Analysis of Active Magnetic Bearings

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***Abstract*—Stress developed due to the contact between mating surfaces i.e. Contact stresses and forces are the main factors inhibiting the further increase of efficiency of a system. Bearings are an integral part of all major mechanical systems. Thus, it has become essential to eliminate such induced losses. Also, due to the presence of contact stress, wear is induced, decreasing the life of the bearing. Active Magnetic bearing is a contactless bearing technology that aims to eliminate the drawbacks of roller bearings as well as journal bearings. Active Magnetic bearing is based on fundamentals of electromagnetic levitation through attractive forces. The load bearing rotor is suspended at the center of the stator. This project intents to analyze the existing practices in providing suspension to the rotor, and to indigenously design an active magnetic bearing based on the analysis. Another aspect of this project deals with the theoretical analysis of the active magnetic bearing. This is achieved through the estimation of slew rate and specific Load capacity. The estimation of force efficiency factor is achieved by means of experimental analysis on the Active magnetic bearing. We also aim to simulate magnetic fluxes and the forces generated in commercially available electromagnetic solvers based finite element method. The outcomes of our analysis will aid in the shrinking of this technology as well as aid in implementation to a wide range of mechanical systems.**

I. Introduction

Bearings are an integral part of all major mechanical systems, they are used to reduce friction when there is relative motion between two parts like shaft and housing. Generally, bearings are classified in two categories rolling contact and sliding contact bearings.

In rolling contact bearings, stresses developed due to the contact between mating surfaces i.e. contact stresses (hertz contact theory) and forces are the main factors inhibiting the further increase of efficiency of a system. Due to the presence of contact stress, wear is also induced. In Sliding Contact bearings, the viscosity of the lubricant induces the friction loss.

Thus, it has become essential to eliminate such induced losses. Magnetic bearing is a contactless bearing technology that aims to eliminate the drawbacks of roller bearings as well as journal bearings. Magnetic bearing is based on fundamentals of electromagnetic levitation. The load bearing rotor is suspended at the center of the stator. In current practice, this technology is being implemented in large scale turbomachinery.

Active magnetic bearings (AMBs), made of eight poles find their wider usage in flywheel energy storage systems, turbomolecular vacuum pump, artificial heart blood pump, etc., due to their built-in fault diagnostics, vibration free operation, and friction and wear [2] characteristics. Each pair of pole makes an electromagnet consists of iron-core and copper-winding. On passing the current through the copper wire of electromagnet, it attracts the rotor. Using four pairs of electromagnets, the motion of rotor in horizontal and vertical (x and y) directions can be controlled. The detailed description of working of electromagnet has been provided by Schweitzer and Maslen [1].

Here, N is the number of turns in single coil, I is the current, A_g is the area of air gap for one pole, G is the air gap, and g is the loss due to magnetic flux leakage and fringe effect. The value of g can vary from 0.6 (for very closely spaced poles with leakage) to 0.9 (for very well-spaced with low leakage). We have calculated this factor in our experimental analysis.

$$F = \eta \frac{\mu A_g}{G^2} (NI)^2 \cos(\alpha) \qquad (1)$$

From Eq. (1), it can be inferred that designing a magnetic bearing with more number of turns, higher current, and lesser air gap increases the magnetic force. But with more number of turns, the volume of the electromagnet increases. Increase in the current is limited by wire diameter and material saturation. Reducing the air gap reduces the reaction time for the controller to react and increases the complexity of controller. Therefore, there is a need to follow a systematic procedure [6] for designing the AMB.

Hsiao et al. [11] optimized the load carrying capacity and force slew rate by constraining the bearing geometry. Hsiao et al. [11] did not consider the losses, such as copper loss and iron loss, which constraint the performance of magnetic bearing. Further, Hsiao et al. [11] put a constraint on the minimum distance between the tips of the poles, which does not ensure the complete separation between the tips of winding. In the present study, both the aspects (separation between winding, copper, and iron losses) have been accounted for maximization of the magnetic force.

Shelke and Chalam [3] optimized the weight of the electromagnet and analyzed the losses (copper and iron loss) considering different number of poles and concluded that eight pole radial magnetic bearing reduces the total losses. As per Shelke and Chalam [3], on reducing outer diameter of magnetic bearing copper loss increases. This may be due to higher current to be provided in shorter stator radius compared larger radius stator to achieve same magnetic force. On the other hand, increase in outer diameter of the stator increases the core losses because the core loss proportionally increases with the increase in volume. Based on these considerations Shelke and Chalam [3] suggested a wire of cross-sectional area of 1.48 cm2 (1.38cm diameter) for 30A. Bakay et al. [8] explored the effect of angular velocity of rotor on copper and iron losses of AMB. As per Yanhua and Lie [6], the iron loss is proportional to the thickness of lamination and it is a higher-order function of flux density (B).It is noteworthy that various researchers [8–10] analyzed the losses in electromagnet but did not consider losses as a constraint. In the present study, the losses as constraints have been accounted.

After reviewing the literature, it appears that researchers have either considered geometrical constraints or analyzed the losses occurring in the electromagnet. Designing an efficient AMB requires considerations of all the geometrical constraints and losses. In the present work, constraint due to losses have been included by equating the heat generation and heat liberated and an appropriate winding interference constraint have been considered. In the present research, an effort has been made to maximize load carrying capacity using numerical method, for the given outer diameter of stator, shaft diameter, axial length, and the maximum permissible current.

Active magnetic bearings are a typical mechatronic product. They are composed of mechanical components combined with electronic elements such as sensors, power amplifiers and controllers which may be in the form of a microprocessor.
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II. Details about your design or method

Construction of the test rig involves fabrication of parts and its positioning. The positioning of components plays a pivotal role in the modularity of the test rig. The primary design consideration of the test rig is to provide rigid mounting for the bearings. The figure 2 shows the test rig through the means of CAD model. The test rig contains the two active magnetic bearings. This involves the one being manufacture with copper windings and the other manufactures with aluminum windings. This is done to increase the specific load capacity of the bearings. The details of this dimensionless factor are discussed in the next chapter. The fabricated model is shown in figure 5. The motor is treated as a shelf component and hence no included in the fabricated model and design.

Equations

Governing equation for the force generated

$$L_o = \frac{N^2 \mu_o S}{2g} \tag{2}$$

$$F = \frac{L_o}{2g} \cos(\theta)\, i^2 \tag{3}$$

$$F = \frac{N^2 \mu_o S}{2g} \cos(\theta)\, i^2 \tag{4}$$

Parameter	Value
Inner diameter of core	76 mm
Diameter of rotor	75.7 mm
Wire Diameter	0.5192 mm (24 AWG)
No. of turns	115
Pole Width	10 mm
Air Gap	0.35 mm
Area of Pole	724.24 mm^2

Table 1. Geometric Parameters

Using the Geometric parameters from Table 2 in the above stated equations following equation is obtained.

$$F = \eta\ 90.73\ i^2 \tag{5}$$

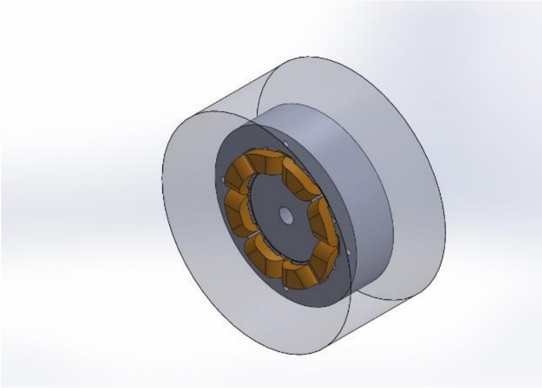

Figure 1. Solidworks model of the Active Magnetic Bearing

III. Simulation Results

The finite element simulation is conducted to visualize the generation of magnetic flux and visually understand the effects of change in geometry. The secondary aim was to verify the non-conventional method of manufacture of magnetic bearings used would perform as theorized. The finite elemental simulation was conducted in the **Electromagnetic simulation (EMS) suite** of the software developed by **EM Works** Inc. This suite was run on **SOLIDWORKS interface**. The steps involved in this type of simulation remain similar to conventional procedure i.e. Preprocessing, solving and postprocessing.

	Conductivity [Mho/m]	Relative permeability
Copper	57e6	1
Cold rolled Non-Grain oriented – Electrical Steel	1.1e6	4000
Air	0	1

Table 2. Material properties

Mesh Parameter	**Value**
Global Size	8.00037 mm
Tolerance	0.008
Avg. number of elements per diagonal of each solid body	38

Table 3. Material properties

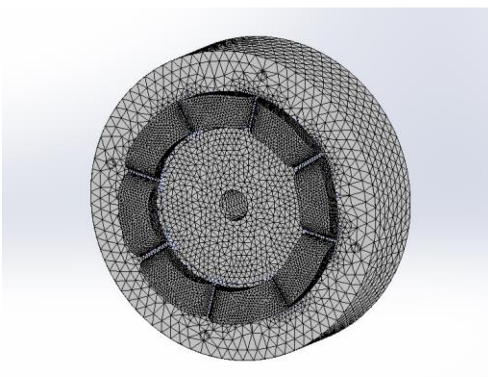

Figure 2 Generated Mesh

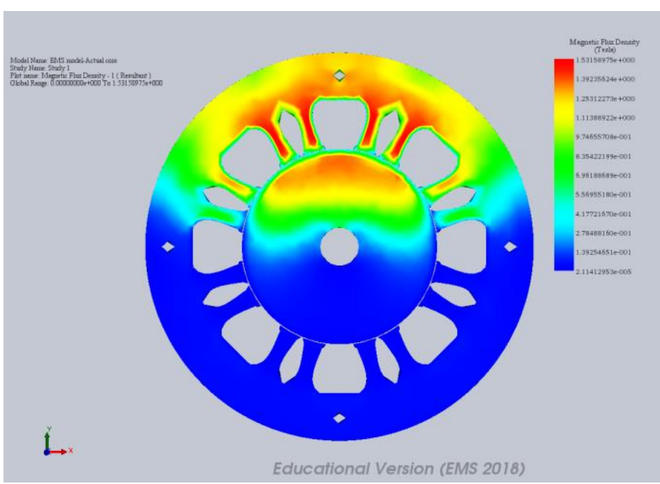

Figure 3 Contour Result of Magnetic Flux for Single Pole Actuation

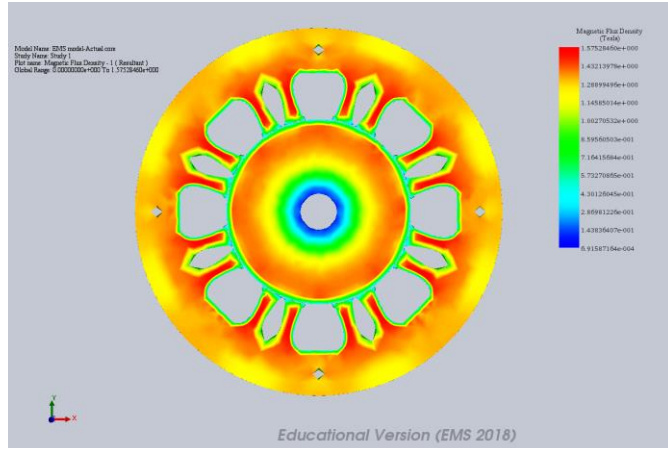

Figure 4. Contour Result of Magnetic Flux for complete actuation

The results are calculated in two stages:

- Single pole – Reluctance path visualization
  These results are generated to analyze the magnetomotive force per pole. The results are displayed in Figure 3. These results also help in the visualization, that the magnetic bearing works in accordance to Gauss Law. The forces generated in Single pole actuation are tabulate in Table 4.
- Complete Core Magnetization- This is performed to compute the magnetic flux saturation. The magnetic flux saturation in the major limiting factor in active magnetic bearings. These results are displayed in figure 5. The maximum saturation flux is 1.57 Tesla.

Force	**Current**
3.6292	**0.2**
14. 5168	**0.4**
32.6628	**0.6**
58.0672	**0.8**
90.73	**1**
130.65	**1.2**
177.83	**1.4**
232.68	**1.6**
293.96	**1.8**
362.92	**2**

Table 4. Simulation results

IV. Experimental Results

The experimental analysis is performed on the bearing with the following aims:

- To find the Force Efficiency Factor (η).
- To find the load vs current graph for the magnetic bearing.

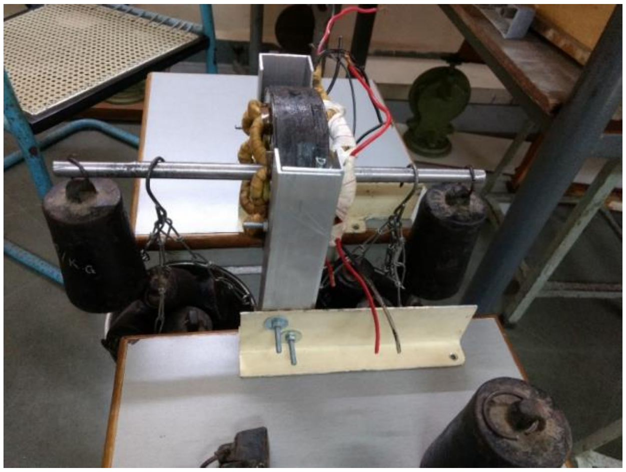

Figure 5. Contour Result of Magnetic Flux for complete actuation

Force	**Current**
2	**0.2**
10.5	**0.4**
20	**0.6**
40	**0.8**
60	**1**
84.92	**1.2**
111.5	**1.4**
150	**1.6**
195	**1.8**
220	**2**

Table 5. Experimental results

V. Comparison of Results

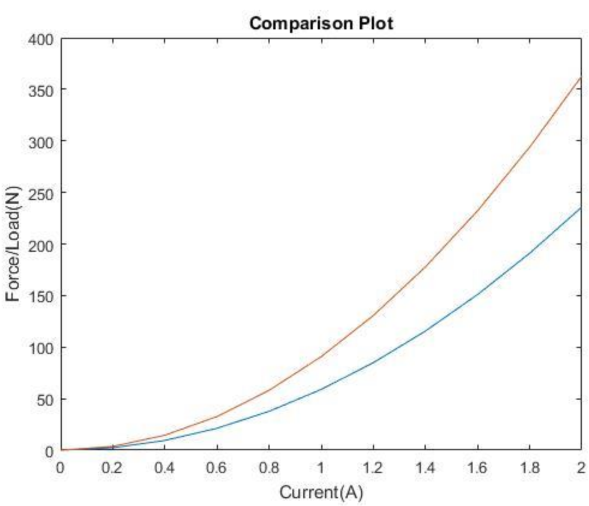

Figure 9.2 Comparison plot of the results (red line denotes Simulation results and blue line denotes the experimental results)

VI. Conclusion

A. The Load vs current characteristic curve is parabolic in nature. The force efficiency factor acts as a scaling factor to the curve. The force efficiency factor for simulation is found out to be 0.87. The force efficiency for experimental setup was found out to be 0.65.

B. The practical limitations of the magnetic bearing are studied and an attempt to theoretical analyze the slew rate for larger displacements is made. We can draw a conclusion that the slew rate is proportional to the velocity in the direction of motion.

$$\frac{dF_{res}}{dt} = k_1 \frac{dx}{dt}$$

$$\frac{dF_{res}}{dt} = k_1 V$$

C. The force efficiency factor depends on the slot leakage and the fringing effect.

D. The finite elemental results have aided in the analysis but computing the values of the saturation flux and aided in the selection of the material- Iron silicon steel Non – grain Oriented.

E. The current use of active magnetic bearings is limited to certain devices due to many factors. But largely used in flywheel energy storage and power generations, where the fluctuations are minimum.

F. The Active Magnetic bearings are based on a simple two pole electromagnet which is connect to an active feedback loop.

G. The rotor dynamics are an essential part of the analysis as the rotor is levitated. Through the basic theoretical analysis, governing equations are put forth. This is required as the damping present is minimal.

H. The electronic components are integral part of the bearing system. The different control techniques are studied and compared. PID techniques is the most simple and robust.

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