Development of a Passive Magnetic Bearing System for a Flywheel Energy Storage

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Abstract: Magnetic bearings are an attractive alternative to mechanical bearings in flywheel energy storage systems since they greatly reduce friction and wear. However, new problems are introduced in terms of stabilization; particularly the magnetic bearing must provide enough damping to reduce excessive vibrations. Two novel configurations of passive magnetic bearings are introduced to meet system requirements. The first configuration, utilizing two Halbach arrays, is proposed to introduce a levitating force as well as lateral stability. The second configuration uses a null-flux coil passive magnet array to add lateral stability. This paper will focus on lateral stability. Displacements in the lateral direction will result in a correction of rotor motion based on its velocity. In this work, firstly the configuration of the Halbach and null-flux coil arrays is presented. Finite element models are then developed for both cases to investigate the resulting magnetic field, its reaction to rotor velocity, and its effects on the system. As a result, it shows the effectiveness of the proposed configuration to stabilize the lateral dynamics of a flywheel energy storage system.

1. Introduction

It has been proposed that a flywheel energy storage system could be implemented to capture and store the energy captured from diverse energy production systems until it is needed. Later it can be converted into electrical energy. However, a major issue with this approach is the friction caused by traditional ball bearings as well as any potential support system for the flywheel. This friction will remove energy from the system, and in most cases will need to be greatly reduced for the system to function efficiently. To this end, magnetic bearings have been proposed as an alternative method of stabilizing and supporting the flywheel system. Magnetic bearings are placed either on the rotor or the stator with matching permanent magnets to produce a force.

Due to the dynamics of the system, the magnetic field being produced will experience motion relative to the permanent magnet. This results in eddy currents being created and dissipated; the force produced is a damping force proportional to the velocity of the change in magnetic flux. Hence, the resultant force will depend on both the position and velocity of the rotor. (Sze Kwan Cheah, 2008)

This paper will focus on the use of passive magnetic bearings (PMB) in this application. Though rotor motion cannot be corrected as accurately, PMB do not have to be controlled; thus, they consume less power.

In this paper, two magnetic bearing configurations are presented for use in a flywheel energy storage system. The first PMB configuration is composed of two Halbach arrays. These arrays can be used for stabilization as well as levitation of a vertical flywheel with coils placed on the perimeter and underneath the PMB. It has been shown in previous research that the magnetic field is concentrated on one side of the array and canceled on the other (Thompson W. K., 2006). This leads to the attractive motion correcting and levitation forces required in this system. In this paper, only the forces contributing to torsional damping and lateral motion correction will be discussed.

The second configuration proposed is a null-flux coil array. A null-flux coil uses two juxtaposed magnets with opposite coil windings to produce a magnetic field. Due to eddy current effects a small permanent magnet moving over the PMB will experience a correction in its motion to the center of the two magnets. This will result in the lateral correction of motion in a flywheel rotor. Damping
forces are also produced in the torsional direction, but these will not be investigated.

Once the configuration is fully described and the mathematics is rigorously defined the magnetic fields resulting from these PMB configurations will be modeled. For the Halbach configuration, the damping due to torsional velocity will be discussed as well as forces correcting its lateral motion. These results will be compared for various rotor velocities. For the null-flux coil array, only lateral correcting forces will be discussed.

Some assumptions must be made about the system to ensure accurate results. Neither torsional stability nor angular displacement will be considered in this paper to simplify analysis. The magnetic field results will also be limited to a 2-D plane. With more advanced work in this field these assumptions may be reconsidered and hence more in depth analysis could be performed to investigate the effects of Halbach and null-flux coil arrays in flywheel suspension.

2. System and Configuration

Halbach Array
For the system under consideration, a flywheel rotor will be positioned vertically. As it spins along its axis, several stability issues need to be explored. The rotor will need to be suspended against the force of gravity acting downward. This issue hopes to be solved by the use of the Halbach array; it will be attached to the bottom of the rotor. The magnetic field produced by the Halbach array will act against coils wound vertically. According to the following equation, this should result in a force counteracting gravity. More specifically, this force is given by a pressure over the surface area of the rotor. In the equation below, $\mu_0$ denotes the permeability of a vacuum, which is a constant. $P_{mag}$ denotes the magnetic levitation pressure. $B$ is the value of the magnetic field. It is this value that is to be investigated and determined in this paper.

$$P_{mag} = \frac{B^2}{2\mu_0} \tag{1}$$

It should be noted that this repelling force is due to the most attractive feature of the Halbach array: the magnetic field will be concentrated on the bottom of the array while canceled on the top. While this phenomenon will has been explained, it will not be investigated analytically due to simulation limitations.

The system described in this paper involves two concentric Halbach arrays with similar magnetization patterns. The first array is located on the end of the rotor, with the rotor occupying the center. The second Halbach array can be seen on the stator surrounding the rotor. It is believed that the interaction of these two arrays will result in a horizontal restoring force as well as damping forces that should be confirmed by analysis.

![Figure 1. Double Halbach Array Configuration.](image)

The effects of the Halbach configuration producing a restoring force in the radial direction are of the most importance. To describe the force produced by a current and magnetic field, the simple equation below is used.

$$F_r = B \phi \times I_z \tag{2}$$

Now an expression must be found for the magnetic field. The following equation describes the magnetic field in terms of a differential element of the field. For a circular ring magnet, the magnetic flux density $B$ has the differential equation below, where permeability and magnetization per unit length are given by $\mu_0$ and $M_0$ respectively (Cheng, 1992).

$$d\mathbf{B} = \frac{\mu_0 M_0}{4\pi} L \int_0^{2\pi} \frac{dt}{|r_1|^3} \tag{3}$$

where $\mathbf{R}$ is a position vector describing the position of the magnet in question. $d\mathbf{l}$ is a length vector describing a differential element of length along the magnet (Cheng, 1992).

$$d\mathbf{l} = -b \sin \phi \, d\phi \mathbf{i} + b \cos \phi \, d\phi \mathbf{j} \tag{4}$$

The drag force produced by Lorentz effects needs to be described. It can be shown that this force, which is dependent on velocity, is given by the following equation. $B_C$ gives the field in the center of the coil wire. $N_C$ is the number of coil turns. $L$ is the inductance. $R$ is the resistance, and $w^2$ is the excitation frequency of the circuit (Han, 2000).

$$F_x = \frac{\nu B_C^2 w^2}{2R} \frac{N_C}{(\frac{N_C}{R}) + 1} \tag{5}$$

Null-Flux Coil
The null-flux coil array uses two magnets with opposite coil windings to produce a force correcting rotor position if it is not centered between the two magnets. (Thompson M. T., 2000) A schematic of this configuration can be seen below.
Two forces produced by this configuration will be introduced. The first is the horizontal restoring force correcting the rotor’s motion. Though background theory will not be explained here, it can be shown that this force is given by the following equation (Han, 2000).

\[
F = \left(\frac{1}{2}\right) \left(\frac{a^2 \omega^2}{R^2 + \omega^2 L^2}\right) x + \left(\frac{1}{2}\right) \left(\frac{a^2 R (R^2 - \omega^2 L^2)}{(R^2 + \omega^2 L^2)^2}\right) \dot{x}
\]  

In the equation above, \(\alpha\) represents the magnitude of the magnet’s flux linkage with the lift magnets, \(\omega\) is the frequency at which the magnet passes the passive magnetic bearings, and \(R\) and \(L\) are the resistance and inductance of the bearings respectively. The \(x\) variable represents the position of the permanent magnet while \(\dot{x}\) can be thought of as its velocity.

A drag force is also produced by this array. Fortunately, the drag force falls at higher speeds. Though a drag force can be helpful in stabilizing the rotor under high speeds, an excessively high drag force can result in too much energy loss (Pilat). This drag force can be seen below (Han, 2000).

\[
F = \left(\frac{\pi}{2}\right) \left(\frac{a^2 x^2 \# \omega}{R^2 + \omega^2 L^2}\right)
\]  

In practice the materials chosen may deviate from those described here, but for the sake of analysis and simulation some materials will be assumed. Aluminum 2024 is assumed for the material making up the bulk of the rotor shaft. This is a common material chosen for such an application. In practice, however, a composite could be chosen to increase potential energy storage.

For the permanent magnet attached to the top of the rotor, which is used in combination with the null-flux coils to correct position, basic iron was used as the material. This basic ferromagnetic material should react appropriately under the influence of a magnetic field to correction rotor position.

The passive magnetic bearings to be utilized for the Halbach array and null-flux coils are assumed to be neodymium. Attractive features of this material include a high resistance to being demagnetized, as well as high saturation magnetization. The particular makeup of this material, along with its properties, can be seen in the appendix. In practice, wound coils may be used to create the passive magnetic field, with options for active control later.

### 3. Analysis and Simulation

#### Halbach Array

The Halbach array was modeled with a top-down view, with the rotor protruding out of the page. To simplify analysis and to aid in possible manufacturing of this rotor system, eight Halbach magnets were modeled in a cylindrical configuration with the rotor occupying the center.

Another Halbach array magnetized in similar directions is located around the perimeter of the array attached to the rotor. The magnetic field produced by this configuration should result in forces correcting the position of the array attached to the rotor.

The material chosen for the magnets was neodymium. This material, which is commonly used for passive magnets, has a magnetic strength value of roughly 750,000 A/m. For the rotor core, the material was chosen to be iron. This ferromagnetic material should respond accordingly to the induced magnetic field. The finite element mesh of this simulation can be seen below.

The simulation created was a parametric model. To this end, the velocity was varied and a magnetic field solution was plotted for each. Maxwell stress tensors were also output for each of these cases. Specifically, the velocity varied from 0 m/s to 100 m/s with a 10 m/s increase for each case. The velocity in question describes the tangential angular velocity of the inner Halbach ring. The magnetic field solution for the case with a velocity of 100 m/s can be seen below.
The magnetic flux density was also investigated. Along with the Maxwell stress tensor forces acting on the inner Halbach ring, it was plotted as a contour over the geometry. These results assumed a velocity of 100 m/s. It can be seen that the forces act to restore the rotor to its central position.

The velocity was chosen to act in a clockwise direction. It stands to reason then that the damping forces, otherwise known as Lorentz forces, act in the opposite direction. While these will reduce energy from the system, this damping force is critical to stabilizing the rotor. This is especially true at high speeds. The Lorentz forces were plotted graphically for the inner Halbach ring at a velocity of 100 m/s along with the magnetic flux density.

Unlike the Maxwell stress tensor forces and the magnetic flux density, the Lorentz forces depend on the angular velocity of the Halbach ring. To see this relationship, a cross section contour plot of one of the magnets making up the inner Halbach ring was created. The Lorentz forces on this section were compared for the various velocities used. This plot can be seen below.

Further information based on this model can be seen in the appendix. While more data was collected, those presented here is considered the most pertinent to the analysis.

Null-Flux Coil

The null-flux coil configuration was modeled using a radially symmetric, two-dimensional simulation. In the simulation considered, each magnet in this array has a square cross section measuring 0.2”x0.2”. Though this is a very small magnet, they could be scaled up in practice. Choosing the material to be neodymium, a conservative magnetic field strength value of 750,000 A/m was chosen. A full table of neodymium properties can be seen in the appendix. An iron ring with dimensions of 0.1”x0.1” was placed on the upper and outer edge of the rotor. The finite element mesh of this configuration can be seen below.
In the finite element mesh above, the dark lines represent boundary surfaces while the gray lines represent meshing elements. For this simulation, parabolic triangular elements were used.

The magnets were then magnetized as described in the theory; the rightmost magnet was magnetized with a value of 750,000 A/m into the plane and the leftmost magnet was magnetized with a value of 750,000 A/m into the plane. These magnetizations arise from the currents running through the wound coils. Maxwell surface stress tensor boundary variables were then computed. The forces on the rotor due to the magnetic field, along with a contour of the magnetic potential, can be seen below. As the model is axially symmetric about the left edge, these arrows indicate a radial force pointing inward, hence correcting rotor motion.

![Figure 9. Magnetic Field and Forces on Rotor.](image)

The value of the Maxwell stress tensor, which produces the force on the rotor, was also investigated along the length of the iron magnet boundary. Below can be seen a plot of how the magnitude of this radial correcting force varies over the magnet’s length.

![Figure 10. Maxwell Stress Tensor on Iron Magnet.](image)

Further information based on this model can be seen in the appendix. While more data was collected, those presented here is considered the most pertinent to the analysis.

### 4. Conclusion

In this paper, two configurations were considered for use as magnetic bearings in a flywheel suspension system. The radial Halbach array utilizing two concentric rings was considered for levitation of the rotor as well as lateral stability. A null-flux coil configuration was also considered for the top of the structure to further correct lateral motion. The Lorentz forces arising from the angular motion of the rotor were then investigated for a number of speeds. The null-flux coil array was then simulated. Using an axially symmetric 2-D model, the magnetic field and forces correcting to the rotor motion were modeled. The analysis results show the effectiveness of the proposed magnetic bearing configuration to stabilize the lateral dynamics of a flywheel energy storage system.

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### 5. References