
Analysis of the magnetic field for MR damper working in shear mode

Titikshya Biswal and
Lokavarapu Bhaskara Rao*

School of Mechanical and Building Sciences,
VIT University, Chennai Campus,
Chennai-600127, Tamil Nadu, India
Email: titikshya.biswal2014@vit.ac.in
Email: bhaskararao@vit.ac.in
*Corresponding author

Abstract: Seismic control, restorative and mechanical vibrations speak about a wide range of research that is emerging rapidly. Magneto-rheological dampers have as of late turned into an object of concentrated studies because of their interesting physical features and their ability to control damping in mechanical systems. In this paper an MR damper is analysed as a 2D model to be axisymmetric and finite element analysis using ANSYS is done to simulate the distribution of the magnetic field in the damper for a given current. Then the design for assembly (DFA) software tool is used for estimating cost of assembly of the final product.

Keywords: MR damper; magnetic field; design for assembly; DFA; shear mode.

Reference to this paper should be made as follows: Biswal, T. and Rao, L.B. (2016) 'Analysis of the magnetic field for MR damper working in shear mode', *Int. J. Structural Engineering*, Vol. 7, No. 1, pp.48–62.

Biographical notes: Titikshya Biswal is currently pursuing her Master degree in CAD/CAM from VIT University, Chennai, India. She received her Bachelor's degree in Mechanical Engineering from College of Engineering Bhubaneswar, BPUT University, India. Her research area is computational mechanics, FEM, nanotechnology and vibration analysis.

Lokavarapu Bhaskara Rao is as an Associate Professor of School of Mechanical and Building Sciences, VIT University Chennai Campus, Chennai. He obtained his Bachelor's degree in Mechanical Engineering from Bapatla Engineering College and Master's degree in Design Engineering from National Institute of Technology, Durgapur, India. He received his PhD from Osmania University, Hyderabad. He teaches undergraduate and postgraduate courses like engineering mechanics, mechanics of solids, strength of materials, design of machine elements, machine design, and advanced strength of materials. His research interests are in computational mechanics, stability and vibrations of mechanical systems, fracture, bio mechanics and biomedical engineering, nano technology and FEM. He has published more than 40 research papers in various refereed journals and conference proceedings.

1 Introduction

A magneto-rheological fluid (MR fluid) is a sort of smart fluid in a carrier liquid, normally a kind of oil. At the point when subjected to a magnetic field, the fluid extraordinarily increases its apparent viscosity to become a viscoelastic solid. Essentially when the fluid is in active state, its yield stress can be controlled precisely by differing the magnetic field intensity. The consequence of this is that the fluid's capacity to transmit power can be controlled with an electromagnet, which is advantageous for its numerous conceivable applications based on vibration control. MR fluid is not quite the same as a Ferro liquid which has smaller particles (Khan, 2012). Size of the MR liquid particles are in micrometres, they have ellipse or spherical shape and it is not quite easy for Brownian motion to keep them floating in the lower density transporter liquid because they are excessively thick. Ferro fluid particles are principally nanoparticles that are suspended by Brownian movement and would not settle under typical conditions.

In ordinary circumstances the magnetic particles are suspended inside the carrier oil and distributed haphazardly. However when a magnetic field is connected, the microscopic particles which are in the micrometer range adjust themselves alongside the magnetic flux lines. At the point when the liquid is limited between two plates of opposite poles (usually this partition range is kept between 0.5 and 2 mm), movement of the fluid is limited by the resulting chains of particles to be at right angles to the magnetic flux direction, adequately expanding the viscosity (Wereley and Pang, 1997; Zhang, 1992). Imperatively, the MR fluid shows anisotropic mechanical properties in its active state. Hence in outlining a MR device, it should be guaranteed that the magnetic flux lines are maintained perpendicular to the path of the movement to be confined.

On account of MR fluids a magnetic field causes the chain like arrangement of the suspended particles by actuating a magnetic moment. MR fluids exhibit a yield stress expanding with the connected field, and both a pre-yield region, described by elastic properties, and a post-yield region, portrayed by viscous properties (Ahmadian, 1999). Because of their qualitatively similar conduct, phenomenological models of ER and MR liquid gadgets can basically be connected to either material.

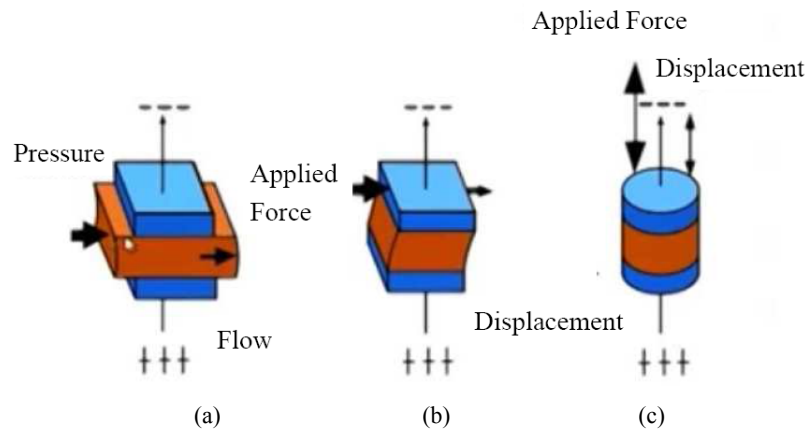
2 Modes of operation

A MR fluid is utilised as a part of one amongst the three principle modes of operation, which are valve (flow) mode, shear mode and squeeze-flow mode as shown in Figure 1.

- a In the valve (flow) mode, MR fluid is made to flow between static plates by a pressure drop, and the flow resistance can be controlled by the magnetic field which runs normal to the flow direction. Example of the flow mode includes actuators, servo-valves and dampers.
- b In the shear mode, the MR fluid is placed between plates moving in relation to each other and the magnetic field flows perpendicular to the course of motion of those shear plates. The magnetic field produced controls the characteristics of shear rate versus the shear stresses (Jansen and Dyke, 2000).

- c In the squeeze mode the change of distance between the parallel pole surfaces leads to a squeeze flow. In this mode generally high forces are achieved. So squeeze flow mode is particularly appropriate for the damping of vibrations with high dynamic forces and low amplitudes (in millimetres) (Gong and Xuan, 2014).

Figure 1 Modes of operation of MR fluid (see online version for colours)

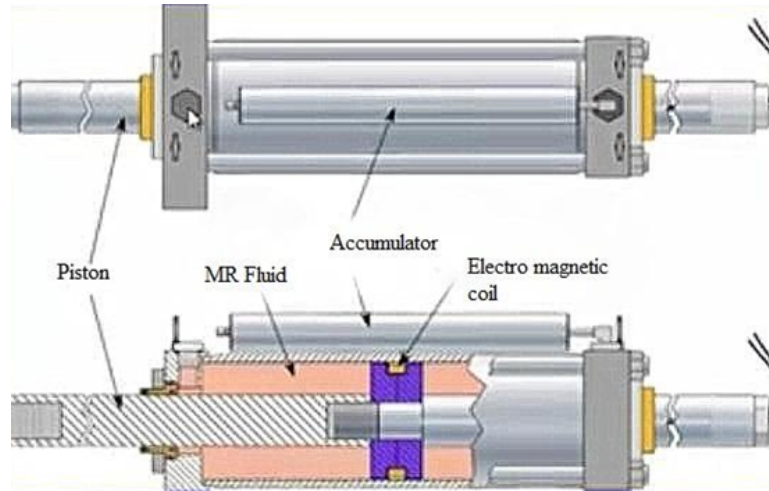


There are numerous applications making use of the different modes. Flow mode which utilises the movement to compel the fluid to be controlled through channels across which a magnetic field is applied can be utilised as a part of shock absorbers. Shear force is especially helpful in applications which need rotational motion to be controlled such as in clutches, brakes. Squeeze flow mode is most suitable for applications controlling small, millimetre-order movements yet including large forces (Yoshioka et al., 2002). Generally speaking, involving these modes of operation, MR fluids are effectively applied to an extensive variety of use.

3 MR dampers

MR dampers have, as of late, turned into an object of concentrated studies because of their interesting physical features and their ability to control damping in mechanical systems. On exposure to a magnetic field MR fluid changes from free flowing linear viscous liquids to partially solids having convenient yield strength. This transition occurs in milliseconds. This peculiarity gives basic, quiet, rapid response interfaces between electronic controls and mechanical systems.

MR fluid dampers are new semi-active devices that utilise MR fluids to give controllable damping strengths. These devices overcome large portion of the costs and technical challenges connected with semi-active devices previously considered. The designed linear MR damper is an actuator that permits controlling performance characteristics. The magnetic field strength in the working gap and the speed of the piston decides the resisting force. MR dampers are described by huge damping force, less power consumption and hence are utilised as a part of different vibration control frameworks (Ashfak et al., 2009). The various parts of MR damper are shown in Figure 2.

Figure 2 Parts of a MR damper (see online version for colours)

3.1 Finite element modelling of MR Damper

The external magnetic field decides the MR effect of the MR fluids. So design of the magnetic field is the most important part of the MRFs damper. In this paper the finite element analysis is done to simulate the distribution of the magnetic field in the damper using ANSYS (ANSYS APDL R14.5 User Manual). In our study we will consider a MR damper working in shear mode. An MR damper is to be analysed as a 2-D axisymmetric model. For a given current, we can determine the distribution of magnetic field and magnetic flux density in the damper. In this study the MR damper consists of a copper coil wound on piston, piston made of carbon steel, steel plates made of steel SAE 1045 and MR fluid used is the Lord MRF-132 DG (SolidWorks 2013 User Manual).

3.2 Assumptions for electromagnetic analysis in ANSYS APDL

- The MR damper is considered as a 2-D axisymmetric model.
- Flux leakage out of the housing and engine of the model is assumed to be negligible enough. This assumption is taken for the material to not get saturated.
- Amongst the variety of elements that ANSYS includes to represent the electromagnetic phenomenon, PLANE13 is taken to be the most apt element for our model because it is a 2-D quadrilateral coupled-field-solid containing four nodes (Zheng and Wang, 2014).
- To specify material properties in ANSYS the constant relative permeability for each material is specified, which for MR fluids can be defined by the B-H curves.

The following steps are followed to carry out the analysis:

- A 2D axisymmetric model of the MR damper is created. The different areas in the model represent the piston engine, MR fluid gap, electrical coil and plastic liner air gap as shown in Figure 3.

- Plane 13 element is used to model the electromagnetic phenomena.
- Material properties for different components are defined. For different materials used in the model, the constant relative permeability is defined and for MR fluid the properties are defined by the B-H curve. Properties for the materials used are shown in Table 1 and the material properties specification in ANSYS is shown in Figure 4.
The B-H curve values for MR fluid Lord MRF-132 DG are taken from Figure 5 and plotted in ANSYS to assign fluid properties.
- Meshing the model: after assigning attributes to all regions, meshing of all the areas is done using mesh attribute.
- Applied boundary conditions and load: loads and boundary conditions can be applied to a 2-D static magnetic analysis either on the finite element model or the solid model. In this model, the magnetic vector potential is specified to be zero. The model after applying boundary conditions is shown in Figure 6 (Thakkar et al., 2013).

Figure 3 2D axisymmetric damper piston in ANSYS (see online version for colours)

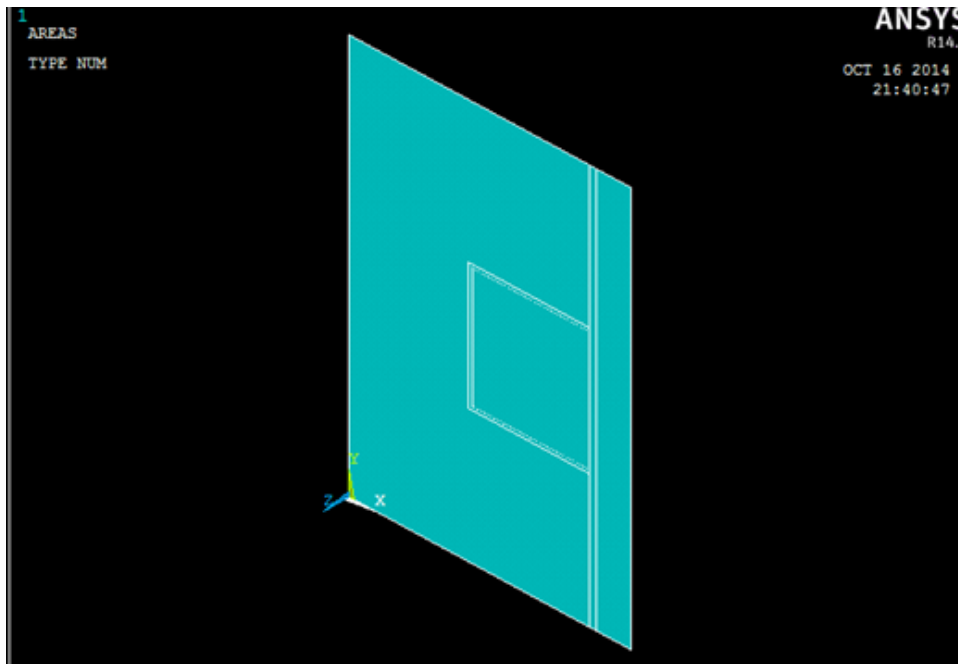


Table 1 Material used for this analysis

<i>Components</i>	<i>Material type</i>	<i>Permeability</i>	<i>Saturation flux density</i>
Material housing	Carbon steel	200	1.35
MR Fluid	MRF132-DG	B-H Curve	B-H Curve
Piston	Carbon steel	200	200
Coil	Copper	1	-
Air gap	-	0.005	-

Figure 4 Specifying material properties in ANSYS (see online version for colours)

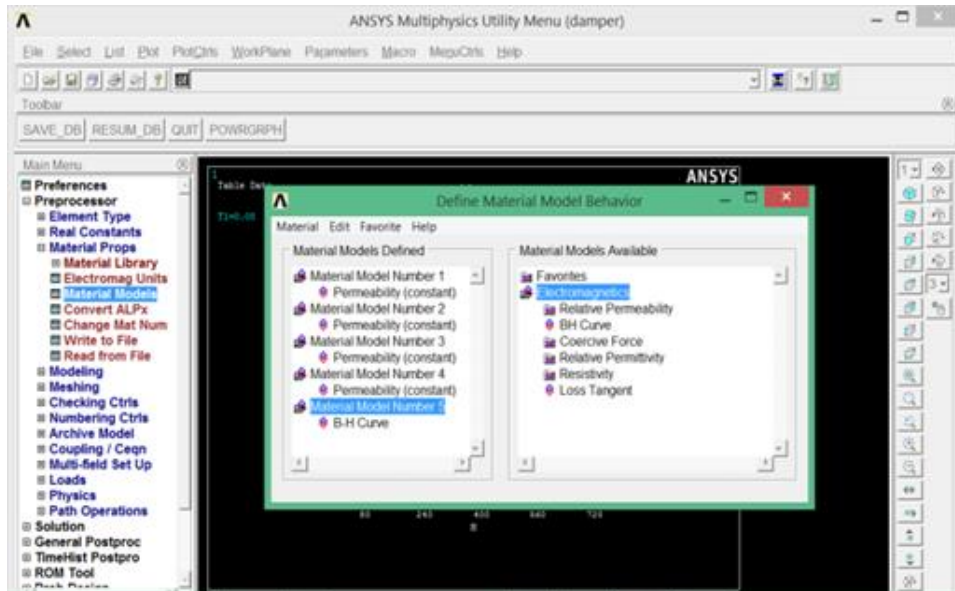


Figure 5 B-H curve for MR fluid

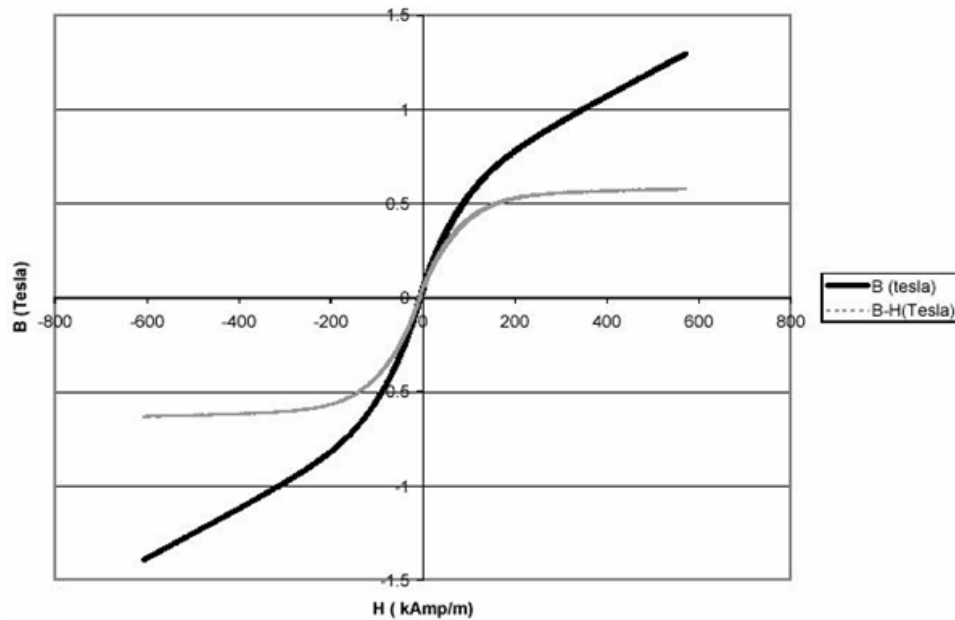
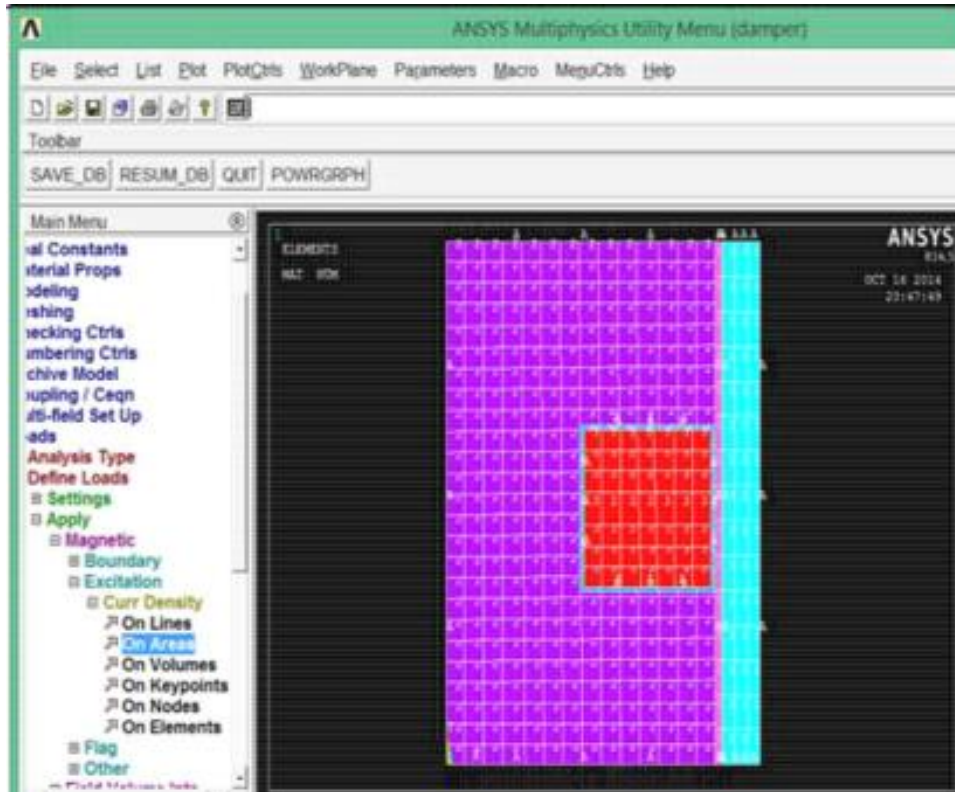


Figure 6 Meshing and boundary conditions applied in ANSYS (see online version for colours)

4 Cost of assembly

DFA Tool (Design for Assembly 9.4 User Manual) is used to assist in the design of the product such that production happens at a minimum assembly cost, concentrating on the number of parts and taking care of the simplicity of assembling.

The damper consists of three major parts, a cylinder, a piston and a coil and DFA tool is used to estimate the cost and time of assembly of these parts. The labour rate is considered to be 30.00 \$ per hour. For every part the properties data are defined as shown in the Figures 7, 8 and 9.

Figure 7 Part characteristics – cylinder (see online version for colours)

The screenshot shows the Design For Assembly 9.4 software interface for a part named 'Cylinder'. The interface is divided into several sections:

- Tree View:** Shows the assembly hierarchy: Damper > Cylinder (selected), Piston, and Coil.
- Definition:** Name: Cylinder, Part number: (empty), Repeat count: 1. Item type: part (selected), sub-assembly.
- Securing method:** Includes icons for secured later, thread, snap, push/press, rivet, self-stick, crimp, stake, and electric.
- Minimum part criteria:** Item theoretically must be separate because of: material, movement, assembly, base part.
- Item is a candidate for elimination:** fastener, connector, other.
- Envelope dimensions, in:** 4.724 (width) and 7.874 (height).
- Symmetry:** Options for one way, either way, and any way.
- Handling difficulties:** Includes nest tangle, severe tangle, flexible, difficult grasp, tweezers, grasp tools, bulky, two hands, two persons, swing crane, mobile crane, gantry crane.
- Insertion difficulties:** view, access, align, resist, severe, holding down, regrasp, support weight, large depth.
- Labor time:** Item fetching distance: within easy reach, Item handling and fetching time, s: 1.95, Insertion/operation time, s: 1.50.
- Manufacturing data table:**

	Item	Product
Piece part cost, \$	0.00	0.00
Item cost per item, \$	0.00	0.00
Tooling investment, \$	0	0
Weight per item, lb	0.00	70.55
- Material:** Stainless Steel
- Process:** (empty)
- Picture:** 3D model of a green cylinder.
- Buttons:** Load, Clear, Scale to fit, Transparent.
- Notes:** (empty text area)
- Visit tracking:** not visited, partially visited, fully visited.
- Results Table:**

Results	Entry totals	Product
Count	1	3
Minimum count	1	3
Labor time, s	3.45	12.25
Labor cost, \$	0.03	0.12
Other op. cost, \$	0.00	0.00
Assy. tool/fixture, \$	0.00	0.00
Item costs, \$	0.00	0.00
Total cost, \$	0.03	0.12
DFA Index		71.8

Figure 8 Part characteristics – piston rod (see online version for colours)

The screenshot shows the Design For Assembly 9.4 software interface. The main window displays the 'Piston' part characteristics. The interface is divided into several sections:

- Tree View:** Shows the assembly structure: Damper > Cylinder > Piston.
- Definition:** Name: Piston, Part number: (empty), Repeat count: 1, Item type: part.
- Securing method:** Includes options like secured later, thread, snap, push/press, rivet, self-stick, crimp, stake, and electric.
- Minimum part criteria:** Item theoretically must be separate because of: material, movement, assembly, base part.
- Item is a candidate for elimination:** fastener, connector, other.
- Envelope dimensions, in:** 4.646 and 11.811.
- Symmetry:** one way, either way, any way.
- Handling difficulties:** nest tangle, severe tangle, flexible, difficult grasp, tweezers, grasp tools, bulky, two hands, two persons, swing crane, mobile crane, gantry crane.
- Insertion difficulties:** view, access, align, resist, severe, holding down, regrasp, support weight, large depth.
- Labor time:** Item fetching distance: within easy reach, Item handling and fetching time, s: 1.80, Insertion/operation time, s: 1.50.
- Manufacturing data:** Piece part cost, \$: 0.00 (Item), 0.00 (Product); Item cost per item, \$: 0.00, 0.00; Tooling investment, \$: 0, 0; Weight per item, lb: 55.12, 70.55; Material: Cast Iron; Process: (empty).
- Picture:** A 3D model of the piston rod assembly.
- Results Table:**

Results	Entry totals	Product
Count	1	3
Minimum count	1	3
Labor time, s	3.30	12.25
Labor cost, \$	0.03	0.12
Other op. cost, \$	0.00	0.00
Asy. tool/fixture, \$	0.00	0.00
Item costs, \$	0.00	0.00
Total cost, \$	0.03	0.12
DFA index		71.8

Figure 9 Part characteristics – coil (see online version for colours)

The screenshot displays the Design For Assembly 9.4 software interface for a part named 'Coil'. The interface is organized into several panels:

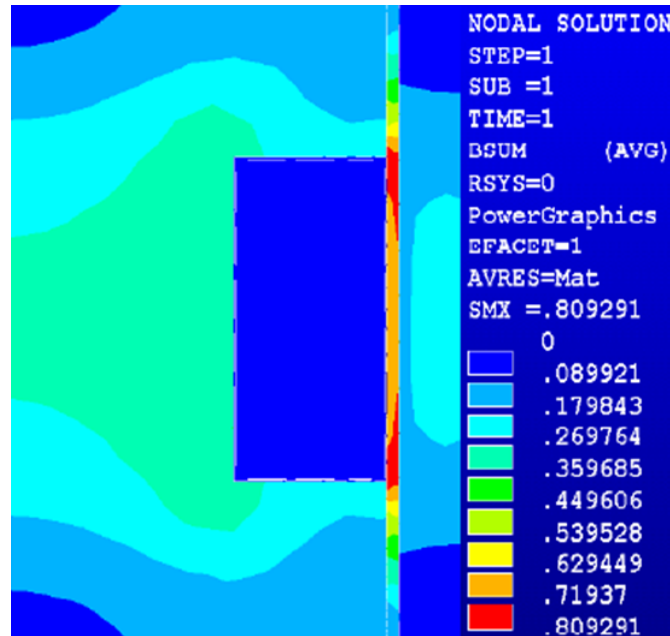
- Tree View:** Shows the assembly hierarchy: Damper > Cylinder > Piston > Coil.
- Definition:** Name: Coil, Part number: (empty), Repeat count: 1, Item type: part.
- Securing method:** Includes options like secured later, thread, snap, push/press, rivet, self-stick, crimp, stake, and electric.
- Minimum part criteria:** Lists reasons for separation such as material, movement, base part, and assembly.
- Envelope dimensions:** Shows a 3D model of the coil with dimensions 4.646 and 0.591.
- Symmetry:** Offers options for one way, either way, and any way.
- Handling difficulties:** Includes categories like nest/tangle, severe tangle, flexible, difficult grasp, tweezers, grasp tools, bulky, two hands, two persons, swing crane, mobile crane, and gantry crane.
- Labor time:** Item fetching distance: within easy reach, Item handling and fetching time: 1.80 s, Insertion/operation time: 3.70 s.
- Manufacturing data:** A table comparing Item and Product values for Piece part cost, Item cost per item, Tooling investment, and Weight per item.
- Material:** Set to Copper.
- Picture:** A 3D rendering of the coil part.
- Results Table:** A summary table of costs and labor times.

Results	Entry totals	Product
Count	1	3
Minimum count	1	3
Labor time, s	5.50	12.25
Labor cost, \$	0.05	0.12
Other op. cost, \$	0.00	0.00
Assy. tool/fixture, \$	0.00	0.00
Item costs, \$	0.00	0.00
Total cost, \$	0.05	0.12
DFA Index		71.8

5 Results and discussion

We had placed the flux parallel boundary condition around the model. We have assumed negligible flux leakage out of the model. This implies the flux is acting parallel to the surface. As shown in Figure 10, the coil is surrounded by the flux path and if we minutely observe at the MR fluid gap, concentration of many flux lines can be seen (Thakkar et al., 2013). Additionally, in this model the magnetic vector potential is specified to the lines shifting as soon as they hit the gap indicating the effect of the MR fluid on the electric circuit. Once the magnetic induction vectors hit the MR fluid gap they change directions. This is because the properties of the MR fluid differ from that of the damper housing and engine.

Figure 10 Magnetic flux lines around the electrical coil (see online version for colours)

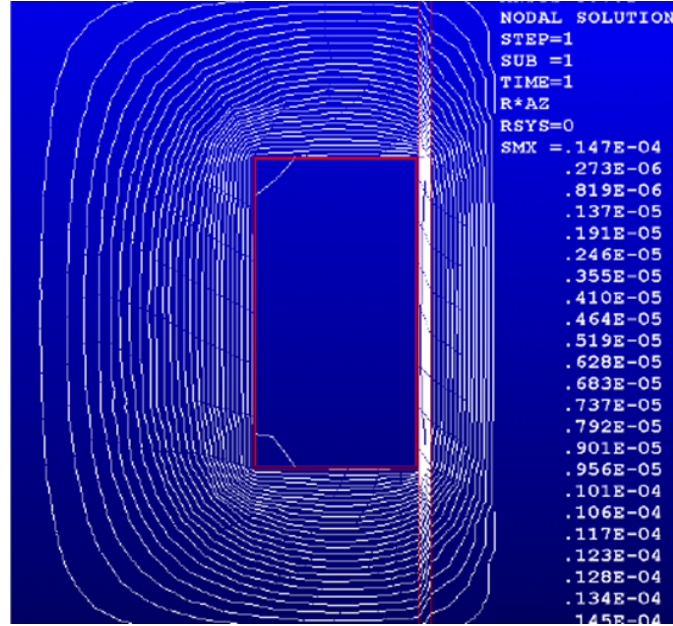


The magnetic flux density vectors are represented by the magnetic flux lines. As shown in Figure 11 through the side of the gap is a high magnetic induction, this implies the magnetic flux lines are concentrated and this concentration will decrease when rheological saturation is reached.

We need to obtain results at each node of an element for which Nodal solution proves to be helpful. Also the ANSYS model helps to generate the magnetic induction at the gap of the MR fluid. Each time the electrical current to the coil is increased the magnetic induction will increase and we'll get new results (El-Aouar, 2002).

In this study the current applied varies from 0–2A. Results obtained from ANSYS APDL module shows that with increasing current the magnetic flux increases. From that flux density, the yield stress at the MR fluid gap, flux density shear stress, pressure drop and damper force can be analysed using the formulas (1), (2) and (3) (Sternberg et al., 2014).

Figure 11 Magnetic flux density (see online version for colours)



$$(kPa) = 52.962B^4 - 176.51B^3 + 158.79B^2 + 13.708B + 0.1442 \quad (1)$$

$$\Delta P = \Delta P_\eta + \Delta P_\tau = \frac{12\eta QL}{g^3 w} + \frac{c\tau_y L}{g} \quad (2)$$

$$F = F_\eta + F_\tau = \frac{\eta SA}{g} + \tau_y A \quad (3)$$

where

τ fluid stress

τ_y field dependent yield stress

H magnetic field

n plastic viscosity ($H = 0$)

ΔP pressure drop

ΔP_η viscous component of pressure drop

ΔP_τ field dependent induced yield stress component of pressure drop

Q pressure driven fluid flow

L length of fluid flow orifice

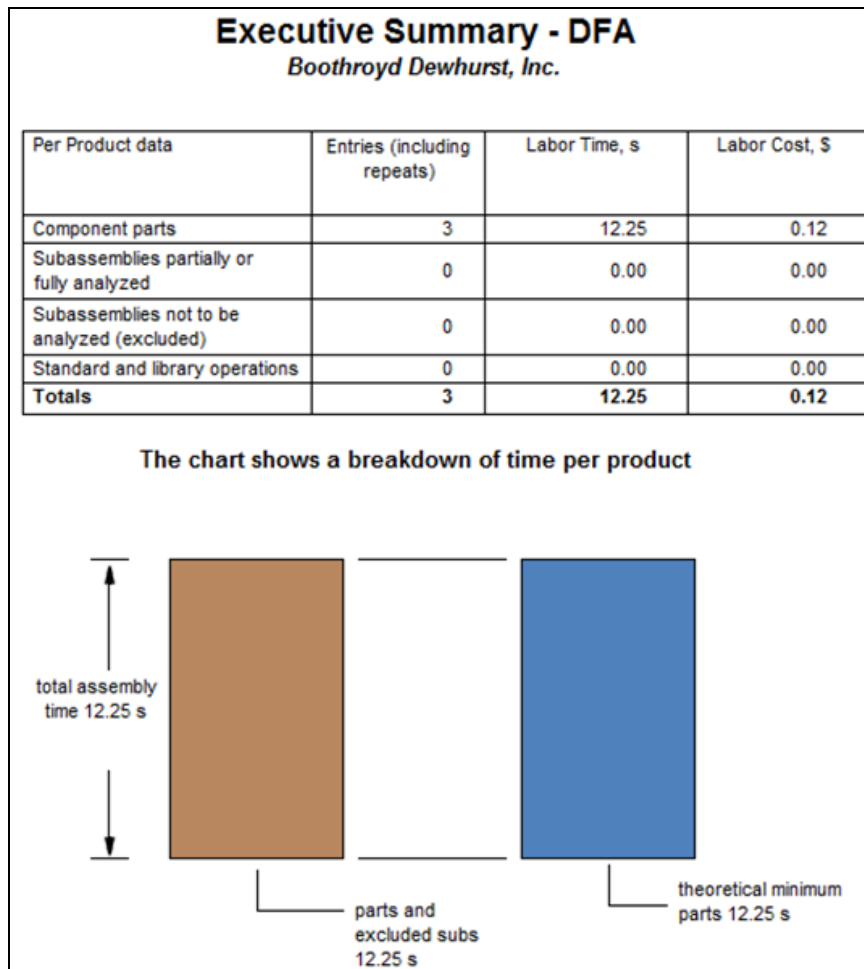
G fluid gap

w width of fluid flow orifice

- c constant
- F force that is developed between pole plates in shear mode
- $F\eta$ viscous shear force
- $F\tau$ magnetic dependent shear force
- S relative velocity between pole plates used in shear mode
- A pole area.

Formulas (1), (2) and (3) are derived based on the assumption that the MR fluid is modelled according to the Bingham model. The constant c depends on $\Delta Pt/\Delta P\eta$ and varies from 2 to 3.

Figure 12 Executive summary (see online version for colours)



From DFA analysis it can be estimated that the assembly time for the three parts is 12.25 seconds, the labour cost per product is 0.12 \$ and the DFA index is found to be 71.8 which is near to ideal case scenario. This is shown in Figures 12 and 13.

Figure 13 Analysis totals

Design for Assembly: Analysis Totals							
Boothroyd Dewhurst, Inc.							
Per product data							
	Entries (including repeats)	Number of different parts	Total time, s	Labor cost, \$	Item costs (including tooling), \$	Weight, lb	
Parts	3	3	12.25	0.12	0.00	70.55	
Subassemblies:							
Partially or fully analyzed	0	0	0.00	0.00	0.00	0.00	
Named only	0	0	0.00	0.00	0.00	0.00	
Excluded	0	0	0.00	0.00	0.00	0.00	
Operations:							
Standard	0	0	0.00	0.00	-	-	
Library	0	0	0.00	0.00	-	0.00	
Column Totals	3	3	12.25	0.12	* 0.00	** 70.55	
Cost totals based on a product life volume of 10,000							
	Labor cost, \$	Other operation cost, \$	Manuf. piece part cost, \$	Total cost without tooling, \$	Assy. tool or fixture cost, \$	Manuf. tooling cost, \$	Total cost, \$
Cost per product	0.12	0.00	0.00	0.12	0.00	0.00	0.12
Production life cost	1,200	0	0	1,200	0	0	1,200
*Note: Manufacturing piece part costs not given for some items. Total cost may be incomplete.							
**Note: Weight not given for some items. Total weight may be incomplete.							
DFA Index							
Theoretical minimum number of items					3		
DFA Index					71.8		
Production data							
Overall plant efficiency, %					85.00		
Labor rate, \$/hr					30.00		

Reference

Ahmadian, M. (1999) ‘Design and development of magneto rheological dampers for bicycle suspensions’, *American Society of Mechanical Engineers*, Dynamic Systems & Control Division Publication, DSC, Vol. 67, pp.737–741.

ANSYS APDL R14.5 User Manual.

Ashfaq, A., Saheed, A., Abdul Rasheed, K.K. and Jaleel, J.A. (2009) *Design, Fabrication and Evaluation of MR Damper*, World Academy of Science, Engineering and Technology, Connecticut, USA.

Design for Assembly 9.4 User Manual.

El-Aouar, W.H. (2002) *Finite Element Analysis Based Modeling of Magneto Rheological Dampers*, Virginia Polytechnic Institute and State University, Blacksburg, Virginia.

Gong, X.L. and Xuan, S. (2014) *Magneto Rheological Damper Working in Squeeze Mode*, Hindawi Publishing Corporation, New York, USA.

Jansen, L.M. and Dyke, S.J. (2000) 'Semi-active control strategies for MR dampers: a comparative study', *ASCE Journal of Engineering Mechanics*, Vol. 126, No. 8, pp.795–803.

Khan, M.S.A. (2012) 'Analysis of magneto rheological fluid damper with various piston profiles', *International Journal of Engineering and Advanced Technology*, Vol. 2, No. 2, pp.77–83.

SolidWorks 2013 User Manual.

Sternberg, A., Zemp, R. and de la Llera, J.C. (2014) 'Multiphysics behavior of a magneto-rheological damper and experimental validation', *Engineering Structures*, Vol. 69, No. 1, pp.194–205.

Thakkar, R.M., Shah, D.R. and Modan, M.M. (2013) 'Modeling and simulation of magneto rheological fluid damper for predicting the saturation limit to applied field current', *Global Research Analysis*, Vol. 2, No. 3, pp.69–71.

Wereley, N.M. and Pang, L. (1997) 'Nondimensional analysis of semiactive electrorheological and magneto rheological dampers using approximate parallel plate models', *Smart Materials and Structures*, Vol. 7, No. 5, p.732.

Yoshioka, H., Ramallo, J.C. and Spencer Jr., B.F. (2002) 'Smart' base isolation strategies employing magneto rheological dampers', *Journal of Engineering Mechanics*, May/ASCE, Vol. 128, No. 5, pp.540–551.

Zhang, R.S. (1992) 'Seismic design of viscoelastic dampers for structural applications', *Journal of Structural Engineering*, Vol. 118, No.5, pp.1375–1392.

Zheng, J. and Wang, J. (2014) 'Magnetic circuit design and multiphysics analysis of a novel MR damper for applications under high velocity', *Advances in Mechanical Engineering*, No. 2, pp.1–16, Hindawi Publishing Corporation, New York, USA.