Modeling of Heteropolar Radial Magnetic Bearing in COMSOL 6.0

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Abstract
This paper investigates different pole configurations and their impact on passive radial magnetic bearings (PMBs) performance using COMSOL Multiphysics software. PMBs are magnetic bearings that utilize electromagnets to levitate a rotating shaft without needing external feedback control. These bearings offer advantages such as low friction, high speed, low maintenance, and long life. However, they also face challenges related to low stiffness, large axial forces, and nonlinear behavior. The study considers the NSNS type of pole configuration. The study aims to investigate magnetic flux density, radial stiffness, and axial force under different operating conditions. COMSOL Multiphysics software enables accurate modeling and simulation, facilitating a comprehensive analysis of the PMBs' behavior under various operating conditions. These findings can guide engineers and researchers in developing efficient and reliable Magnetic Bearings for various applications.

Keywords: Magnetic Bearing, Transverse Forces, Magnetic Flux Density,

Introduction

In precision manufacturing, magnetic bearings have emerged as revolutionary devices that challenge conventional machining bearing systems. These incredible creations harness the power of magnetic fields to counteract the physical interactions of rotating objects, ushering in a new era of frictionless and nearly destructive movement. This paper comes from travel entirely down into the world of magnetic bearings. At its core, magnetic bearings are sophisticated mechanical systems designed to suspend and control rotating objects by interacting with magnetic fields. Unlike traditional bearings that rely on physical contact, magnetic bearings use electrical power to maintain stability. The method offers many advantages, such as reduced maintenance, increased service life, and increased performance in harsh environments. Magnetic bearings come in two main types: radial and axial. Radial magnetic bearings provide stability in the radial direction, supporting rotating objects perpendicular to their axis of rotation. On the other hand, axial magnetic bearings are designed to control movement along the axis of rotation, providing axial stability. Furthermore, magnetic bearings can be classified as homopolar or heteropolar depending on the orientation of the magnetic poles. Equipolar magnetic bearings use magnetic poles facing each other, while heteropolar magnetic bearings use opposite magnetic poles to achieve lift and control.
Applications of magnetic bearings span a wide range of industries and technologies. These sophisticated devices have found their footing in exotic fields such as aerospace, where their ability to operate in an airtight environment and deliver exceptional performance under extreme conditions makes them incredibly valuable. Where machines and tools are enabled with unparalleled accuracy and speed, this paper delves into the complexity of magnetic bearings, investigates the underlying principles, explores the nuances of radial and axial systems, and sheds light on applications with their unique capabilities that dominate the rich fabric of the role.
For modeling, radial magnetic bearing is the choice that effectively balances the radial force. The author has set up coils around the soft iron bars of the stator to implicate the use of electromagnets as magnets. Balancing forces in magnetic bearing is difficult in cases where the field is nonuniform. This leads to constant change in the forces upon the center.

Modeling of the Magnetic Bearing
Essentially, we are modeling an 8-pole Radial magnetic bearing. It can easily be understood as a set of 4 electromagnets governed by an electrical circuit.

Geometry
In precision engineering, the geometry of magnetic bearings plays a vital role in their functionality. This section provides a concise overview of the geometric configuration used in an 8-pole magnetic bearing system, utilizing four electromagnets to control the direction of motion.
The fundamental design of 8-pole magnetic bearing centers on achieving stability and precise control over the levitated object. This configuration comprises four pairs of electromagnets, each creating opposing magnetic fields. These electromagnets are positioned around the axis, forming an octagonal pattern. The fundamental principle behind this geometry is to generate a balanced magnetic force that counters any displacements in the object's position, ensuring it remains suspended with minimal deviation. The detailed dimensions of the Magnetic Bearing is listed in the Table 1.

Parameter	Value
Rotor Radius (r_r)	28.8 mm
Journal Radius, (r_j)	40 mm
Radius of Pole Faces, r_p	41.1 mm
Radius of depth of coils, r_c	66 mm
Stator Outer Radius, r_s	77.2 mm
Width of the Pole, w_p	22.3 mm
Mean Air Gap	1.1352 mm
Pole Surface Area	1200 mm^2

Table 1: Dimensions of Magnetic Bearing

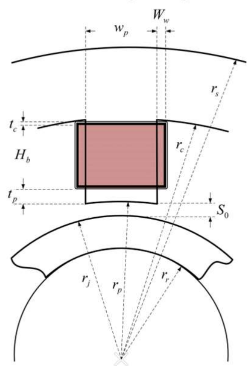

Figure 1: Dimensions used in geometry []

For modeling the Magnetic Bearing as a whole, we have replicated the magnetic bearing over 8 similar configurations.
A section of geometry for the MB is shown in Figure 1. This configuration allows using 4 electromagnets to create 8 poles formed in alternate succession, thus the Heteropolar configuration. Below is the Figure 2 depicts the same:

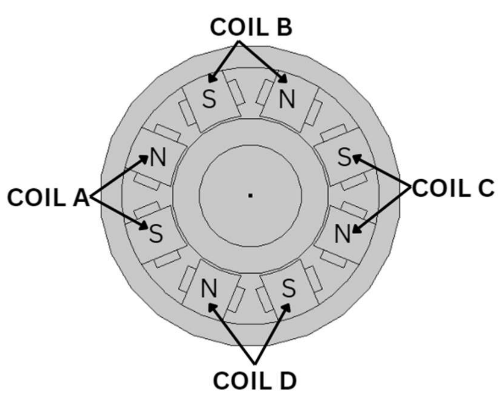

Figure 2: Showcase of Heteropolar geometry in Magnetic Bearing

Magnetic Fields

The primary law in Magnetism that is used is Lorentz force.

$$\vec{F} = \int \left(\vec{J} x \vec{B}\right) da$$

Where:
$\vec{J}$ = is the vector of the surface current density
$\vec{B}$ = is the vector of external magnetic flux density
da = an elementary element of surface

During the magnetization of the magnet, all of the atoms' magnetic moments are parallel. Atoms' free electrons cause the magnet's molecular current to be produced. The resulting current in the magnet is equal to zero since the free electrons are moving in the opposite direction.
Only in the magnet wall does the molecular current deviate from zero since the freely moving electron is moving in the same direction. The surface current density $\vec{B}$ can be determined by the following:

$$\vec{B} = \vec{M} x \vec{n}$$

Where:
$\vec{M}$ = is the magnetization of the magnet
$\vec{n}$ = is the normal vector of the magnet
The magnetic flux density that is generated by a static /stationary magnet is determined by the Biot-Sarvart's law:

$$\overrightarrow{B(r)} = \frac{\mu_0}{4\pi} \int \frac{\overrightarrow{K(r') x R}}{\left|\vec{R}\right|^2} da$$

Where:
$\overrightarrow{B(r)}$ = is the magnetic flux density at a point r
$\vec{R}$ = the vector between r an r'
Using the 3 equations above, we can calculate the forces in the magnetic bearing. After making the necessary assumptions, these equations lead to a complicated and complex math model of the bearing. The simplest way to do this is to use the finite element method.

COMSOL Multiphysics Model

COMSOL is a widely used FEM software to solve complex mathematical models. We have developed a COMSOL model using the NSNS Configuration, also known as Heteropolar Configuration.

Creating Geometrical Model

To recreate the geometry of the magnetic bearing itself, the measurements from Table 1. After creating the Geometry within COMSOL, the geometric model can only be used if materials are defined for all domains. Below is a colored image of the geometry that helps assign the materials.

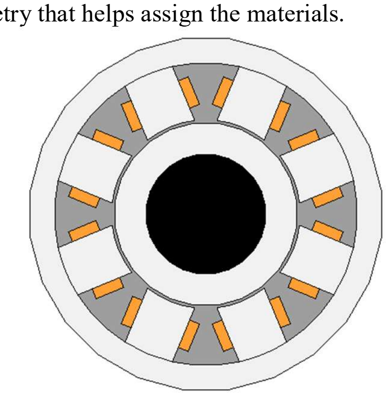

Figure 3: Representation of the materials for building model

Domains	Material	Color
Windings of the slots	Copper	Orange
Slots, Stator, Outer sheath of Rotating shaft	Soft Iron	White
Rotating Shaft	Structural Steel	Black
Between Slots, Air Gap	Air	Grey

Table 2: Allocating materials in Multiphysics Software

The Soft Iron used to model this magnetic bearing has the relative μ = 1000 for modeling purposes because an ideal value of 1 would void the solvers, and the model would not function.

Modeling Steps

After creating the geometric model along with materials, the model requires physics to be assigned to the domains. The "Magnetic Fields" physics was used to form the Heteropolar Model of the Magnetic Bearing.

The coils are assigned with the slots to create poles in our desired polar configuration.

The following are the conditions used in the coils:

Material Type	Solid
Conductor Model	Homogenized Multiturn
Current	5A (sinusoidal)
Number of Turns	160
Round wire diameter	1.22mm

Table 3: Configuration of coils used in the model

The rotating shaft is assigned a rotating domain mesh so that its effects can also be studied. The values in Table 3 are used to generate and implement the mesh for simulating the model. For the Study steps, two types of study are used: Stationary and Time-Dependent. For the Stationary solver, the time the static model is run is Physics-Controlled. In the case of the time-dependent solver, the timesteps are chosen from 0 to 0.1 seconds with a time interval of 10E4 to allow for better convergence of the results.

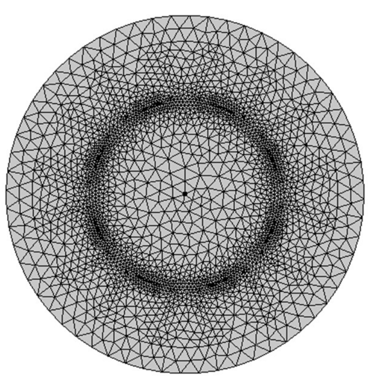

Figure 4: Visual representation of the meshing of the model

In figure 4 fine mesh size was used. Below are the details of element values for different mesh sizes.

Properties	Coarse	Normal	Fine
Number of elements	3366	5224	5214
Minimum Element Quality	0.467	0.427	0.491
Average Element Quality	0.795	0.8142	0.8158
Element Area Ratio	0.00656	0.006481	0.009504
Maximum Element size (in mm)	15.4	10.3	8.17
Minimum Element size (in mm)	0.308	0.0462	0.0462

Table 4: Values used during the simulation of each meshing

Results and Discussion

For the model simulation, mesh size was varied from coarse to fine to normalize the results. The following are the results of the simulation.

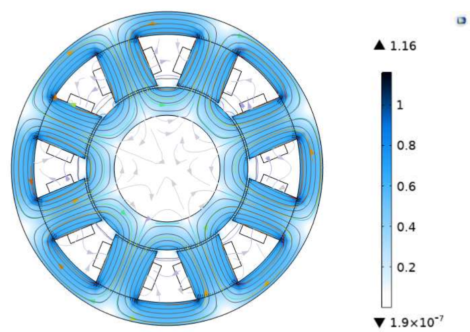

Figure 5: Plot of Magnetic Flux Density for Fine Mesh size

The figure 5 has a magnetic flux density of 1.16 T at maximum in the fringes of the poles. From the 2D plot of the Magnetic Flux density at t = 0.1s, we can see the existence of 8 poles. The Existence of Heteropolar configuration can be seen with the flux lines of each pole, resulting in 8 distinct and equal in magnitude poles. The flux generated flows through the soft iron surrounding the rotating shaft, thus showing the forces acting on the shaft. The current provided is sinusoidal in nature, and it can be verified by the graph of the concatenated flux density with time.

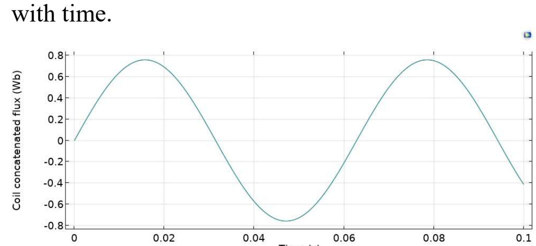

Figure 6: Plot of Coil Concatenated Flux with time

Convergence of the FEM model is further shown by the nature of the coil concatenated flux concerning time.
The magnitude of the Magnetic Flux Density on the surface of the shaft is shown below.

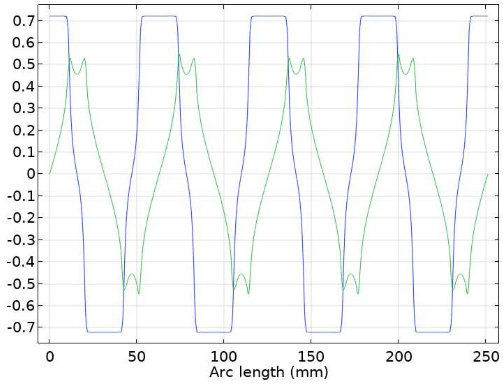

Figure 7: Plot of Magnetic Flux Density for Radial and Tangential axis

From the plot of magnetic flux density, we can infer that the magnitude of the magnetic field produced by the coils directly affects the rotating shaft. Hence the FEM model works its intended purpose.
With the time-dependent study in the COMSOL model, polar plots can be generated for the electromagnetic force in the x and y directions, respectively. Polar plots help highlight the frequency response characteristic of the system and also assist in determining the system's stability. Below is the polar plot for the FEM model over a range of timesteps.

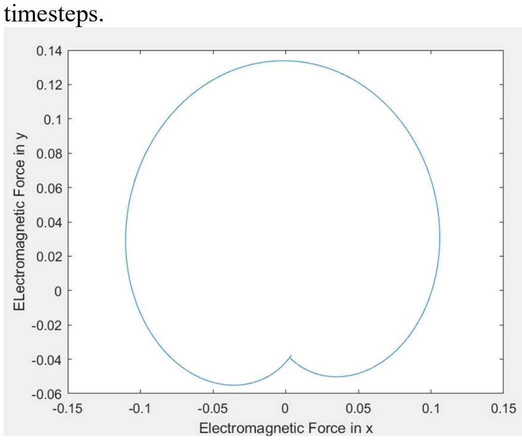

Figure 8: Polar Plot of Electromagnetic Forces in X and Y direction between 0.0057s and 0.0257s

With the help of polar plots, we can infer that the forces in the x direction appear to be balanced in the positive and negative direction for the range of timesteps used for this plot. On the other hand, the Forces in the y direction are more towards the positive y direct or the vertically upwards direction than the vertically downwards direction.
For a different set of timestep, we can observe the following polar plot:

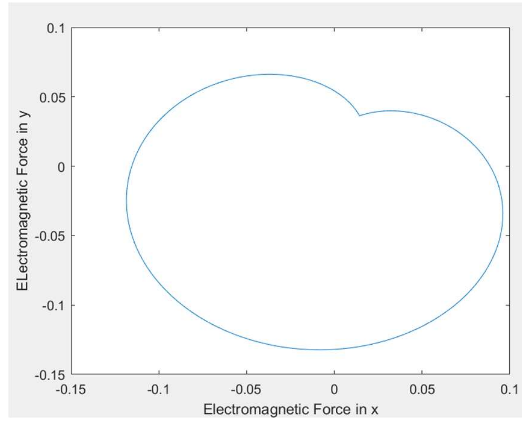

Figure 9: Plot of Electromagnetic Force in x and y direction between 0.04s and 0.06s

This differs from the previous plot, implying that the time-dependent simulation allows forces to vary constantly with time, thus showing the system's stability.
To verify the model's validity, the mesh size can be varied to prevent ambiguity.
While performing the same simulation on a "Normal" mesh, the following was the plot of magnetic flux density.

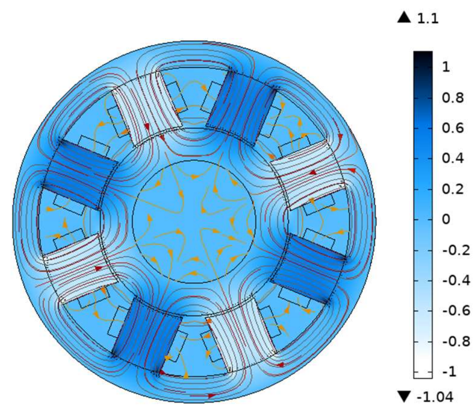

Figure 10: Plot of Magnetic Flux density for mesh size "Normal"

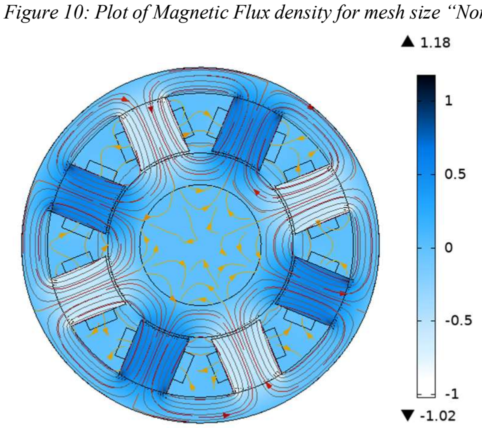

Figure 11: Plot of Magnetic Flux density for "Coarse" meshing

The magnetic flux density on the rotating shaft's surface remains the same.

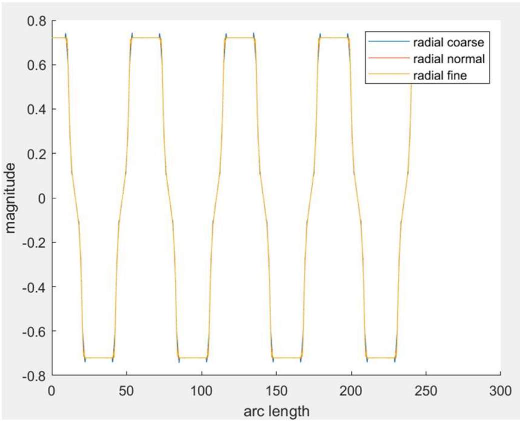

Figure 12: Plot of Magnetic Flux density for radial direction in all types of meshing

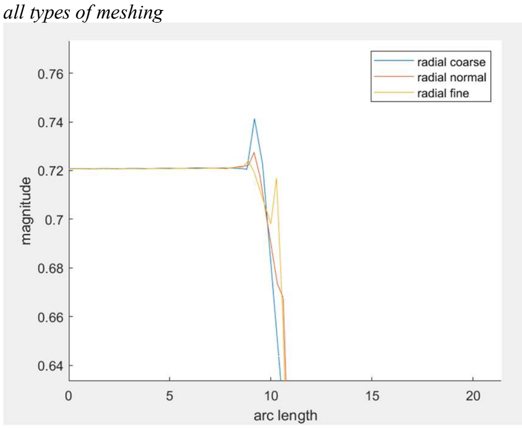

Figure 13: Expanded plot of Magnetic Flux density for radial direction in all types of meshing

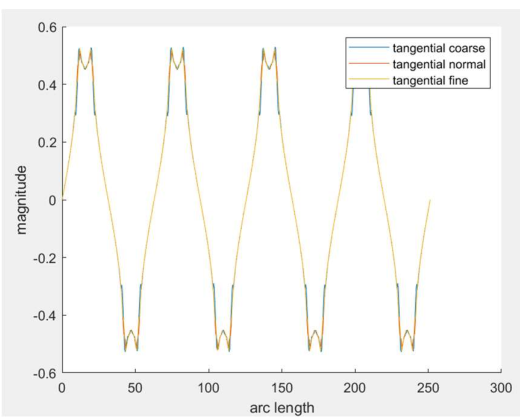

Figure 14: Expanded plot of Magnetic Flux density for tangential direction in all types of meshing

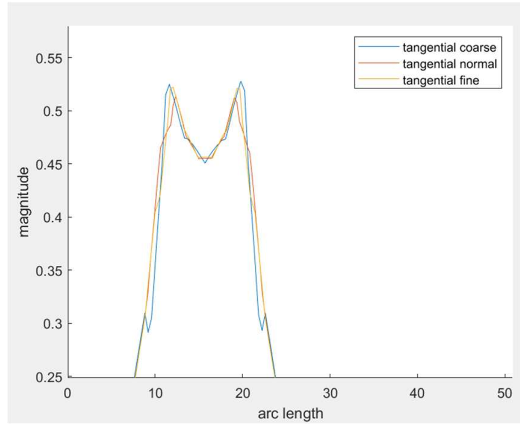

Figure 15: Expanded plot of Magnetic Flux density for tangential direction in all types of meshing

Forces due to Current variation

To ensure that the model can balance the rotating shaft properly, it is important to show the effect of imbalances in current to create a net force in the direction of increase. Using the model with a "Normal" mesh size as in Table 4, a calculated change variation in currents is simulated to show the generation of a force vector. Figure 16 represents the magnetic flux density of the Magnetic Bearing when we have increased the current to 6A in coil B.

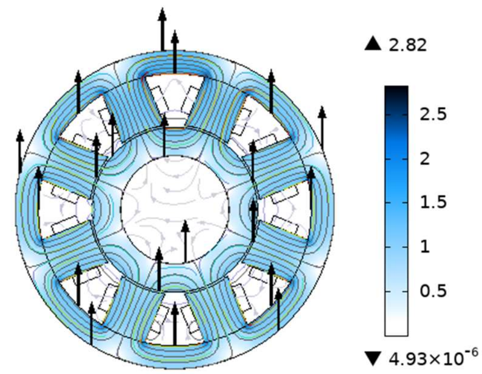

Figure 16: Plot of Force and its direction with simulated current variation

Figure 16 also shows accurately the direction of the forces due to the increase in current in coil B. From the figure it is clear that the direction of the force is non zero and in the positive y direction. The effect of forces is also visible in the plot of Radial and Tangential electromagnetic forces on the outer forces of the rotating shaft.

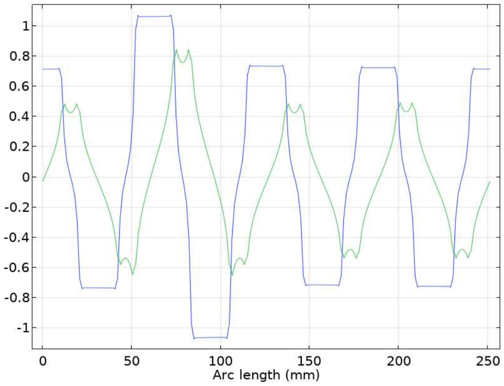

Figure 17: Expanded plot of Magnetic Flux density for radial and tangential direction arounf the outer surface of the shaft. The increase in the Manetic field more that the other magnetic field represents the increase in current from the other coils

The polar plots are further indicators of the values of the force in x and y.

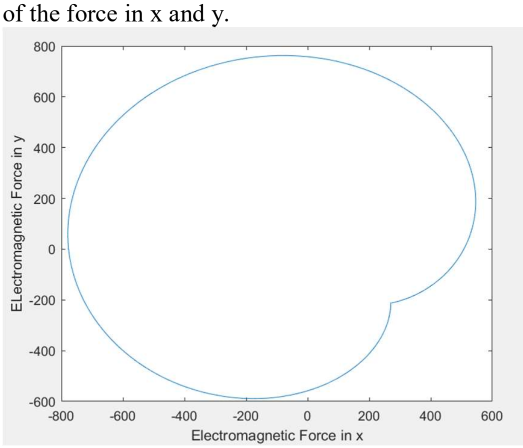

Figure 18: Polar plot of Force and the direction of the forces generated. The slight deviation from Y direction is due to the partial magnetization of the soft iron cover of the shaft

The polar plot is not perfectly in the vertical direction due to the partial magnetization of the outer surface of the rotating shaft, which is materialized as soft iron.

Conclusions

This study delved into the intricacies of modeling heteropolar radial magnetic bearings (PMBs) using COMSOL Multiphysics software. PMBs, characterized by using electromagnets to suspend and control rotating shafts without external feedback control, offer an enticing array of advantages, including low friction, high-speed capabilities, low maintenance requirements, and extended operational lifespans. However, they pose challenges, including low stiffness, substantial axial forces, and nonlinear behavior.

Our investigation shows the NSNS heteropolar configuration of the magnetic bearing, to assess its impact on magnetic flux density, radial stiffness, and axial force under varying operational conditions.

Our modeling endeavors, executed with precision and accuracy through COMSOL Multiphysics software, provided a comprehensive understanding of Magnetic Bearing behavior across various operational conditions. The rich simulation results offered a holistic view of these complex systems, from magnetic flux density distributions to forces acting on the rotating shaft.

Furthermore, our exploration extended to polar plots of electromagnetic forces in the x and y directions over varying time steps. These polar plots provided valuable insights into the frequency response characteristics of the system and aided in evaluating system stability. They underscored the dynamic nature of MBs and their capacity to adapt to changing conditions, adding depth to our comprehension of their behavior.

In conclusion, our research endeavors have shed light on the intricacies of modeling and optimizing heteropolar radial magnetic bearings. We've laid the groundwork for future advancements in precision engineering and magnetic bearing technology by considering different pole configurations.

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Acknowledgments

The authors greatfully acknowledge to Government of India for the availability of the COMSOL Multiphysics 6.0 software through ISTEM India platform.