Chapter

Finite Element Magnetic Method for Magnetorheological Based Actuators

Ubaidillah and Bhre Wangsa Lenggana

Abstract

Magnetorheological materials based actuators have been currently exciting research topic for more than half-decades. Some actuators have been developed based on magnetorheological fluids and elastomers such as dampers, brakes, haptic devices, clutches, mountings, etc. These devices have their exciting properties which are capable of changing characteristic based on the amount of magnetic flux applied to them. Due to this capability, they are usually called semi-active devices. These devices employ an electromagnetic coil for magnetic flux production. Therefore, during the design process, magnetostatic simulation using the finite element method magnetic is carried out to make a better magnetic circuit. This chapter will consider several discussions such as necessary magnetostatic using free software finite element method magnetic (FEMM); design consideration for the magnetic circuit of the device and case studies of several type simulation in magnetorheological materials based devices.

Keywords: finite element, magnetostatic, magnetorheology, actuator, magnetic flux

1. Introduction

The finite element method (F.E.M.) is a numerical procedure that can be applied to solve various problems in engineering and science. In general, this method is used to solve steady, transient, linear, and nonlinear problems in electromagnetics, structural analysis, and fluid dynamics [1]. The finite element method has the main advantage of being able to handle all kinds of geometries and non-homogeneous materials without the need to change computer code formulations. The idea of this method is to break the problem into a large number of areas, each with simple geometry to facilitate problem-solving. As a result, the domain breaks down into a number of small elements, and the problem goes from small but challenging to solve into large and relatively easy to solve. Through the process of discretization, linear algebra problems are formed with many unknowns. In the case of electromagnetics, a discretization scheme, as implied by F.E.M., which implicitly combines most of the theoretical features of the problem analyzed is the best solution for obtaining accurate results in problems with complex, nonlinear geometries, etc. [2, 3]. This method can also be used for complex differential equations that are very difficult to solve. In the case of electromagnetic or magnetic fields, the finite element method is also known as FEMM.

FEMM is a suite of programs for solving low-frequency electromagnetic problems on two-dimensional planar and axisymmetric domains. The program currently addresses linear/nonlinear magnetostatic problems, linear/nonlinear time-harmonic magnetic problems, linear electrostatic problems, and steady-state heat flow problems. In the problem of this method, there are generally three parts to the problem [4].

Interactive shell program is a Multiple Document Interface pre-processor and a post-processor for various types of problems that are solved by FEMM. This case is a CAD-like interface for laying out the geometry of the problem to be solved and for defining material properties and boundary conditions [5]. The program also allows the user to inspect a field at specific points, as well as evaluate several different integrals and plot varying amounts of interest along with a user-defined contour [6]. Triangle breaks down the solution region into a large number of triangles, a vital part of the finite element process. Furthermore, Solvers, each solver takes a set of data files that describe problems and solves the relevant partial differential equations to obtain values for the desired field throughout the solution domain [7].

Finite Element Method Magnetics (FEMM) software has been developed for reasons of dealing with some of the limiting cases of Maxwell equations. The magnetic problem that is handled can be considered as a low frequency (L.F.) problem. In some cases, this problem can ignore displacement currents. This program discusses 2D planar and 3D axisymmetric linear and nonlinear harmonic magnetic, magnetostatic, and linear electrostatic problems [8].

Computer-assisted field distribution analysis for electromagnetic devices or component performance has become a simple, profitable, and fast method with good accuracy [9]. The magnetic field calculation problem aims to determine the value of one or more unknown functions, such as magnetic field intensity, magnetic flux density, scalar magnetic potential, and magnetic vector potential.

From a mathematical point of view, Maxwell equations can generally explain physical electromagnetic phenomena. Specifically, this point of view is a differential equation with specific boundary conditions. With this method, the correct solution to the problem is obtained. It is an analytical method that can be used to solve problems [10]. Analytical methods (method of appropriate representation, method of variable separation) are often applied to solve relatively simple problems. However, the problems that occur in practice are sometimes more complex regarding loading conditions, boundary conditions, geometric construction, and material heterogeneity, so that the integration of differential equations is challenging to solve by analytical methods. Therefore, the analytic solution can only be done by making a simplified model that allows the integration of the differential Equations [11]. Sometimes it is better to come up with a more realistic estimate of the value, rather than a precise solution from a simplified model. The approximate solution by the finite element method obtained by the numerical method reflects reality better than the exact solution of the simplified model [12].

Specific forms of electromagnetic field law for static magnetic fields are overcome by considering solving the magnetic problem through FEMM. Some of them are considering the model of the relationship between magnetic induction and the intensity of its magnetic field, the enunciation of static magnetic fields, passing conditions through discontinuity surfaces, enunciation of scalar magnetic potential - magnetostatic field problems and enunciation using magnetic vector potentials [13]. Some geometric configurations conform to the general formula for the unique conditions of a particular shape. The solution to this problem also depends on the relationship between magnetic intensity and magnetic field induction, the choice of material types such as linear and non-isotropic materials, linear and isotropic materials, nonlinear and non-isotropic materials with hysteresis, and nonlinear and isotropic materials, without permanent magnetization [14].

In other cases, such as in the development of magnetorheological devices (dampers, brakes, mounting, etc.), FEMM is used to solve the problem of magnetic flux density. Using the help of FEMM, solving magnetic problems can be solved quickly. The magnetic flux density, which is complex and challenging to be solved by numerical methods, can be determined by simulating the FEMM by using the material properties data to obtain the magnitude of the magnetic flux density. The simulation results are then used to determine the predicted values such as the pressure difference (in the case of the damper valve) using numerical or calculation methods [15].

2. General description of M.R. devices

The magnetorheology (M.R.) device is a device that implements intelligent materials as a working medium such as magnetorheological fluids (MRFs) and magnetorheological elastomers (M.R.E.s). M.R. devices are types of the controllable (semi-active) category. During its development, this device has been developed into a working medium such as M.R. damper, brake, and mounting for various applications. On the commercialization side, this device is not popular enough because of several things such as higher costs, more difficult production levels, and still under development. However, compared to other types of devices in its application (active and passive), M.R. devices have more advantages. MRFs and M.R.E.s are materials that are often used for research and development of M.R. devices.

As new technologies are developed, these materials have been discovered and developed in several applications. This material is unique because external stimuli can alter it. In this case, magnetorheological fluids are materials with properties that can be controlled by magnetic fields [16]. The MR fluids condition can be altered by using a varying magnitude of the magnetic field. This fluid is composed of magnetic particles that are pressed into a viscosity fluid. The absence of a magnetic field in this fluid causes its lower viscosity. These particles have a tiny size, ranging from 3 to 10 microns [17]. The magnetic particles of M.R. fluids are equipped with a special coating to weaken their magnetism and reduce the tendency to bond with each other between the particles. One of the weaknesses in M.R. fluid is the deposition, which occurs due to differences in density and gravitational force so that the fluid only focuses on the point where it is treated. Another disadvantage is the possibility of leakage into unwanted areas in the mechanism and thickening after long-term use, so component replacement is required. However, the application of M.R. fluid is extensive due to its precise control capabilities and dynamic response [17, 18]. The resulting output is relatively faster and more accurate because it uses an electric current as a conductor when compared to conventional mechanical mechanisms [19].

The structure and properties of the M.R. fluid outside or under the influence of the magnetic field are shown in **Figure 1**. The changes that occur when the M.R. fluid is under the influence of a magnetic field occurs in less than ten milliseconds. M.R. fluids regain their properties in the temperature range − 40 to 150 C, while the yield points of M.R. fluids range from 50 to 100 kPa [20].

The particle chain blocks the flow and converts the liquid to a semi-solid state in milliseconds. This phenomenon develops yield stress which increases with the magnitude of the applied magnetic field [21]. M.R. devices typically consist of hydraulic cylinders containing micron-sized magnetically polarized particles suspended in the fluid [17, 18].

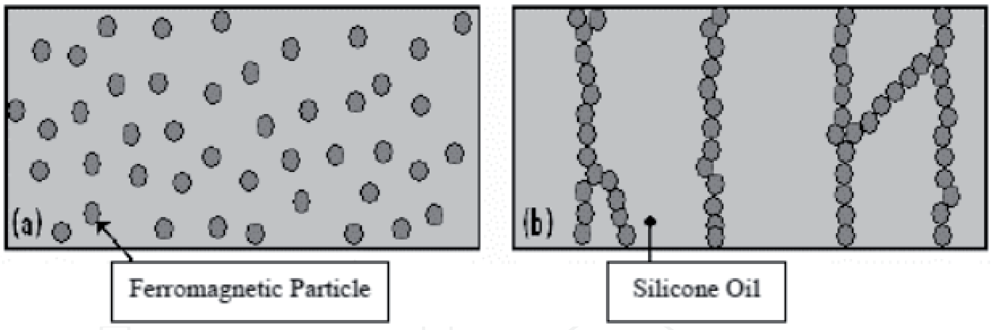


Figure 1.
Structures of M.R. fluid, ferromagnetic particles in silicon oil suspension: (a) without magnetic field effect, and (b) with magnetic field effect [17].

M.R. fluids work in several modes, including shear mode, valve mode, and squeeze mode [22]. MRF has been widely applied through shear mode and valve mode. Meanwhile, the application of MRFs which work with the new squeeze mode, has recently been developed. Also, MRFs can be operated in a combination of common MRFs working modes.

The shear mode is an operating mode in which the MRFs are influenced by a magnetic field between two parallel surfaces. One of the surfaces will move, and the other will be in a fixed condition. The shear mode is mostly applied to brakes and clutches. However, some dampers use a shear mode. The second is flow mode or valve mode; this mode is an operating mode in which the MRFs flow between two parallel surfaces that are at rest and simultaneously subjected to a magnetic field perpendicular to the direction of flow. Many applications of valve mode are found in dampers. Squeeze mode is an operational mode in which the MRFs flow-through two parallel surfaces and are subjected to a magnetic field that is perpendicular to the direction of flow. Squeeze mode is different from shear mode, the force exerted by one of the surfaces is the compression force, while in the shear mode it provides the shear force. **Figure 2** shows an illustration of the working principle of each MRFs working mode.

The commercialization of the use of MRFs technology was first used in 1995 for braking on stationary bicycles. MRFs technology tends to be cheaper and easier to use when compared to previous eddy-current-based braking technologies [24]. The world is full of potential applications for MRFs. Systems that require fluid motion control by changing viscosity, solutions based on MRFs technology may be applied to save functionality as well as costs. Simple and smart technology that can produce better products is the crucial factor of MRFs technology. Superior features such as fast response, simple application of electrical power input and mechanical power output, and controllability make MRFs technology the choice of many engineering

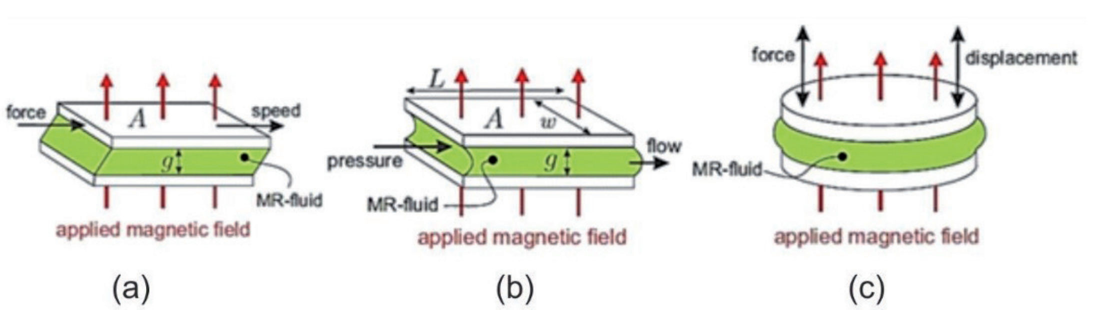


Figure 2.
MRFs working mode; (a) shear mode; (b) flow mode; (c) squeeze mode [23].

technologies. The sliding mode (used in brake and clutch) and valve mode (used in shock breakers) have been thoroughly studied, and several products are already on the market [25].

Besides MRFs, magnetorheological elastomers (M.R.E.s) are also intelligent materials that are currently a topic of development. In the last 20 years, the number of publications related to the creation, characterization, and application of M.R.E. has increased significantly. This significant increase occurred after 1995 regarding the viscoelasticity properties of M.R.E. initiated by Rigby and Jilken in their 1983 publication [26] when it is compared with the number of publications in the field of MRF and MRF applications.

The development of intelligent components based on M.R.E.s must pay attention to the composition of M.R.E.s because it can be formed with a variety of fill materials. The characteristics of the pre-blended matrix greatly influence the physical properties of M.R.E.s, which can make M.R.E.s solid or hollow. However, in general, M.R.E.s use a non-hollow matrix. To obtain a non-hollow matrix, the degassing method can be used to remove air bubbles or voids in the matrix. The magnetizable particles have an essential role in the magnetic induction properties of M.R.E.s. Much research has focused on these magnetized particles to achieve better rheological properties. Particles that are generally used are iron particles because they have a high permeability value and can be magnetized well [27]. M.R. effect is greatest due to the relationship between iron particles, this property can be achieved with high permeability and particle saturation. However, high saturation is also followed by an increase in the residual magnetic field that appears [28]. Therefore, the use of alloy particles in M.R.E.s, such as iron and cobalt or nickel alloys, is not as widely used as the use of C.I.P. The residual magnetic field in the particles will remain after the magnetic field has been lost so that the M.R. properties cannot return to their original state [29]. The size of the particles must be considered because it affects the properties of M.R.E. in receiving several magnetic domains.

3. Reluctance circuit for M.R. devices

Magnetic reluctance, or magnetic resistance, is a concept used in the analysis of magnetic circuits. It is defined as the ratio of magnetomotive force (mmf) to magnetic flux. It represents the opposition to magnetic flux and depends on the geometry and composition of an object.

Magnetic reluctance in a magnetic circuit is analogous to electrical resistance in an electrical circuit in that resistance is a measure of the opposition to the electric current. The definition of magnetic reluctance is analogous to Ohm law in this respect. However, the magnetic flux passing through a reluctance does not give rise to the dissipation of heat as it does for current through a resistance. Thus, the analogy cannot be used for modeling energy flow in systems where energy crosses between the magnetic and electrical domains. An alternative analogy to the reluctance model, which correctly represents energy flows is the gyrator–capacitor model. The magnetic circuit is derived using Kirchoff law, as illustrated in **Figure 3** [30, 31].

The symbols 1 dan Mrfluid are used to illustrate the reluctance of the design. So that it can be obtained as in the Eq. (1):

$$\Re = \frac{L}{\mu A} \tag{1}$$

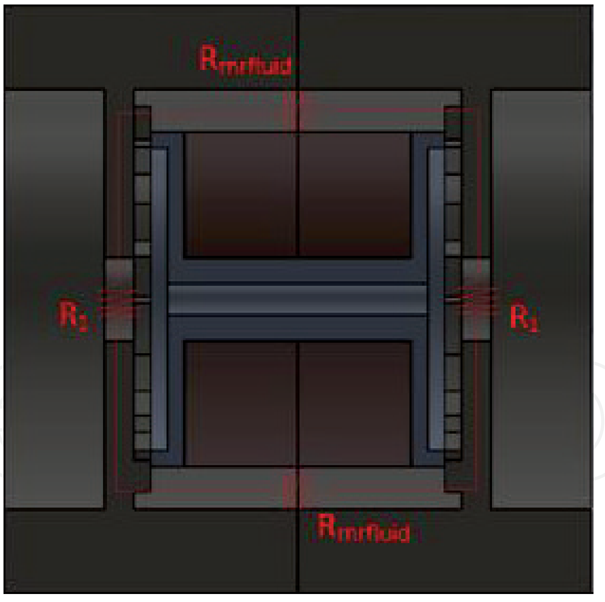


Figure 3.
Illustration of reluctance circuit on M.R. device.

where L is the effective distance that magnetic flux passes in each slice, μ is the magnetization property, and A is the effective area of the magnetic flux. Eq. 2 shows the total magnetomotive force generated from the sum of the magnetomotive force on all parts contained in one loop. So that we get the direct magnetomotive force for magnetic flux and reluctance as illustrated below,

$$\Phi_1 + \Phi_2 - (2\Re_1) - (2\Re_{mrfluid}) = 0 \tag{2}$$

Magnetic flux depends on a large number of copper coils and the current flowing in the coil so that Eq. (2) can be rewritten as Eq. (3),

$$NI - (2\Re_1) - (2\Re_{mrfluid}) = 0 \tag{3}$$

where N and I are the numbers of copper turns on the coil and the current flowing in the coil.

4. FEMM simulation procedure

4.1 Two-dimensional device sketch

The dimensions of the M.R. device depend on the target performance required, the function, and the space to be used. Dimensions determine the level of difficulty or ease in the M.R. device manufacturing process. Besides, according to the control classification of M.R. devices, dimensions will affect the value of pressure drop and damping force as well as the appearance of the device. One example is the configuration of a geometric arrangement that relies on the length of the fluid flow path in the equation to determine the predicted value for pressure drop.

4.2 Considering the target to achieve the predicted value

In this case, suppose that the target to be achieved is the pressure drop and damping force. The target pressure drop and damping force should be considered according to the needs and functions of the device. The milestones are related to the dimensions of the devices that have been designed. It is the determination of the number of devices that must be used with the available space and the targets that must be achieved.

4.3 FEMM simulation

FEMM can be simulated with some software. In general, all simulation procedures in some software are almost the same, such as FEMM and Ansoft Maxwell. The simulation process starts by making a design that will be simulated in a two-dimensional sketch. However, to perform a FEMM simulation, in general, the design to be simulated is made in two dimensions. Next is the material selection stage, coil configuration, meshing, and simulating as described below:

4.3.1 Set the initial simulation settings in the FEMM software

The initial settings made in the FEMM software are problem settings to be simulated. In this case, the problem to be simulated is a magnetic problem with axisymmetric.

4.3.2 Material selection

After making the initial setup and exporting the 2D design, then select the material according to the design that has been made. Material selection can be done

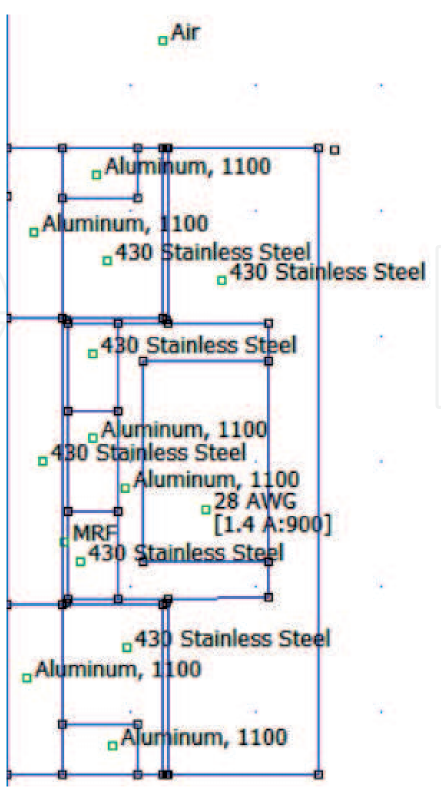


Figure 4.
Material selection.

by taking the existing software library or creating materials that have not been provided by FEMM by inputting all material property data to be used. Material selection can be seen in **Figure 4** above.

4.3.3 Coil configuration

The coil that will be used is inserted when performing the magnetic simulation with the FEMM software. In determining the coil, it is needed to input the type of wire, the number of turns, and the current that will be used.

4.3.4 Meshing

This process is an essential part of the simulation. The meshing process is a process of dividing an area which is divided into several areas to simplify the simulation process. **Figure 5** shows the results of the FEMM simulation meshing.

4.3.5 Running and plotting the result

The simulation software used is the Finite Element Method Magnetics (FEMM). The software is used to simulate the magnetic valve design that has been made. 2D designs that have been created are then exported to FEMM. Next, the problem setting to be simulated is determined, namely the magnetic problem with the symmetrical type. After the basic settings for the simulation are carried out, then adjust the material selection and coil selection according to the design that has been made.

The materials selection in the valve circuit is considered to get optimal results. Material selection is based on a predetermined valve design. Thus the direction of magnetic flux can be bent by nonmagnetic materials and produce a magnetic flux direction that is perpendicular to the direction of fluid flow. This is under the coil

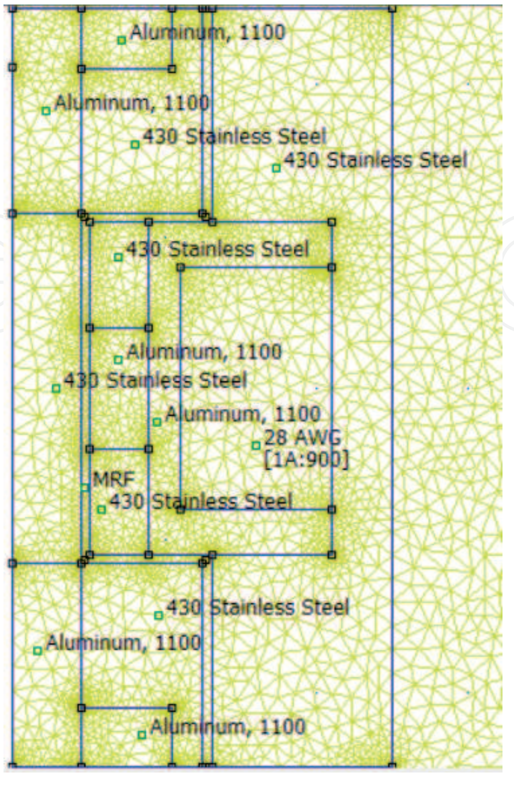
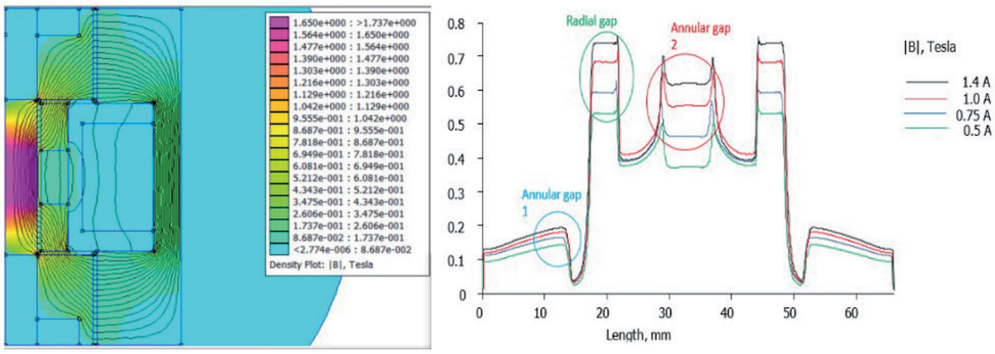


Figure 5.
Meshing result.



(a) (b)

Figure 6.
(a) Magnetic flux density results from the FEMM simulation; (b) magnetic flux density plot.

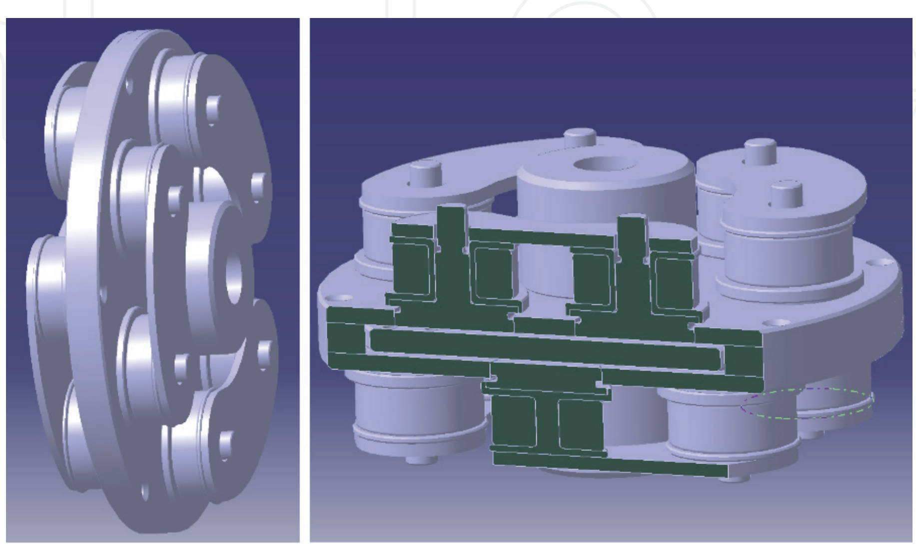
configuration, and the fluid flow path geometry arrangement used to obtain the magnetic flux direction perpendicular to the fluid direction.

After all the parameters have been adjusted, proceed with the meshing process and simulate to get the magnetic flux density (B) results, as shown in **Figure 6**.

5. M.R. devices simulation

5.1 Magnetorheological multi-coil brake

This study describes a 3D magnetic simulation design of a magnetorheological multi-coil brake (M.R.B.). The design used in this study is an axial M.R.B. design with a configuration of more than one coil that is placed outside the casing. The placement of the device aims to simplify the brake maintenance process. **Figure 7** shows the multi-coil M.R. brake design in vertical and horizontal views. The simulation process is only carried out on a pair of coils that represent the entire coil and can distribute the magnetic flux to the entire electromagnetic part. The purpose of this simulation is to determine the results of the magnetic flux on the surface of the disc brake rotor. This simulation uses the FEMM modeling approach assisted by Ansoft Maxwell software.



(a) (b)

Figure 7.
Multi-coil MR brake design; (a) vertical view; (b) horizontal view.

The result is that the magnetic flux value of M.R.B. with a multi-coil configuration is higher than the magnetic flux value in conventional M.R.B. which only uses one coil with a larger size. Furthermore, the simulation results that have been obtained are used to determine the effect of different fluids on each variation. This study used several types of magnetorheological fluids (MRFs), MRF-122EG, MRF-132DG, and MRF-140CG, which were injected into each device design. Variations in the electric current input of 0.25 amperes, 0.50 amperes, 0.75 amperes, and 1.00 amperes are given in the simulation process. The results of magnetic flux distribution for MRF-132DG with the difference in current input can be seen in **Figure 8** below.

The resulting magnetic flux values were obtained from the FEMM simulation. The simulation is carried out by taking several variations of the electric current input and the difference in the fluid flow gap given to the device. The results show an increase in magnetic flux with each increase in electric current input and an increase with each narrower gap. As an example is the MRF-132DG design simulation for the MRF-132DG type, as shown in **Figure 9** below.

5.2 Fabrication and morphological characterization of anisotropic magnetorheological elastomer (M.R.E.)

In this study, silicone R.T.V. based anisotropic magnetorheological elastomer with 70% weight fraction of iron particle were fabricated using a validated mold and capable of aligning the particle in several angles (0°, 45°, dan 90°). This study begins with the fabrication of anisotropic M.R.E. curing mold, which covers the stage of design, simulation, prototype fabrication, and validation. Anisotropic M.R.E. mold was designed using Autodesk Fusion 360. To determine the value of magnetic flux density and distribution throughout the print, it was examined using simulations on Ansoft Maxwell. The simulation results show that the best magnetic flux density value on the mold is 0.3 T to form a good particle alignment in the matrix. At the same time, the magnetic flux density value of 0.3 T can be achieved by providing an electric current input of 0.2, 0.1, and 1 ampere respectively for the mold angles of 0°, 45°, and 90° during the curing chamber. This curing process is carried out for three hours under a magnetic field and left for one day before the sample is taken.

Magnetostatic simulation has a vital role in this research. The simulation process is carried out using Ansoft Maxwell software. This simulation is useful in estimating the magnetic flux density value in the curing chamber and knowing the direction of the magnetic field vector formed. The mold design that has been made will be simulated with various current values so that it can be seen as the current value needed to

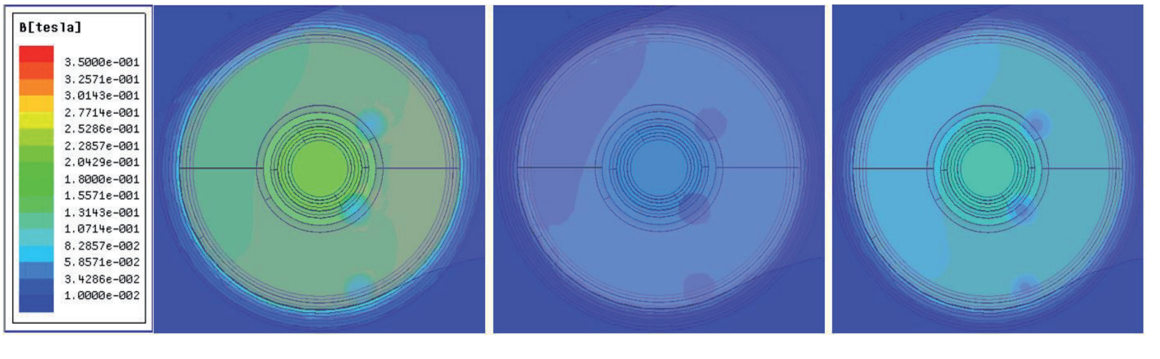


Figure 8.
Comparison of magnetic flux distribution to variation of MRFs; (a) 0.5 amperes; (b) 0.75 amperes; (c) 1 ampere.

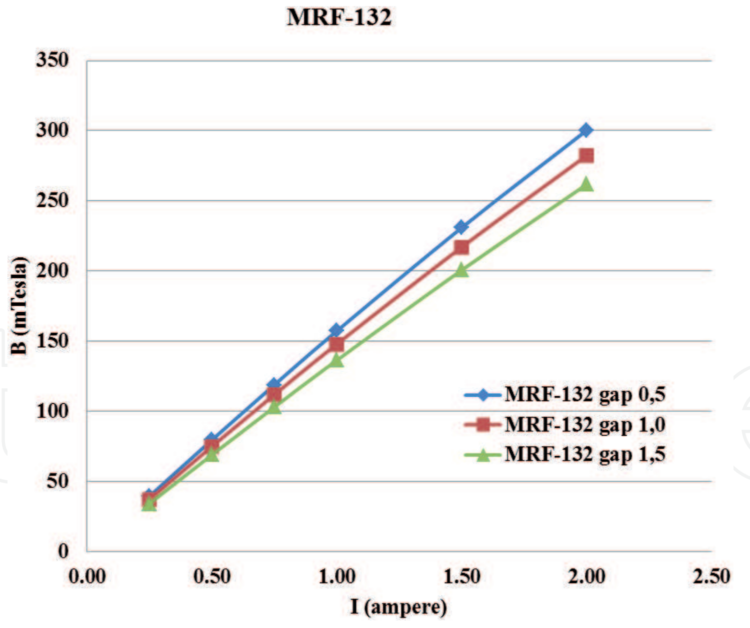


Figure 9.
FEMM simulation results for magnetic flux.

generate a magnetic flux density value of 0.3 T in the curing chamber. The magnetic properties data from V.S.M. are used to create new materials in the simulation. Thus, the material formed in the simulation is the same as the material used as the mold material. After the material in the simulation is the same as the actual condition, it is expected that the results of the simulation will not differ much from the measurement using a gauss-meter.

The simulation was carried out by providing variations in the angle of formation of M.R.E. with 0°, 45°, and 90°. One of the simulation results using an angle of 45° is shown in **Figure 10** below.

Figure 10 shows the distribution of the magnetic flux over a 45° curing space. The distribution of magnetic flux density in the curing chamber is marked in green color, which means that the value of the magnetic flux density in the area is medium. By changing the angle of the curing space by 45° relative to the direction of the magnetic field vector, anisotropic M.R.E. with a particle arrangement of 45° can be produced. After simulating several current values, the current required to produce 0.3 T in the curing chamber is 0.1 A. The graph in **Figure 11** shows the low magnetic flux density values on the left and right of the graph. This is because the measuring line of the magnetic flux density value touches the wall of the curing chamber, which is made of nonmagnetic aluminum.

5.3 Characterization torque of T-shaped magnetorheological brake

In recent research, M.R.B. T-shaped usually used more than one wire coil electromagnetic to maximize magnetic flux reaching all Magnetorheological Fluids (MRFs) gap. This research was focused on the reduction of wire coil on Magnetorheological Brake (M.R.B.). Serpentine flux was used to maximize all MRFs gaps that only use a single coil. The research was begun by designing M.R.B. design, followed by magnetostatic simulation using Finite Element Method Magnetics, calculate braking torque based on simulation, prototyping M.R.B. to get real braking torque measurement, and the last was measure braking torque using a torque sensor with constant angular velocity. The result of magnetostatic simulation shows the magnetic flux that reaches all MRFs gap. The most excellent magnetic flux density was 0,45 T at 1 A current on the outer annular. This result was used to

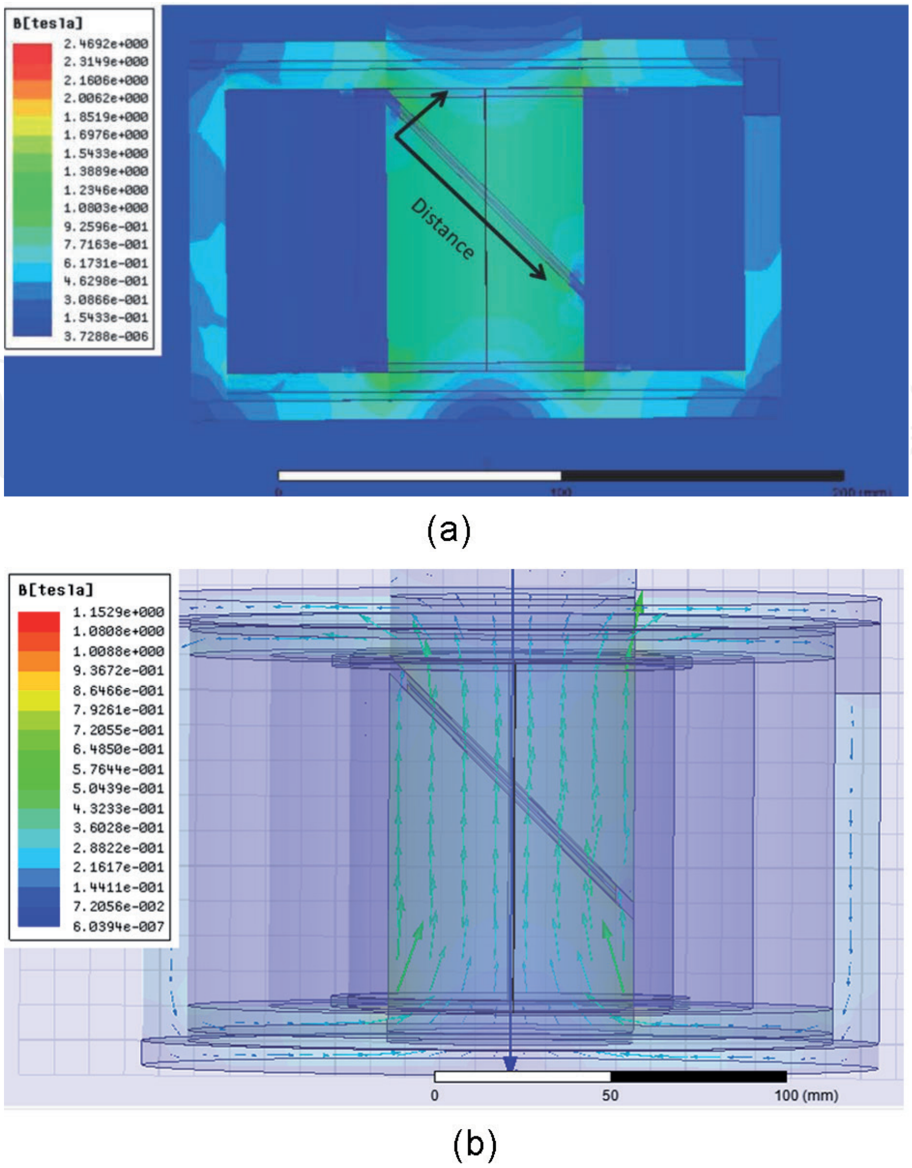


Figure 10.
Simulation results of a 45°: Vector magnetic (a) distribution of magnetic flux and (b) vector.

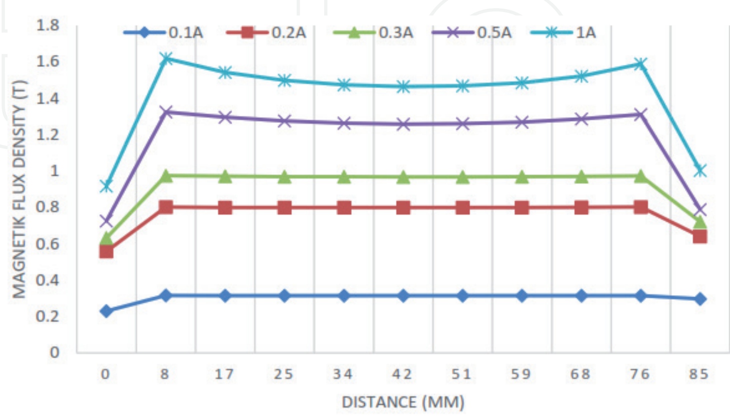


Figure 11.
Magnetic flux density distribution values in a 45° curing chamber at a current of 0.1; 0.2; 0.3; 0.5; and 1 A.

calculate shear stress based on Bingham Model that would generate braking torque. The braking torque generated on modeling torque and experiment was 1,51 Nm and 1,91 Nm at 1 A current with 20% difference, respectively. **Figure 12** shows an exploded design of M.R. brake.

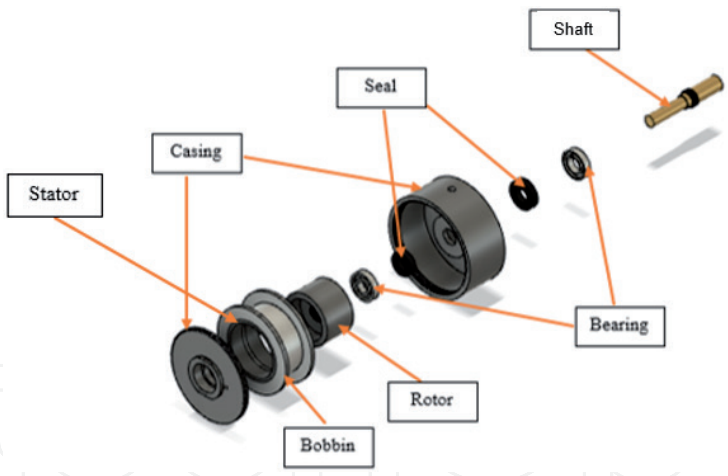


Figure 12.
Exploded design of M.R. brake.

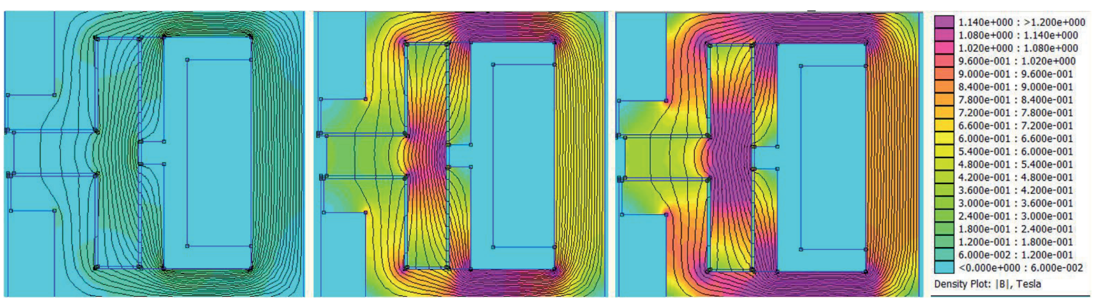


Figure 13.
Simulation results for magnetostatics: (a) 0.1 A; (b) 0.5 A and (c) 1 A.

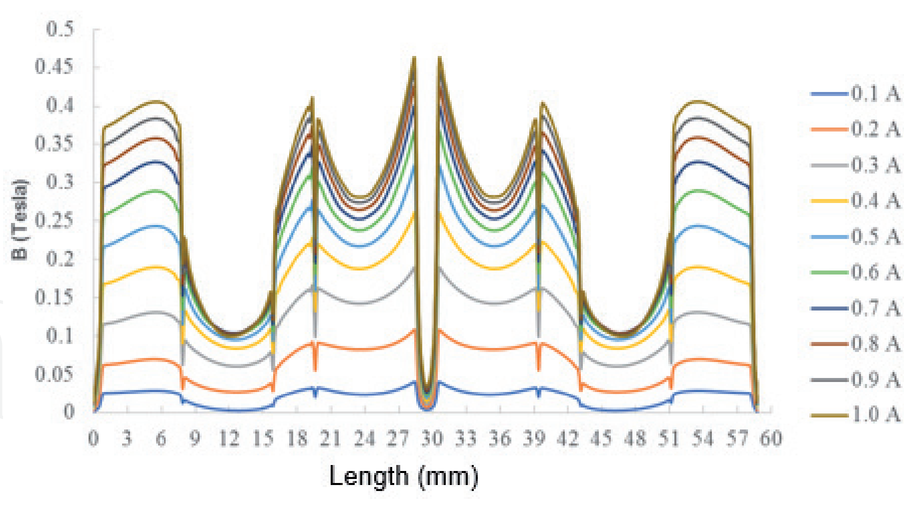


Figure 14.
Distribution of magnetic flux density along the MRF gap at variations of electric current 0.1–1 A.

The use of an electric current greatly affects the magnetic flux density. The greater the electric current used, the greater the magnetic flux density produced. It can be illustrated in **Figure 13**. The results given show the change in the resulting magnetic flux density, which is marked in a darker color, accompanied by more flux lines produced. The change has a limit point due to the ability of the material [32] as well as the flux that attaches to a particular component.

Figure 14 shows the distribution of magnetic flux density along the MRF gap with different variations of electric current. At current 1 A, the greatest magnetic flux density value exceeds 0.45 T, which is in the outer annular part. The higher the current applied, the lower the increase in magnetic flux density. This is because the direction of the magnetic flux is getting closer to the wall so that the resulting flux is limited. The ability of the copper wire to distribute magnetic flux also affects the result.

5.4 Performance prediction of magnetorheological damper for seismic

The new concept of a magnetorheological (M.R.) damping device used in the seismic building is discussed in this paper. The damper is aimed to deliver a comparable damping performance with the existing semi-active seismic damper design but with lower M.R. fluids volume requirement. This capability is achieved through the improvement in the M.R. valve performance using a meandering flow structure which was placed in the bypass line. **Figure 15** shows the sectional design of M.R. damper for seismic building and its valve.

This research is focused on the performance analysis of the M.R. valve pressure drop using an analytical approach. There are two main steps needed for the analytical approach, the magnetic field simulation, and the analytical pressure drop calculation. The simulation work of the M.R. valve magnetic circuit performance was carried out using finite element method magnetic (FEMM) software to calculate the distribution of magnetic flux density values. The simulated magnetic field density values would then be matched with the M.R. fluids characteristics data to predict the yield stress value of the fluids to be used in the pressure drop calculation. As a result, the M.R. valve is predicted to generate maximum off-state pressure drop of 5.35 MPa and a piston speed of 0.184 m/s. Meanwhile, at on-state condition (1.4 A), the valve is generating pressure drop up to 9.13 MPa at a piston speed of 0.184 m/s. The generated total pressure drop of the M.R. valve reaches 16.39 MPa. The MR fluids that are used in this design are only 1.5 x 10^{-4} m^3. From the generated total pressure drop, the peak of the damping force is obtained with 1.4 A, which is 32.19 kN. Meanwhile, the calculation result of the seismic force is 125.3 kN. Thus, it can be concluded that with the peak generated damping force, this seismic damper design will be capable of providing a damping performance which is appropriate to the seismic force with four parallel devices.

In this study, the FEMM simulation was used to obtain the magnetic flux density value in the valve section. The magnetic flux density value is used to calculate the predicted yield stress value, which is then used to predict the value of the pressure drop and the damping force. Yield stress is obtained through magnetic simulation using FEMM software which aims to obtain a magnetic flux density graph. Then the

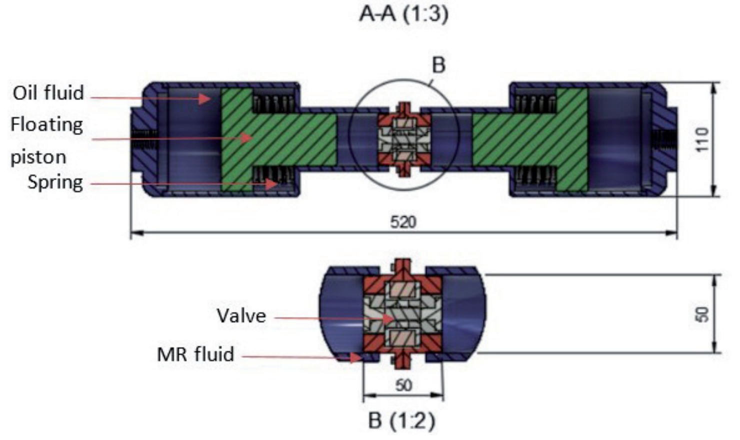


Figure 15.
M.R. damper for seismic building design.

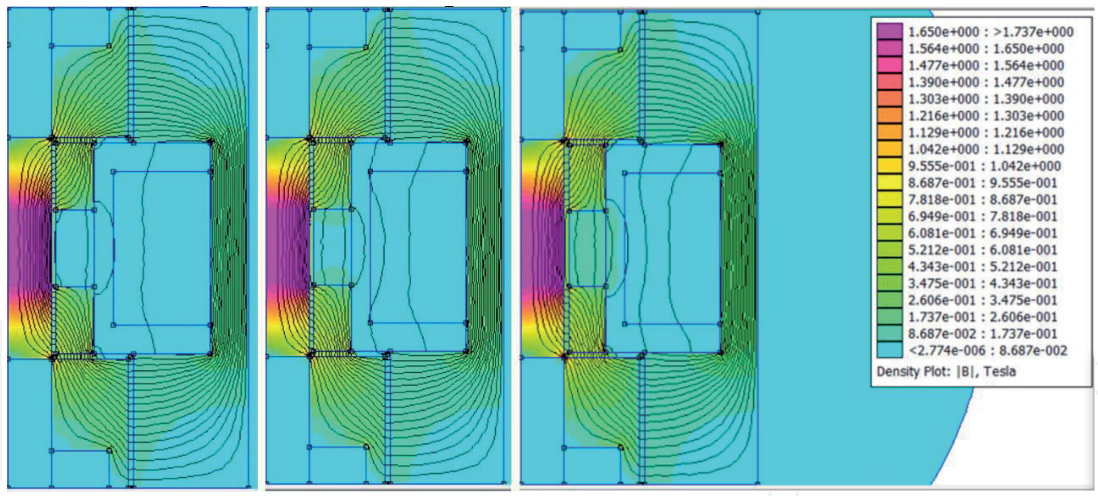


Figure 16.
Result of FEMM simulation.

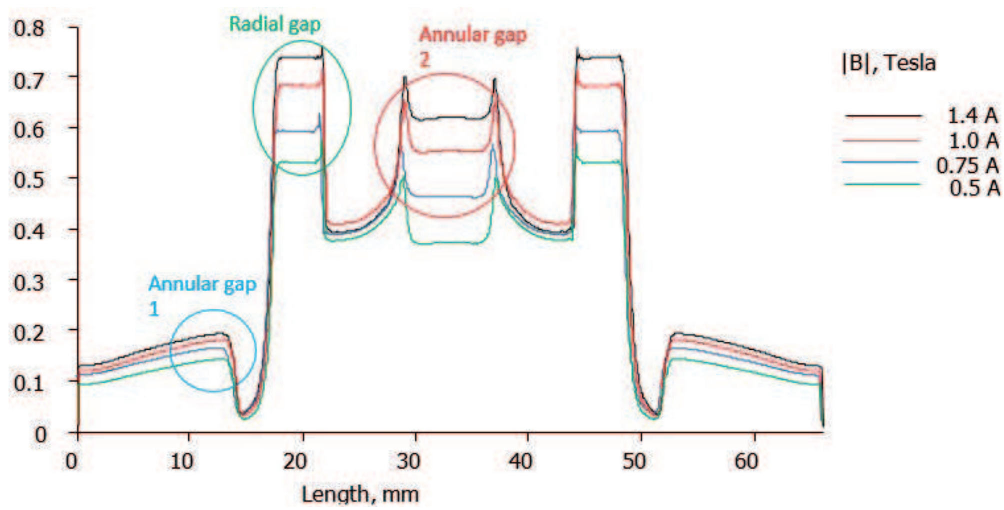


Figure 17.
Magnetic flux density result.

resulting magnetic flux density value is included in the calculation to get the yield stress value. The simulation process used is a magnetic simulation of the working fluid with a viscosity of 0.112 Pa.s which is obtained from the MRF132-DG property data by Lord Corp [33]. **Figure 16** shows the results of 2D magnetic simulations with FEMM and magnetic flux density graphs obtained through the simulation process.

Figure 17 above is obtained from a FEMM simulation based on a 2D design with an MRF132-DG working fluid and 900 coils. The wire used uses copper wire 28 A.W.G. with a diameter of 0.3211 mm with a resistance of 213 Ω/km. The graph shows the results of the magnetic flux density at the annular and radial channel against the variation of current input 0.5 A; 0.75 A; 1.0 A; 1.4 A.

6. Conclusion

Finite element magnetic is a method that can be used to facilitate an intricate work or may not even be completed by other methods. In this case, the field of magnetorheology is an example of a problem by using the finite element method solution. The magnetorheological device is a device that uses iron particle materials whose working principle is to change its rheological properties due to the influence of a magnetic field. This magnetic field gives rise to a magnetic flux density in the device whose magnitude can be determined by solving the finite element method. To find out the magnitude of the magnetic flux density value, some finite element method magnetics software can be used, such as FEMM and Ansoft Maxwell. The solution to these problems can be resolved with the existence of boundary conditions and initial setups that are following the procedure, such as the type of problem, the use of materials, and a clear design configuration. Thus, problems requiring the finite element method can be resolved with good accuracy. Problem-solving with the finite element method simulation is considered more accurate than other methods. In the case of magnetorheological devices, magnetic simulation with the finite element method is very helpful to achieve the research objectives.

Acknowledgements

The authors gratefully thank the ministry of research and technology (RISTEK/BRIN) for the funding of Hibah World-Class Research 2020-2021.

Conflict of interest

The authors have no conflict of interest.

Notes/thanks/other declarations

The authors thank Ariyo Nurachman Satiya Permata, Ilham Rizkia Nyaubit, Ilham Bagus Wiranto, and Rivananda Rama S that have been doing the simulations for finite element magnetic in magnetorheological devices so the authors could do this book chapter as well.

Author details

Ubaidillah* and Bhre Wangsa Lenggana
Universitas Sebelas Maret, Surakarta, Indonesia

*Address all correspondence to: ubaidillah_ft@staff.uns.ac.id

References

[1] K.B. Baltzis, The finite element method magnetics (FEMM) freeware package: May it serve as an educational tool in teaching electromagnetics?, Educ. Inf. Technol. 15 (2010) 19-36. doi:10.1007/s10639-008-9082-8.

[2] D. Meeker, Finite Element Method Magnetics Version 4.2 User Manual (2015)

[3] W.H. Li, H. Du, N.Q. Guo, Finite element analysis and simulation evaluation of a magnetorheological valve, Int. J. Adv. Manuf. Technol. 21 (2003) 438-445. doi:10.1007/s001700300051.

[4] C. Jędryczka, FE analysis of electromagnetic field coupled with fluid dynamics in an M.R. clutch, COMPEL - Int. J. Comput. Math. Electr. Electron. Eng. 26 (2007) 1028-1036. doi:10.1108/03321640710756357.

[5] M. Barham, D. White, Finite element simulation of permanent magnetoelastic thin films, IEEE Trans. Magn. 47 (2011) 1402-1405. doi:10.1109/TMAG.2010.2088382.

[6] A. Boczkowska, L. Czechowski, M. Jaroniek, T. Niezgoda, Analysis of magnetic field effect on ferromagnetic spheres embedded in elastomer pattern, J. Theor. Appl. Mech. 48 (2010) 659-676.

[7] Z. Parlak, T. Engin, I. Çalli, Optimal design of M.R. damper via finite element analyses of fluid dynamic and magnetic field, Mechatronics. 22 (2012) 890-903. doi:10.1016/j.mechatronics.2012.05.007.

[8] T.A. Voronina, G.M. Molodavkin, S.A. Sergeeva, O.I. Epstein, Anxiolytic Effect of Proproten under Conditions of Punished and Unpunished Behavior, Bull. Exp. Biol. Med. 135-136 (2003) 120-122. doi:10.1023/A:1024771906306.

[9] J. Morozionkov, J.A. Virbalis, Investigation of electric reactor magnetic field using finite element method, Elektron. Ir Elektrotechnika. (2008) 9-12. doi:10.5755/j01.eee.85.5.11150.

[10] H. Zhou, M. Bai, Y. He, S. Ren, F.E.M. analysis of magnetorheological fluid seal of circular cooler and its experimental research, Int. J. Appl. Electromagn. Mech. 41 (2013) 419-431. doi:10.3233/JAE-121622.

[11] V. Pendefunda, A.C. Pendefunda, N. Ioanid, A. Apostu, Finite element analysis of periodontal stresses in fixed prosthodontics, 5 (2013) 82-87.

[12] Y. Li, J. Li, Finite element design and analysis of adaptive base isolator utilizing laminated multiple magnetorheological elastomer layers, J. Intell. Mater. Syst. Struct. 26 (2015) 1861-1870. doi:10.1177/1045389X15580654.

[13] Z. Chao, F. Tyan, S. Tu, W.S. Jeng, Finite Element Analysis of a Magnetorheological Fluid Damper, 24th CSME Conf. CYCU, Chungli, Taiwan, R.O.C. (2015) 3145-3149.

[14] M.Y. Salloom, Z. Samad, Finite element modeling and simulation of proposed design magnetorheological valve, Int. J. Adv. Manuf. Technol. 54 (2011) 421-429. doi:10.1007/s00170-010-2963-1.

[15] B. Yang, J. Luo, L. Dong, Magnetic circuit F.E.M. analysis and optimum design for M.R. damper, Int. J. Appl. Electromagn. Mech. 33 (2010) 207-216. doi:10.3233/JAE-2010-1115.

[16] Ubaidillah, J. Sutrisno, A. Purwanto, S.A. Mazlan, Recent progress on magnetorheological solids: Materials, fabrication, testing, and applications,

Adv. Eng. Mater. 17 (2015) 563-597. doi:10.1002/adem.201400258.

[17] P. Skalski, K. Kalita, Role of Magnetorheological Fluids and Elastomers in Today's World, Acta Mech. Autom. 11 (2017) 267-274. doi:10.1515/ama-2017-0041.

[18] M. Schwartz, Smart Materials, Taylor & Francis Group, Boca Raton (2009)

[19] D. Baranwal, T.S. Deshmukh, MR-Fluid Technology and Its Application - A Review, Int. J. Emerg. Technol. Adv. Eng. 2 (2012) 563-569.

[20] K.D. Weiss, J.D. Carlson, D.A. Nixon, Viscoelastic properties of magneto- and electro-rheological fluids, J. Intell. Mater. Syst. Struct. 5 (1994) 772-775. doi:10.1177/1045389X9400500607.

[21] M.R. Jolly, J.W. Bender, J.D. Carlson, Properties and applications of commercial magnetorheological fluids, J. Intell. Mater. Syst. Struct. 10 (1999) 5-13. doi:10.1106/R9AJ-XYT5-FG0J-23G1.

[22] F. Imaduddin, S.A. Mazlan, H. Zamzuri, A design and modelling review of rotary magnetorheological damper, Mater. Des. 51 (2013) 575-591. doi:10.1016/j.matdes.2013.04.042.

[23] M. Avraam, M. Horodinca, I. Romanescu, A. Preumont, Computer controlled rotational MR-brake for wrist rehabilitation device, J. Intell. Mater. Syst. Struct. 21 (2010) 1543-1557. doi:10.1177/1045389X10362274.

[24] G. M. Webb, Exercise apparatus and associated method including rheological fluid brake (1998)

[25] A.G. Olabi, A. Grunwald, Design and application of magnetorheological fluid, Mater. Des. 28 (2007) 2658-2664. doi:10.1016/j.matdes.2006.10.009.

[26] Z. Rigbi, L. Jilkén, The response of an elastomer filled with soft ferrite to mechanical and magnetic influences, J. Magn. Magn. Mater. 37 (1983) 267-276. doi:10.1016/0304-8853(83)90055-0.

[27] M. Lokander, B. Stenberg, Improving the magnetorheological effect in isotropic magnetorheological rubber materials, Polym. Test. 22 (2003) 677-680. doi:10.1016/S0142-9418(02)00175-7.

[28] L.C. Balbas, G. Borstel, J.A. Alonso, Nonlocal density functional calculation of the electron affinity of atoms, Phys. Lett. A. 114 (1986) 236-240. doi:10.1016/0375-9601(86)90214-8.

[29] S. Mantripragada, X. Wang, F. Gordaninejad, B. Hu, A. Fuchs, Rheological properties of novel magnetorheological fluids, Int. J. Mod. Phys. B. 21 (2007) 4849-4857. doi:10.1142/s021797920704575x.

[30] E.C. Sekaran, Magnetic circuits and power transformers, Elsevier Inc., 2016. doi:10.1016/B978-0-12-804448-3.00011-6.

[31] S.A. Afsari, Optimal Design and Analysis of a Novel Reluctance Axial Flux Magnetic Gear, (n.d.).

[32] K. Karakoc, E.J. Park, A. Suleman, Design considerations for an automotive magnetorheological brake, Mechatronics. 18 (2008) 434-447. doi:10.1016/j.mechatronics.2008.02.003.

[33] C. Load, MRF-132DG Magneto-Rheological Fluid, Lord Prod. Sel. Guid. Lord Magnetorheol. Fluids. 54 (2011) 11. doi:)D DS7015 (Rev.1 11/11).