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ARTICLE OF PROFESSIONAL INTEREST

Optimization of Magneto-Rheological Damper for Maximizing Magnetic Flux Density in the Fluid Flow Gap Through FEA and GA Approaches

Hemanth Krishna[1] · **Hemantha Kumar**[1] · **Kalluvalappil Gangadharan**[1]

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Abstract A magneto rheological (MR) fluid damper offers cost effective solution for semiactive vibration control in an automobile suspension. The performance of MR damper is significantly depends on the electromagnetic circuit incorporated into it. The force developed by MR fluid damper is highly influenced by the magnetic flux density induced in the fluid flow gap. In the present work, optimization of electromagnetic circuit of an MR damper is discussed in order to maximize the magnetic flux density. The optimization procedure was proposed by genetic algorithm and design of experiments techniques. The result shows that the fluid flow gap size less than 1.12 mm cause significant increase of magnetic flux density.

Keywords MR damper · Semi-active vibration control · Design of experiments · Genetic algorithm

Introduction

Semi-active control device offers reliability comparable to that passive device, versatility and adaptability of fully active system, without requiring large power source. In semi active suspension the amount of damping can be tuned in real time, the variation of damping may be achieved by introducing solenoid valves (electrohydraulic dampers), or by the use of fluids which may vary their viscosity, if subject to an electric or magnetic field. Electro Rheological (ER) and MR dampers are semi-active control devices that use ER and MR fluids to produce controllable damping force.

MR fluid consists of ferrous particles dispersed in a carrier medium. Rheological properties of the fluid change drastically in the presence of a magnetic field, which creates a resistance against the fluid flow. Under field-responsive effect, particles inside the MR fluid are excited by the applied magnetic field to form strong chains along the direction of the magnetic flux lines. The interaction between the particles acts as a resistance to the applied force. The degree of deformation resistance is contingent upon the applied magnetic field strength. In the absence of the magnetic field, the fluid returns to its original (free-flowing) state. The researchers have [1] conducted the optimization studies of an MR damper used in the front loaded washing machine. Further, the experimentation was conducted on the Finite Element Analysis (FEA) by using 2D axis symmetric element in ANSYS software. For optimization, the investigators have used the golden section algorithm of ANSYS optimization tool. Some of the researches have shown the geometrically optimized MR damper based target damper force and maximum magnetic flux density as objective function [2]. They optimized MR damper using goal driven optimization tool in FEA. The investigators have also [3] designed the damper for an automobile front suspension, wherein magnetic circuit in the piston was examined by using Finite Element Method (FEM). Also, the properties of designed damper were determined by conducting experiments. Some researchers [4] have conducted the study on MR damper with combination of shear and squeeze mode by using Finite Element Method Magnetics (FEMM). Whereas, some researchers [5] have analyzed the fluid flow through the annular gap by quasi-static analysis and CFD analysis of MR damper has been studied. The prior investigators [6] have considered the

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✉ Hemanth Krishna
ckh4545@gmail.com

[1] National Institute of Technology Karnataka, Mangalore 575025, Karnataka, India

magnetic saturation analysis of magnetorheological damper for single coil and double coil arrangement by using FEM and developed nonparametric model, based on magnetic flux density in the fluid flow gap. It has been conducted experimentation earlier [7] on the disk type MR damper and performed magnetic field analysis using FEM. The effect of excitation current in a coil on the induced magnetic flux density in the fluid flow gap has been studied theoretically and experimentally. Some researchers have [8] designed a statistical model of MR damper using the design of experiment approach, various factors such as magnetic field strength, volume fraction of the magnetic particle, shearing gap between piston and cylinder, amplitude and frequency of vibration were considered in their experimentation.

Optimization of electromagnetic circuit of an MR damper is important to meet engineering application and help to obtained better performance of MR damper in a semiactive vibration control.

Methodology

The methodology shows the maximization of magnetic flux density by electromagnetic circuit parameters of a magneto-rheological damper. The optimization procedure was carried out by two techniques such as, Genetic algorithm and Design of experiments technique as shown in Fig. 1.

Magnetic Field Analysis

The flow of magnetic field depends upon the magnetic permeability of the material. The relative permeability of the MR fluid is little bit higher than air, while magnetic core and inner cylinder block are ferromagnetic media; their relative permeabilities are very high. Therefore, according to the fundamental properties of electromagnetic field theory, the magnetic induction line almost parallel at the interface between boundaries of air, MR fluid, piston and cylinder block. Also the magnetic lines of force leaked out side are little. Ohm's law can be used to analyze the relationship of magnetic flux and magneto-motive force in the circuit [9].

$$\emptyset = \frac{NI}{R_m} \tag{1}$$

where $\emptyset$ is magnetic flux in a circuit. NI is magneto-motive force of whole magnetic circuit. R_m is magneto-resistive of the whole magnetic circuit, $R_m = \frac{1}{\mu A}$, μ is magnetic permeability and A is cross sectional area of magnetic circuit.

Current density applied to the coil is,

$$J = \frac{NI}{A} \tag{2}$$

where, N is number of turns in a coil and I is current through coil.

The purpose of modeling MR fluid based device is to find out the relation between input electric power (usually the current applied to the coil) and output mechanical power (damping force for MR damper). In order to deal with the modeling of MR based devices, firstly the magnetic circuit of the MR based devices should be solved. In general, the magnetic circuit can be analyzed using the magnetic Kirchoff's law as follows,

$$\sum Hl = NI \tag{3}$$

where H is the magnetic field intensity of the circuit and l is the overall effective length. The magnetic flux conservation rule of the circuit can be stated as,

$$\emptyset = BA \tag{4}$$

where $\emptyset$ magnetic flux of the circuit, A and B is are the cross sectional area and magnetic flux density respectively. At low magnetic field, the magnetic flux density (B) increase in proportion to the magnetic field intensity (H) as follows,

$$B = \mu_0 \mu_r H \tag{5}$$

where μ_0 magnetic permeability of free space ($4\pi 10^{-7}$ Tm/A) and μ_r is the relative permeability of material. As magnetic field become large, its ability to polarize the magnetic material diminishes and material almost magnetically saturated. From the Kirchoff's law, magnetic flux conservation rule of magnetic circuit the relation between magnetic field intensity in the MR fluid and the applied current can be approximated as [10],

$$H_{MR} = \frac{NI}{2g} \tag{6}$$

and

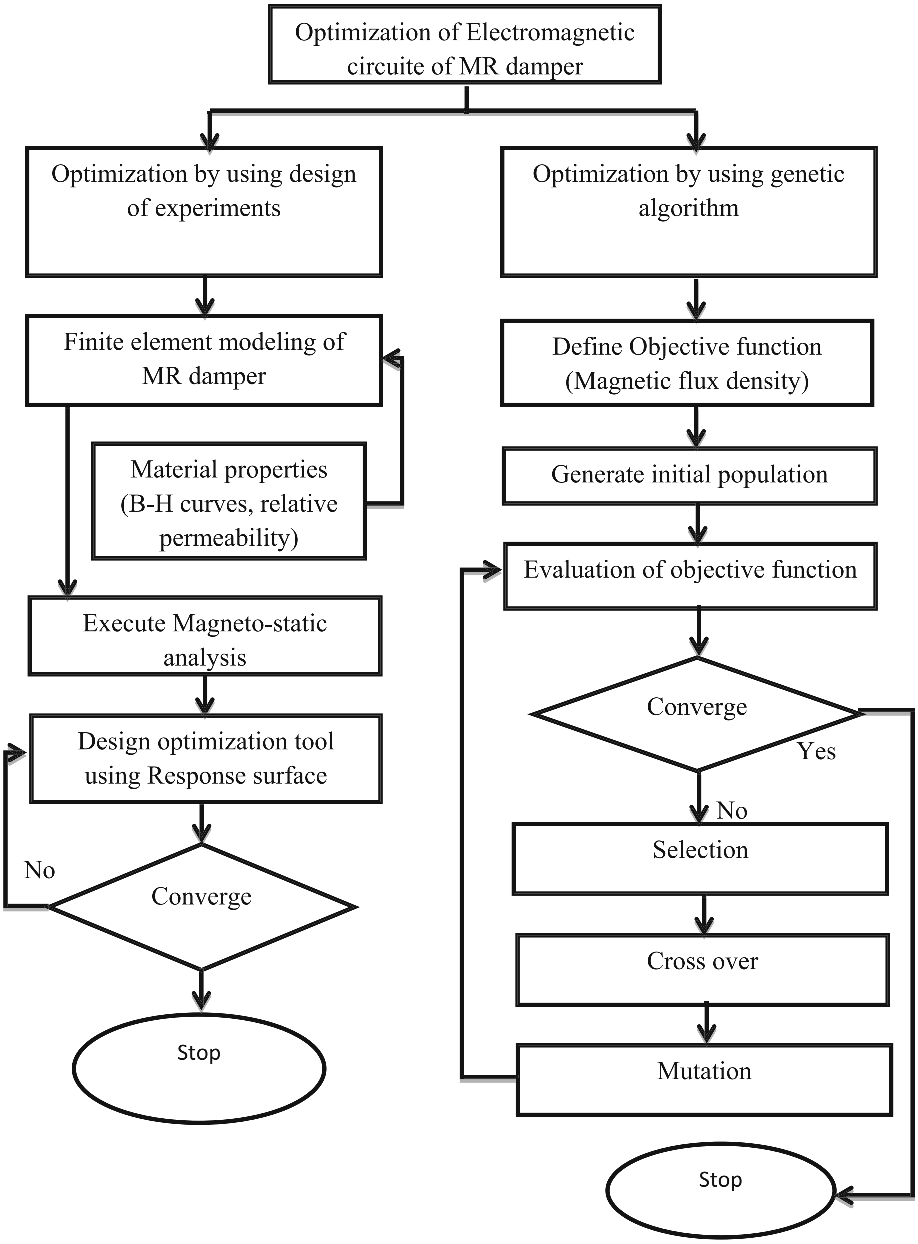
$$B = \frac{\mu_0 \mu_{MR} NI}{2g} \tag{7}$$

where g is fluid flow gap and μ_{MR} relative permeability of MR fluid.

Finite Element Modeling of MR Damper

The study of the MR damper is a promising topic as it provides a controllable damping force just by varying the current in its electromagnetic coil. The damping force being produced by a MR damper depends mainly

Fig. 1 Methodology



on the magnetic field induced in the working fluid clearance between piston and cylinder [11]. The finite element model of twin tube MR damper is as shown in the Fig. 2. Because of symmetrical geometry only one fourth of computational domain has been constructed for the analysis. The twin tube MR damper consist piston having electromagnetic coil, inner cylinder and outer cylinder. In this FEM modeling the piston and inner cylinder is taken as steel and the outer cylinder considered as aluminum alloy. The properties of MR damper component is given in the Table 1. The electromagnetic circuit in the piston consist of 1000 number of turns and it is subjected to a maximum current of 1 A and 9 V electric potential.

Figures 3 and 4 depicts the typical magnetic properties of the steel (SA1008) and MR Fluid (LORD MRF132-DG) and it signifies the saturation of the material. In saturable materials the permeability is not constant, it depending on magnetic field strength. The magnetic flux density is increases proportional to magnetic field strength up to certain limit, there after the magnetic flux density is not increases further more even the magnetic field strength continuous to increase.

The static magnetic analysis of MR damper provides the nodal solution at the clearance space (fluid flow gap) of MR damper under its magnetic induction. The total magnetic flux density of MR damper at fluid flow gap is as shown in Fig. 5.

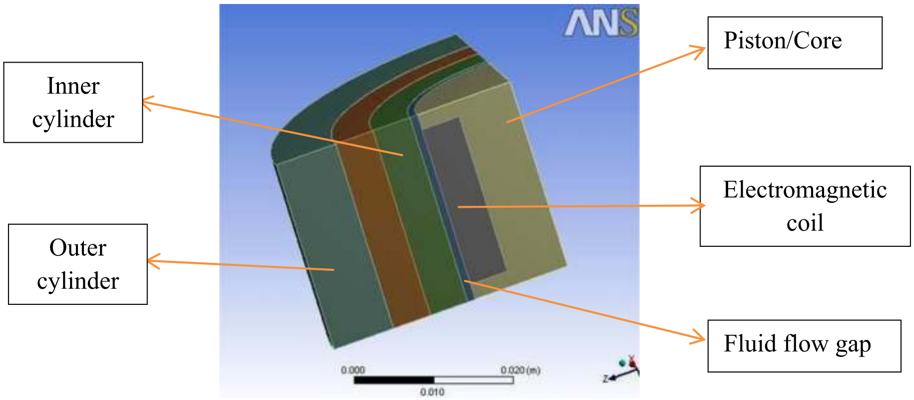


Fig. 2 Finite element modeling of MR damper

Table 1 Magnetic properties of MR damper component

Material	Relative permeability
Steel (SA1008)	B–H curve (Fig. 3)
Copper	1
MR Fluid (MRF132-DG)	B–H curve (Fig. 4)
Aluminum alloy	1

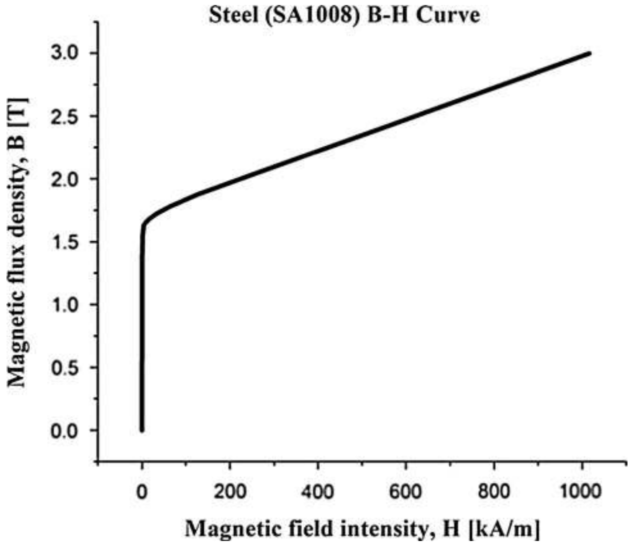


Fig. 3 B–H curve of steel

Optimization of MR Damper Using FEA

In the analysis, the value of variable parameters that yields maximum magnetic flux density is evaluated as optimal damper geometry. Response Surface Methodology (RSM) was used as a design optimization tool. The objective is to optimize the response where the response of interest is influenced by design variables. RSM is useful for

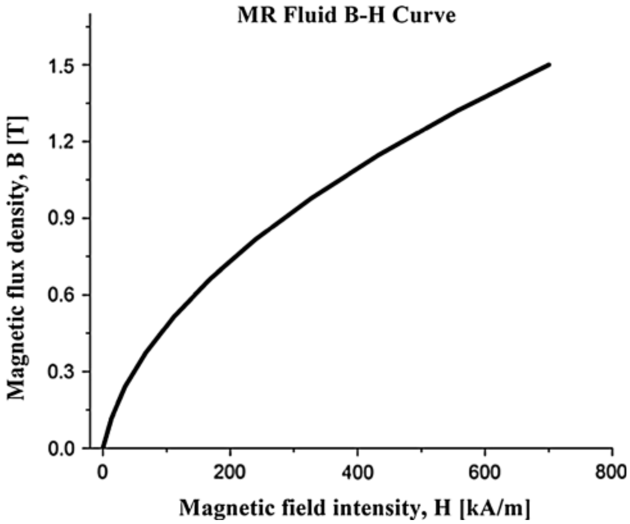


Fig. 4 B–H curve of MR fluid

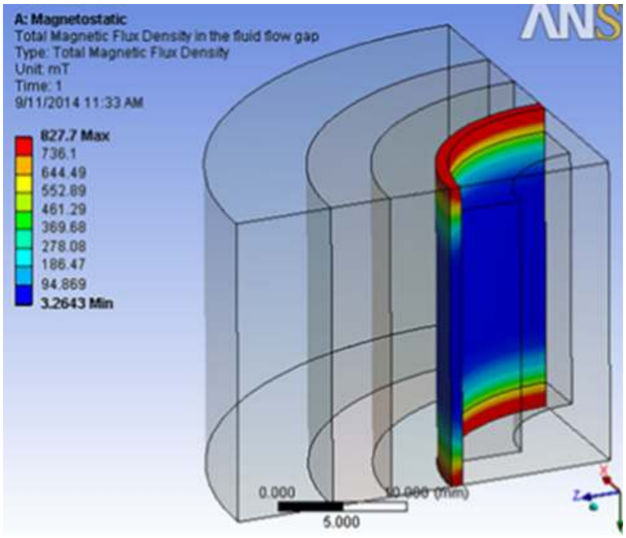


Fig. 5 Total magnetic flux density in the fluid flow gap

developing, improving and optimizing the response variable. Main purpose of RSM design optimization is to reduce the expensive analysis methods [12].

The design variables were identified between lower and upper boundaries is given in the Table 2. The parametric studies were conducted to investigate the effect of parameters on magnetic flux density. In the analysis, the current is varied from 0.1 to 1 A. The analysis result shows that the magnetic flux density increases with increase in current applied to the coil of an MR damper as shown in the Fig. 6. From the Fig. 6, it is observed that the magnetic flux density increases linearly with increase in current up to 0.5 A, however this rising decays gradually between 0.5 and 1 A due to saturation. The numbers of turns in a coil greatly influence the inductance. The inductance of the coil is due to magnetic flux around it, stronger the magnetic flux for a given value of current, grater will be the inductance. Hence, the magnetic flux density increases proportional to the number of turns (Fig. 7). Increase in flow gap leads to more flux leakage, which results decrease in magnetic flux density (Fig. 8). The magnetic flux density is passing perpendicular to the flow direction through the flange length develop field dependent resistance on MR fluid flow. Any magnitude of magnetic field has to pass through smaller flange length that causes bigger magnetic flux density on the MR fluid flow gap (Fig. 9). The magnetic flux density increases by increasing the core diameter or increasing the core length. In both the cases, more wire is required to construct the coil, thus more lines of force exists to produce the required back emf. Hence, the magnetic flux density increases gradually with increase of core length (Fig. 10).

Table 2 Lower and upper boundaries of the parameters

Parameters	Lower bound	Upper bound
Core length (l)	18 mm	22 mm
Flange length (w)	2 mm	5 mm
Fluid flow gap (g)	0.5 mm	2 mm
Number of turns in a coil (N)	500	1000
Current magnitude (I)	0.1A	1A

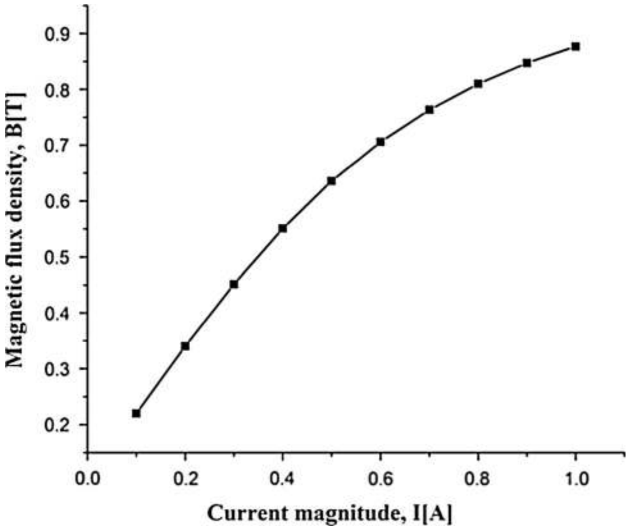


Fig. 6 Magnetic flux density against current magnitude

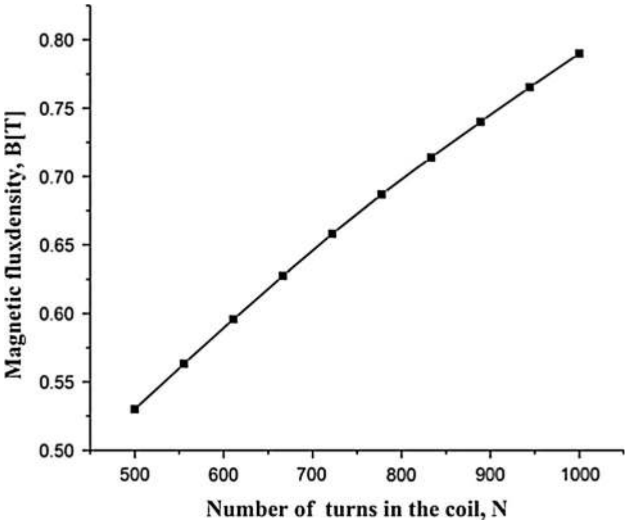


Fig. 7 Magnetic flux density against number of turns in the coil

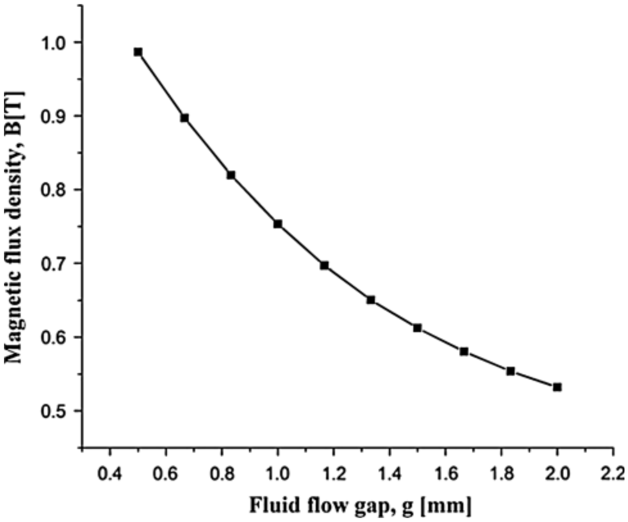


Fig. 8 Magnetic flux density against fluid flow gap

Figure 11 represents the response surface, which is plotted with design variable (flange length and fluid flow gap) against response (magnetic flux density). The surface plotted will make easy to understand the variation of magnetic flux density along with design variables. The optimal parameter of MR damper provides targeted

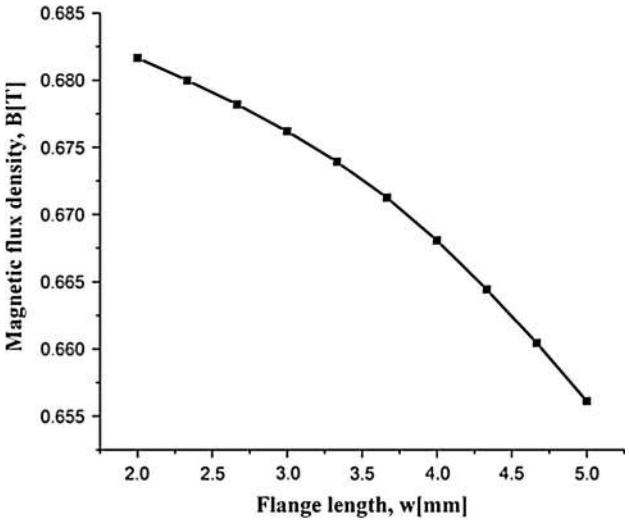


Fig. 9 Magnetic flux density against flange length

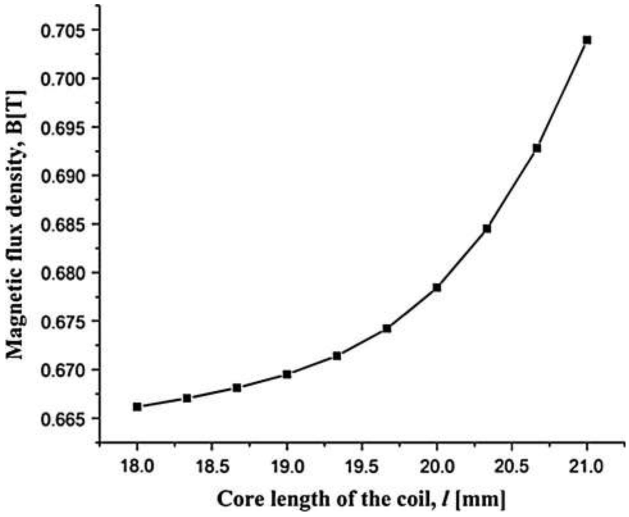


Fig. 10 Magnetic flux density against core length of coil

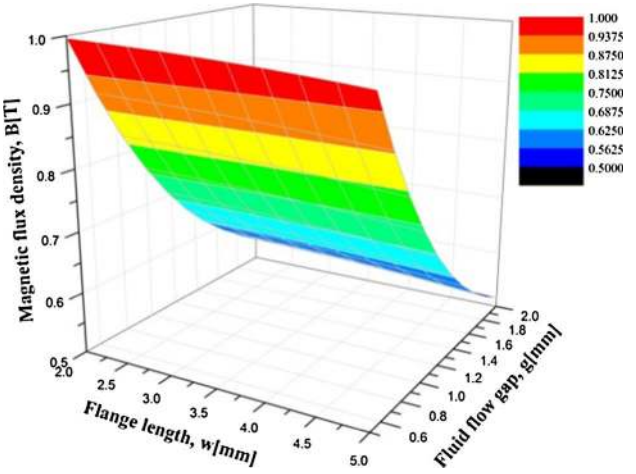


Fig. 11 Surface plot of Magnetic flux dnesity against fluid flow gap and flang length

maximum magnetic flux density, which is obtained from the FEA optimization as three candidates is given in Table 3.

Optimize the Parameters Using GA

A Genetic algorithm is an intelligent probabilistic search algorithm which can be applied to a variety of optimization problems. The idea of GAs is based on the evolutionary process of biological organisms in nature. During the course of the evolution, natural populations evolve according to the principles of natural selection and “survival of the fittest”. Individuals which are more successful in adapting to their environment will have a better chance of surviving and reproducing, whilst individuals which are less fit will be eliminated. In optimization terms, each individual in the population is encoded into a string or chromosome which represents a possible solution to a given problem [13].

The GA process starts with the initialization of the population with the calculation of the fitness function. The fitness of an individual is evaluated with respect to a given objective function (Eq. 7). The best individual is selected and the mating is prioritized based on the fittest individual. The crossover phenomenon is carried out at certain sites called as the “Cross-Over sites” which determine that the best genes are passed on the next set of individuals. The probabilities of crossover and mutation in GA are chosen as 0.95 and 0.05 respectively. The optimal solutions obtained by using GA in between lower and upper boundaries are given as in Table 4.

The upper plot of the Fig. 12, describes the best fitness at each generation, shows little progress in lowering the fitness value (black dots). The lower plot illustrates average distance between individuals at each generation, which is good measure of diversity of population. For this setting of initial range, there is too little diversity of the algorithm to make progress.

Conclusion

Magnetorheological damper is a semi-active device filled with magnetorhelogical fluid. The damping force of an MR damper is continuously controlled by varying the magnetic field. The performance of MR damper is highly influenced by the magnetic flux density induced in the fluid flow gap. The purpose of optimization of electromagnetic circuit of an MR damper is to maximize the magnetic flux density in the fluid flow gap. The optimization is carried out by using genetic algorithm and design of experiments. In the present work, the parameters of an electromagnetic circuit such as

Table 3 Optimal parameters obtained from FEA

Parameters	Flange length (w) (mm)	Fluid flow gap (g) (mm)	Core length (*l*) (mm)	Current magnitude (I) (mA)	Number of turns (N)	Magnetic flux density (B[T])
Candidate A	3.4175	0.6618	19.5488	630.37	758	0.96394
Candidate B	3.5255	0.8728	19.5652	682.21	810	0.92295
Candidate C	3.7955	1.1233	19.3924	811.81	732	0.83979

Table 4 Optimal parameters obtained from GA technique

Number of turns (N)	Current magnitude (I) (A)	Flow gap (g) (mm)	Magnetic flux density (B[T])
838	871.44	0.511	0.89672

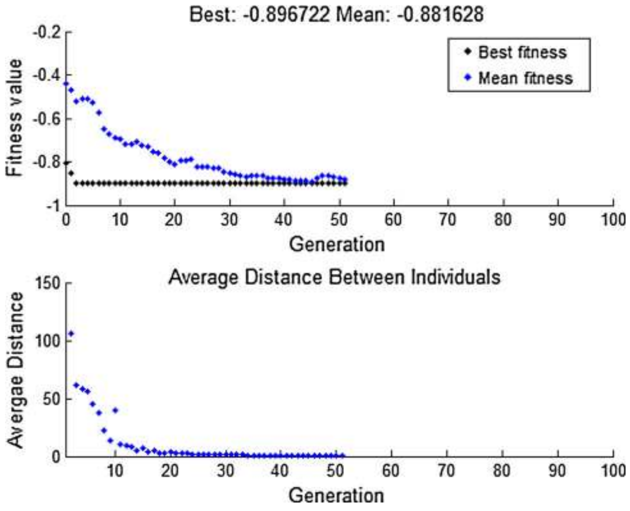


Fig. 12 Fitness value and average distance against generation

number of turn, current magnitude, fluid flow gap, core length and flange length has been optimized to get maximum magnetic flux density. The optimum value of electromagnetic circuit of an MR damper parameters were searched between lower and upper boundaries. The optimum result obtained from the both the methods are well correlated. The result shows that the fluid flow gap size is less than 1.12 mm cause significant increase of magnetic flux density.

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