ANALYSIS OF MAGNETO-RHEOLOGICAL (MR) DAMPER AND ITS APPLICATION IN VEHICLE SUSPENSION SYSTEM

DISSERTATION-II

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IN

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(SPECIALIZATION IN DESIGN)

By

Mr. WASIM RUSKIN KHAN

(Regd. No. 11007920)

UNDER THE GUIDANCE OF

Mr. ANIL GHUBADE

(UID-18325)

LOVELY PROFESSIONAL UNIVERSITY

PHAGWARA (DISTT. KAPURTHALA), PUNJAB

Mechanical Engineering Department

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Certificate

I hereby certify that the work which is being presented in dissertation-II entitled, **"ANALYSIS OF MAGNETO-RHEOLOGICAL (MR) DAMPER AND ITS APPLICATION IN VEHICLE SUSPENSION SYSTEM"** in the partial fulfillment of the requirement for the award of degree of **Master of Technology** submitted in the Mechanical Engineering Department, Lovely Professional University, Phagwara (Punjab) is an authenticated record of my own work carried out period of pre-dissertation and dissertation-I under supervision of **Mr. Anil Ghubade** (Assistant Professor) at Lovely Professional University.

The matter presented in this report has not submitted by me anywhere for award of the degree to any other institute.

Date: **Wasim Ruskin Khan**

(Reg. No. 11007920)

This is to certify that the above statement made by candidate is correct to best of my knowledge.

Date: **Mr. Anil B. Ghubade**

(UID-18325)

Abstract

To control vibration, magneto-rheological (MR) damper is one of the best semi-active dampers. One of the reasons for its increasing use in the suspension system of vehicles is because of its flexibility in the on-state and off-state damping forces. But there are some parameters that need to be improved like MR fluid's sedimentation, geometry design optimization, use of materials. This research aims at developing and enhancing the performance of an MR damper system facility by means of simulation by ANSYS 15 and algebraic equations in order to accommodate various input loads. The development of the suspension system began with a comprehensive research in this particular field so as to identify various areas for improvement. The aim of this research is to increase the on-state damping forces of a standard model of an MR damper by altering different geometric parameters, changing material properties and materials. Different models are identified and analyzed to improve the on-state damping force. The study revealed two cases, first is high on-state force at low current and second, overall maximum on-state force.

Acknowledgements

I wish to express my deep sense of gratitude to my respected mentor, Mr. Anil Ghubade for his able guidance and useful suggestions, which helped a lot in completing the Thesis work, in time.

I would also like to express my heartfelt thanks to my friends who helped in successful completion of this project.

And lastly and most importantly I would like to thank my parents who made my study at Lovely Professional University possible.

Wasim Ruskin Khan

(Reg. No. 11007920)

Declaration Statement

I, Wasim Ruskin Khan, a student of B.Tech-M.tech (Dual Degree) - ME dual degree under the Department of Mechanical Engineering of Lovely Professional University, Punjab, hereby declare that all the information furnished in this thesis report is based on my own intensive research and is genuine.

This thesis does not, to the best of my knowledge, contain part of my work which has been submitted for the award of my degree either of this university or any other university without proper citation.

Date: **Wasim Ruskin Khan**

(Reg. No. 11007920)

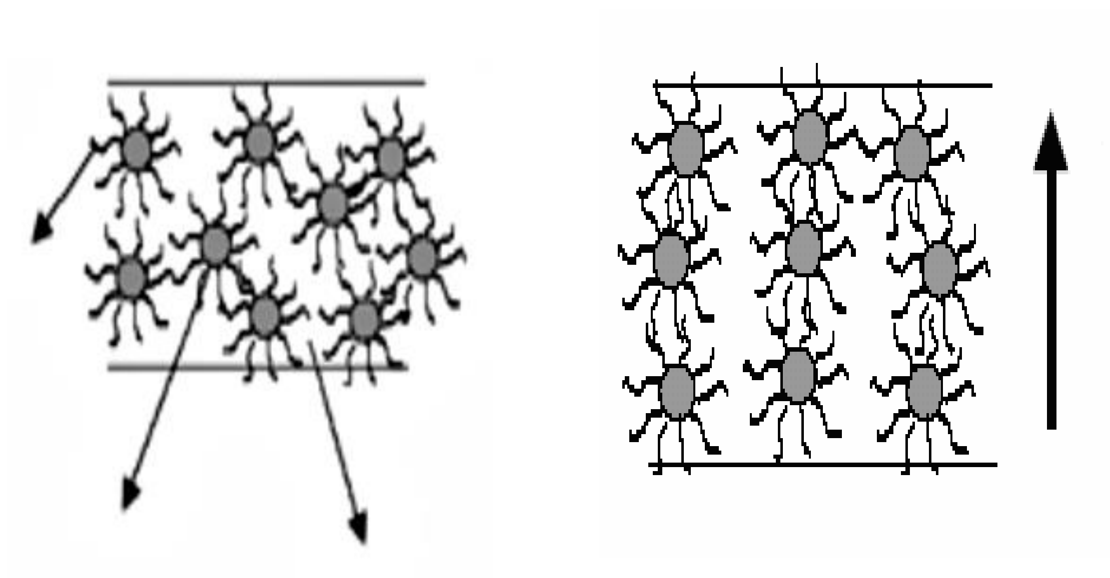
Contents

List of figures

Figure | Page

1. Introduction

Magneto-rheological (MR) fluids are smart materials, meaning the rheological properties are capable of alteration. MR fluids respond to an applied magnetic field. It is composed of micro-sized magnetic particles (20-40% of the volume of the fluid) such as carbonyl iron particles suspended in an insulating carrier liquid like hydrocarbon oil, silicon oil, glycol etc. [1, 2, 3]. The suspended particles become magnetized and align themselves in chain like structure in the direction of the magnetic field as shown in figure1.1. These chains restrict the movement of the MR fluid and thereby increase the yield stress of the fluid. In “off” state, the fluids behave alike to liquid paints and show comparative levels of viscosity at low shear rates of order 0.1 to 1 Pa-s [4]. Their viscosity alters dramatically (105 −106 times) more in a few milliseconds with the application of magnetic field. With the removal of magnetic field the change in viscosity is completely reversed [5].



(a) Absence of magnetic field (H) (b) Presence of Magnetic field (H)

Figure 1.1 Behavior of magnetic particles with and without magnetic field [5]

1.1 Why MR fluid?

MR fluid can be called as a smart fluid because of its versatile characteristics. There is one another fluid known as electro-rheological (ER) fluid which shows rheological changes with the application of electric field. But, there exist some flaws in the ER fluid such as it is vulnerable to change in temperature viz. extreme property changes with temperature. The volume of ER fluid required in a damper is 100-1000 times more that of MR fluid for same performance and also ER fluids have relatively small rheological changes to MR fluids [3, 6].

The MR effect is interesting in the field of control of vibration as the effect can be applied to a hydraulic damper. MR fluid replaces the mechanical valves commonly used in passive suspension to control the damping force in the damper. MR fluid in a damper possess a better quality than passive damper system because if the MR damper stops to be controllable then it acts as a passive damper suspension system.

1.2 MR damper

The design of vehicle suspension plays an important factor in the vehicle dynamics because it has to satisfy the demanding factors in providing good vehicle handling, good ride comfort as well as stability. There are broadly three types of vehicle suspension systems- active, semi-active and passive suspensions. The commonly used passive suspension having an oil damper provides design simplicity and cost-effectiveness in practical application but due to lack of damping force controllability, its performance is limited. The active suspension however, having separate actuators that can exert an independent force provides high performance in control in a wide range of frequency but the cost and complexity of the system limits its commercial applications. To solve these issues, researches on vibration control using semi-active suspensions have significantly increased since semi-active suspensions can provide performance benefits over passive suspensions and without the requirement of large power sources and expensive hardware like active suspensions. Recently, MR dampers as semi-active suspension systems are being used in a large number of vehicles which can meet the demanding requirements in a wide range [7, 8]. Researchers and engineers have interests in MR damper because of its flexible damping character, simple mechanics, less power requirement, quick response and compliance with electronics [9].

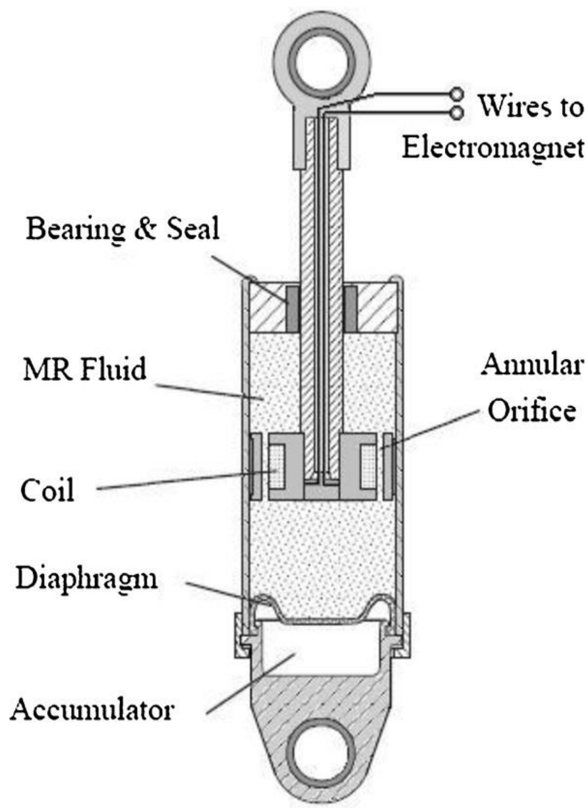


Figure 1.2 Schematic representation of an MR damper (RD-1005-3) manufactured by the Lord Corporation company [10, 11]

1.3 Classification of MR damper

MR dampers are basically classified into three categories- *mono tube MR damper*, *twin tube MR damper* and *double-ended* MR damper. Out of these, the mono tube damper is the most compact in size and also it can be installed in any direction of requirement. Because of these it is the most widely used MR damper. Schematic representation of the mono tube MR damper is shown in Figure 1.3. It consists of one reservoir. An accumulator mechanism is installed at the right end of the damper below is used to compensate the volume change that occurs due to the movement of the piston. Accumulator piston acts as a barrier between the compressed gas which is usually nitrogen and the MR fluid of the damper. This accumulator piston is used to compensate the change of volume which occurs when the piston rod enters the housing of the damper.

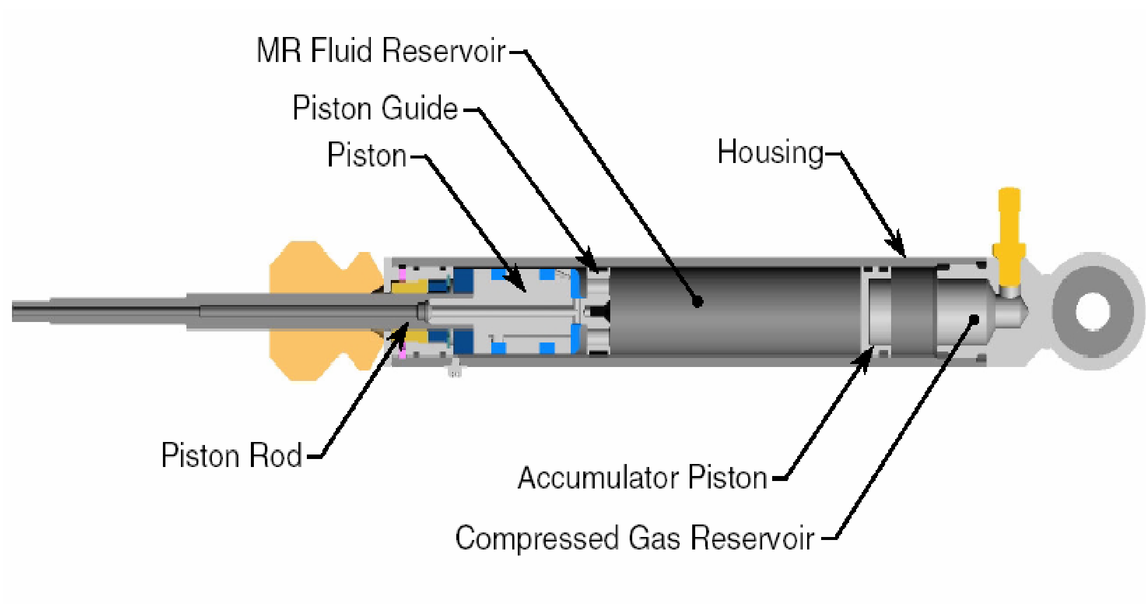


Figure 1.3 Schematic representation of a mono tube MR damper [12]

The twin tube MR damper however, has two chambers of fluid, one is inside of another. Schematic representation of twin tube MR damper is shown in Figure

1.4. The inner housing and the outer housing of the damper are separated by a foot valve. The piston rod assembly is guided by the inner housing of the damper in the same manner as in case of mono tube damper. Inner reservoir space is the volume bounded by the inner housing of the damper. Similarly, outer reservoir space is the volume that is enclosed between the inner and the outer housing of the damper. The inner reservoir of the damper is installed with MR fluid is installed in the inner reservoir to avoid occurrence of air pockets.

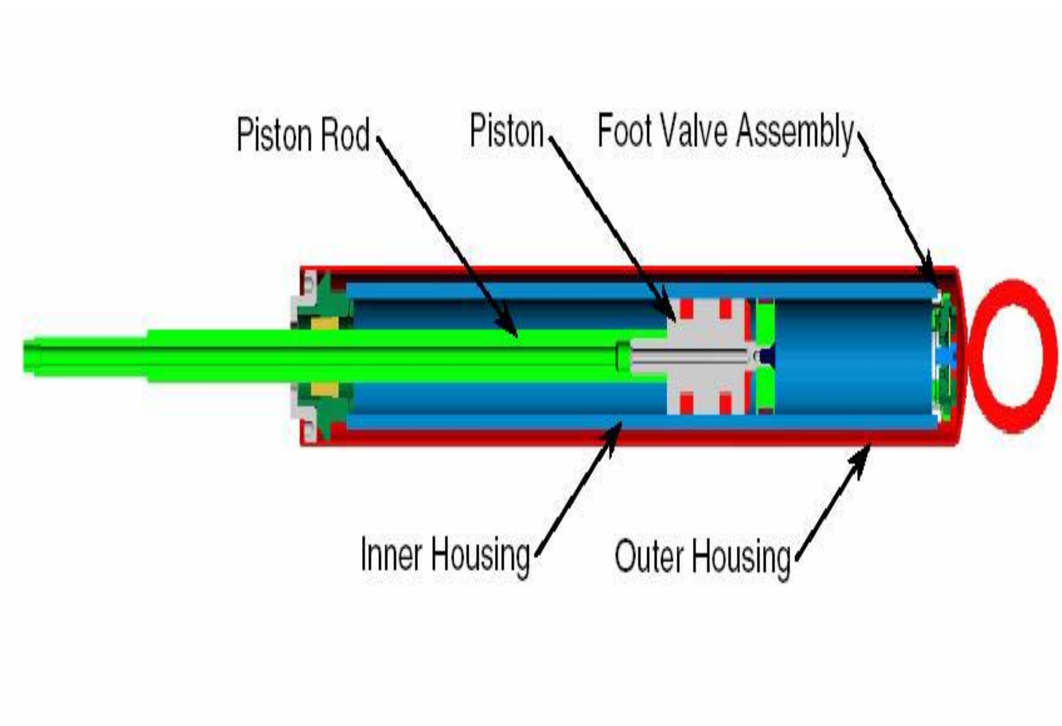


Figure 1.4 Schematic representation of twin tube MR damper [12]

The third type is double-ended MR damper. Here two piston rods of same diameter are inserted from both terminus of the housing of the damper. Schematic representation of a double-ended MR damper is shown in figure 1.5. As the piston rod moves relative to the housing of the damper, there is no change in volume MR fluid, one piston simply pushes the other piston, so the double-ended MR damper does not have an accumulator. This damper is used in lot of applications like damping the force of gun recoil [13], bicycle applications [14], building applications to protect it from earthquake and windflaw [15].

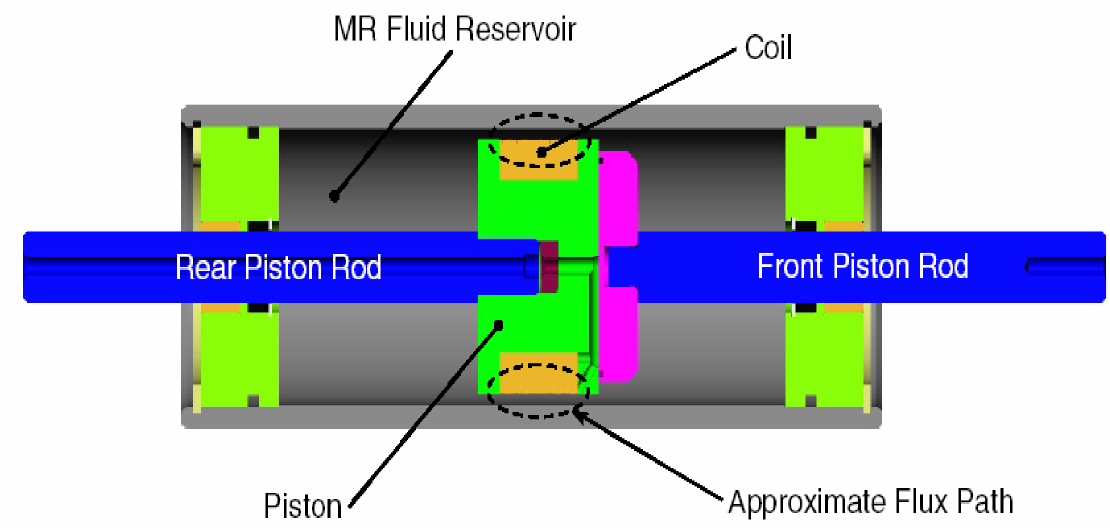


Figure 1.5 Schematic representation of double ended MR damper [12]

2. Terminology

Some terminologies used in the optimization of MR damper suspension system are defined below.

Piston head: It is the head of the piston of the damper embedded with engine, coil, and air gap.

Engine: It is a part of the piston head around which the coil is winded.

Coil: It is the windings of conducting wires around the engine for the purpose of generating magnetic field around it.

Housing: It is the outer layer of the damper covering the components like piston head, MR fluid, accumulator, piston rod etc.

MR fluid: It is composed of magnetic particles suspended in an insulating carrier fluid.

On-state force: It is the force provided by the damper when current is on causes magnetic fluid particles to align themselves due to magnetic flux and restrict the motion of the fluid.

Off-state force: It is the force provided by the damper when there is no current, this force is similar to force provided by passive damper system.

3. Review of literature

This section briefly describes a summary of suspension systems, MR dampers, MR fluids devices that have already been proposed or commercialized.

The basic requirements like minimization of dynamic road-tyre forces, minimization of relative motions between the vehicle bodies, ride comfort, less cost and less requirement of external power supply should be fulfilled by the optimal suspension design.

S. Sigla et al [8] have compared the three classifications of suspension systems-passive, semi-active and active, and have concluded that the ride comfort can be improved by both active and semi-active suspension system but in case of active suspension system the major drawback is that it has the requirement of large power supply. The cost and complexity of active system is also higher than that of semi-active.

Magneto-rheological (MR) damper have fluids which respond to an applied magnetic field with a change in the rheological behavior.

M. Aslam et al [5] have investigated the properties of MR fluids and have shown the volume fraction and particle size dependence, linear visco-elasticity, stability, temperature effect and rheology of MR fluids.

Mark R. Jolly et al [6] have discussed several commercial MR fluids and the rheological and magnetic properties of these fluids. Various advantages and disadvantages of different MR fluids were computed and presented. They illustrate that the properties and attributes of commercially available MR fluids are wide-ranging with the presentation of examples.

S. Guo et al [1] analyzed the nonlinear vibrations of MR damper vehicle suspension systems. In the light of the solutions in isolation of single degree of freedom systems with MR dampers, they have presented the harmonic responses of suspension systems of a quarter car model with MR dampers with some formulations and reasonable assumptions, the results of sprung and unsprung transmittances for the system are also presented. Numerical simulations approximately verified the theoretical analysis solutions.

Dalei Guo and Haiyan Hu [2] have focused on nonlinear behavior of MR damper for analyzing the phenomenon of hysteresis between the input velocity and the restoring force. They have illustrated the damping forces and the nonlinear stiffness of the MR dampers with the use of the equivalent damping and linear stiffness of an RD-1005 MR damper a model by Lord Corporation. Their **research shows that the additional nonlinear stiffness of an MR damper** eminently exists and affects the performance of the control system with help of an experiment for a semi-active suspension system of a quarter car model and the numerical simulations

L. Balamurugan et al [7] have presented an algebraically solved model for MR damper semi-active suspension in order to the stationary reaction of a quarter car model of vehicle crossing a rough road with a constant velocity. The algebraic model can characterize MR damper dynamics in an accurate manner. With the proposed algebraic model along with a suitably designed skyhook sliding mode controller with the controller of continuous-state damper, the model MR damper is applied to a model quarter-car suspension system. The performance characteristics and the robustness of the semi-active suspension are evaluated by two nested controllers, and then compared with the active as well as passive suspension. Results prove that the performance of semi-active controller based on the proposed algebraic model is better than the performance of the passive suspension and also can achieve congruous performance as that of the active suspension controller except for a small deterioration.

Many research work have been proposed on semi-active control systems in the last decade. A significant quantity of academic publications are presented. Researchers have shown a significant improvement in semi-active control systems using magnetic field controlled fluid. Finite element methods for analysis, Computational Fluid Dynamic analysis of MR flow and electro-magnetic analysis of magnetic field are been used to design MR dampers.

Z. Parlak et al [9] have presented a new finite element analyses method to optimize the design of MR damper. This method uses Computational Fluid Dynamic (CFD) and electromagnetic analysis to optimize design parameters of an MR damper and also optimize magnetic field that provides maximum control of the MR damper. They have manufactured the optimal damper configurations at the end of FEM analysis and then the results are tested. Test results have shown that the optimal design of MR damper has provided the expected damper force and there is a very close difference between the simulated data and the experimental data and can be accepted in numerous cases.

W. H. El-Aouar et al [12] developed a 2D axisymmetric model of MR damper. They solved the force-velocity characteristics after optimizing different geometric configurations of the damper. This model helped in the design of MR damper.

M. M. Ferdaus et al [16] have built 2-D as well as 3-D axisymmetric model of MR Damper and FEM analysis is done for the improvement of design parameters. Simulation of various configuration parameters of MR damper piston head, MR fluid gap, and damper housing are done for comparing the variation of damper’s performance. Finite element simulation has done with ANSYS 14.5 software. Various design configurations have been developed and generated and five models with different physical parameters in piston shape, MR fluid gap etc. are considered. These models are then simulated at a current range of 0 to 1 Amp, at various velocity of piston and at various length of stroke. After analyzing the entire simulation, optimal design configuration result is concluded. The simulated results of the optimized model have been compared with the experimental results for a range current, length of stroke and rate of stroke. By comparing all the results, it has been cleared that optimum model shows the best outcome in all cases.

M. Y. Salloom et al [17] have proposed an MR valve model which shows good strength of magnetic field in the valve gap region. The effective region of MR fluid is outside the valve coil and total length of the valve is less. The efficiency of the MR valve is higher than that of the damper having two coil annular fluid resistance gaps and as well as damper having one coil annular fluid resistance gap and these results are proved after the simulation of the proposed models. The proposed model MR valve can produce more fluid flow block force than the MR valves with one and two coil annular fluid flow resistance gaps simultaneously.

4. Rationale and Scope of the Study

Semi-active control suspension system is one of the most important system because it provides reliability of passive system and also versatility of active system without the requirement of heavy power source. MR damper suspension system is one of the most important semi-active suspension system because of its supple characteristic in the control of on-state and of-state forces. It is used widely in vehicles, buildings, bridges, weapons, human body etc. It is important to extract more from it in the most efficient envelope. Scope of this research is the optimization of on-state damper force. This can be obtained by optimizing geometry parameters and using more efficient materials.

5. Objectives of the study

The research objectives are-

1. To obtain a finite element analysis (FEA) model for 2D axisymmetric model of MR damper's engine, coil, air gap, MR fluid gap and housing.
2. To study the effect of different geometric parameters that affect the magnetic field and on-state force of the damper.
3. To study the effect of different materials and material properties that affect magnetic field and on-state force of the damper.
4. To obtain on-state force-current relationship of the dampers.
5. To obtain an optimized model that can produce large on-state damper force at less current.
6. To obtain an optimized model that can produce maximum on-state damper force.

6. Research Methodology

In this work, the piston head of a standard model of an MR damper is analyzed by finite element methods using ANSYS 15 [16]. Different geometric parameters, materials and material properties are modified that affects the magnetic field and thereby the on-state force of the damper. These affects that helps in optimizing the model and increasing the on-state damper force are studied with the help of finite element methods and algebraic equations.

6.1 Mathematical formulations

The on-state damper force of the MR damper, ***F*** can be expressed as [17];

$\boldsymbol{F} = \Delta \boldsymbol{P}_{\boldsymbol{\tau}} \boldsymbol{A}_{\boldsymbol{\tau}}$ **; w**here ,

$\Delta \boldsymbol{P}_{\boldsymbol{\tau}}$ = on state pressure component or field dependent induced yield pressure component

$\boldsymbol{A}_{\boldsymbol{\tau}}$ = active fluid area

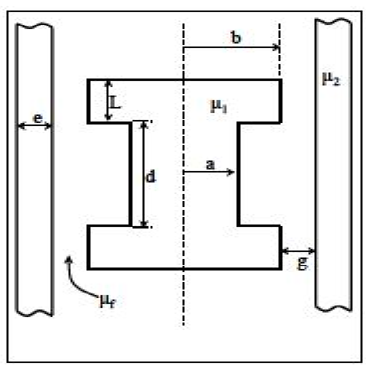


Figure 6.1 Schematic representation of piston head, housing and MR fluid gap

The field stress component ΔP_τ and active fluid area A_τ can be written as;

$$\Delta \boldsymbol{P}_{\boldsymbol{\tau}} = \frac{c\tau_y L}{g}$$

$\boldsymbol{A}_{\boldsymbol{\tau}} = 2\pi b(L+g)$ **;**Where,

c= constant (c=3, in this case)

$\tau_y =$ field dependent yield stress or fluid shear stress

L= length of fluid flow orifice

g= fluid gap (annular gap)

Now, the fluid shear stress (τ_y) can be expressed as a function of magnetic flux density or magnetic induction (B) as[12];

$$\tau_y = 6.298B^4 - 25.824B^3 + 26.639\, B^2 - 0.438B$$

The magnetic flux density(B) in the above equation is analyzed by Finite Element Methods using ANSYS 15. The magnetic flux density is calculated in the MR fluid gap by the following equation.

$$B = \frac{B_{max} + B_{min}}{2}$$

There is saturation of on-state force for a particular current value, after that if we keep on increasing the current there will be no increase in the on-state force. So in this way we can optimize the current and thereby the damper on-state force value.

6.2 Optimize the geometry of the model

The different geometric designs, materials and material properties have a significant affect in the design analysis of the damper. These parameters affect the on-state force-current relationship of the damper. The magnetic induction is associated with the magnetic permeability of a material. The more we increase permeability the more magnetic flux field will be generated. Use of material having higher magnetic permeability tends to produce higher magnetic field density in the material.

Evaluation of different design shapes like chamfered or fillet ends of the MR fluid gap corners, increasing and decreasing the MR fluid gap and the housing area respectively, use of different magnetic fluids having different BH curves etc. are done and the models with optimal results are selected. Also how changing the geometry, use of materials having different magnetic permeability and use of different MR fluids in the fluid gap of the piston head affect the on-state force that the damper can provide are also studied.

7. Results and discussion

In the design of MR dampers, one of the primary goal of the researchers' is to obtain maximum force at minimum space. So it is necessary to study the related parameters to optimize the MR damper. The purpose of this chapter is to discuss about the results of the research. 2D axisymmetric model of piston head of an MR damper is analyzed using the software, ANSYS 15.

The magnetic flux density at the MR fluid gap is obtained at various currents ranging from 0 -2 Amp. The mathematical equations given in previous chapter are used to determine the on-state forces at various current levels.

Then on-state force vs. current graphs are plotted and then we get the optimal on-state damper force for each model. Eight models are studied and their parameters and results are summarized as follows:

Model 1. Standard model

<u>Geometry</u>

Inner piston shape of the damper= plain ended

Engine area= 11.25×17.5 mm

Housing area= 3.25×17.5 mm

Coil area= 2.5×7.5 mm

MR fluid gap area= 0.5×17.5 mm

Air gap area= 5.25 mm^2

Number of coil windings= 100

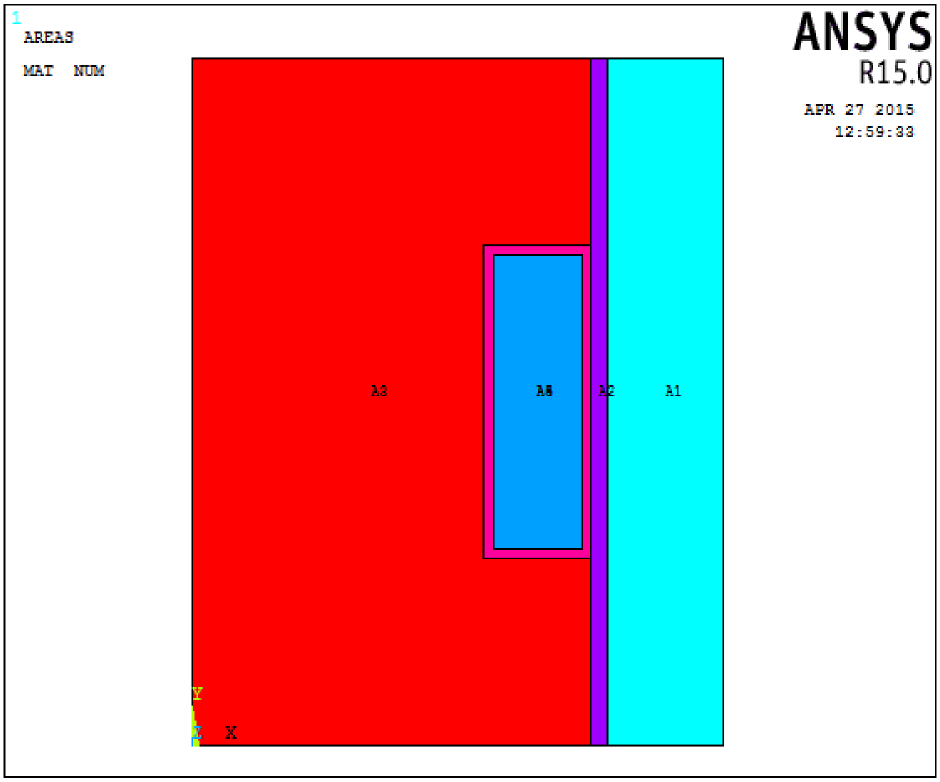


Figure 7.1 2D axisymmetric model of an MR damper

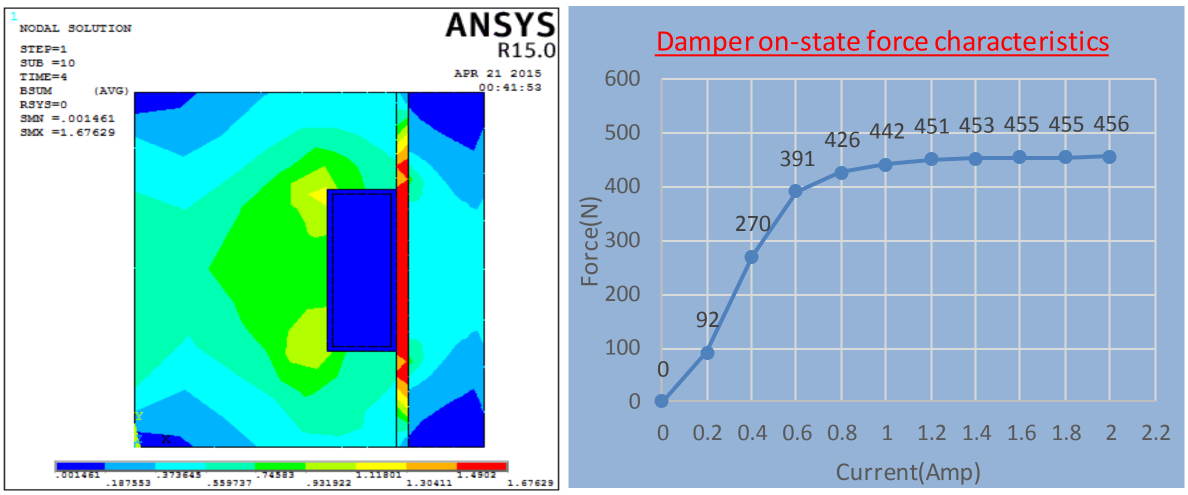
Material properties

Relative permeability of engine and housing=80 (Martensitic stainless steel)

MR fluid particles= silicon cored iron

Relative permeability of coil=0.99(copper)

Relative permeability of air gap=1(air)



(a) (b)

Figure 7.2 (a) ANSYS model at max. on-state force (b) Graph between on-state Force and Current

Maximum On-state force=456 N

Current=2.0 Amp

Average B_{sum}=0.84 T

Model 2. Chamfered ends

Material chamfered from each corner of the MR fluid gap= 1mm

<u>Material properties</u>

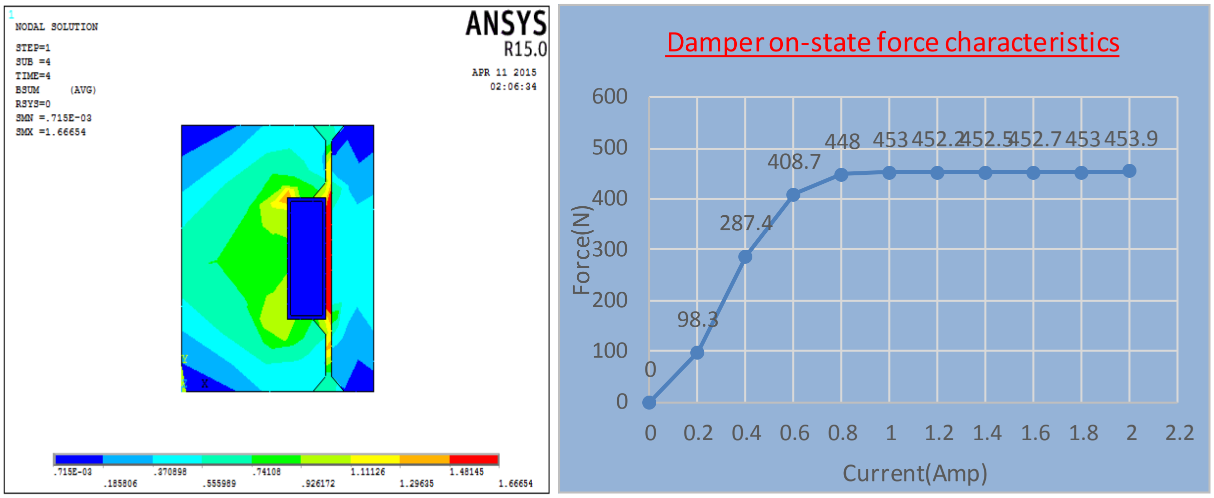
Relative permeability of engine and housing=80

(Martensitic stainless steel)

MR fluid particles= silicon cored iron

Relative permeability of coil=0.99(copper)

Relative permeability of air gap=1(air)



(a) (b)

Figure 7.3 (a) ANSYS model at max. on-state force (b) Graph between on-state Force and Current

Maximum On-state force=453.9 N

Current=2.0 Amp

Average B_{sum}=0.834 T

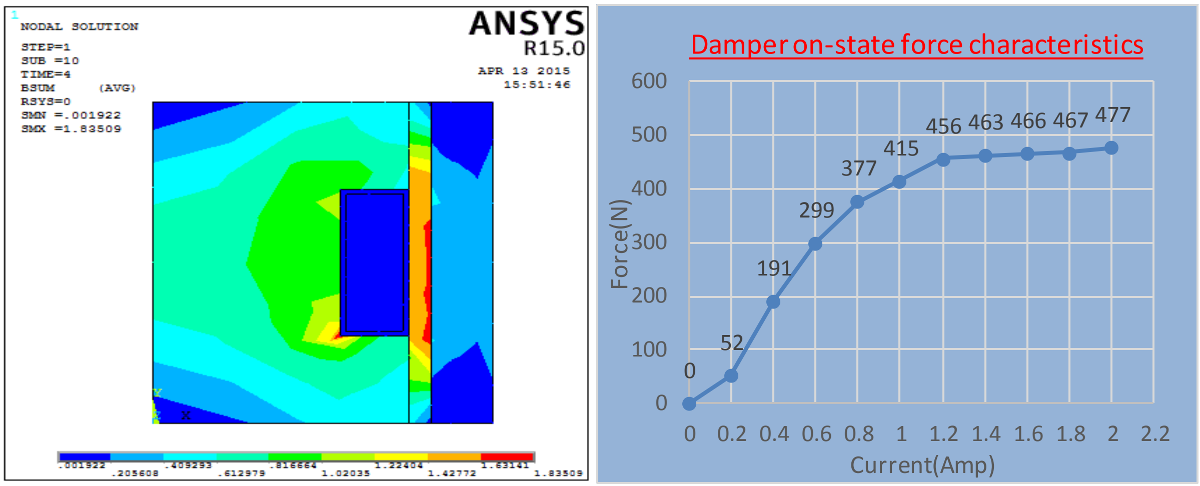
Model 3. Fluid gap increased by 0.5 mm and housing area reduced by 0.5mm (A)

<u>Material properties</u>

Relative permeability of engine and housing=80 (Martensitic stainless steel)

MR fluid particles= silicon cored iron

Relative permeability of coil=0.99(copper)



(a) (b)

Figure 7.4 (a) ANSYS model at max. on-state force (b) Graph between on-state Force and Current

Maximum On-state force= 477 N

Current=2.0 Amp

Average B_{sum}=0.918 T

Model 4. Fillet Ends (A)

Fillet radius=1.5mm

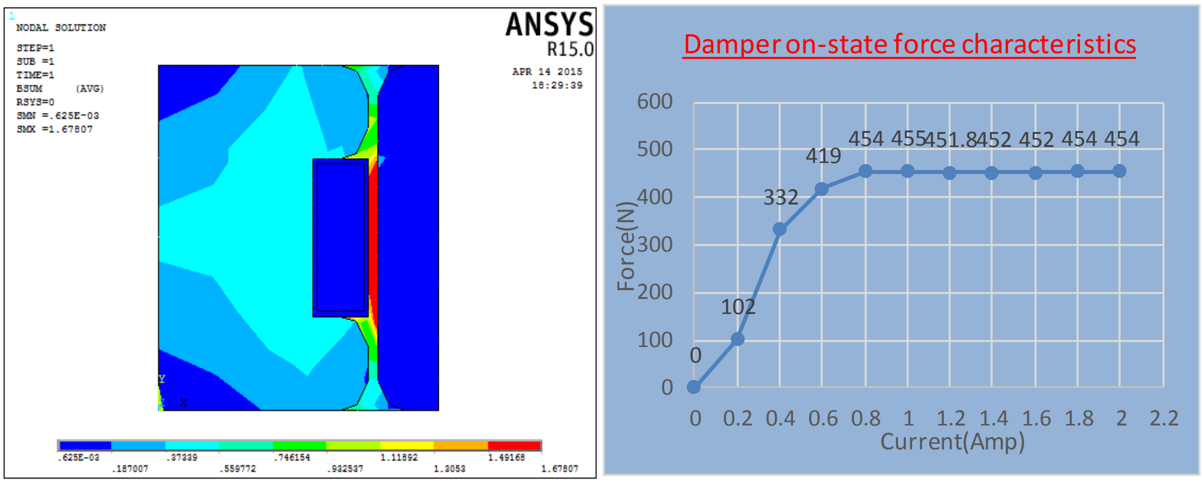
<u>Material properties</u>

Relative permeability of engine and housing= 80 (Martensitic stainless steel)

MR fluid particles= silicon cored iron

Relative permeability of coil=0.99(copper)

Relative permeability of air gap=1(air)



(a) (b)

Figure 7.5 (a) ANSYS model at max. on-state force (b) Graph between on-state Force and Current

Maximum On-state force= 455 N

Current=1.0 Amp

Average B_{sum}=0.84 T

Model 5. Fillet Ends (B)

Fillet radius=1.5mm

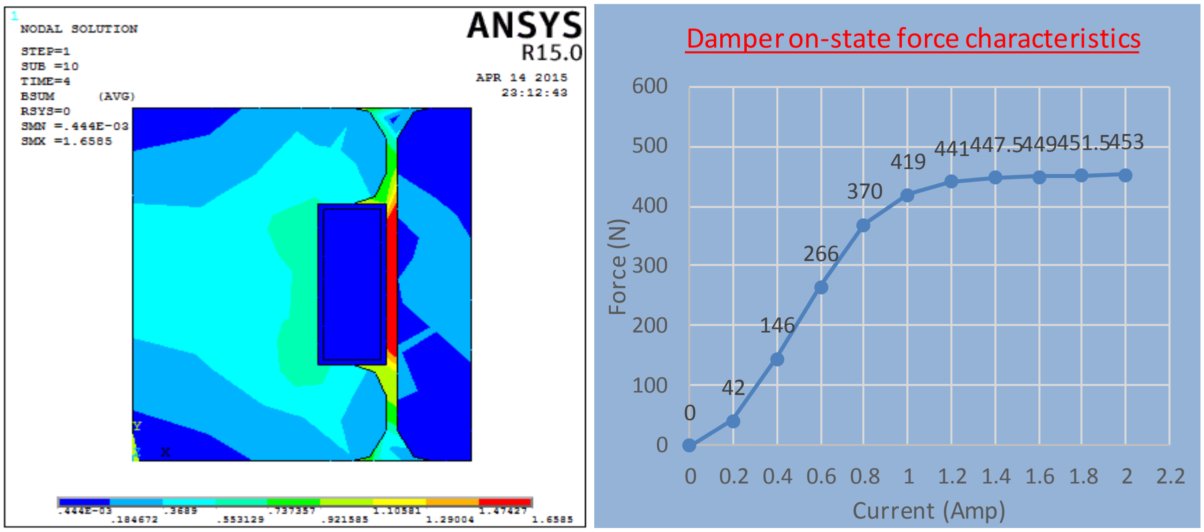
<u>Material properties</u>

Relative permeability of engine and housing= 45 (Martensitic stainless steel)

MR fluid particles= silicon cored iron

Relative permeability of coil=0.99(copper)

Relative permeability of air gap=1



(a) (b)

Figure 7.6 (a) ANSYS model at max. on-state force (b) Graph between on-state Force and Current

Maximum On-state force= 453 N

Current=2.0 Amp

Average B_{sum}=0.829 T

Model 6. Fillet Ends (C)

Fillet radius=1.5mm

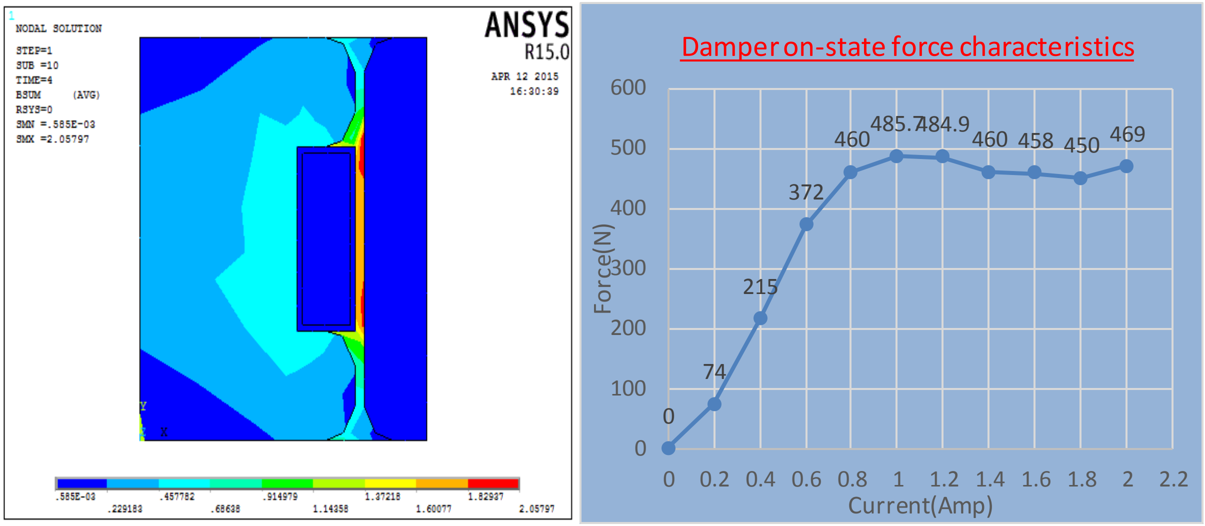
<u>Material properties</u>

Relative permeability of engine and housing=80 (Martensitic stainless steel)

MR fluid particles= Ferro Cobalt: 34.5% Co

Relative permeability of coil=0.99(copper)

Relative permeability of air gap=1(air)



(a) (b)

Figure 7.7 (a) ANSYS model at max. on-state force (b) Graph between on-state Force and Current

Maximum On-state force= 485.7 N

Current=1.0 Amp

Average B_{sum}=1.03 T

Model 7. Fluid gap increased by 0.5 mm and housing area reduced by 0.5mm (B)

Material properties

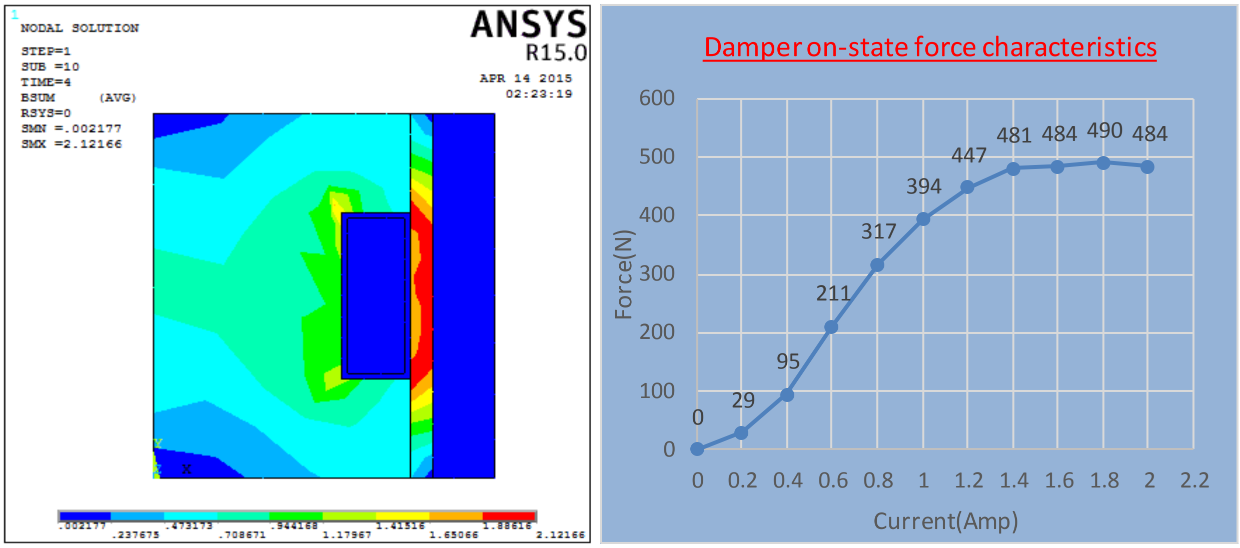
Relative permeability of engine and housing=80

(Martensitic stainless steel)

Relative permeability of coil=0.99(copper)

MR fluid particles= Ferro Cobalt: 34.5% Co

Relative permeability of air gap=1(air)



(a) (b)

Figure 7.8 (a) ANSYS model at max. on-state force (b) Graph between on-state Force and Current

Maximum On-state force= 490 N

Current=1.8 Amp

Average B_{sum}=1.06 T

Model 8. Fillet ends and fluid gap increased by 0.5 mm and housing area reduced by 0.5mm

Fillet radius=1.5mm

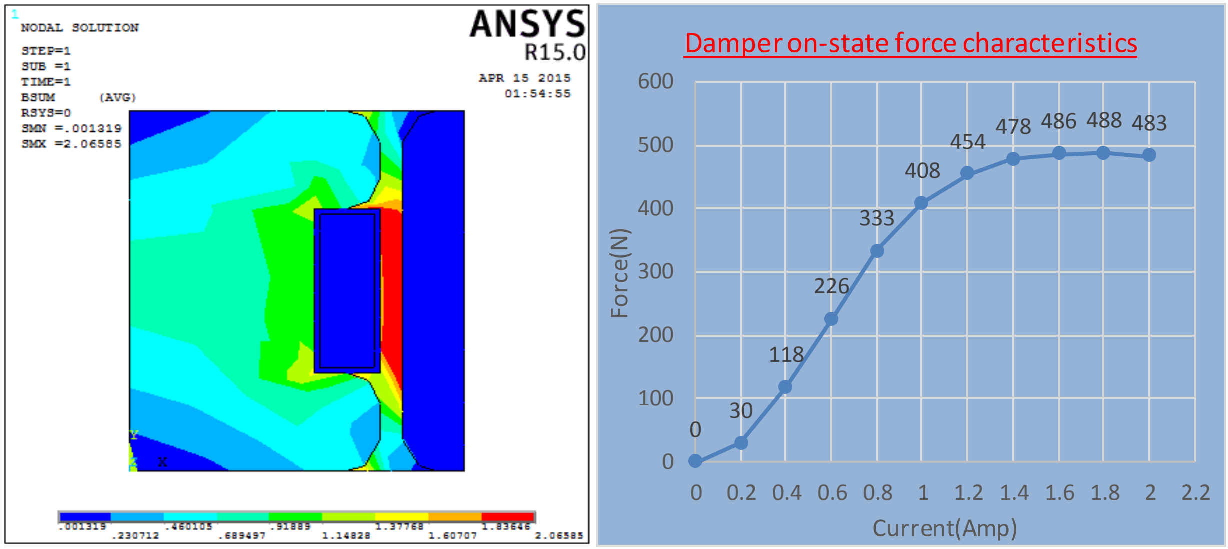
Material properties

Relative permeability of engine and housing=80 (Martensitic stainless steel)

MR fluid particles= Ferro Cobalt: 34.5% Co

Relative permeability of coil=0.99(copper)

Relative permeability of air gap=1(air)



(a) (b)

Figure 7.9 (a) ANSYS model at max. on-state force (b) Graph between on-state Force and Current

Maximum On-state force= 488 N

Current=1.8 Amp

Average B_{sum}=1.033 T

From the above analysis, it is clear that Model 6 generates maximum force at least current. The changes in Model 6 from Model 1(standard model) are in geometry as well as in the materials used. The fillet ends and the use of Ferro Cobalt: 34.5% Co as magnetic fluid particles in Model 6 give rise to an on-state force of 485.7 N in 1 Amp compare to 442 N in 1 Amp in Model 1.

However, if minimization of current is not a factor and the requirement of maximum force is concerned only, then Model 7 is the most optimized model for this case. This model generates maximum on-state force of 490 N at 1.8 Amp compare to maximum on-state force of 456 N at 2 Amp in Model 1.

The flow chart of all the above eight models with their maximum on-state force (F_{max}) with respective current is represented below.

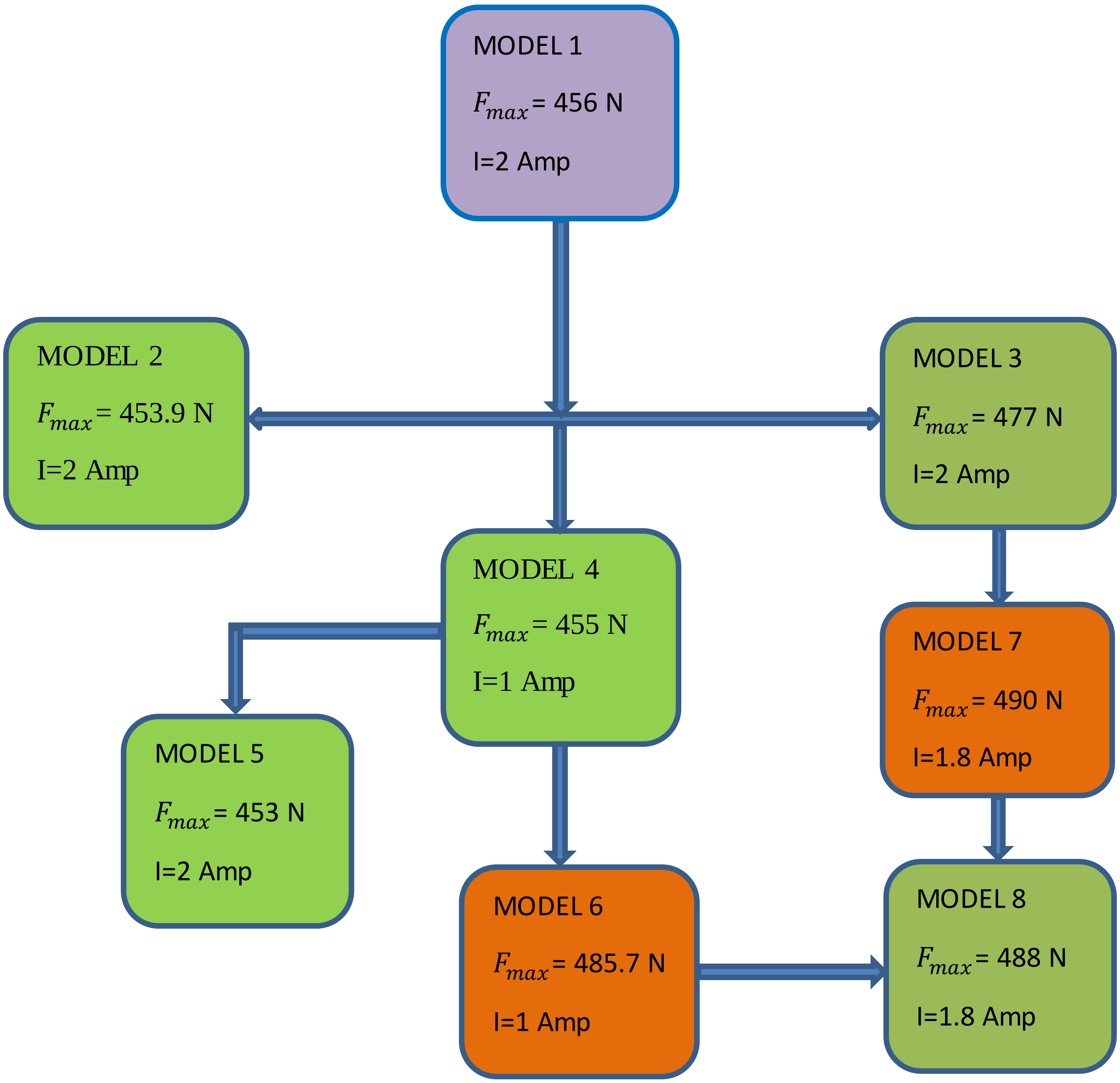


Figure 7.10 Flow chart of the models

If the properties of Model 6 and Model 7 are merged, the resultant Model 8 doesn't show any optimal value. Hence for a maximum on-state force at low current and for an overall maximum on-state force, Model 6 and Model 7 respectively are the most optimized models.

8. Conclusion and Future Scope

One of the most important parameters in designing MR dampers is to obtain maximum force at minimum space. In order to identify the best geometrical configuration, several configurations of the MR damper are studied to ascertain how altering different parameters affects the on-state damper force**.** The best configurations which give the maximum on-state force as output are considered.

A finite element analysis (FEA) model for 2D axisymmetric model of MR damper's engine, coil, air gap, MR fluid gap and housing is obtained. For a 2-D axisymmetric model of an MR damper, different geometric parameters, materials and material properties that affect the magnetic field and on-state force of the damper are studied and the relationship between on-state force and current is obtained. After simulating and analyzing different models it can be concluded that, Model 6 provides the maximum on-state force at least current and Model 7 provides the overall maximum on-state force at a current of 1.8 Amp. Model 7 can be used in applications where a large on-state force is required and current minimization is not a factor.

The optimized models will help with the design in MR dampers and will help in providing the force-velocity characteristics of the MR damper without the use of mathematical formulations. Since few decades, the use of MR dampers are increasing tremendously in vehicles, bridges, tall buildings, guns, artificial arms and legs etc. It can be used in more number of applications in order to control vibration and to damp unwanted forces with more optimization.

9. References

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10. Appendix 1

1.

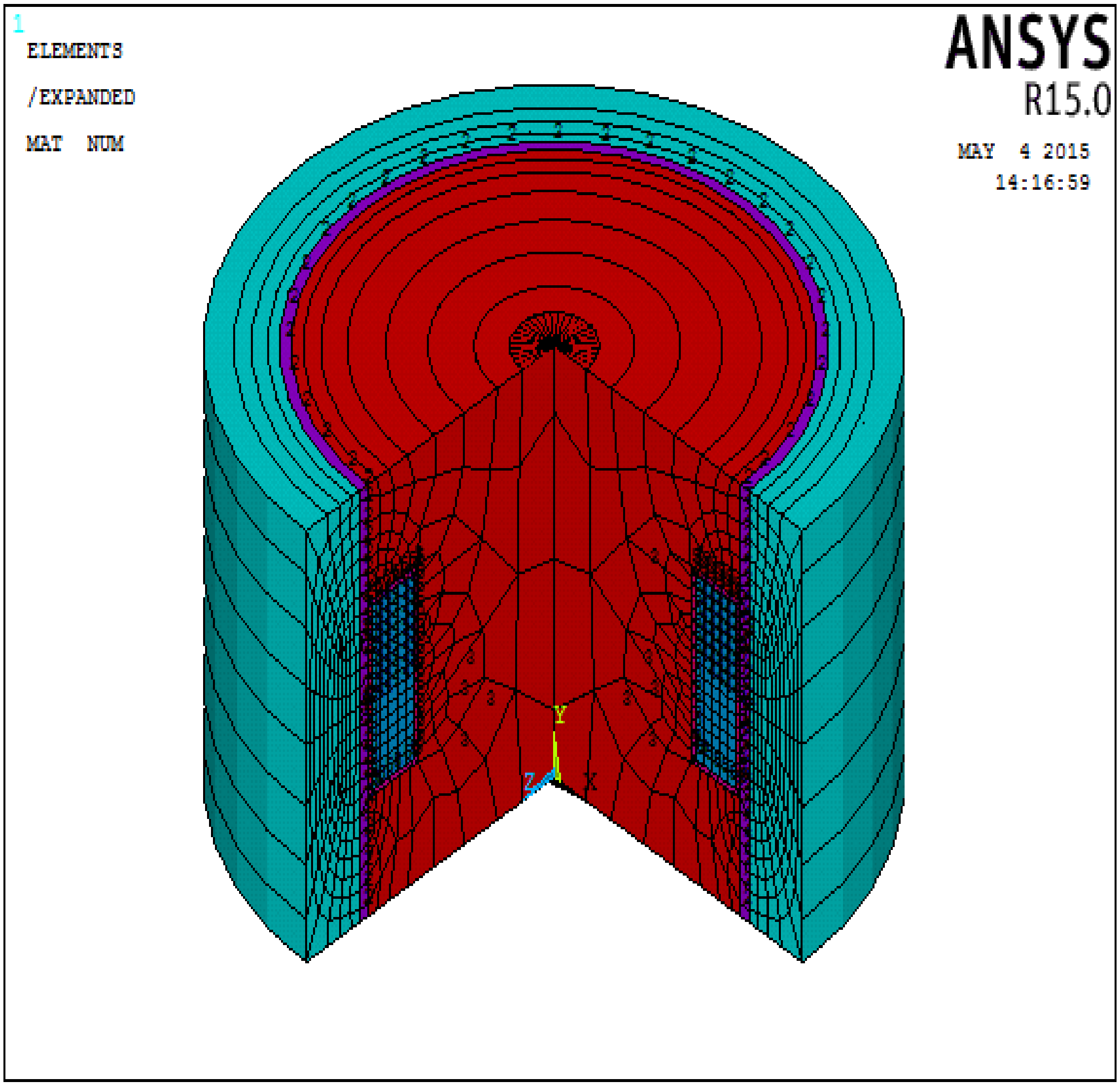

Figure 10.1 3/4th expansion of meshed 2D axisymmetric standard model

2.

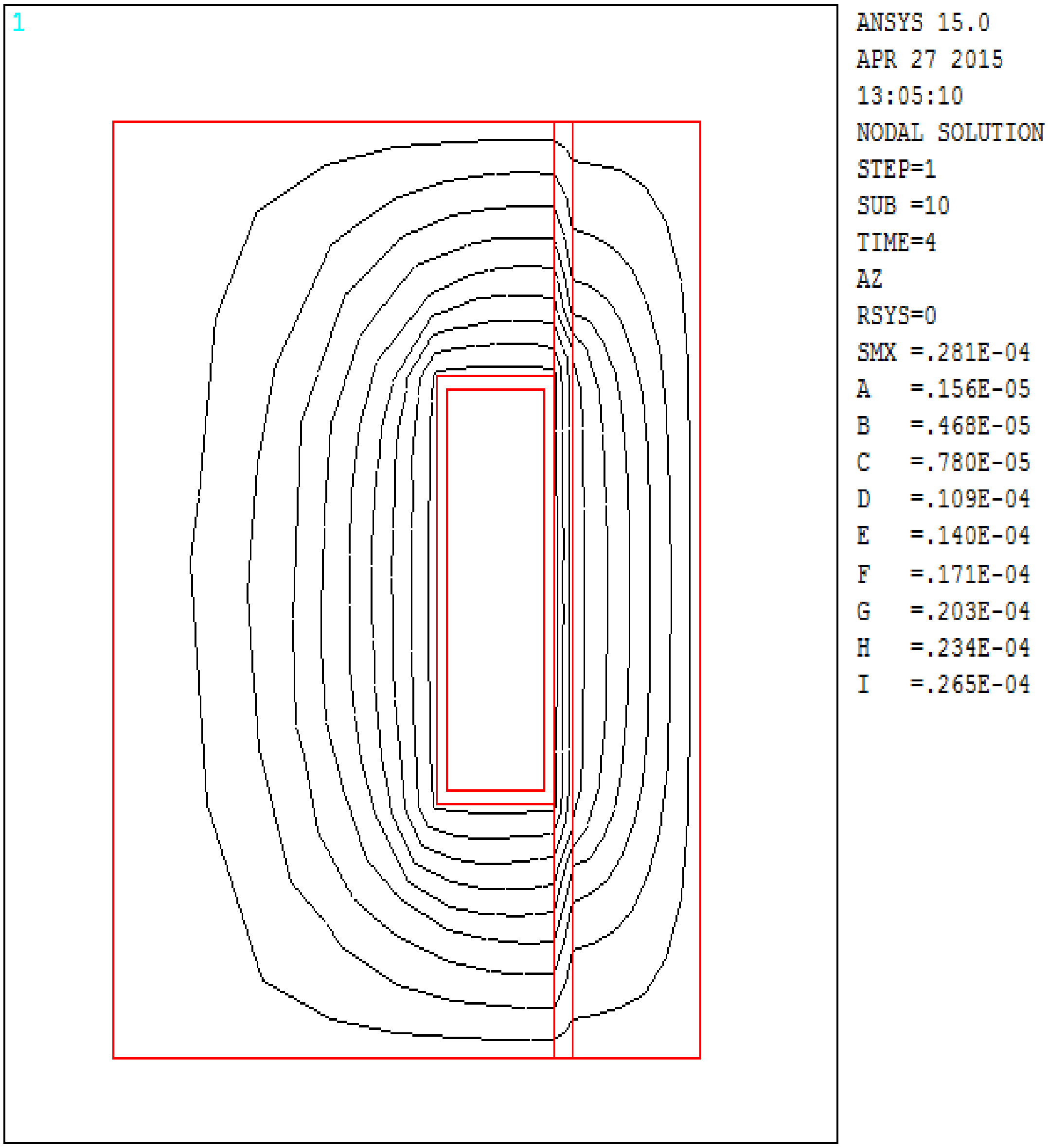

Figure 10.1 Magnetic flux lines around the electrical coil of standard model at 2A current

3.

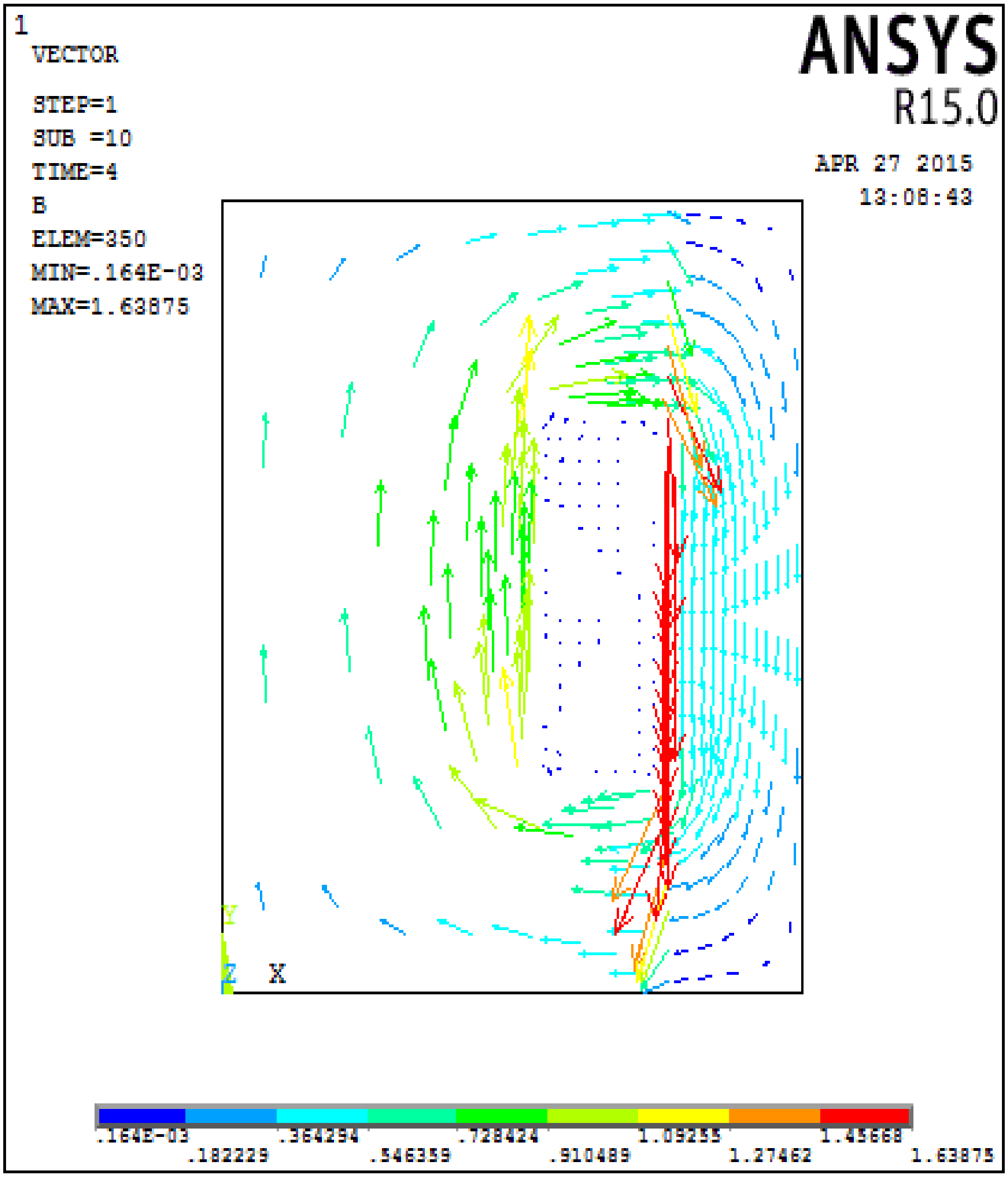

Figure 10.3 Magnetic flux gradient vector of 2D axisymmetric standard model at 2A current

4.

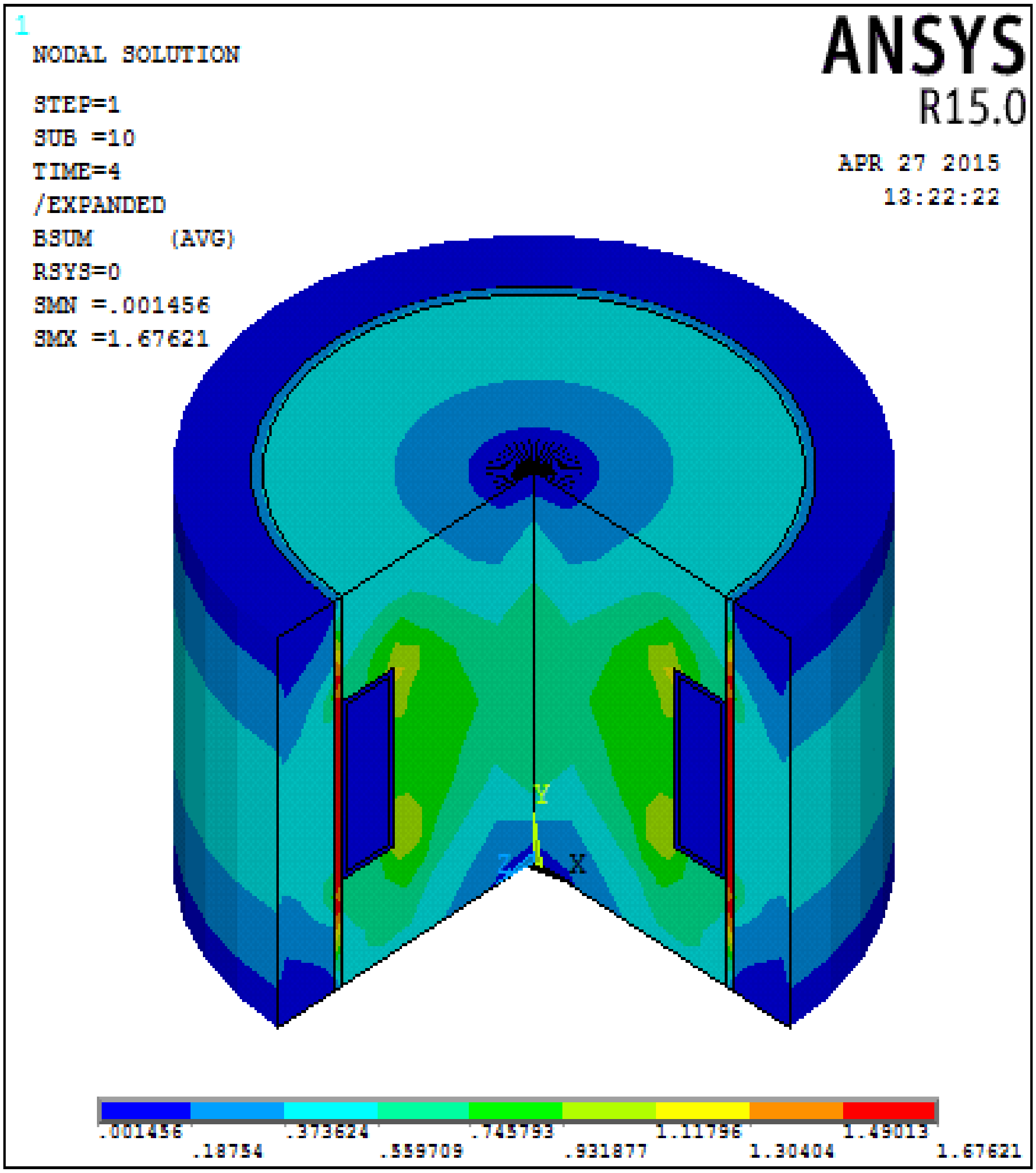

Figure 10.4 3/4th expansion of 2D axisymmetric standard model at 2A current