, these periodic changes of the magnetic field cause periodic voltages, which, in case of conductive rotors, cause eddy currents in the rotors.

One of the unpleasant outcomes is that eddy currents generate heat in the rotor and cause mechanical drag.

The other outcome is even more unpleasant. As any other electrical currents, eddy currents induced in a spinning rotor produce their own magnetic field, which gets superimposed on the external magnetic field. The end effect is known as a skin effect - the net magnetic field gets expelled from most of the rotor instead of very thin (skin-deep) layer on the surface of the rotor. The thickness of this layer can be estimated using the equation (4) below:

$$\delta = \sqrt{\frac{1}{\pi\mu_0\mu\sigma} \frac{1}{f_e}} \tag{4}$$

Where  $\mu$  and  $\sigma$  are permeability and conductivity of the rotor material respectively and  $f_e$  is an equivalent electric frequency, which is equal twice the rotor spin frequency for the arrangement shown in Fig. 8a and four times for the arrangement shown in Fig. 8b.

For example, electrical silicon steel has  $\mu \approx 4500$  and  $\sigma \approx 2.5 \cdot 10^6$  S/m. If the rotor has a bias pole arrangement shown in Fig. 8a and spins at 30,000RPM (f=500Hz,  $f_e$ =1000Hz), the skin depth would be only 0.15mm (0.006"). Since the magnetic flux density in ferrous materials is limited by material saturation to approximately 1.5T for regular steels and about 2.1T for cobalt alloys, very limited magnetic flux will be able to flow in this thin surface layer. In other words, the bias flux, and similarly, the control flux, will be expelled from the rotor and the bearing will cease to function at speed.

In order to avoid expelling the magnetic flux from a spinning rotor, rotor portions interacting with stationary parts of magnetic bearings are normally made out of electrically insulated steel laminations stacked in the axial direction. The electrical insulation between the laminations breaks up the paths for eddy currents. Note that there still will be eddy currents within each lamination and the radial bearing capacity will start deteriorate once the skin depth calculated using equation (4) becomes smaller than the lamination thickness.

The radial magnetic bearings illustrated in Figs. 7 and 8 are called heteropolar because the polarity of the bias poles changes around the rotor circumference. This is a consequence of the magnetic fluxes being constrained to one plane normal to the rotation axis (magnetic flux lines always form closed loops - if they exited at one pole they always will have to come back in the other, and in case of heteropolar bearings both poles lie in the same plane).

# PM Bias, Homopolar Magnetic Bearings

Calnetix has pioneered commercial use and holds several key patents on another type of radial active magnetic bearing – the homopolar, PM-biased active magnetic bearing. The basic structure of such a radial active magnetic bearing is shown in Fig. 9, a 3D illustration in Fig. 10 and the operational principle is explained in Fig. 11.



FIG. 9



FIG. 11

To better understand the operation of this type of radial magnetic bearing, we need to note that the magnetic field in the air gap between the electromagnet poles and the rotor is proportional to the control current. Thus there is a bias magnetic field component  $B_0$  that is proportional to  $I_0$ . Similarly, there is a control magnetic field component  $B_c$  that is proportional to  $I_c$ . Then, equation (3) can be rewritten in terms of magnetic fields (magnetic flux densities) instead of currents:

$$F \sim 2B_0 B_c \sim 2B_0 I_c \tag{5}$$

One important difference between the radial active magnetic bearing shown in Figs. 9 through 11 and the one shown in Figs. 7 and 8 is that the bias magnetic field  $B_0$  in Figs. 9 - 11 is generated by permanent magnets rather than currents in coils. A critical advantage of permanent magnets is that they produce the bias magnetic field without consuming power, and even more importantly, without generating heat. This translates into a smaller size for the PM bias active magnetic bearing compared to an equivalent EM biased active magnetic bearings. The explanation is as follows.

When a certain magnetic field is generated by a coil, the resistive heat generated by this coil in the process depends inversely on the amount of a conductive material (typically copper) in the coil: more copper means less heat. Because the coil temperature rise and subsequent heat generation must be limited, the size of a typical electric coil needed to generate a certain magnetic field in an active magnetic bearing is several times bigger than a modern rare-earth magnet needed to generate the same field.

While it is possible to use a dedicated coil to generate the bias magnetic fields in EM biased active magnetic bearings, in most commercial implementations a single coil accommodates both the bias and control currents. The advantages of this approach are fewer terminal wires, less complexity and less cost, while the disadvantage is a lower dynamic force capacity due to increased inductance of the combined bias/control coil. In any case, either the net size of both dedicated bias and control coils or a the size of a combined bias/control coil in and EM biased active magnetic bearing would be significantly larger than the combined size of a permanent magnet and a control coil in a PM-biased active magnetic bearing. A smaller magnetic bearing normally leads to better rotordynamic performance of a machine and more robust operation.

In Calnetix Radial AMBs, the permanent magnet generating the bias magnetic field is sandwiched axially between a radial pole assembly and so called "dead" pole as shown in Figs. 9 through 11. The bias magnetic field generated by the magnets is delivered by the "dead" pole to a soft-magnetic shaft, which further transfers the field to a laminated actuator target. The field exits the target radially, crosses radial air gap, enters the radial pole assembly and travels within it towards the magnet to complete the loop.

The radial pole assembly has two pairs of diametrically opposite magnetic poles with electrical windings around them. The electrical windings associated with each pole pair are connected in series so that they produce magnetic fields in the same direction along the pole axis.

Fig. 11 illustrates generation of a radial force along the vertical *Y* axis as an example. When the coils wound around poles 2 and 4 are energized with a current *I* as shown in Fig. 11, they produce a control

magnetic flux that adds to the bias flux in the top air gap under the pole #4 and subtracts from it in the bottom air gap under the pole #2. As a result, the net magnetic flux density becomes larger in the top air gap, and the magnetic force pulling the rotor toward the pole #4 (up) becomes larger than the force pulling it towards the pole #2 (down). Thus applying a control current *I* to coils #2 and #4 results in a net magnetic force directed upwards (positive *Y* direction). Reversing the current reverses the direction of the force. Applying a current in a similar manner to coils #1 and #3 will produce a force in the *X* directions and a combination of two currents allows generating a force in any direction in the radial plane.

A very important advantage of the bearing shown in Figs. 9-11 over the bearing shown in Figs. 7-8 is that the bias magnetic polarity is uniform around the circumference of the rotor. For example, in Figs. 9-11 each of the control poles #1 through #4 has "South" polarity and the entire ID of the dead pole has "North" polarity. Therefore, almost no bias flux will be expelled from the rotor due to eddy currents induced when the rotor spins as opposed to the design shown in Figs. 7-8 (a small portion of the bias flux will be expelled because of discontinuities between active poles 1-4). If we were only concerned about the bias field, the actuator target on the rotor would not even have to be laminated.

When the bearing shown in Figs. 9-11 generates a radial force, such as  $F_Y$  force in Fig. 11, however, the control component of the magnetic field will be non-uniform around the rotor and it will tend to be expelled by the eddy currents. Even if we lose only  $B_c$  component in equation (5), however, we still lose the load capacity. Therefore, the actuator target in the design per Figs. 9-11 still has to be laminated.

Important advantages of the design shown in Figs. 9-11 over the design shown in Figs. 7-8 at speed is that

a.) There is no loss of  $B_0$ . Therefore, if the same laminations as in heteropolar bearings are used, and even if we assume that  $B_c$  is the same as in heteropolar bearings, the load capacity would already be retained better at speed than in heteropolar bearings. (In reality  $B_c$  in homopolar bearings will also be higher at speed than in heteropolar ones as explained below in item b.).

b.) The frequency of the control magnetic field variations that the rotor sees at speed are at least two times lower in the design per Figs. 9-11 than in the design per Figs. 7-8. According to eq. (4), this means that either  $B_c$  will be retained better at speed, or thicker (cheaper) laminations can be used.

Both items a.) and b.) above lead to better retention of the load capacity in homopolar bearings at speed (provided that the same lamination thicknesses are used).

# **Axial Magnetic Bearings**

In addition to radial support, turbomachinery rotors normally require axial support as well. The structure of a conventional axial magnetic bearing used by most magnetic bearing companies is shown in Fig. 12. The operation of this bearing is identical to the operation of the radial bearing shown in Figs. 7-8.

Depending on the situation, Calnetix sometimes also uses the axial bearing shown in Fig. 12 as well as a variety of PM-biased radial bearings. In most cases, however, Calnetix selects a patented unique magnetic bearing design that combines functions of both axial and radial bearing in one device - combo magnetic bearing. The structure of this bearing is shown in Fig. 13, 3D representation in Fig. 14 and the operational principle is explained in Fig. 15.

The structure of the combination bearing shown in Figs. 13 and 14 is largely similar to the structure of the radial bearing shown in Figs. 9-10 but the dead pole is replaced with two axial poles located on the axially opposite sides of a solid axial actuator target. The bias flux generated by the permanent magnet flows radially in the radial pole assembly exactly as it does in the radial bearing per Figs. 9-11, but on return it gets divided between two axial poles (see Fig. 15).

If the axial actuator target is centered between the inner and outer axial poles, the magnetic flux density on the left side of the target would be almost the same as on the right side and the net axial force on the target would be approximately zero. An axial control coil sandwiched between two axial poles induces magnetic axial control flux in those poles when energized with a current. This flux circulates in a loop formed by the axial control poles magnetically connected to each other on the OD and an axial actuator target. It does not propagate much into the radial pole assembly because it is difficult for it to cross the permanent magnet (the permanent magnet has a large magnetic reluctance).

When the axial control winding is energized with a current directed as shown in Fig. 15, it adds to the bias flux in the inner (left) axial pole and subtracts from it in the outer (right) axial pole, resulting in a higher magnetic flux density on the left side of the actuator axial target than on the right side, and, consequently, an axial force pulling the rotor to the left (positive *Z* direction). Reversing direction of the axial current reverses the direction of force.

The compensation coil sandwiched between the radial pole assembly and the inner axial pole serves to stabilize the bias magnetic flux when the axial control coil is energized with a current. The compensation coil and the axial control coil are connected in series but wound in the opposite directions.

Mechanism of generating radial forces in the combo bearing is exactly the same as in the radial bearing and can be understood from Fig.11 and the accompanying description.



FIG. 12







FIG. 14





Advantages of using a combination bearing per Figs. 13-15 instead of an arrangement of separate radial and axial bearings such as shown in Fig. 12 include:

- 1. Shorter axial length leading to a more compact design and better rotordynamics
- 2. Lower aerodynamic drag due to lower axial actuator target OD
- 3. Lower stresses in the rotor due to lower axial actuator target OD
- 4. Lower part count
- 5. Lower cost
- 6. In many cases, better axial bandwidth (more load capacity at higher frequencies)
- 7. Lower, and nearly constant, negative stiffness.