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# An Overview on Electrodynamical Bearings

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**ABSTRACT** In electrostatics, the levitation ensues when there is a relative motion between a stator and a conductor owing to which high eddy currents are induced. The repulsive forces generated by eddy currents are large enough to carry the moving body passively without violating Earnshaw's criterion. Electrodynamic bearings (EDB) use this technique to levitate the rotor in axial or radial degrees of freedom. The present article reviews the literature on electrodynamic passive magnetic bearings to provide an in-depth examination of EDB modeling, analysis, and development. Different types of EDB configurations are highlighted, along with improvements in their technology. In addition, essential advancements in mathematical modeling, finite element techniques, and experiments used to determine the bearing characteristics in terms of accuracy are highlighted. Furthermore, critical developments in rotordynamic analysis in terms of high-speed application have been reviewed. Finally, advances in the application of EDB are discussed.

**INDEX TERMS** Eddy current, electrostatics bearing, force, stiffness, damping, rotordynamics.

## I. INTRODUCTION

The evolution of high-speed technology has particular importance concerning traditional machinery. This high-speed machinery has advantages over conventional machinery, i.e., greater power and efficiency. Designing high-speed machinery requires the need to tackle different issues like vibrations, rotordynamics, maintenance, etc. The choice of bearing used in high-speed applications is crucial and is also regarded as tricky. If a ball bearing is used, its lifetime is less and also there will be noise due to vibrations. Bearings that have higher stiffness will transmit vibrations to the housing, which should be averted; finally, in other situations, such as hydrocarbon settings, the bearing must be lubrication-free. Bearings like ceramic, air, or fluid film can be used in high-speed applications. Bearings of this type can cause major problems in motor drive applications in outer space, as well as in hard environments containing radiation and toxic substances. Furthermore, lubrication cannot be used in conditions of high vacuum, ultra-high, and low-temperature environments [1]. Hence a new type of bearing, the magnetic bearing, has been developed that can be used in high-speed applications.

Magnetic bearings use magnetic forces developed by the interaction of rotor and stator magnets to support or lift the rotor. There is no contact between moving parts, which

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reduces friction as well as mechanical wear, and the bearing has a long functional life, which is attractive. Magnetic bearings are subdivided into two categories: active magnetic bearings and passive magnetic bearings. Active magnetic bearings (AMB) achieve non-contact suspension through the control systems, whilst passive magnetic bearings (PMB) achieve shaft suspension using only permanent magnets (PM) [2]. Nevertheless, owing to Earnshaw's theorem [3], a passive suspension merely by PM is not viable, as it will be unstable in one of the degrees of freedom. Superconductors, eddy currents, electromagnets, and mechanical bearings can all aid in achieving stability. In EDB, levitation is caused by the Lorentz force generated by the conductor's movement in the magnetic field [4]. In PMB, the suspension of the rotor is induced by the reluctance force generated by the interaction of diamagnetic materials [5]–[7]. The reluctance force that exists between a superconductor's superconducting current and a magnet's magnetic flux density causes a suspension in superconducting magnetic bearings (SMB) [4].

Section 2 of this paper introduces the core concept of EDB, while Section 3 discusses various forms of bearing configuration. Section 4 discusses EDB modeling methodology as well as developments in EDB modeling and analysis for force, stiffness, and damping using mathematical approaches, finite element analysis (FEA), and experimentation. Sections 5 and 6 contain investigations into bearing characteristics and rotordynamic analysis. Section 7 goes on about major advancements in EDB technology. Section 8

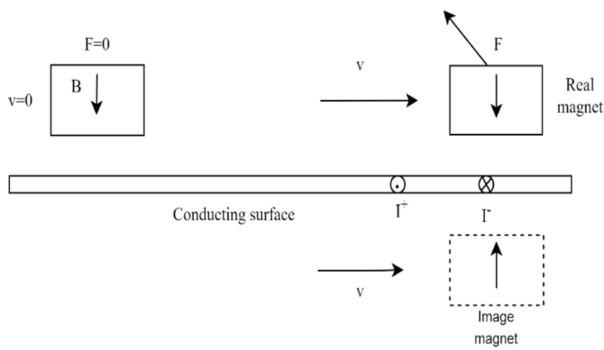


FIGURE 1. Electrodynamic levitation principle applied to a linear bearing [8].

discusses the applications where EDB has been employed. Table 1 summarises the significant findings and methodology used to solve the issues for the benefit of the readers concerning EDB.

II. WORKING PRINCIPLE OF ELECTRODYNAMIC BEARING

In EDB, the repulsive and attractive forces are generated due to eddy currents that are responsible for levitation. The eddy current is generated either by electromagnets which produce alternating current or due to relative movement between a conductor and a constant magnetic field due to which there will be Lorentz force that causes the rotor to levitate in the axial or the radial direction.

Fig.1. depicts the electrodynamic levitation method applied to linear bearings with a conducting plate above which the moving magnet levitates. When the magnet speed is zero, there are no eddy currents. As a result, there is no change in flux and force. Due to the mirror currents  $I^+$  and  $I^-$  being induced at such high speeds, the mirror effect is observed. Because the conductor has resistance as well as a restricted speed, the mirror is shifted and phase-shifted. As a result of phase-shift, the angle of the resultant force  $F$  changes, and a braking force component is generated. A force is generated between a magnet and its generated current, which is denoted by the letter 'F' and can also be computed from the interaction between the magnet as well as its mirror image.

III. ELECTRODYNAMIC BEARING CONFIGURATION

Depending upon the degrees of freedom of the rotor, two configurations of EDB are radial and axial.

A. RADIAL EDB

In radial EDB, the rotor is supported in the radial direction and can also be classified into active and passive EDB. In the active, the coil is used to supply alternating current. In contrast, in passive EDB, eddy current is generated as a result of interaction between the conductor and a magnetic field produced by a PM, which serves as the rotor's restoring force. The passive ones can also be classified into two types depending upon the number of reversals of the magnetic field a conductor goes through when it takes one rotation,

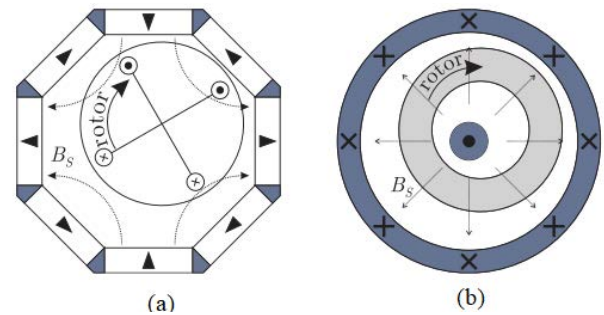


FIGURE 2. Two possible configurations of radial EDB (a) heteropolar & (b) homopolar [10].

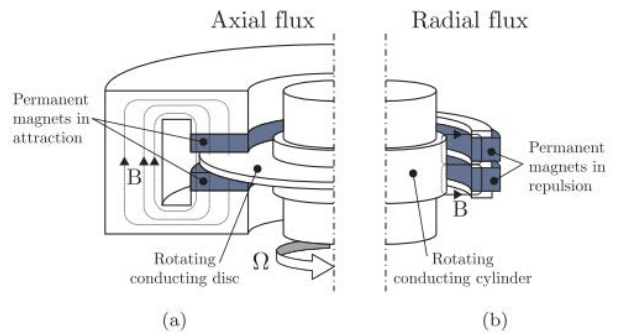


FIGURE 3. Two homopolar EDB flux configurations (a) axial flux and (b) radial flux [10].

i.e., heteropolar (Fig. 2(a)) EDB that has  $n$  reversal of magnetic field and in homopolar (Fig. 2(b)) EDB have no reversal of magnetic field [9]. While homopolar rotors are typically made of solid conducting objects (cylinders or discs), heteropolar rotors are usually wound, conductors.

The configurations of homopolar bearings fall into two categories: axial and radial flux. Fig. 3(a) shows axial magnetic flux flowing parallel to the rotating conductor, while Fig. 3(b) shows radial magnetic flux flowing radially through the conductor. When the axis of rotation is parallel to the magnetic field, there is no drag torque [9]. As a result, when fabricating EDB, the tolerance required for the conducting parts is less since there is no need to align the rotor and magnetic field axes. There will be no substantial rotational loss even if there is a slight misalignment. Moreover, homopolar bearings are not affected by the centrifugal expansion of the rotor.

B. AXIAL EDB

Axial EDB (Fig. 4) are similar to radial in that they can be magnetized either radially or axially. Compared with radial EDB, axial EDB has a levitation system that is more similar to maglev trains. Axial EDBs, like radial EDBs, can take advantage of both radially and axially oriented magnetic fields.

IV. METHODS TO ASCERTAIN THE LEVITATION USING EDDY CURRENT EFFECT

Both analytical and numerical simulations have been used to estimate the eddy current. When there is a relative

**TABLE 1. Significant findings.**

Focus Area	Issues	Methodology adopted	Type of bearings	Reference	Findings
Dynamic characteristics	Suspension, damping	Analytical model(Time varying magnetic fields)	Radial bearing	[11]	Damping was improved by employing shunted coils, and there was a small amount of rotational loss.
Dynamic characteristics	Stability, magnetic levitation	Analytical and computer models	Radial bearings( homopolar and heteropolar)	[12]	Presented null-flux configuration, which generated zero flux when the rotor was in a centered position.
Dynamic characteristics	Force, stiffness, and damping	Analytical model (Perturbation method to solve Maxwell equations)	NA	[13]	Stiffness and damping are low compared to conventional bearings.
Dynamic characteristics	Damping, Stability	Analytical model (Null flux bearing)	Radial bearing	[14]	Halbach array improved the stability, and both thickness of magnet and airgap is an essential factor in stability.
Dynamic characteristics	Force, damping, and stability	Analytical model, FEM, experimental	Radial bearing (homopolar)	[8], [15]	Bypassed Earnshaw’s theorem issues by developing a Homopolar EDB.
Dynamic characteristics	Rotational loss, Stability	Theoretical model	Radial bearing	[16]	Developed a model of radial bearing with low rotational loss.
Dynamic characteristics	Levitation force	Analytical model (Principle of Superposition), FE-simulations, and experimental	Thrust bearing	[17]	Bearing parameters predicted by the analytical model were experimentally verified.
Dynamic characteristics	Levitation force	Analytical model and FE-simulations	NA	[18]	Value of resistance and inductance plays an essential role in levitation
Dynamic characteristics	Modeling of bearing for quasi-static and dynamic conditions and stability	Analytical model (R-L dynamics) and experimental	Radial bearing	[19]	Developed a new model using R-L dynamics. Non-rotating damping is essential to attain stability.
Dynamic characteristics	Rotordynamic, Stability	Analytical model ( R-L dynamics) and experimental	Axial bearing	[20]	Stable levitation was achieved, when threshold speed was overcome.
Dynamic characteristics	Damping	Analytical model (R-L dynamics) , FE-simulations, and experimental	Radial bearing	[21]	Two concentric magnets improved maximizes transverse damping.
Dynamic characteristics	Stability	Analytical model (R-L dynamics) and experimental	Radial bearing	[22]	Unified modeling of homo and heteropolar bearings were developed. Also, increasing pole pairs reduced the threshold speed.
Dynamic characteristics	Modeling and stability	Analytical model (R-L dynamics)	Axial and radial bearing	[23]	Developed a unified model for axial and radial bearing.
Dynamic characteristics	Modeling and stability	Analytical modeling (Bond graph approach to derive the state equations) and experimental	Axial bearing	[24]	A dynamic model of an axial EDB with no flux was created, and complete passive levitation was achieved above the threshold speed.
Dynamic characteristics	Guidelines for design of null flux bearing	Analytical model (Magnetic flux intercepted by winding) and FE-simulations (Magnetic vector potential)	Radial bearing	[25]	An analytical model was validated using FEM.
Dynamic characteristics	Stiffness	Analytical model ( Magnetic flux intercepted by winding) and FE-simulations	Radial bearing	[26]	The lack of a ferromagnetic yoke prevents the bearing's stiffness from becoming negative at low speeds.
Dynamic characteristics	Damping	Analytical model, FE-simulation	Thrust bearing	[27], [28]	Developed a analytical model of damper which was verified with FEM and experiment
Dynamic characteristics	Damping	Analytical model, FE-simulation	Thrust bearing	[29]	Accuracy of analytical model was estimated using the 3D FEM simulations.
Dynamic characteristics	Modeling, Stability	Analytical model (State space model)	Radial bearing	[30]	An analytical model was developed without previous limitations.
Dynamic characteristics	Modeling, Stability	Analytical model (State space model)	Thrust bearing	[31]	An analytical model for thrust bearing was developed.
Dynamic characteristics	Modeling, Stability	Analytical model (State space model)	Thrust bearing	[32]	Developed an analytical model describing axial, radial, and angular dynamics.
Dynamic characteristics	Stiffness	FE-simulation	Radial bearing	[33]	It was discerned that the bearing volume can be reduced without reducing the radial stiffness at high speed.
Dynamic characteristics	Geometrical properties	FE-simulation	Radial bearing	[34]	The time required for selecting the geometrical and physical property of bearing was significantly reduced depending upon different constraints.
Dynamic characteristics	Modeling	Analytical model	Radial bearing	[35]	Even if a conductive sheet was used, the generated eddy currents were not sufficient for achieving stability.
Dynamic characteristics	Levitation	FE-simulation	NA	[36]	A conductive sheet was used to overcome inherent instability.
Dynamic characteristics	Damping	FE-simulation	Radial bearing	[37]	A large amount of damping was required for greater force angles.

TABLE 1. (Continued.) Significant findings.

Dynamic characteristics	Stability	FE-simulation and experimental	Radial bearing	[38]	Stable levitation was achieved above 11000 rpm.
Dynamic characteristics	Levitation, drag force	Numerical and experimental	Radial bearing	[39]	Forces generated in the EDB can be improved by changing the materials or geometry.
Dynamic characteristics	Rotordynamic analysis	FE-simulations	Radial bearing	[40], [41]	Rotor suspended on EDB was free of vibration.
Dynamic characteristics	Optimization (Stiffness and damping)	NSGA-2	Radial (Heteropolar) EDB	[42]	There was a clear trade-off between stiffness and stability.
Dynamic characteristics	Stiffness, Stability	Experimental	Axial bearing	[43]	Non-rotating damper improves the rotor's stability
Dynamic characteristics	Eddy current generation	Experimental	Radial bearing	[44]	It was seen that for constant spin speed, the bearing forces and displacement are constant.
Dynamic characteristics	Forces due to eddy current generation	Experimental	NA	[45]	Due to the bearing configuration used here, no eddy losses occur in the nominal condition.
Dynamic characteristics	Bearing forces, Stability	Analytical model (R-L dynamics) and experimental	Radial bearing	[46]	A new approach to stabilizing the EDB was determined.
Dynamic characteristics	Stability	Analytical model	NA	[47]	By implementing either non-rotating damping or anisotropic stiffness of radial stabilizers, the EDB can be made stable.
Dynamic characteristics	Stability	Analytical model (Electromechanical model), FE-simulation	Radial bearing (Homopolar)	[48]	They found that when non-rotating damping was introduced, the rotor was stable.
Dynamic characteristics	Stability	Analytical (Electromechanical model), FE-simulation, Experimental	NA	[49]–[52]	To determine force due to eddy current, both rotations as well whirl motion was taken into consideration.
Dynamic characteristics	Stability	Analytical model (R-L dynamics), FE-simulations	Radial bearing (Homopolar)	[53]	It was determined that rotational power loss was independent of rotor spin speed but depended upon rotating damping introduced by the EDB.
Dynamic characteristics	Stability	Analytical model (Coulombian approach)	NA	[54], [55]	Two Halbach arrays to create the requisite levitation in order to address the instability in the vertical direction.
Dynamic characteristics	Stability	Experimental	Axial bearing	[56], [57]	Developed Halbach arrays to stabilize the bearing.
Dynamic characteristics	Stability	Analytical model (R-L dynamics), FE-simulation	NA	[58]	Electric pole has an influence on stability.
Dynamic characteristics	Stability	Analytical model	Radial bearing (Homopolar)	[59]	Rotor's stability was observed to be dependent upon the polar and transversal moment of inertia.
Dynamic characteristics	Stability	Analytical model (R-L dynamics), FE-simulation, and experimental	NA	[60]	EDB coupled with AMD provide stable levitation.
Dynamic characteristics	Stability	Analytical model (Electromechanical model), FE-simulation, experimental	NA	[61]	Designed an analytical model of ECD, validated it using FEM and experimentation.
Dynamic characteristics	Stability	Analytical model	NA	[62]	Increasing the number of pole pairs in a bearing improves its stiffness.
Dynamic characteristics	Stability	Analytical model (R-L dynamics), FE-simulation, and experimental	Radial bearing	[63]	When the rotor was coupled with both EDB and AMDs, it allowed the rotor to levitate from zero speed.
Dynamic characteristics	Stability	Numerical, experimentation	Radial bearing	[64]	There was agreement with numerical and experimental simulation.
Static and dynamic characteristics	Stability	Analytical model (Electromechanical model)	Thrust bearing	[65]	External damping improved the stability.
Dynamic characteristics	Stability	Experimental	Radial bearing	[66]	Developed a null flux configuration.
Dynamic characteristics	Stability	Experimental	Radial bearing	[67]	Developed null flux configuration with cross-connected loops for radial bearing.
Dynamic characteristics	Axial and radial restoring force	Experimental	Radial bearing	[68]	A null flux coil with a hexagonal shape to save space, which was mounted in a radial configuration on the stator.
Dynamic characteristics	Rotational losses	Experimental	Radial bearing	[69]	Closed conductors, which were arranged orthogonally in a four-pole magnetic field.
Dynamic characteristics	Rotational losses, Stability	Experimental	Radial bearing	[70], [71]	Halbach array to produced the magnetic field. Reduced damping in the system.

TABLE 1. (Continued.) Significant findings.

Dynamic characteristics	Stability	Experimental	Radial bearing	[72]	Reduced damping in the system.
Dynamic Characteristics	Stability	Experimental	NA	[73]	Null flux coils were developed. And it was self-regulating.
Dynamic characteristics	Stability	Experimental	Radial bearing	[74]	Obtained null flux configuration by using closed conducting loops.
Dynamic characteristics	Stability	Experimental	Radial bearing	[75]	Stability is achieved through the interaction of currents induced in shortened conducting loops installed on the disc with the axial component of a magnetic field emanating from immovable, PM.
Dynamic characteristics	Stability	Experimental	Radial bearing	[76]	Developed EDB for friction pump.
Dynamic characteristics	Stability	Experimental	Radial bearing	[77]	Suspended rotor using eddy current.
Dynamic characteristics	Stability	Experimental	Radial bearing	[78]	With the help of generated eddy current, rotor of the vacuum pump was levitated.
Dynamic characteristics	Restoring force	Analytical, FE-simulation, experimentation	Radial bearing	[79]	Radial forces and large losses indicate that the proposed layout may not be suitable for rotor levitation.
Dynamic characteristics	Levitation force	Experimental	Axial bearing	[80]-[83]	Distributed coils generated steady restoring force.
Dynamic characteristics	Torque and centering forces	Analytical, simulation, experimental	Radial bearing	[84], [85]	The prototype fabricated had sufficient damping to negate the instabilities in the system.
Dynamic characteristics	Stiffness, damping	Analytical model, simulation	NA	[86]	Stability was achieved using rotating PM and stationary conductors.

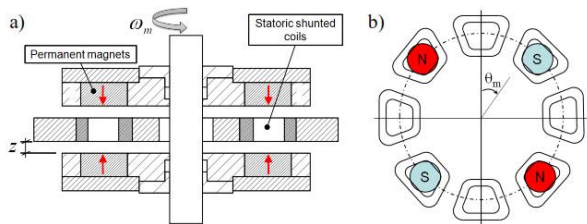


FIGURE 4. Null-flux coils are used in the schematic illustration of an axial bearing (a) front view (b) top view [8].

motion between a conductor and the magnetic field that is used to levitate the rotor, eddy currents are generated. For calculating generated eddy current, damping, stiffness, and levitation, different analytical methods employ Lorentz force equations, Maxwell’s equations, or the superposition principle. Alternatively, numerical simulations can be used, but they require a large amount of computational time that can be solved using various commercial applications like ANSYS and COMSOL MULTIPHYSICS.

A. ANALYTICAL APPROACHES

This section describes various mathematical models for predicting the damping force, stiffness, and levitation force of the EDB.

1) SHORTENED CONDUCTING LOOPS

Non-contact levitation can be achieved when a conducting rotor interacts with the time-varying magnetic fields. As part of such a system, there is a type of system that utilizes closed conducting loops that are fixed on the rotor which move within a magnetic field produced by the stator.

The key concept in designing such a system is to place multiple conducting loops on the rotor. During rotation, small displacements in the radial direction cause periodic variations in flux through rotating loops, as well as periodic electromotive forces. A periodic current will be induced by

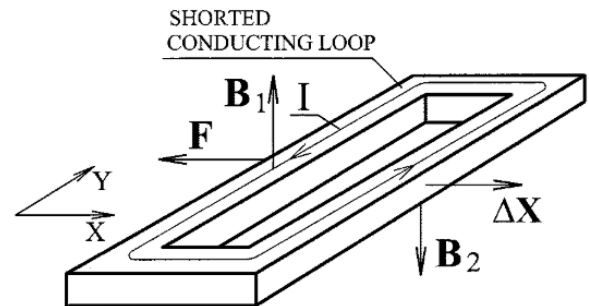


FIGURE 5. Schematic of shortened conducting loops for non-contact levitation [11].

the electromotive force, which in turn will interact with the magnetic field to produce a restoring force on the rotor.

Fig. 5 depicts a basic design of such a concept, which consists of a planar rectangular conducting loop. The loop is subjected to a magnetic field B1 normal to the loop plane, while the opposite side is subjected to a magnetic field B2 in the opposite direction. It is assumed that there is no loop resistance and that there is a point in the loop where no current flows. The loop will induce a current in a magnitude and direction equal to that of the magnetic flux change in the loop interior if it is moved away from this position. The current required to cancel the flux change is

$$I = (\Delta\Phi/l)/(L/l) \tag{1}$$

The lateral force acting on the loop is given by

$$F = 2BIl \tag{2}$$

Which acts in the opposite direction. There will be a restoring force without any external energy use, if the loop resistance is zero (superconducting loops).

2) LINEAR SUPERPOSITION

According to the superposition principle, for a linear system, “the net response resulting from two or more stimuli is

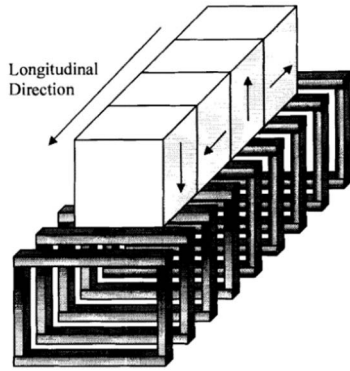


FIGURE 6. Halbach array over shorted conductor circuit to be used in electrodynamic levitation [18].

equal to the sum of the responses caused by each stimulus individually”.

By employing the linear superposition principle, the magnetic flux density is determined for a Halbach array. This method derives the magnetic flux density as the curl of the vector potential. The closed-form solutions are obtained which need to be solved numerically. Flux, electromotive force (emf), and force calculations are carried out by employing Faraday’s law and Ohm’s law.

### 3) INDUCTRACK TECHNIQUE

It involves electrodynamic interaction between an array of moving PM and a densely packed array of coils consisting of shorted electrical circuits. The Inductrack method’s theoretical foundation is built on Maxwell’s equations and standard electrical circuit theory.

The Inductrack concept comprises a special magnet arrangement, the Halbach array, and a one-of-a-kind conducting track construction as shown in Fig. 6. By closely packing the coils consisting of window frame-like shorted circuits, the track’s inductive coupling with the moving Halbach arrays is improved. The active area responsible for the levitation force is maximized using this method.

### 4) ELECTROMECHANICAL MODEL

A simple linear damper model is presented in Fig. 7(a). This device comprises a loop of wire moving in the x-direction in a steady magnetic field with flux density B. The emf that generates eddy currents in the coil is calculated using Faraday’s law. Kirchhoff’s voltage law is used to compute the induced eddy currents. The Lorentz force is produced by the interaction between the generated current and the magnetic field.

$$F = N \int i \vec{dl} \times \mathbf{B} \tag{3}$$

where F is Lorentz force, N is the number of turns, i is current through the loop of wire, and B is the constant magnetic field.

When working with electromechanical systems such as eddy current dampers (ECD), it may be more intuitive to formulate the system’s equations in terms of mechanical quantities, therefore the above linear damper model is turned

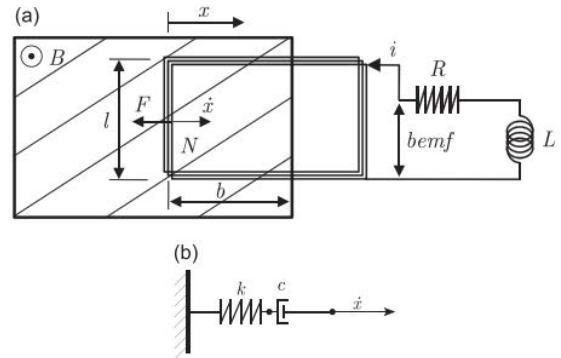


FIGURE 7. (a) Simple linear eddy current damper (ECD), (b) mechanical equivalent of ECD [61].

into a mechanical counterpart of a motional eddy current damping system (Fig. 7(b)). The mechanical equivalent system’s stiffness and damping are determined. The Lorentz force equation is used to calculate the eddy current forces created by a conductor spinning radially inside an axisymmetric magnetic field.

## B. NUMERICAL SIMULATIONS

Finite element simulations can be used to determine the EDB forces. Different formulations were used by the researchers to simulate eddy currents in moving conductors. To simulate relative motion between a conductor and a magnetic field, the most general method is to use separate reference frames and a moving mesh in time-stepping solutions. In this section, different methodologies used for determining eddy currents have been discussed.

### 1) MINKOWSKY TRANSFORM

In 2D simulations, time steps were in the trend. However, 3D simulations proved to be time-consuming. As a result, the Minkowsky transform was applied. This transformation allows the rotating field issue to be solved in a single calculation [8] and the number of equations in the eddy current elements is multiplied by two Minkowsky transformations requires less number of time steps.

### 2) MAXWELL STRESS TENSOR

The Maxwell stress tensor is a symmetric second-order tensor in classical electromagnetism that explains the interaction of electromagnetic forces and mechanical momentum. The Lorentz force law can be used to determine forces on a charge in basic instances, such as a point charge traveling freely in a homogenous magnetic field. This simple procedure can become impractical as the situation becomes more complicated, with equations spanning multiple lines. Many of these terms can thus be collected in the Maxwell stress tensor and solved using tensor arithmetic. Maxwell stresses must be used if ferromagnetic materials are used in the rotor because Lorenz forces do not account for the attracting and destabilizing influence of iron and magnets [8].

The equation for Maxwell stress tensor is

$$T_{ij} = \epsilon_0 \left( E_i E_j - \frac{1}{2} \delta_{ij} E^2 \right) + \frac{1}{\mu_0} \left( B_i B_j - \frac{1}{2} \delta_{ij} B^2 \right) \quad (4)$$

where  $\epsilon_0$  is the electric constant and  $\mu_0$  is the magnetic constant,  $\mathbf{E}$  is the electric field,  $\mathbf{B}$  is the magnetic field, and  $\delta_{ij}$  is Kronecker's delta.

### 3) QUASI-STATIC FE MODELING

Using a simpler and quicker method, moving conductors with perpendicularly oriented cross sections can be analyzed. The movement of conductor can be described by the expressions  $\mathbf{v} \times \mathbf{B}$ , where  $\mathbf{v}$  being velocity field of the conductor and  $\mathbf{B}$  being the magnetic flux distribution.

The forces of an eddy current damper (ECD) can be analyzed using this formulation, ECD is made of either cylinder or disc.

The FE problem formulation for this type of analysis is as follows:

$$\nabla \times (1/\mu) \mathbf{B} - \sigma \mathbf{v} \times \mathbf{B} = 0$$

$$\nabla \cdot \mathbf{J} = 0 \quad \text{For copper } (\Gamma_c) \quad (5)$$

$$\nabla \times ((1/\mu) (\mathbf{B} - \mathbf{B}_r)) = 0 \quad \text{For magnets } (\Gamma_m) \quad (6)$$

$$\nabla \times (1/\mu \mathbf{B}) = 0 \quad \text{For magnets } (\Gamma_{moff}) \quad (7)$$

$$\nabla \times (1/\mu \mathbf{B}) = 0 \quad \text{For air } (\Gamma_{air}) \quad (8)$$

This set of equations explains the electromagnetic fields involved in the question at hand. Eq. (5) relates to the conductor, Eq. (6) to the ECD's moving magnets, Eq. (7) to the conductor's static magnets, and Eq. (8) to the surrounding air. The physical factors involved are conductivity of conductor  $\sigma$ , the magnetic permeability of the material  $\mu$ , and  $\mathbf{B}_r$  the remanent magnetic flux density of the PM,  $\mathbf{J}$  is the current density distribution inside the conductor.

Solving the above equations and associated boundary conditions will yield the distribution of the flux density  $\mathbf{B}$  and the current density  $\mathbf{J}$  inside the conductor. Eddy currents produce Lorentz forces which can be calculated using Eq. (9).

## V. EXPLORATION OF BEARING CHARACTERISTICS

The interaction of a fast-moving conductor in the presence of a magnetic field generates force and stiffness in electrodynamic bearing. This section discusses the mathematical methodologies, finite element analysis (FEA), and experimentation that are utilized to compute the force, stiffness, and damping properties of the EDB in terms of accuracy and clarity.

### A. MATHEMATICAL MODELS

It is necessary to compute vital bearing factors such as force, stiffness, and damping for the development of EDBs.

Basore [12] studied a null-flux EDB configuration in the field of heteropolar bearings and investigated the effect of PM on heteropolar and homopolar EDB in the application of flywheel energy storage systems (FESS). He demonstrated a null flux configuration of heteropolar EDB, as illustrated in Fig. 8. This configuration consists of two permanent

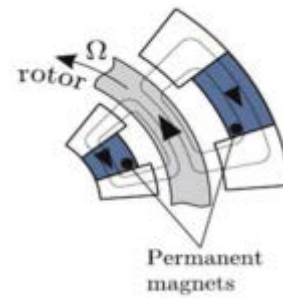


FIGURE 8. Null flux configuration proposed by basore [12].

ring magnets in repulsion, with a thin sheet of conductors sandwiched between them. A rotor in the center position produces a flux that is in the direction of rotation, which means that there are no eddy currents generated. As soon as the rotor was offset by some distance, due to induced eddy currents restoring force is generated. Despite high stiffness and load capacity, rotational losses were high when the rotor was not aligned relative to the stator. In the authors' homopolar EDB, PMB was used to give axial stiffness, and EDB was applied to give radial stiffness. To take advantage of the PMB's homopolar magnetic field, an EDB design with a thin conducting cylinder attached to a rotor was designed. The author also scrutinized the application of discrete conductors in a conducting cylinder such as the shape of an induction motor's squirrel cage. It was discovered that it provided a more unsatisfactory performance. The rotational losses and load capacity were predicted using an analytical model. However, the analytical model was not used to investigate the system's stability.

In contrast, Ting *et al.* [13] solved Maxwell equations to find out the theoretical estimate of force and stiffness and damping coefficient of eddy current damping. It was observed that the bearing had low stiffness and low damping than the traditional bearings. Filatov and Maslen [11] developed an electrodynamic bearing for a FESS based on a thorough theoretical model based on time-varying magnetic fields. A bearing with virtually zero rotational losses was proposed. Davey *et al.* [14] developed a homopolar null flux EDB and eddy current damper for stable FESS operation based on the model proposed in [10]. Lembke [8], [15] converted electromagnetic properties into valuable data to develop analytical expressions for bearing parameters in a novel low loss homopolar EDB. The author analyzed a magnetic circuit with and without conductors to identify the path of the eddy current. The path of the eddy current was compared with currents developed in the conventional generator theory. The resistance and inductance of such a system were analyzed in detail. Based on work done by Post *et al.* [16], Eichenberg *et al.* [17] developed an axial Halbach array magnetic bearing. The presented analytical model effectively predicted the emf, lifting force at lower speeds. But due to the skin effect and the increased effective resistance of the stator winding, both current and lifting forces were reduced. Storm [18] later investigated the configuration developed in [16] and performed analytical calculations on the linear

Halbach array, and the author applied it to a circular Halbach array based on the resistance and inductance of the circuit. The circuit with lower resistance and inductance gave a greater levitation force.

A model which describes EDB behavior in both quasi-static and dynamic conditions was proposed by Amati *et al.* [19]. Complex notations were used to derive the eddy current equations by considering an agreement between the state equation of the linear voice coil and that of the spring and damper system. This system was adopted because the reference frame can be recognized with an insightful basis, which is essential when considering rotating machinery. Tonoli *et al.* [20] developed a bond graph model to describe the behavior of axial electrodynamic bearing under both quasi-static and dynamic behaviors. Authors developed a model that accounts for the R-L dynamics of a conductor in the magnetic field both in quasi-static and dynamic conditions.

One of the major challenges in PMB is low damping, hence a new type of eddy current damper [21] was developed to decrease the amount of vibration. Here two concentric ring magnets were placed around the rotating shaft. This design produced no transverse magnetic field across the conductor, but enhanced transverse damping. The damper was theoretically modeled. The magnetic flux density of ring magnets was calculated using the superposition principle. To discern the similarities and differences between homopolar and heteropolar EDB configurations, a unified modeling approach [22] was utilized. An analytical solution of the magnetic field in the air area around the rotor for electrodynamic bearings with an even number of magnetic pole pairs was used to develop the model. The electromechanical model's state equations were written in terms of complex quantities. Furthermore, for axial and radial bearing, Amati *et al.* [23] created a uniform modeling process. The models were generated by solving the magnetic field analytically in the air gap. State equations were derived for the electromechanical model. Since models for quasi-static and dynamic behaviors of a supported rotor with an axial EDB are still lacking in the literature, Impinna *et al.* [24] modeled axial EDB by applying the bond graph approach to derive the state equations. The magnetic flux linkage approach was used to model the axial EDB using some assumptions. The above models involve assumptions on the rotor kinematics, or they solve Faraday's current law; a model without these limitations was developed. In another study, a set of guidelines were developed for null flux electrodynamic bearing [25]. These design guidelines resulted from an analytical study of the magnetic flux and force in a bearing with a radial magnetic field and an arbitrary winding. Magnetic flux intercepted by windings was used to develop an analytical model. By choosing rotor ( $q$ ) and winding ( $p$ ) pole pairs that satisfy  $mq = np + 1$  or  $mq = np - 1$ , the null flux criterion can be met. The harmonics  $m$  and  $n$  are odd integers. Increasing the stiffness of EDB is a crucial issue because the stiffness of EDB reaches a negative value when there is an increase in speed. Hence a yokeless radial EDB was built [26]. With some assumptions, a 2-D analytical model was built to estimate the force between the inductor

and the winding of such a bearing. The model was derived using the vector potential of the PM.

An analytical model of the damper was developed [27], [28] for a high-speed compressor that employed a Halbach array. Maxwell's equations were used to obtain the equation for the damping force which was then solved in MATLAB. Since remanence intrinsic magnetization was calculated using harmonic components in [27] and [28], which was accurate in many cases. Hence a 2D analytical model was developed without these limitations [29].

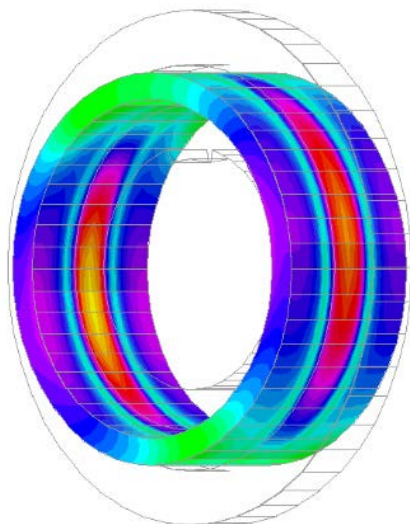
To overcome the problem of removing the constraints placed on bearing geometry imposed by earlier developed models, a null-flux radial EDB was developed without restrictions to study its dynamic behavior [30]. The governing equations were derived using Faraday's law for an R-L circuit. The state-space model was derived by reducing the number of variables. A linear state-space representation of heteropolar null-flux thrust EDB was derived to remove the limitation of windings with two phases [31]. Electromechanical equations were derived by making necessary changes in the winding, the force, and the torque equations by applying Faraday's law. Taking into account the rotor's axial, radial, and angular displacements, as well as its gyroscopic effects, a linear state-space representation of its comprehensive dynamics was developed in [32]. The electrodynamic model was derived from the flux linkage expressions, which have been validated through a practical case. Six complex and four real state-space equations were obtained by integrating the electrodynamic and detent models into the rotor mechanical model, which describes the rotor's axial, radial and angular dynamics.

## B. FINITE ELEMENT ANALYSIS

With the help of FE techniques, the force, stiffness, and damping force of EDB have been found. Since 2D analytical simulations are time-consuming, an improvement in FE modeling techniques allowed for the consideration of conductors of different shapes and to find out the 3D distribution of flux. Due to this, FE models were used to study the magnetic flux distribution to evaluate the EDB properties. The work of Lembke [8] is most important in FE simulations. He developed a novel homopolar radial flux EDB for high-speed applications and performed FE simulations of forces generated during EDB rotation. Parameters required for an accurate solution in FE modeling were described. Eddy current generated by the conductor was estimated (Fig.9).

In another study [18], an FE simulation was performed to authenticate the analytical model. In addition to the first 2D simulation of linear Halbach array in two different software packages, a 3D simulation of linear Halbach array was also performed to examine flux density distribution. Based on the results obtained from the analysis of the linear Halbach array, the circular Halbach array was analyzed to see how the magnetic field will react when the linear array is bent to the circular array. The force between PM was estimated using 3D COMSOL, which uses Maxwell's stress tensor. To improve





**FIGURE 9.** Eddy current distribution in a solid conductor [8].

the accuracy of the simulations, a small air gap was used, and the mesh node was smaller than the air gap separation.

The theoretical model of the magnetic field developed by Cheah and Sodano [21] was validated by FEA. 2D FEA was accomplished using Ansys by employing the plane53 element. For the reason that it allowed for axisymmetry and the formulation of scalar potentials. The effective stiffness was calculated using 3D FEA. The element Solid96 was used. The effective stiffness was measured at 8500 N/m. FEM was employed by Amati *et al.* [33] to find the geometrical parameters that affect the electrical characteristics and the dynamic behavior of rotor systems supported by EDB. It was found that the bearing volume could be reduced without reducing radial stiffness at high speeds. To decrease the FEM analysis during the EDB design stage, without resorting to comprehensive FE analysis, a first approximation design was proposed [34]. It was observed that by employing this method, the time required for selecting the geometrical and physical property of bearing was significantly reduced depending upon different constraints. But FE analysis was still required for detailed analysis of the bearing.

In a different study [25], The FE simulation results were compared to the predictions of the magnetic vector potential and magnetic flux intercepted by a winding for null flux EDB. It was seen that the rotor and armature pole pairs should be  $q = p \pm 1$  to amplify the magnetic flux and EMF with FE simulations. The FEA was used to authenticate the 2D analytical model described in [26] and used to determine the effect of rotor off-centering on winding inductances and magnetic field distribution. To validate the 2D analytical model developed in [27] and [28] the bearing was simulated using ANSYS.

Musolino *et al.* [35] studied different configurations of heteropolar EDB and the main aim was to study the numerical model of electromechanical devices. Different bearing configurations and their dynamic stability were also studied. It was seen that even if a conductive sheet was

introduced to generate the eddy current between rotor and stator, it was not adequate to make the system stable unless an active control system was used. The configuration employed was based on their earlier work [36] where NdFeB magnets were used in both rotor and stator in repulsion mode. It was observed that there was a large amount of rotational loss in that type of configuration. Filatov *et al.* [37] used 3D FE techniques to investigate homopolar EDB and induced eddy current was calculated. The frequency analysis was carried out using an unrolled model. It was discovered that greater force angles necessitated more damping. The stiffness at 35 krpm was 210 N/mm and a damping coefficient of 244 Ns/mm was observed. A radial homopolar EDB was modeled using FEA [38] to understand its dynamic behavior under quasi-static conditions and the results of the simulations were used to compare with the analytical model developed by Amati *et al.* [19]. The hexahedral mesh was used to model the EDB. Additionally, to predict the levitation and drag forces of an EDB [39] FEM was used and it was observed that for smaller air gaps, both levitation and drag forces were high. In addition, it was seen that changing materials or/and geometry can improve the forces in an EDB. In other studies [40], [41], with the help of 3D FEM, electromagnetic stiffness and damping characteristics of EDB were found for the entire operating speed range.

Damping characteristics of the EDB were simulated in COMSOL Multiphysics [28] and simulated results were used to substantiate the analytical results. Different axial, radial and rotational speeds of the rotor were used to simulate the eddy current distribution. Optimization of yokeless heteropolar EDB was performed to evaluate its performance [42]. The objective function was to optimize the stiffness and damping because it is an essential parameter for stability analysis. A Pareto front solution was obtained, and it was compared with the existing EDB in terms of stiffness to volume ratio. Kluyskens *et al.* [49]–[52] validated the electromechanical model by FEM. There was nonlinear evolution of damping with the distance  $d$ .

### C. EXPERIMENTATION

Experiments have been carried out to investigate bearing forces, losses, and the dynamics of EDB-equipped applications. The majority of the experiments were carried out in quasi-static conditions, with an off-centered shaft rotating at a constant speed. Several experimental studies have been conducted to ascertain the stiffness, damping coefficient, and bearing forces of EDB [43]–[45]. Filatov and Maslen [11] conducted experiments on EDB for the application of FESS. There was a noticeable rotational loss of about 1.2 W at the rotational speed of 1900 rpm, which increased linearly. The rotational loss was due to eddy currents. Lembke [8], [15] built two prototypes to validate the analytical and simulation results. Multiple experiments were performed using various magnet configurations at subcritical speeds, as well as at supercritical speeds, but significant vibrations were observed. It was also determined whether this type of homopolar bearing has thermal problems. Therefore, the tool spindle was

mounted with a bearing and radial load applied to generate eddy currents in the copper rotor. The temperature rise of 2°C was observed. The model developed by Eichenberg *et al.* [17] was tested experimentally at 500 and 2000 rpm. It was seen that lift and drag forces were limited due to the introduction of inductive circuits in the coil. Moreover, the model developed in [19], [38] was validated experimentally. A test rig was built, and tests were performed by exciting the EDB's stator using a force introduced by an instrumented hammer. An accelerometer fixed in the axial position corresponding to the center of the EDB was used to measure the stator's response. The rotor's lateral degrees of freedom were kept constrained during this experimental characterization. Tonoli *et al.* [20] conducted experimental tests to address the calibration of the model's main parameters as well as to study the system's quasi-static behavior to validate the developed model. The authors developed a vertical axis rotor for a complete levitation of passive magnetic bearings. A PMB was used to achieve radial levitation of the rotor, EDB to attain axial levitation, and an eddy current damper was used to decrease the vibration of the rotor. Stable levitation was achieved only when threshold speed was overcome. Using experiments [21], the damping coefficient and stiffness of the damper determined by the theoretical model and FE analysis were validated. The electromagnetic shaker was utilized to supply excitation energy to the rotor during modal testing. Its response was measured using an accelerometer. The damping was found to be proportional to the square of the magnetic field. So, for larger systems, this would provide effective damping. To validate the model developed in [24], an experimental test rig was developed. Passive levitation was achieved using EDB in the axial direction and PMB in the radial direction. EDB provides stabilizing stiffness, while PMB and dampers provide tilt stability. The model proposed in [19] was experimentally validated [46] in steady-state and dynamic conditions. There was a good correlation between experimental and analytical results. Sotelo *et al.* [39] performed a simple electrodynamic experiment. Based on the results, a radial homopolar EDB was developed.

## VI. ROTORDYNAMIC ANALYSIS

Rotordynamic analysis is concerned with the analysis of rotating systems. In rotating systems, the presence of rotating damping affects rotordynamic stability. When analyzing rotating systems, it is usually necessary to differentiate between rotating and nonrotating damping. Because the former has a stabilizing influence, it can be employed to provide the requisite stability within the operating limit of the machine, while the latter reduces vibration amplitude at subcritical speeds but has destabilizing effects at supercritical speeds [87]. The EDB is typically made up of a rotating conducting object in a stationary magnetic field. In supercritical speed operations, rotating damping is introduced, causing instability. This section presents the research contributions to gain insight into the rotordynamic stability of EDB. To understand destabilizing effects Jeffcott rotor model was commonly used. Jeffcott rotor models have

been utilized in numerous studies to analyze conditions for stable levitation of EDB [19], [22], [23], [47], [48]. The results of these studies suggest that the threshold speed can be reduced by implementing either non-rotating damping or anisotropic stiffness of radial stabilizers, or by increasing the number of pole pairs. The non-rotating damping, however, increases power consumption and induced stiffness. Non-rotating damper was also utilized by Bender and Post [43] to improve the rotor's stability. According to the results, when fixed magnets and a rotating disc are used, the damper becomes a source of whirl instability.

By assuming that the electromagnetic force acting on the rotor is unaffected by lateral motion, Filatov and Maslen [11] determined rotordynamic stability using the Routh-Hurwitz criterion. Whereas Davey *et al.* [14] found out necessary requirements for the damping in both axial and radial directions. The stability of the system was achieved by using the Halbach array. Depending on the thickness of the magnet, the axial force and stability were observed to be affected. Radial stability was achieved by increasing the gap between the magnet and steel/aluminum. Lembke [8], [15] also discovered that system stability required external non-rotating damping, and small changes in damping had a significant effect on the stability limit.

Due to the eddy current generated in EDB, destabilizing forces are induced. The effect of destabilizing forces was studied by Kluyskens *et al.* [49]–[52]. An electromechanical model based on assumptions that the rotating part has a resistance  $R$  and inductance  $L$  was proposed. The skin effect on rotordynamic stability was studied. With the help of 3D FEM and experimentation, the mechanical properties of EDB were understood. The force developed by eddy currents can be defined as the phase shift between the flow of current in a conductor and the magnetic flux generated. Both rotations and whirl motion were considered when determining the force caused by eddy currents. The analytical model developed by Amati *et al.* [19] was employed to study the rotational loss generated by radial EDB [53]. The model was verified with the help of FE simulations. Rotational power loss was determined to be independent of rotor spin speed, but dependent on rotating damping introduced by the EDB. An equation was derived to determine the power lost in the bearing. Two strategies for improving the system's stability were investigated [46]. The first is a traditional method of stabilization centered on the introduction of non-rotating damping amongst the rotor and the casing via a contactless electromagnetic device. In the second one, a dissipative element was added in parallel to a compliant one, located between the non-rotating part of the bearing and the machine's case. Both stabilization approaches were scrutinized by using root loci plots in the desired speed range. According to Impinna *et al.* [24], a tiny amount of damping between the rotor and the machine's stator was found to eliminate the instability. The model's validity was experimentally verified. In both axial and radial directions, the rotor rotated stably above the speed of 2800 rpm when the EDB and PMB supported it.

Bachovchin [54] and Bachovchin *et al.* [55] used Halbach stabilizers in between two Halbach arrays to create the requisite levitation in order to deal with the instability in the vertical direction. The design of the levitation system was as per earlier designed by Post [56], [57]. Superposition of fields and forces were employed to calculate the magnetic field and magnetic force. Genta *et al.* [58] performed sensitivity analysis on the electrodynamic bearing model designed by Amati *et al.* [19] to get an understanding of which geometric parameters influence the dynamic behavior of bearing as well as electrical parameters. When the radius of the conductor was reduced, the electric pole of the system also decreased. It was observed in [19] that when the electric pole was reduced, the speed at which the system stably levitates was reduced. The state-space model derived by Dumont *et al.* [30] was used to investigate the dynamics of the rotor with 2 degrees of freedom (DOF). The root locus of the state-space model was utilized to analyze the stability of the system. In contrast to radial electrodynamic bearings, axial EDB was stable at low speeds, even with a damping factor of zero. Verdegheem *et al.* [31] used an improved state-space model to describe the dynamics in the quasi-static conditions of the 1-DOF rotor supported by EDB. The root locus of the state-space model was derived by calculating the Eigen values. The rotor stably rotated at the speed of 16395 rad/s after that system was unstable.

By employing the unified model gyroscopic effect of a 4 DOF rotor supported by EDB was studied [59]. Rotor's stability was observed to be dependent upon the polar and transversal moment of inertia. If the ratio of the polar and transversal moment of inertia ( $J_p/J_t > 1$ ), the rotor was in stable mode. Impinna *et al.* [60] used EDB with active magnetic dampers (AMD) to ensure stable levitation for a wide range of speeds. Non-rotating dampers are directly introduced to the rotor. Simulations were performed on the designed test rig, and it was observed that the rotor was able to levitate at a higher rotation speed with this hybrid setup. In the analytical equations, damping coefficients are subject to several errors. As result, Detoni *et al.* [61] proposed an electromechanical model of an eddy current damper (ECD) that computed the Lorentz force that arises in the conductor in combination with 3D FE models and the radial damping properties were calculated for the rotordynamic model. Curve fitting between model and simulation findings was used to obtain numerical values for the ECD's parameters. Finite element simulations were carried out for quasi-static conditions and experimentation was performed to verify both analytical and simulation results. The simulation's goal was to calculate the distribution of eddy currents inside the conductor in order to calculate the forces.

Szolc and Falkowski [40] performed dynamic analysis of rotors supported by EDB, journal bearing, and rolling bearings. When results from different bearings were compared, it was seen that EDB could isolate vibration modes from synchronous external excitations. As a consequence, the steady-state and transient lateral vibrations of the rotor-shaft systems under consideration suspended on the

electrodynamic permanent magnet bearing (EDPMB) were devoid of resonant amplifications over their full rotating speed range. The analytical model developed in [26] was used to study the stability of the EDB with the help of root loci [62] for different yoke materials and different speeds. With an increase in speed of the bearing, stability could be obtained. Furthermore, bearing with a ferromagnetic yoke has better stiffness and better stability.

To overcome the instability owing to rotating damping arising in the conductor, Qingwen [63] proposed a hybrid solution, where EDB is combined with active magnetic dampers (AMD). The modeling of EDB was centered on the electromechanical dynamics of a conductor as done in [19]. FE simulation and experimentation of EDB were done in quasi-static conditions. Identification and modeling of AMD were in FEM, and PD architecture was used in AMD to provide proper stiffness and damping. COMSOL was used to calculate current stiffness and displacement stiffness. Additionally, the electromagnetic distribution in the coils and the rotor with coils was determined. State-space representation was used for the complete model of the system where the rotor is combined with EDB and AMDs. When the rotor coupled with only EDB was tested, it was unstable at any spin speed. But with both EDB and AMD, it allowed the rotor to levitate from zero speed.

Due to the reason that rotor instability plays an essential role in the selection of EDB in various applications, Musolino *et al.* [64] performed a dynamic analysis of the rotor/EDB system based on numerical modeling of the complete system, and the results were verified with experimentation. The root locus was used to analyze the stability of the rotor using a linear model [32]. With help of external damping, two conical whirling modes were stabilized. Also, in the absence of detent stiffness, the precession motion is stable until an instability threshold is reached. Additionally, external angular damping can be used to increase the latter, but precession is less sensitive than forward nutation. Static and dynamic stability of thrust EDB [65] was found using linear state-space representation [31], [32]. Root locus as a function of rotor spin was used to measure the impact of external stiffness and damping. External damping improved the stability. By using three approaches, a rotor supported by EDB was stabilized simultaneously [41]. The amount of external damping required was studied utilizing the Routh-Hurwitz stability criterion. By employing softer EDB and softer and viscous bearing support housing, smaller AMD gains were required for stabilizing the rotor.

## VII. IMPROVEMENTS MADE IN DIFFERENT CONFIGURATIONS OF EDB

The initial EDB configuration [12] developed had some drawbacks, such as high rotational losses, low damping, and stiffness; various configurations have been developed to improve these parameters, which will be discussed in this section.

Pinkerton [66] developed a type of null flux configuration of EDB, as shown in Fig. 10. The rotor had a disc with

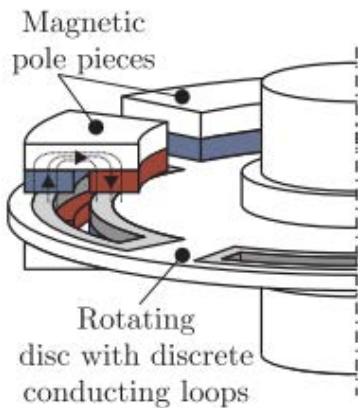


FIGURE 10. Axial flux heteropolar EDB suggested by Pinkerton [66].

conducting loops that were closed. When the rotor started rotating, these conducting loops passed through a string of opposite magnetic fields. Since each loop was subjected to two magnetic fields, the net flux linked was null when the rotor was in a centered position with respect to the stator.

Whereas, Clifton *et al.* [67] developed a null flux configuration with cross-connected loops for radial bearing. The first and second loops are electrically coupled to form closed loops, which is one of the key features of this sort of design. The loops are circumferentially spaced from one another, and they are surrounded by a magnetic field that is also circumferentially spaced. Notably, Post *et al.* [16] conducted first surveys of null flux axial EDB in the context of the application of vehicles with a flywheel. In the preceding application, the EDB presented static conductors and Halbach rotating arrays of PM; the PM was oriented toward repulsion. In addition, Similar to Pinkerton [66], Murakami [68] invented a null flux coil system for producing axial or radial restoring force. An axial type of null flux system was developed to generate an axial restoring force. At both axial ends, the null flux system was used. The author also created a null flux coil with a hexagonal shape to save space, which was mounted in a radial configuration on the stator.

Since rotational losses in EDB were high, Danby [69] described a configuration to reduce that. Closed conductors organized orthogonally in a four-pole magnetic field were employed. Furthermore, the magnetic field might be fixed to either the rotor or stator of the device and the conductors must be fixed to the other member. When the loops are in the center of the magnetic field, there will be no flux. This reduces eddy current losses, which lowers rotational losses. A configuration similar to Danby [69] was studied intensively by Post [70], [71], where a Halbach array was used to produce the magnetic field. Halbach arrays were rotating in nature, and the stator was shortened conductor, as shown in Fig. 11. Due to this type of configuration, there was a null flux condition when the rotor was in the centered position. This condition was achieved when magnetic pole pairs were more than two for a magnetic circuit. It was observed there was an improvement in rotational losses and stability.

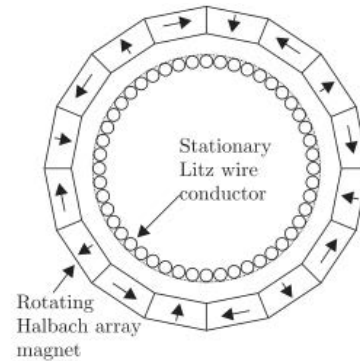


FIGURE 11. Radial Flux heteropolar configuration using Halbach array by R. F. Post *et al.* [57].

Another advantage of this type of configuration is employing a Halbach array in the rotor and windings in the stator. Therefore it can be utilized in the case of an electric motor/ generator [72]. Because conductors were used as stators, the main disadvantage of the proposed configuration was that it reduced the damping of the system, which was dependent on the rotor displacement [71]. To provide stability in both translational and rotational applications, Davey [73] developed a null flux coil. The essential benefit of such a system was that the common null flux coil provided both axial and transverse stabilization. Such a type of system was self-regulating, and it did not require any active systems. Filatov *et al.* [74] developed a passive magnetic bearing based on Pinkerton's [66] concept by using closed conducting loops that rotated to create a null flux configuration when the rotor was in the centered position. Because the magnetic flux is constant in the centered position, no current flows in the loop, and the induced electric field is constant, the null flux condition was not obtained in homopolar EDB [75].

Because null flux electrodynamic bearing uses a ferromagnetic yoke, its effect on the stiffness was investigated [62]. A bearing's performance is not dependent on the yoke material for small rotor shaft radii and increasing the number of pole pairs increases its stiffness. Still, it was less advantageous for a bearing with a ferromagnetic yoke, when the yoke is close to the PM. To remove the drawbacks associated with the null flux radial EDB, a yokeless heteropolar EDB was developed [26]. The lack of a ferromagnetic yoke prevents the bearing's stiffness from becoming negative at low speeds. The centering force was shown to be more important at greater speeds. But a small amount of damping is necessary due to the presence of the disturbing force.

## VIII. APPLICATION

This section presents the review of applications in which the rotor was supported on EDB. Basore [10] investigated the use of PM heteropolar and homopolar EDB in flywheel energy storage systems. The author found that for  $10^8$  Joule of energy storage, the rotor would weigh 1000 kg and would require 25 kg of ceramic magnets to provide lift. The system's maximum speed would be 200 Hz, but it would be stable above 6 Hz. Filatov and Maslen [11] built a FESS with

EDB that achieves a stable suspension of 3.2 kg rotor when rotated over 1200 rpm. Bender *et al.* [43] developed a FESS supported by EDB. The bearing was rotated up to a speed of 50000 rpm. For spatial application [37] a homopolar EDB was designed and developed 2.6 kWh 6.4 kW FESS was found to be feasible for low earth orbit satellites based on an initial study.

A null flux configuration was designed by Post [72] for the motor/generator. Halbach arrays and special windings were used to obtain the null flux condition. A new set of windings were added to the rotor to be used as motor windings. A friction pump supported by a magnetic bearing was proposed by Conrad and Lembke [76]. An electric conducting material was used in rotating discs and PM on opposite sides supported by stationary discs. Lembke [8] developed homopolar induction bearing with touchdown bearings for turbomolecular pumps [77] and vacuum pumps [78]. An EDB was developed by Takanashi *et al.* [79] for an anti-corrosion pump to improve the restoring force and reduce the braking torque developed. A permanent magnet was placed in the periphery of the impeller, and auxiliary magnets of opposite polarity were positioned along the rotational direction.

Sandtner and Bleuler [80] and Bleuler *et al.* [81] developed an electrodynamic thrust bearing for flywheel application. Halbach arrays were used in repulsive mode. Damping was achieved due to stationary magnet rings. The rotor was levitated up to the speed of 4800 rpm stably. This work was extended to improve the system's stiffness for constant speed application by Sandtner and Bleuler [82]. Two coupled LCR circuits in different configurations were utilized to obtain higher stiffness. Sandtner and Bleuler [83] modified the design proposed in [80] for open flywheel applications. The bearing was redesigned to be compact and cylindrical, and discrete coils were replaced with distributed coils. The restoring force generated by these distributed coils was steadily acting. Instead of the Halbach array, the alternating permanent configuration was used. The incorporation of the back iron core into the cylindrical structure resulted in a stronger restoring force.

An EDB for a self-bearing PM machine was designed and developed in [84] and [85]. The windings of the armature were short-circuited to obtain the eddy currents only when the rotor is in an off-centered position. FE simulations were performed on two models of the bearing. A bearing prototype was constructed based on FE simulations, similar to the C sufficient damping to negate the instabilities in the system.

Szolc *et al.* [86] designed EDB for an automotive turbocharger rotor. EDB of the rotor was supported by the rotating PM and a stationary conductor that generated additional damping, which was sufficient to stabilize the rotor for all eigenmodes.

## IX. CONCLUSION

With the recent contributions of several researchers in maximizing bearing characteristics and damping solutions, EDB could be used to replace traditional bearings in a variety of applications for supporting low- and high-speed rotating

shafts. The following are the findings from the review of modeling, analysis, and application of EDB for supporting rotating shafts.

- Both heteropolar and homopolar EDB can be used for high-speed applications due to their higher stiffness values. In homopolar EDB, in case of rotor unbalance, the rotor can spin around its axis without transmitting forces to the house. In addition, EDB is most suitable for applications requiring gyroscopic effects. In this case, if EDB is heteropolar, windings could be used to create the torque.
- R-L dynamics is best suited for modeling the EDB as it can be used for both quasi-static and dynamic analysis. By reducing R and L values, keeping the air gap small, and changing the material and geometry, the levitation force can be increased.
- To calculate the bearing's stiffness, damping, and generated eddy current, an FE simulation could be used, but it is time-consuming.
- Halbach array is superior in terms of force and stiffness values.
- Damping plays an essential role in rotordynamic stability and it depends upon the magnetic field. The rotor could be made stable by providing the non-rotating damping. A new method of introducing damping on stator and casing of machine was introduced due to which threshold speed was also reduced and it improved the damping. Also, damping can be improved by anisotropic stiffness and by increasing the number of pole pairs. The polar and transversal moments of inertia further influence rotor stability.
- Copper sleeves can also be used as damping elements to enhance damping properties.
- In addition, with the help of AMD, EDB can be made stable for a wide range of speeds. But it increases the complexity and cost of the system.
- Special attention must be paid to the optimization of EDB. Optimization could be performed by changing the material or geometry to improve bearing features.

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