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Analysis of Permanent Magnets Bearings in Flywheel Rotor Designs

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ABSTRACT
This paper discusses analysis of permanent magnet bearing in flywheel rotor designs. This work focuses on the advantages of using permanent magnets in flywheel rotor design as compared to that of the convectional mode of levitating the rotor position. The use of permanent magnet in magnetic bearing design to generate the steady state position of the magnetic field results in less variation of the force exerted on the rotor when it deviates from the nominal position than when an electrical coil is used for the same purpose. Theresults of the analysis shows that the magnetic bearing dynamics as well as its load carryingcapacity improves when the rotor is offset from its central position. The use of permanent magnet compared to current-carrying coils results in smaller overall size of magnetic bearing leading to a more compact system design resulting in improved rotordynamic performance.

***Keywords*:**Flywheel,Levitation, Magneticflux density,Permanent magnet bearing,Rotor,

I. INTRODUCTION

A magnetic bearing is a bearing which supports a load using magnetic levitation. Magnetic bearings support moving machinery without physical contact, for example, they can levitate a rotating shaft and permit relative motion without friction or wear. They are in service in such industrial applications as electric power generation, petroleum refining, machine tool operation and natural gas pipelines. They are also used in the Zippe-type.

“Early active magnetic bearing patents were assigned to Jesse Beams at the University of Virginia during World War II and are concerned with ultracentrifuges for purification of the isotopes of various elements for the manufacture of the first nuclear bombs, but the technology did not mature until the advances of solid-state electronics and modern computer based control technology with the work of Habermann and Schweitzer.

The use of magnetic bearing in flywheel energy sources has become an important topic for industries, universities and research institutes. Recent developments in permanent magnets and super-conductors has strongly contributed to the development of the magnetic bearings, the State of the art permanent magnets and super-conductors design and applications are applied in a flywheel energy storage system application which has

recently contributed to improving the system performance.

Magnet bearing using permanent magnets and superconductors has strongly reduced the energy losses associated with flywheel energy storage designs. Flywheel with magnetic bearing is increasingly becoming a suitable solution for medium term energy [1,2].

There are three types of bearings: the passive bearings, the active bearings and hybrid bearings. Passive magnetic bearings (PMB) are the simplest approach and are based on a permanent magnet. This permanent magnet is designed in order to support and levitate object, making it contact free from the rest of the structure. Active magnetic bearings (AMB) consist on a coil supplied by a current source producing a magnetic force adequate to levitate the object. The AMB coils may be simple conductors, but recent prototypes using high temperature super conductors (HTSC) have been highly developed for high speed rotating rotors [3,4].

II. THE MAGNETIC BEARING AS A CONTROLLED SUSPENSION

Magnetic bearings can be basically categorized into two groups depending on the physical cause of the magnetic effect involved [5]. The first group is referred to as reluctance force bearings, whiles the second group is made up by the Lorentz force bearings. Whereas the latter bearing type has lately gained an increasing importance mainly in the field of the self-bearing motors, it is still the case that the bulk of industrial magnetic bearing applications employ reluctance force bearings.

Active magnetic radial bearing areconstructed with the combination of permanent magnets in order to provide bias force and electromagnets to generate control forces in order to reduce cost and operational energy consumption in all electromagnets designs[6]. Ring-shaped permanent magnet consisting of axial magnetization are attached to a shaft which shares their magnets with the electromagnets. The magnets cores are made of solid iron of simplicity. The electromagnets are constructed with a pair of magnet coils that are wound around the stator positioned on the radially opposing side: the pair of magnet coils are connected in series and are driven by electrical motor.

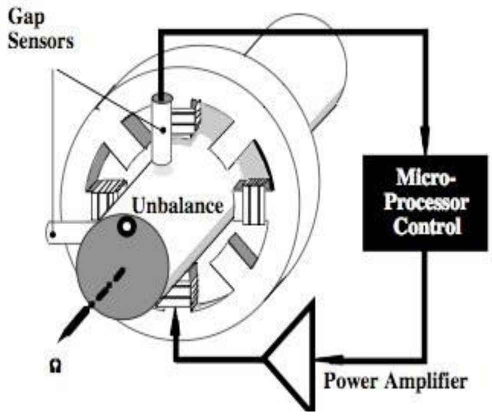


Figure 1. Generic structure of an active bearing [6]

2.1Elements of the Control Loop

Fig. 2 depicts a simple example of a magnetic bearing control loop though comprising all the necessary components of a "standard" active magnetic bearing system. In the following, sections these elements and functionalities are briefly described.

A rotor ("flotor" for non-rotating objects) is to be levitated freely at a prescribed distance $x_0$from the bearing electromagnet. A contact-less position sensor (most often an eddy current or inductive type sensor) steadily measures the deviation between desired position $x_0$and actual rotor position x and feeds this information into a controller (nowadays most often a digitalcontroller). The primary goal of the controller is to maintain the rotor position at its desired value. For this not only an equilibrium of the involved forces here just the magnet force $(f_m)$and the rotor weight (mg) must be established but also, as a most important quality of the control, a stabilizationof the control loop must be achieved (see further below in this section what renders the open-loop system unstable). Finally, the controller sends out a positioning command signal to a power amplifier which transforms this signal into an electric current in the coil of the bearing electromagnet and a magnetic field in the iron of the magnet, thus generating the desired magnet force (f_m)..

Rotational and transverse motions of the rotor cannot be controlled by a single electromagnet and require a more complex arrangement of several magnets and a multi-channel control. Nevertheless, the basic properties of a magnetic bearing control loop can be easily investigated using this simple bearing example, for which a mathematical model is derived in the following section.

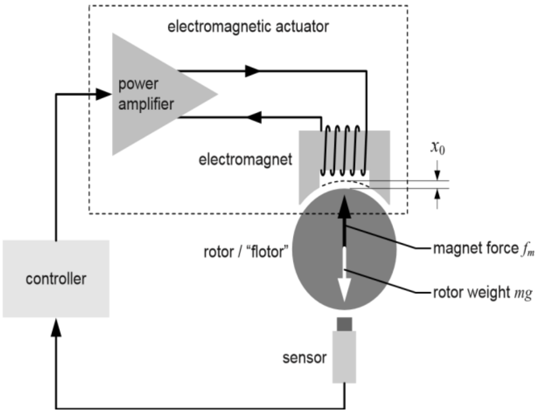


Figure 2. Magnetic bearing control loop and its elements

III. PERMANENT MAGNETS MATERIALS

The choice of the permanent magnet is an important factor on the design of the PMB and HMB. The principal permanent magnets used on magnetic bearings are:

- Neodymium, iron and boron (Nd, Fe and B)
- Samarium, cobalt, boron (Sm Co, Sm Co B)
- Ferrite
- Aluminum, nickel, cobalt (Al Ni, Al Ni Co)

An important characteristic of these magnets is their hysteresis loop. As it is well known, the operation point of the permanent magnets used on magnetic bearings is between point B and C as represented in fig. 3

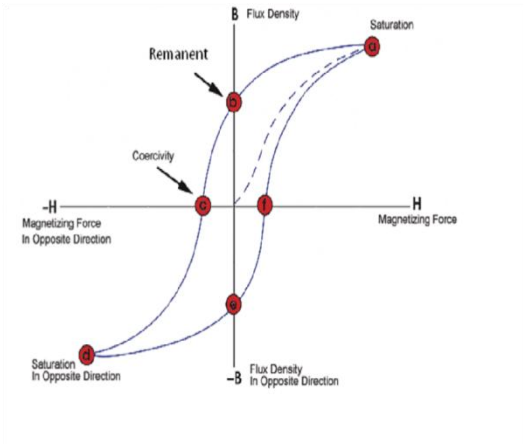


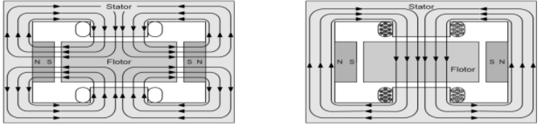
Figure 3. Hysteresis loop

IV. MAGNET CIRCUIT THEORY AND DESIGN

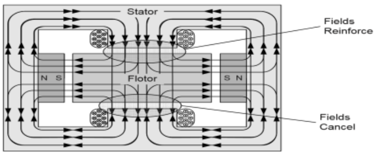
The magnets of an active magnetic bearing can be commonly operated at a bias point. As this principles of biasing tends to linearize the actuator, the bias field tends to do no work, as such it is usually possible to provide the field using a permanent magnet rather than electromagnet.Permanent magnet biased bearing uses permanent magnet to generate the field and electromagnets to redistribute this field to be able to produce net forces.

Advantages associated with such arrangements are electrical power losses which are associated with generating the bias filed are eliminated which ensures that less electrical power is consumed.The magnetic circuit shown in fig. 4 (a-c) illustrates the various essential concepts. The idea of the circuit depicts how a net force is to be produced in the vertical direction to achieve self-centering position of the rotor.

Fig. 4a illustrates the control coils which are not energized and the permanent magnets, produces a bias flux distribution which is then directed towards the center of the flotor.In Fig. 4b, flux due to permanent magnets are not shown, but in this case the control coils are now energized which then produces a flux that passes vertically through the flotor.



(a) Bias field (b) Control field



(c) bias and control fields

Figure 4. Schematic of a very simple PM biased electromagnet.

Fig. 4c illustrates the superposition of the bias and control fields. The field are made to reinforce each other in the upper gap but tends to cancel one another in the lower air gap. The result is that the net flux which exist in the upper gap is larger than that of the lower gap leading to a vertical net force on the flotor.

V. RADIAL BEARING OF A PERMANENT MAGNETIC BIASED MAGNETIC

The structure consists of two stator pieces of homo-polar type radial magnetic bearing depicting its control flux and bias flux. The magnetic bearing stator is configured by two ferromagnetic rings with stator poles which are separated by permanents. Fig. 5Shows the functional principles of radial permanent magnets used in flywheel energy system rotors

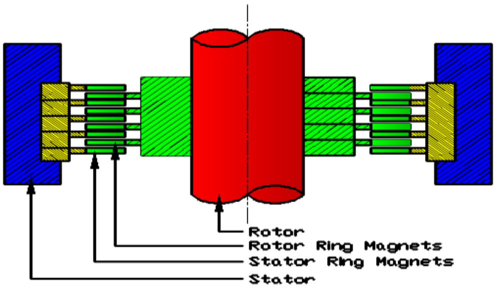


Figure 5. Sketch of a functional principle of a radial PMB

Active magnetic radial bearing is constructed with the combination of permanents in order to provide bias forces and electromagnets to generate control forces in order to reduce cost and operational energy consumption in all electromagnet designs. Ring-shaped permanent magnet consisting of axial magnetization are attached to a shaft which shares their magnet with the electromagnets. The magnets core are made of solid iron of simplicity.

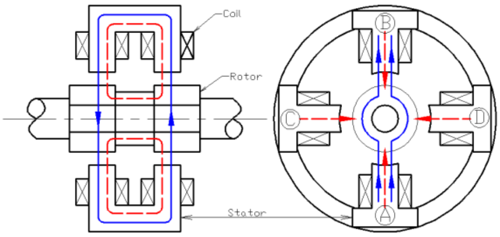


Figure 6.Magnetic flux pathof a radial bearing for a permanent magnetic biased bearing.

The electromagnet are constructed with a pair of magnet coils that are wounded around the stator positioned on the radially opposing side, the pair of magnet coils are connected in series and are driven by an electrical motor. Fig. 6 shows the magnetic flux path of the radial bearing, neglecting flux leakages. The permanent magnetic flux, providing bias flux flows, radially in the iron-core ring and goes into the four poles of the stator through the airgaps and then passes through the stator alongside the axial direction to return to the rotor via the other airgaps. The electromagnet flux generating from the upper and lower magnets coils passes down through the rotor along the radial direction on one side, and passes up through the other side. Thus, if the total flux increases in the lower side, then it decreases in the upper side. The difference of the flux produces a control force with this design, we can cancel out the bias flux with the electromagnet flux. This is a point similar to all electromagnet cases and design principles.

5.1 Force System Diagram.

The resulting force understudy in fig. 7 in this configuration depends on the flux density distribution in the bearing air gap. Before studying the flux density distribution, it is outmost importance to study and describe the forces present in the system.

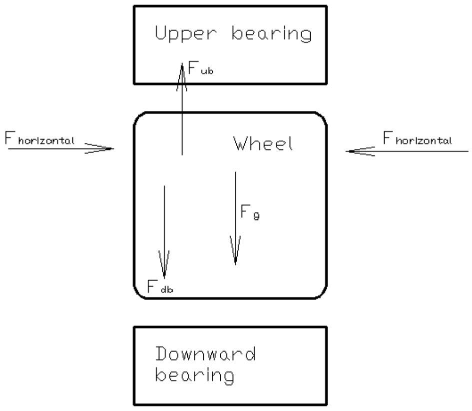


Figure 7. Forces applied to the system

The resulting force is composed of into two components: the vertical and the horizontal force, the various forces present in the system is composed by a wheel weight (f_g), which is the force the downward bearing applies on the wheel and the resulting force by the magnetic circuit of the upper bearing. The results of the forces should automatically be null in order to guarantee the objective of a contact free system. The resulting horizontal force eventually guarantees the centering of the wheel; this horizontal force is maximized to ensure the stability of the system.

The horizontal force ensure that the instabilities do not cause any change or discharge of the wheel.

Equation (1) and (2) represent the influence of the force (effect) and pressure (effect) of the flux density of the air gap in the rotating mass.

$$F = \frac{SB^2}{\mu_o} \quad (1)$$

$$P = \frac{B^2}{\mu_o} \quad (2)$$

From equation (1) and (2), the flux is related with the flux density as shown in equation (3)S

$$\emptyset = B.S \quad (3)$$

From equation (1) and (3) it is possible to verify that the magnetic force in the air gap solely depends on the flux and on the section (S) that is perpendicular to the flux density as shown in

$$F = \frac{\emptyset^2}{S\mu_o} \quad (4)$$

VI. MAGNETIC FLUX DENSITY ANALYSIS

A simplified homopolar active magnetic bearing which has been used in the flux density distribution analysis in this research work. The rotor balance position is suspended by the common effect of the permanent magnet field and electromagnet field as indicated in fig. 8 when there is an experience of an external disturbance the rotor moves up and down from the balance position, the upper air gap becomes big and the lower air gap becomes small. The enlarged air – gap will then decrease the permanent magnetic field intensity and magnetic force, whiles the reduced air gap increases the permanent magnetic intensity and magnetic force, this causes the rotor to continue to move downwards and will not return back to its balance position.

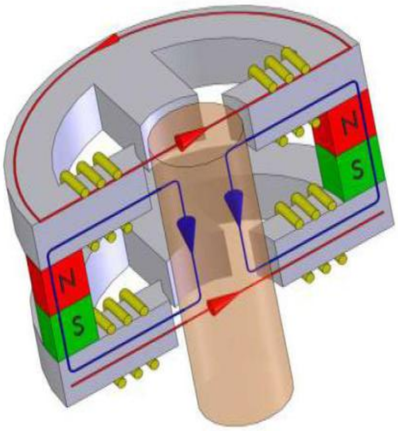


Figure 8. Homopolar active magnetic bearing

If the control current is added into the control coils the upper air gap field and the permanent magnetic field. The lower air-gap field which is the difference between the electromagnet field and the permanent magnetic, so the upper magnetic force is larger than the lower magnetic force and the rotor can come back to its balance position under the resultant force.

The force acting on the rotor are related to the flux density of the air gap, considering the force in the Y-direction(F_y), with a rotor displacement y and a current applied on the coils on the y- axis for both air gap, results in the force in the y direction as

$$F_y = \frac{B_1^2.A_g}{\mu_o} + \frac{B_2^2.A_g}{\mu_o} \tag{5}$$

In which B_1 is the upper air gap magnetic field, B_2 is the lower air gap magnetic field. The relationship between magnetic field intensity and magnetic force, the rotor resultant force equation is

$$F_y = \frac{\mu_o H_c^2 L_m^2 A_m^2}{4A_g}\left[\frac{1}{(g_o+y)^2} + \frac{1}{(g_o-y)^2}\right] + \frac{\mu_o H_c^2 L_m^2 A_m^2 N_i}{2(g_o^2+y^2)} \tag{6}$$

Where the coefficient is the vacuum magnetic conductivity, N is the number of turns of control coil, and the coefficient is the working current of control coil. Magnetic flux density dependent upon the permanent geometry, the turns of coil and the current passing through the coil. Hrepresents the coercive force from the magnet, B_r is the remanence flux density, Ais the cross-sectional magnet surface area, L_m the balance position, the magnetic equation will be achieved as follows

$$F_y = K_y y + K_i i \tag{7}$$

Where K_y the displacement stiffness coefficient is K_i is the current stiffness coefficient.

The material for the stator is chosen as silicon steel iron core, which usually behaves as a linear property around 1.2 tesla flux as flux density. The maximum force capacity depends on the pole area (A_g) and the maximum flux density (B_y). From the foregoing relationship of the above circuit theory the area of the pole shoe area can be formulated below as

$$A_g = \frac{F_{max}\,\mu_o}{2B_s^2} \tag{8}$$

The 3D permanent magnet is designed by FEA magnetic field analysis with ANSYS workbench software which has a computational environment of linear and nonlinear magneto static modelling of all parts including permanent magnet. Fig.9 shows the initial simulation permanent bearing model with zero control current.

The flux path shows that flux permanent magnet bias flux flows into the rear side stator pole then the flux flows into the rotor via air gap. Afterwards, the flux returns from rotor to the permanent magnet via the far side rotor.

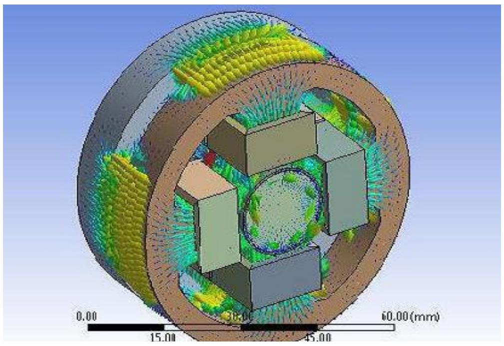


Figure 9.Vector plot of magnetic flux density

At conditions when no static load or any external disturbances are experienced by the rotor, mo current flows through the coil and is only the bias fluxes which are made to flow through the air gaps by permanent magnet, as such the air gap flux densities are almost identical and equal in nature.

The magnetic flux density in difference will act force on the rotor, the rotor at the center position sum of the force must be zero,the rotor without control current radial magnetic flux in the air gap which has equal distribution in all direction so that the total summation of the magnetic force on the rotor is zero and it is levitated on the Centre position, the aim is to provide a bias magnetic flux in air gap to 0.5T, is achieved by different simulation taking place by changing the area of the permanent magnet. The maximum magnetic flux density distribution of the air gap front magnetic bearing 0.516T and in the case of the rear
r magnetic bearing it became 0.499T.

6.1Rotor Displacement

It is usually impossible to control the rotor in the equilibrium state and the rotor displacement is usually controlled in a certain range according to the requirement of the design precision. When the rotor is at a distance of y=0.4mm, x=0. i=0, the air gap flux density distribution for only permanent can be calculated as shown in figure 5, from which it can be detected that the air gap flux density distribution consists of variation as compared with those in equilibrium state. As the rotor moves 0.4mm in y direction. Magnetic flux density is high in the upper air and less in the lower air gap. It can be seen from the foregoing that the +y air gap flux densities are larger than the –y air gap densities because of the +y rotor displacement. The resultant force in the +y direction is produced by the bias fluxes.

When X = 0, Iy = 0, the relation between the radial magnetic force Fy for different displacement y (-0.4 to 0.4mm) are illustrated on the graph in figure 10. For the front bearing position stiffness was determined as 0.425N/μm and the maximum force at 0.4mm was calculated as

198N. In the case of the rear bearing position the stiffness was calculated as 0.268N/μm and the maximum force at 0.4mm was 110N.

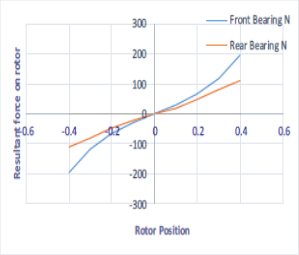


Figure 10.Displacement forces of rotor

6.2 Current force relationship

The resultant force as generated by the bias flux on the rotor in the y direction as the rotor offsets along from the direction is compensated by the control current given in the coil in the opposite direction, when a positive current I_y is applied, the +y air gap flux densities then decreases while the –y air flux densities tends to increases, which eventually decreases the resultant force and cause the rotor to return to its equilibrium.

The current v/s force relation of the front and rear magnetic bearing is illustrated on the graph in fig.11

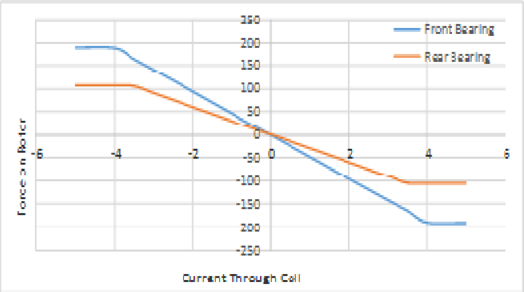


Figure 11. Current v/s force relation of the front and rear magnetic bearing.

Simulation of the analysis continues with the rotor at its centre position and the current in the coil is varied from +5A to -5A. The rotor is set into a position at -4A with current passing into the coil with flux density at this stage in the magnetic bearing is higher in the upper pole and lower in the lower pole by the cancellation of control flux and permanent magnet flux.

The current stiffness at this stage is calculated by changing the coil current from 5A to -5A when the rotor is at its centre position. The force current v/s force relation of the front and rear magnetic bearing is illustrated on the graph is deemed to be linear up to 4A and 3.5A for the front and rear magnetic bearing at a stiffness rate of 46.66 N/A for the front and 28.75 N/A for the rear magnetic bearing.

For the linear relation of current stiffness, the maximum current that is considered for the design is at 4A and 3.5A for the rotor position with its maximum force of 190N and 110N.

VII. CONCLUSION

Simulation of the design magnetic bearing for magnetic flux density and force dependency of current coil and rotor position are performed. From the prediction of current and position stiffness, it was shown that current stiffness provides more linearity than position stiffness. Simulation results of the control model presented shows that the flux permanent magnetic bias fluxes flows into the rear side stator pole, with the flux flowing into the rotor through the air gap when there is no static or external load disturbances on the rotor, on current flows through the coil and only bias fluxes flows through the air gap by permanent magnet.

Flux density distribution plays an important role in balancing the system as a result of the existence of permanent magnet, as it was considered earlier the resulting vertical force in the system must be zero in order to guarantee the levitation of the wheel and the horizontal force was responsible for the wheel centering.

Flux density distribution was considered as an important factor in order to be able to balance the force which existed in the system, as such in order to put the pieces in balance without contact and centering distribution is mandatory in the study of permanent magnet.

The use of permanent magnets to generate the steady position of the magnetic field (bias magnet field results in less variation of the force exerted on the rotor when it deviates from the nominal position than when an electrical coil is used for the same purpose. The results are an improved magnetic bearing dynamics and larger load capacity when the rotor is offset from the central position.

The smaller size of permanent magnet compared to current-carrying coils results in smaller overall size of a magnetic bearing leading to a more compact system design with an improved rotordynamic performance.

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