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(Full length research article)

# ANSYS software based simulation of Four-coil Active Magnetic Bearing

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**Abstract**

*The paper deals with the analysis of 4-coil Active Magnetic Bearing system by the Finite Element Method and the magnetic vector potential formulation. This work proposes an optimal shape and dimensions of the rotor and air gap. This paper also presents how the FEM Analysis can be used to perform the magnetic field analysis in the Active Magnetic Bearing (AMB). This paper reports ANSYS simulation of 4-coil AMB that uses four attraction type magnets are placed in 900 apart from each other. The AMB is an integral part of the industrial rotational machine laboratory model. The nonlinear solution of the magnetic vector potential is determined by using the 2-D finite element method. The force is calculated by Maxwell's stress tensor method. The electromagnetic field distribution and density analysis allow verifying the designed AMB and the influence of the shaft and coil current changes on the bearing parameters.*

***Keywords***: *Electromagnetic field, Active magnetic bearing, Finite Element Method, ANSYS software, Flux pattern.*

## 1. 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. Magnetic bearings are used in turbomolecular pumps where oil-lubricated bearings are a source of contamination. Magnetic bearings support the highest speeds of any kind of bearing; they have no known maximum relative speed. The Active Magnetic Bearing (AMB) use electromagnets to hold the load stable. The AMB is a bearing without physical contact between the rotary and the stationary part. In this way the friction and losses of friction can be fully eliminated. Without this physical contact, higher operation speed can be reached, and the device requires less maintenance, and so the lifetime can be increased, too. Unfortunately, the AMB requires continuous power supply for the electromagnets, and for the controlling electronic. Magnetic bearings are used to in lieu of rolling element or fluid film journal bearings in some high performance turbo machinery applications. Specific applications include pumps for hazardous/caustic fluids, precision machining spindles, energy storage flywheels, and high reliability pumps and compressors. Magnetic bearings yield several advantages. Since there is no mechanical contact in magnetic bearings, mechanical friction losses are eliminated. In addition, reliability can be increased because there is no mechanical wear. Besides the obvious benefits of eliminating friction, magnetic bearings also allow some perhaps less obvious improvements in performance. Magnetic bearings are generally open-loop unstable, which means that active electronic feedback is required for the bearings to operate stably. However, the requirement of feedback control actually brings great flexibility into the dynamic response of the bearings. By changing controller gains or strategies, the bearings can be made to have virtually any desired closed-loop characteristics. For example, flywheel bearings are extremely compliant, so that the flywheel can spin about its inertial axis--the bearings serve only to correct large, low-frequency displacements. Conversely, magnetic bearings in machining spindles must be extremely stiff and have a very broad bandwidth so that tool position is accurately controlled. In each case, the dynamic response is a result of the controller used to stabilize the bearing, rather than a consequence of the bearing's physical design. In recent years a number of machines with Active Magnetic Bearings were designed in order to eliminate the lubricant medium, vibration, noise and to achieve

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high velocities and loads. These systems are complicated due to mechanical, electrical and electronic circuit's construction. A wide range analysis is required during the designing procedure – from the construction stage up to the development of the control algorithm architecture. The finite element method can be a tool for magnetic field analysis. Many scientists working on magnetic bearings or self bearing motors use this method at the designing stage. The numerical analysis allows to check if the new proposed AMB structure is effective with respect to levitation forces, magnetic field properties and electro-mechanical interactions. The finite element method was also used to analyze the air gap flux and radial forces in the miniature self bearing motors [3], [4]. In small-sized systems essential modeling errors are often caused by leakage and nonlinear effects that could be neglected in larger systems. The appropriate AMB construction is a trade-off between many requirements and should be specific for different applications. The development stage of a machine equipped with the AMB demands the co-operation of many experts in mechanics, structure of materials, electronics and control. The proper machine construction, optimal AMB structure and dedicated control algorithm allow achieving a modern industrial unit.

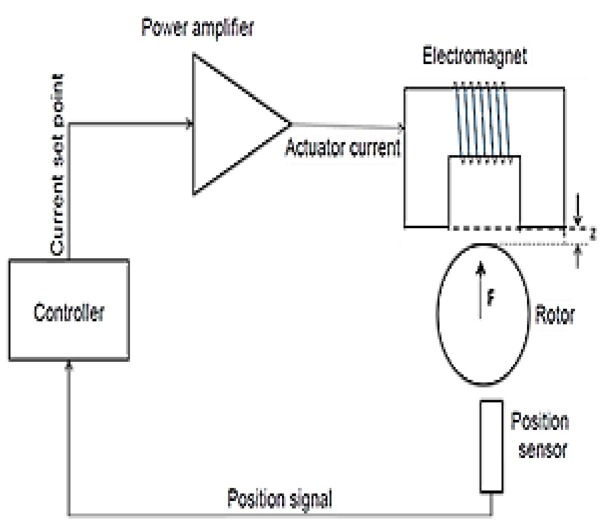


Fig.1. Basic block diagram of the active magnetic bearing

An active magnetic bearing (AMB) consists of an electromagnet assembly, a set of power amplifiers which supply current to the electromagnets, a controller, and gap sensors with associated electronics to provide the feedback required to control the position of the rotor within the gap. These elements are shown in the diagram. The power amplifiers supply equal bias current to two pairs of electromagnets on opposite sides of a rotor. This constant tug-of-war is mediated by the controller which offsets the bias current by equal but opposite perturbations of current as the rotor deviates by a small amount from its center position. The gap sensors are usually inductive in nature and sense in a differential mode. The power amplifiers in a modern commercial application are solid state devices which operate in a pulse width modulation (PWM) configuration. The controller is usually a microprocessor or DSP. Electrodynamics bearings (EDB) are a novel type of bearing that is a passive magnetic technology. The EDBs do not require any control electronics to operate.

**The Finite element analysis of AMB**

Magnetostatic problems are problems in which the fields are time invariant. To solve such a problem in the static case, Maxwell's equations are presented in the following form [7, 8]

$$\nabla X H = J \quad (1)$$

$$\nabla X B = 0 \quad (2)$$

$$\nabla . J = 0 \quad (3)$$

$$H = \frac{B}{\mu} \quad (4)$$

where H, B, J, and μ are the magnetic field intensity, the magnetic flux density, the source current density, and the permeability, respectively. The permeability is supposed to be constant, $\mu = \mu_0$ in air. and the relationship is used

$$B = \mu_0 \mu_r (H + M) = \mu (H + M) \quad (5)$$

where B is the magnetic flux density, H is the magnetic field intensity, J is the current density, M is the magnetization vector, μ is the material permeability, $\mu_0$ is the permeability of vacuum, and $\mu_r$ is the relative permeability of the material. Since the magnetic flux density is divergence free, there exists a magnetic vector potential $A$ such that B = $\nabla \times$A which gives the potential formulation.

$$\nabla X \left(\frac{1}{\mu} \nabla X A - M\right) = J \quad (6)$$

The magnetic vector potentials have been represented by first order vector shape functions which divergence is equal to zero, and it is resulting divergence-free magnetic vector potential (Coulomb gauge),

$$\nabla . A = 0 \quad (7)$$

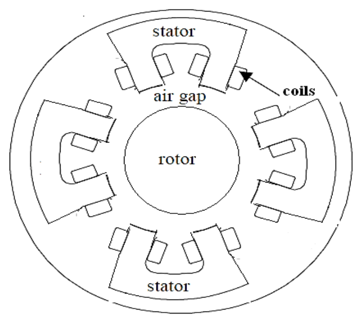


Fig.2 4-coil AMB construction

The designed construction of the AMB consists of rotor and stators with coils. The heteropolar construction of the AMB consists of four pole-pairs at 90 degrees apart (Fig.2). These four electromagnets are generating sufficient electromagnetic forces acting on the rotor for levitation and damping purposes [1, 2]. The considered AMB construction has the following parameters: no of pole pairs - 4, maximal radial air gap –( 0.25-1)cm, rotor outer radius – 50 mm, no of coil turns – (500-800),current range – (0-6) A.

**ANSYS Software based simulation for 4-coil AMB**

The finite element method (FEM) as a tool for solution of magnetostatic problems. In this method, the solution region is discretized into simple geometric shapes called finite elements. For each element, a stiffness matrix is calculated so as to relate the material properties and applied loads to the values at the nodes of the element as:

$$[\mathbf{K}^{e}]\ [\mathbf{x}] = [\mathbf{f}\ ]$$

where, $[\mathbf{K}^{e}\ ]$ is the element stiffness matrix, $[\mathbf{x}]$ is the vector of unknown nodal values and $[\mathbf{f}\ ]$ is the element's force vector. The element stiffness matrix depends on the geometry and properties of the element. For each type of problem, i.e. magnetic, structural or thermal, a specific element stiffness matrix has to be used. The element stiffness matrices will all be inserted into a global stiffness matrix $[\mathbf{K}^{G}]$ which relates all the unknown nodal values of the solution domain to the applied loads, and material properties as:

$$[\mathbf{K}^{\mathbf{G}}\ ][\mathbf{X}] = [\mathbf{F}]$$

where $[\mathbf{X}]$ is the global unknown nodal values and $[\mathbf{F}]$ is the global force vector. In magnetic problems, the two most common solution types are the magnetic scalar potential and the magnetic vector potential. As stated earlier in this chapter, the magnetic scalar potential is suitable for the solution domains in which there is no external source of current density available. On the other hand, the magnetic vector potential solution is suitable for the cases in which there is an external current density available in the solution domain. For the analysis of magnetic levitation systems, the source of the magnetic field is the external current density in the electromagnets and thus the magnetic vector potential formulation is used. In the next section, with the aid of finite element analysis, the design of the magnetic drive unit is addressed.

ANSYS Multiphysics is a powerful interactive environment for modeling and solving all kinds of scientific and engineering problems based on partial differential equations (PDEs). To solve the PDEs, ANSYS Multiphysics uses the proven finite element method (FEM). The software runs the finite element analysis together with adaptive meshing and error control using a variety of numerical solvers. The user can perform a various types of analysis including stationary and time dependent analysis, linear and nonlinear analysis, eigen frequency and modal analysis.

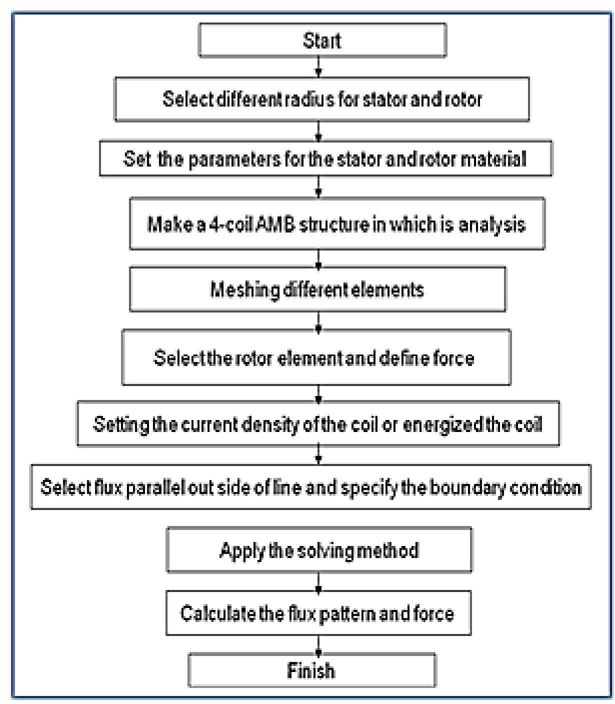


Fig.3 Flow chart of calculation of flux pattern and force by using ANSYS software for AMB 4-coil structure

**Simulation Results and Discussion**

Two-dimensional FEM simulation has been carried out to determine flux pattern, working flux density, force etc. for 4-coil AMB. Commercial FEM software ANSYS (version 12.1) has been used for this purpose

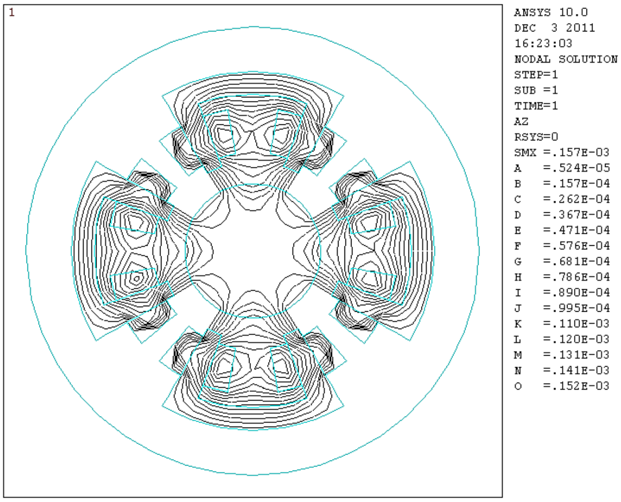


Fig.4 Flux of 4- coil AMB for z=0.5 cm, i=6A and N=500

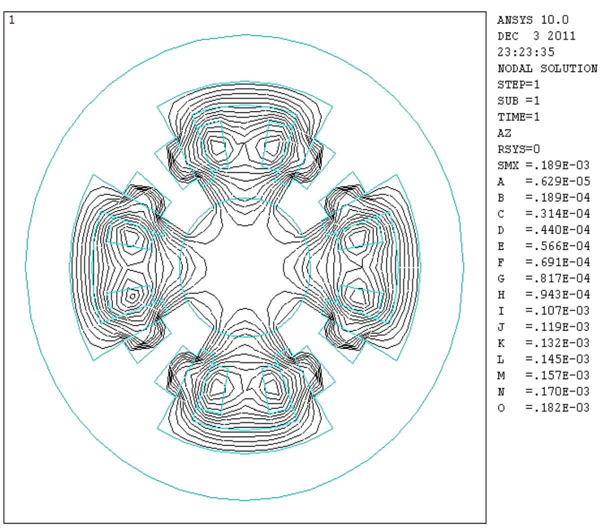


Fig.5 Flux of 4- coil AMB for z=0.5 cm, i=6A and N=600

The flux pattern of 4-coil AMB with air-gap of 0.5 cm and 6A current through the coil are shown in Fig.4.to Fig.6. It has been observed that the generated flux is increased with the increase of number of turns of coil. Fig.11 to Fig.13 represents the characteristic of flux, flux density and force of 4-coil active magnetic bearing for different number of turns of the coil. With the increase of air-gap leakage flux is increased and the flux linkage between magnet (stator) and rotor is decreased. The flux patterns are mutually linked with each other magnet as shown Fig.4 to Fig.6. The flux, flux density and force are decreased with the increase of the air gap between magnet (stator) and rotor as shown Fig.11 to Fig.13.

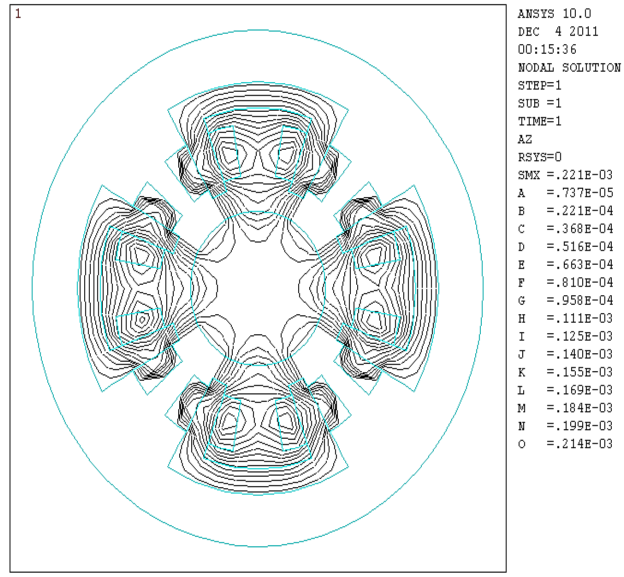


Fig.6 Flux pattern of 4- coil AMB for z=0.5 cm, i=6A and N=700

The generated flux, flux density and force are increased with increase of number of turns of coil and decreased with increase of air gap at the same current value. It has been noticed that the generated flux, flux density and force are decreased with increase of air gap and increased with the increase of coil current at the same number of turns of coil (Fig.14 to Fig.16). It has been noticed that the attractive force developed between stator and rotor has been decreased with the increase of air-gap. In actual situation the force between electromagnet and rotor will vary inversely proportion to the square of the air-gap.

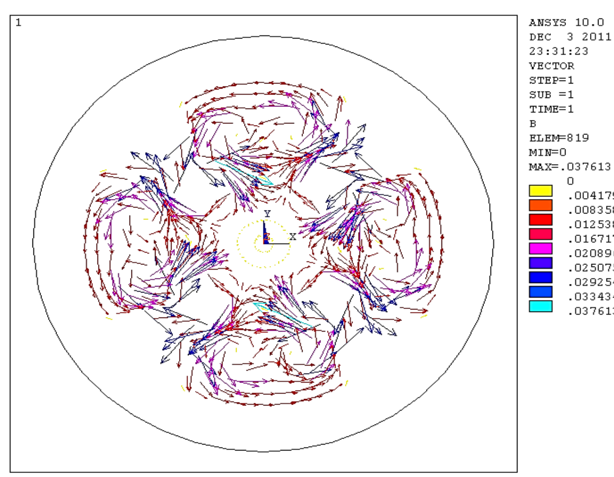


Fig.7 Vector plot of Flux density for 4-coil AMB for N=500, i=6A z=0.5cm

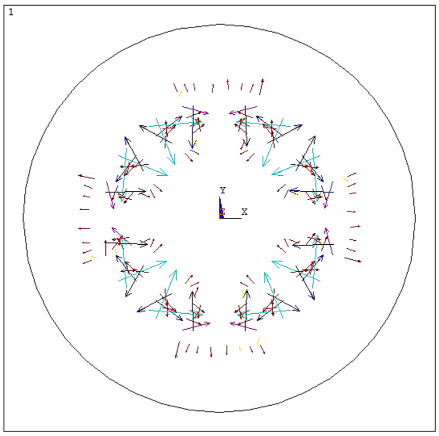


Fig.8 Vector plot of Force for 4-coil AMB for N=500, i=6A z=0.5cm

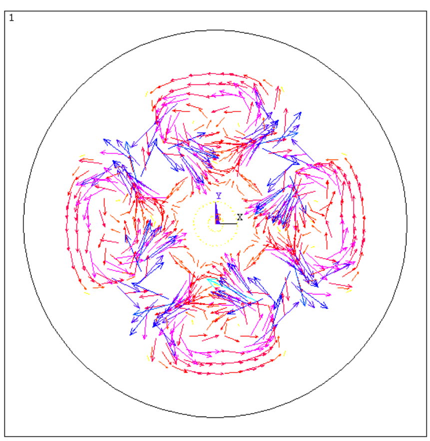


Fig.9 Vector plot of Flux density for 4-coil AMB for N=700, i=6A z=0.5cm

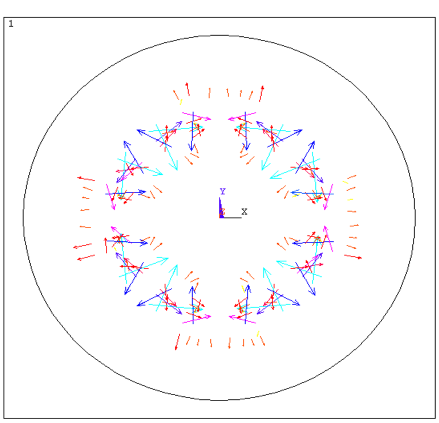


Fig.10 Vector plot Force for 4-coil AMB for N=500, i=6A z=0.5cm

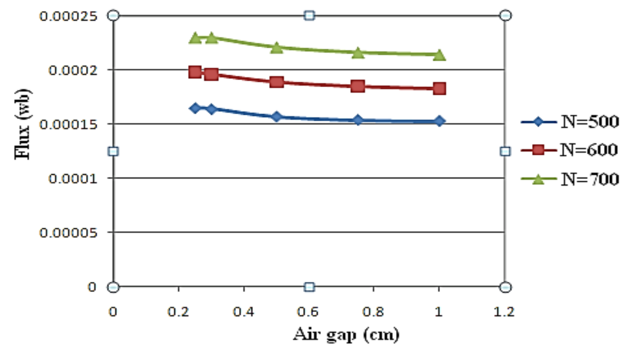


Fig.11 Flux vs. Air gap for different no. of coil of 4- coil AMB (i=6A)

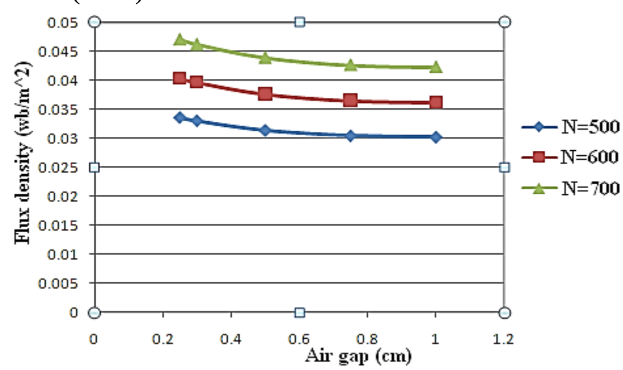


Fig.12 Flux density vs. Air gap for different no. of coil of 4- coil AMB (i=6A)

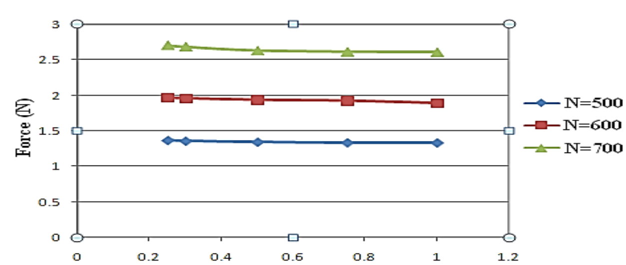


Fig.13 Force vs. Air gap for different no. of coil of 4- coil AMB (i=6A)

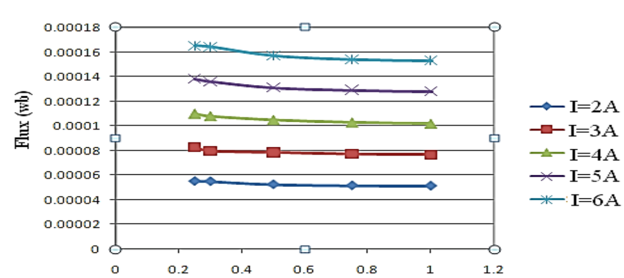


Fig.14 Flux vs. Air gap for diff. current for 4-coil AMB (N=500)

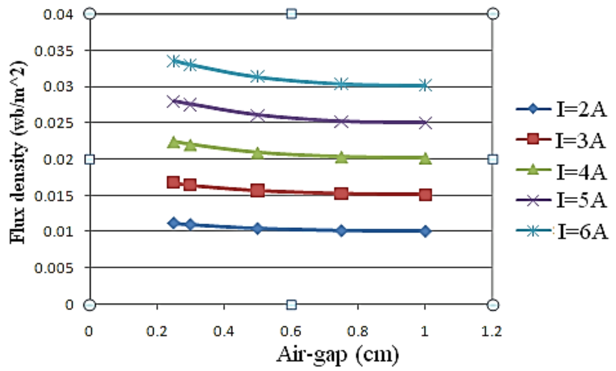


Fig.15 Flux density vs. Air gap for diff. current for 4-coil AMB (N=500)

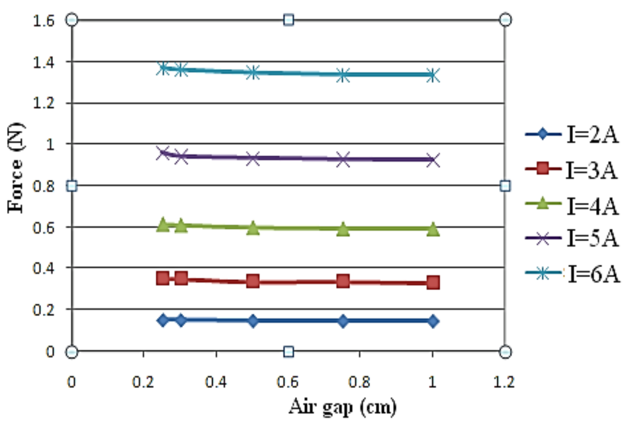


Fig.16 Force vs. Air gap for diff. current for 4-coil AMB (N=500)

## Conclusions

In this paper ANSYS simulation of 4-coil AMB has presented. ANSYS simulation results of 4-coil AMB has presented for different air gap, current of coils and number of turns of the coil. The flux and force are determined by FEM-based analysis using the Maxwell's stress tensor and virtual work. The performed analysis plays an important role in the simulation procedures of AMB and helps in the verification of the construction assumptions. It is essential to use appropriate materials for the rotor and stator. This work is focused on 2D and 3D modeling and analysis using the electromagnetic module with ANSYS software to examine the static AMB behavior in the real operation environment.

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