Design and Fabrication of a Magneto-rheological Fluid Based Torque Sensor for Automotive Application

Muhamad Husaini Abu Bakar and Amirul Qusyaini Alwi

Abstract A magneto-rheological (MR) based torque sensor is a device that transmits the torque by the cutting force of the MR fluid. The magneto-rheological fluids technology has been tested for many industrial applications, such as dampers, actuators, etc. A MR fluid is an intelligent material whose rheological characteristics change rapidly and can be easily controlled in the existence of an applied magnetic field. It presents a viscous coupling controllable by torque, the coupling consists of two types of discs, one is connected to a housing (fixed discs), and the other is connected to an axis (rotating discs). The drive discs and the follower discs are arranged in turn and are interleaved. The MR fluid is filled in the housing. The magnetic fields freeze the fluid so that the shearing torque is generated between the diving discs and the follower discs due to the shears between the slots in the discs below the magnetic fields. The torque is controlled by electromagnets. To have a large pair with small electrical power, the coil turns must be large, so that the response is delayed due to the inductance of the coil. A comparison between the magnetic flux and the intensity of the designs obtained from finite element analysis allow to derive the best design for the prototype in order to proof the concept. The turn of the winding coil and the current as a fixed value is 1500 turn and 1 A current.

Keywords Magneto-rheological (MR) fluid · MR fluid disc brake
Magnetic · Non-magnetic · Finite element

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1 Introduction

Magneto-rheological (MR) fluids are smart and controllable materials, even though at first glance it does not look so impressive. They are a noncolloidal mixture of ferromagnetic particles randomly dispersed in oil or water, plus some surfactants useful to avoid the settling of the suspended particles. The overall aspect is like a greasy quite heavy mud, since the MR fluids density is more than three times the density of water.

The magneto-rheological fluid technology (MRF) is an old "newcomer" that reaches the market at high speed. Several industries, including the automotive industry, are full of possible MRF applications. Magneto-rheological fluid technology has been used successfully in several low and high volume applications. A structure based on MRF could be the next generation in design for products where power density, precision, and dynamic performance are the key features (Fig. 1).

Also, for products in which it is necessary to control the movement of the fluid by varying the viscosity, a structure based on MRF could be an improvement in functionality and costs. Two aspects of this technology, the direct cut mode (used in brakes and clutches) and the valve mode (used in dampers) have been thoroughly studied, and several applications are already present in the market. Excellent features such as fast response, a simple interface between the electrical power input and mechanical output power, and precise control capability make the MRF technology attractive for many applications. The thermal range of working of these materials without decay of their properties are 40–150 °C, depending mostly on carrier properties [1, 2]. The rheological properties of controllable fluids depend on the concentration and density of particles, particle size, shape distribution and properties of the carrier fluid, additional additives, applied field, temperature, and other factors. The interdependency of all these factors is very complicated [3].

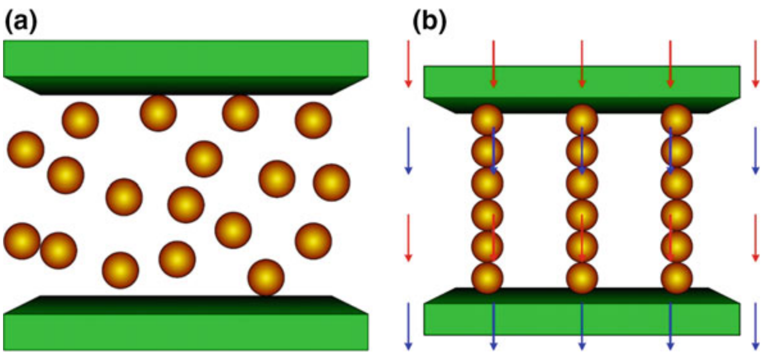

Fig. 1 Working principle of MR Fluid **a** MR fluid with no magnetic field, where particles are randomly dispersed; **b** MR fluid with an applied magnetic field with parallel chains

The magneto-rheological response of fluids is the result of polarization in the particles by applying an external magnetic field. At particle level, a dipole structure is assumed. Depending of an applied magnetic field, the particles are evenly distributed [4]. The fluid has a consistency similar to ordinary mineral oil. Its behavior is similar to a Newtonian fluid, with a linear dependency of the shear stress versus the tangential velocity gradient.

2 Methodology

2.1 Magnetic Proprieties

The magnetic proprieties exhibit approximately linear behavior, as shown in Figs. 2 and 3, where there is a typical induction curve (*B-H* curve) of commercial MR fluids. As can be seen, the MR fluids magnetic properties up to an applied field of about $0.02/\mu_o$ A/m, where μ_o is the permeability in a vacuum. In this region, the differential permeability of the magneto-rheological fluids, that is the slope of B(H), is varying between 5 and 9 times that of a vacuum, can be considered relatively constant. Magnetic saturation can be observed out of the linear regime, which becomes complete for fields of more than 0.4/A/m [5].

2.2 MR Fluid Properties

The magnetic properties of magneto-rheological fluids vary significantly considering the properties of most ferromagnetic materials properties. Ferromagnetic induction can typically be linearized over a much broader range of the applied field,

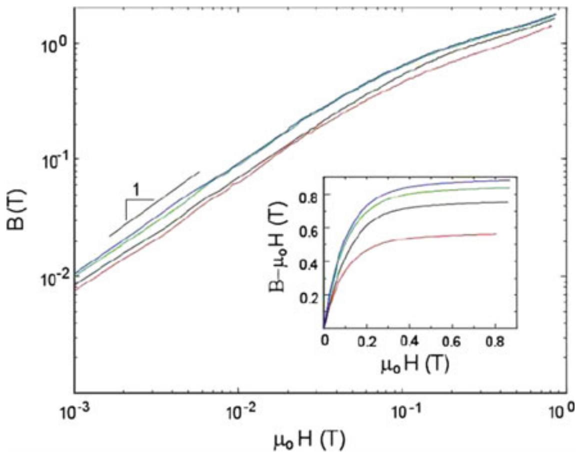

Fig. 2 Magnetic properties of the magnetorheological fluid

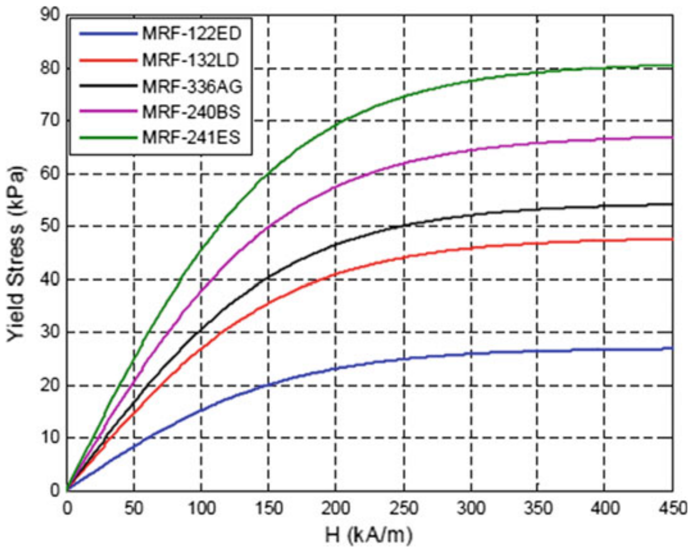

Fig. 3 Predicted yield stress as a function of applied field [6]

and the corresponding permeability is several orders of magnitude greater [7]. Little or no hysteresis can be observed in the induction curves. This super-paramagnetic behavior is a consequence of the magnetically soft properties of the iron used as particulate material in these fluids and the mobility of this particulate phase [8].

The mechanical energy required to yield the formation of MR fluid increases with the increase in magnetic field resulting in the yield shear stress to increase as well. Typical values of the maximum achievable yield strength are given in Table 1. It is observed that MR fluid behaves like Newtonian fluids when there is no magnetic field applied. The MR fluids performances are limited by the magnetic saturation of the particles. Iron particles have the highest magnetic saturation.

A conventional magneto-rheological fluid consists of 20–40 volume percent by volume of relatively pure iron particles, 3–10 μm in diameter, suspended in a carrier liquid such as mineral oil, synthetic oil, water or glycol. Varieties of patented additives, similar to those found in commercial lubricants to discourage gravitational adjustment and promote particle suspension, are commonly added to the magneto-rheological fluid to improve lubricity, modify viscosity and inhibit wear [10].

Table 1 Magnetorheological fluid properties [9]

Property	MR fluid
Yield stress τ	50–100 kPa
Maximum magnetic field	150–250 kA/m
Viscosity η (at 25 °C under no magnetic field)	0.2–0.3 Pa s
Density	3–4 g/cm^3

2.3 Experimental Setup

In order to achieve the aim from this study, there have several stages need to be consider. The stage starts with the analysis of MR fluid in the device. The analysis is conducted by using a commercial software. Several option are possible to select an appropriate software. In general, a magnetic finite element Method solution produce may be broken into the following stages.

2.3.1 MR Fluid Mixing Procedure

The ingredients of 100 ml of two types of magnetorheological fluid are shown in Table 2. Table 2 as weight measures of these ingredients. The table shows that the quantity of iron powder is the same for the two types of magnetorheological fluids, while the difference is only in the weight of the hydrocarbon oil. Thereby, the percentage of the volume is different. The added grease slows the settling and makes it easier to remix. This magneto-rheological fluid recipe results in a fluid having about 20–32% iron by volume. This fluid will have a maximum yield strength and magnetic properties that are somehow similar to the Rheonetic MRF 132-DL magneto-rheological fluid produced commercially by the LORD Corporation (2005). MR 132 was used in this study.

Initially, the appropriate amount of oil, grease and iron powder were measured. Next, the grease was added to the oil and was mixed thoroughly. Mixing is most effectively accomplished with a rotary mixer. The mixture was allowed to sit for a few hours (this allows the grease to dissolve in the oil) and then it was remixed for a few minutes. Finally, the iron powder was added to the oil and grease mixture. It started by adding about half of the iron powder. A stirring stick was used to get the dry iron powder to mix with the liquid. Once the mixture appears to be relatively uniform, and no dry iron powder is visible, the remainder of the iron powder was added and was continued to stir with the stick until the mixture appears without lumps. The final MR fluid was dark gray. The mixture was needed to be remixed or occasionally shaken as the iron particles slowly settle leaving a layer of clear oil on the top.

Table 2 Ingredient of 100 ml of 2 types of magnetorheological fluid [11]

Ingredients	MR 122	MR 132
Iron powder (g)	150	150
Hydrocarbon oil (g)	55	31
White lithium grease (g)	5	5
Percentage volume %	20–22	30–32

2.3.2 Modeling of Yield Shear Stress of MR Fluid

Another important relationship regarding the magneto-rheological fluid behavior is the yield stress as a function of the applied field strength. It is well recognized that the yield stress developed in the fluid increases monotonically with growing magnetic field strength. The yield stress remains to increase until the fluid reaches the magnetic saturation [7] has predicted yield stress as a function of the applied field strength should be predicted based on a theoretical model. The model is general and works for any magneto-rheological fluid. The model relates the yield stress to the magnetic field strength as:

$$\tau_0 = C \cdot 271{,}700 \cdot \Phi^{1.5239} \cdot \tanh(6.33 \cdot H), \quad (1)$$

where Φ is the particle loading and H is the field strength in MA/m. The constant C depends on the carrier fluid and is given in Table 3. Similarly, in this research, the same model has been adopted.

The expression in Eq. (1) accurately represents the yield stress for each of these fluids. The model proposed in this equation is a function of the magnetic field strength and certain fluid properties. However, the model does not account for the condition in which the fluid is being used. This model assumes that the yield stress is developed, regardless of the operating conditions of the fluid. Based on the above discussion the value of the C and Φ was set as 1 and 32% respectively.

2.3.3 The Finite Element Method (FEM) Software

Finite element magnetic method (FEMM) software is capable of reprocessing, post-processing, and monitoring the processing stage of the sewer; yet, the first phase can also be done by other companionable CAD software or even a text editor. The FEMM software package is suitable for the coil design, some turns of the coils wrapping around the core, the electric current values move during the coil, and materials type of each component involved in the device. These parameters were the keys to produce the best value for the magnetic field intensity H, which was associated with the magnetic flux density B the concept mode of squeeze mode, design parameters and conditions were envisaged by FEMM.

Table 3 The constant value for three types of fluid

Constant C	Carrier fluid
0.95	Silicone oil
1	Hydrocarbon oil
1.16	Water

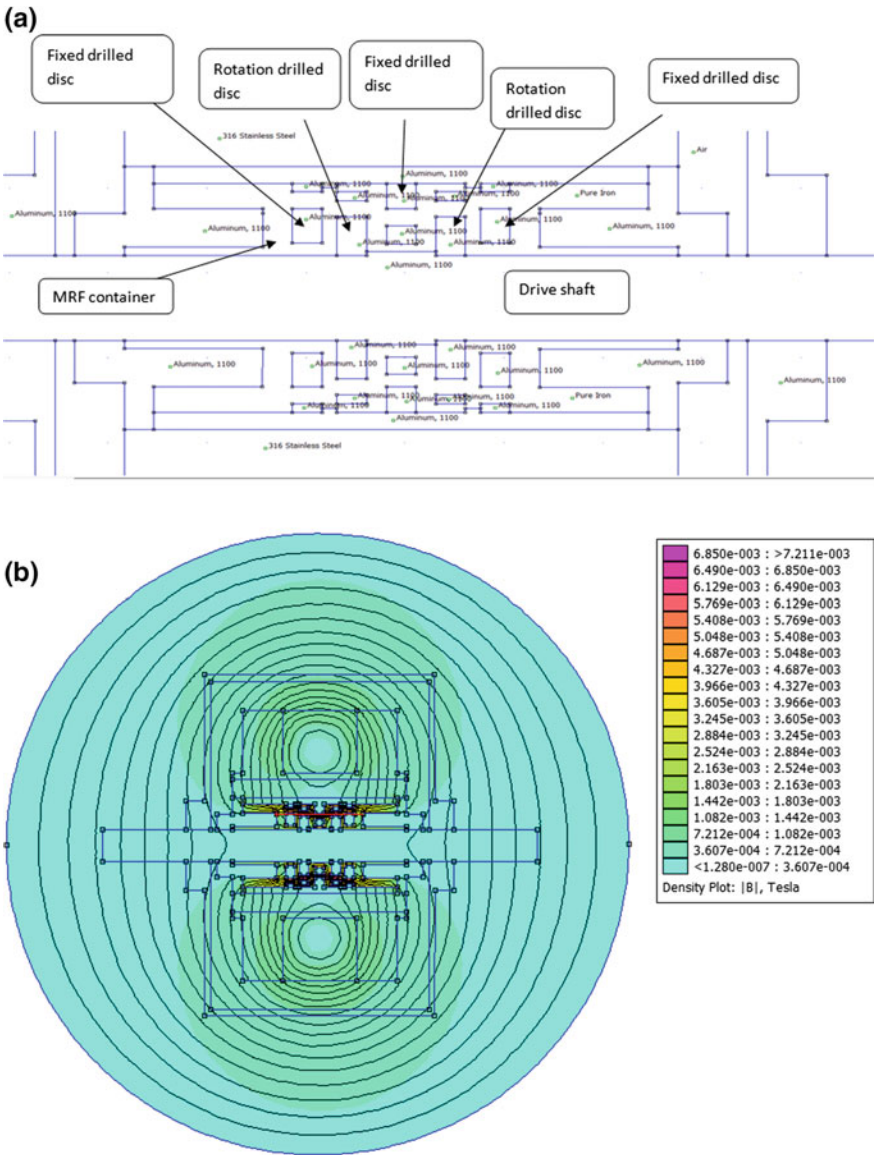

Fig. 4 **a** Finite element model of MRF based torque sensor; **b** magnetic flux density contour of MRF based torque sensor

3 Result and Discussion

In MRF torque sensor, the magnetic field is directly affected by the current. It is essential to study the outcome of current shapes on the magnetic field distribution in MRF based torque sensor to have a maximum magnetic field strength and the behavior of the MR fluid (Fig. 4).

In this research, five different designs have been tested, and five analyzes have been made. For the first analysis, we used a winding coil motor, 2pcs plain disc (1pcs rotation disc and 1pcs fixed disc arranged alternately) and all materials are non-magnetic meterails. For the second analysis, we used a round winding coil, 2pcs plain disc (1pcs rotation disc and 1pcs fixed disc arranged alternately) and all materials are non-magnetic metals. For the third analysis, we used a round winding coil, 2pcs drilled disc (1pcs rotation disc and 1pcs fixed disc arranged alternately), and all materials are non-magnetic metals. On the fourth analysis, we used a round winding coil, 5pcs drilled disc (2pcs rotation disc and 3pcs fixed disc arranged alternately), and all materials are non-magnetic metals. Moreover, the last analysis is fifth analysis; we used round winding coil, 5pcs drilled disc (2pcs rotation disc and 3pcs fixed disc arranged alternately), and all materials are non-magnetic metals, except the drive shaft that only uses pure iron, i.e., magnetic metal (Table 4).

A FEMM software was used to analyze the behavior of the fluid and to characterize the fatigue behavior of the torque sensor structure with the presence of various load amplitudes. In this analysis using FEMM, some settings have been set between them, current is 1 A and turning coil (SWG 30) is 1500 turn.

Based on the magnitude of flux density graph, the maximum point is 7.73357 mT and the value obtained is from the fourth analysis. Moreover, the fourth analysis shows the best performance compared to other analyses (Fig. 5).

Based on the normal flux density graph, the maximum point is 4.17396 mT, and the maximum point for the tangential flux density graph is 7.52218 mT. The value obtained is from the fourth analysis. Moreover, the fourth analysis shows the best performance compared to other analyses (Fig. 6).

Based on the magnitude of field intensity graph, the maximum point is 0.51354 Amp/m, and the maximum point for the normal field intensity graph is

Table 4 Average result for forth analysis

	Fourth analyze
Magnitude field energy (Joules)	1.3964×10^{-6}
Torque (Nm)	7.18467×10^{-2}
Average $B \cdot n^2$ ($tesla^2$)	2.97454×10^{-6}
Average $B \cdot n$ (tesla)	3.68429×10^{-6}
Normal flux density (webers)	6.6557×10^{-8}
Force in x-direction (N)	9.75373×10^{-9}
Force in y-direction (N)	-9.75957×10^{-6}
Average $H \cdot t$ (Amp/m)	0.306232

0.25441 Amp/m. The value obtained is from the fourth analysis. Moreover, the fourth analysis shows the best performance compared to other analyses (Fig. 7).

Based on the tangential field intensity graph, the maximum point is 0.55745 Amp/m and the value obtained is from the fourth analysis. Moreover, the fourth analysis shows the best performance compared to other analyses (Fig. 8).

Several factors affect the magnetic flux density and intensity. Among them is that the number of brake discs loaded into the system will directly affect the entire surface area of the brake disc in the system. Due to the increase in the number of disks, the overall surface area of the brake disc also increases exponentially. At the same time, due to the increase in the number of disks, the fluid will produce a vortex which will produce higher magnetic flux disruptions.

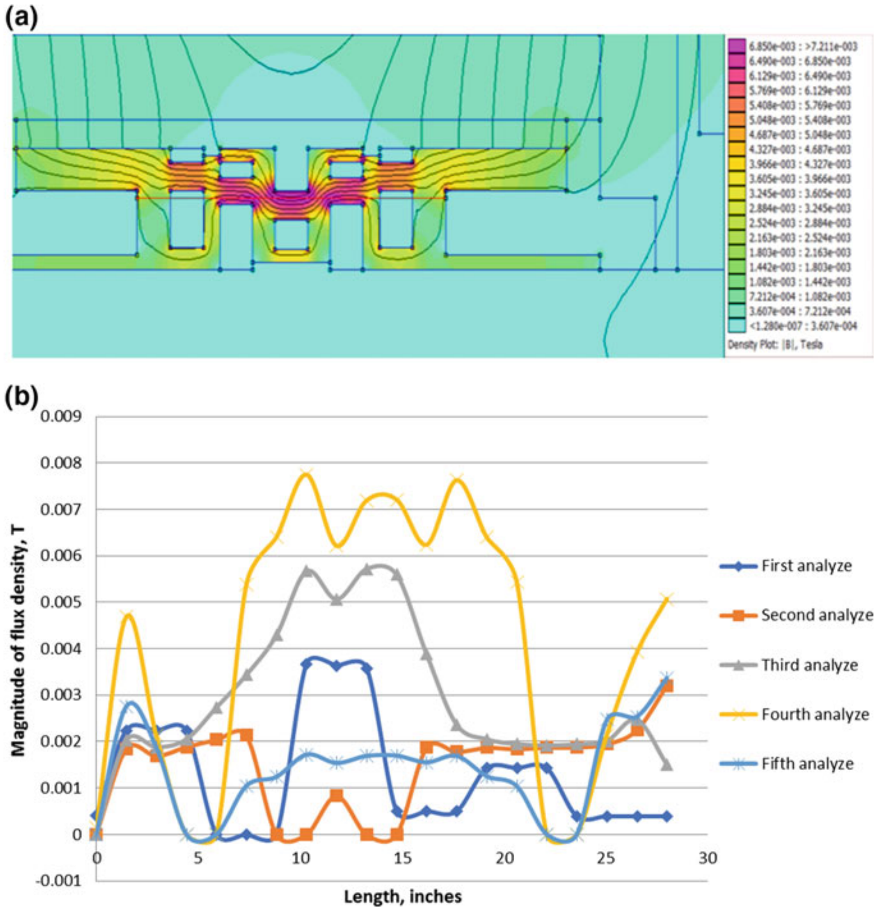

Fig. 5 **a** Magnetic flux density of MRF channel; **b** comparison of magnitude of flux density with various

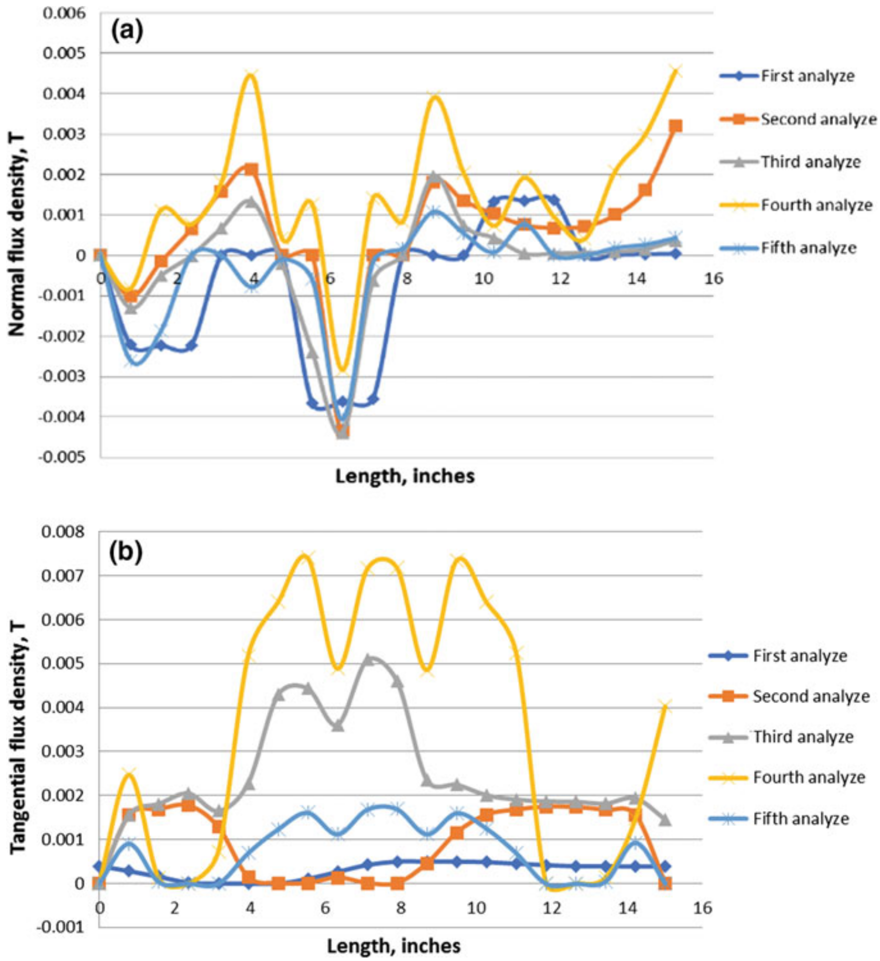

Fig. 6 **a** Analysis result comparison of normal flux density; **b** comparison of tangential flux density

The material selection for the various parts in the disc assembly is crucial, especially regarding the magnetism tendency in it. In the comparison between the usages of magnetic metal to nonmagnetic metal, it is found that the non-magnetic metal is capable of generating better stopping power compared to the magnetic metal. After having a look at the magnetic flux field, the magnetic metal is capable of influencing the magnetic field generated by the electro-magnetivity, resulting in the randomized distribution of magnetic flux and field, where a portion of the magnetivity is guided to the magnetic parts. In the case of non-magnetic metal, the electromagnetism is the focus in the shaft area, resulting in a highest possible density of magnetic flux and field, where the highest stopping power can be achieved when triggered.

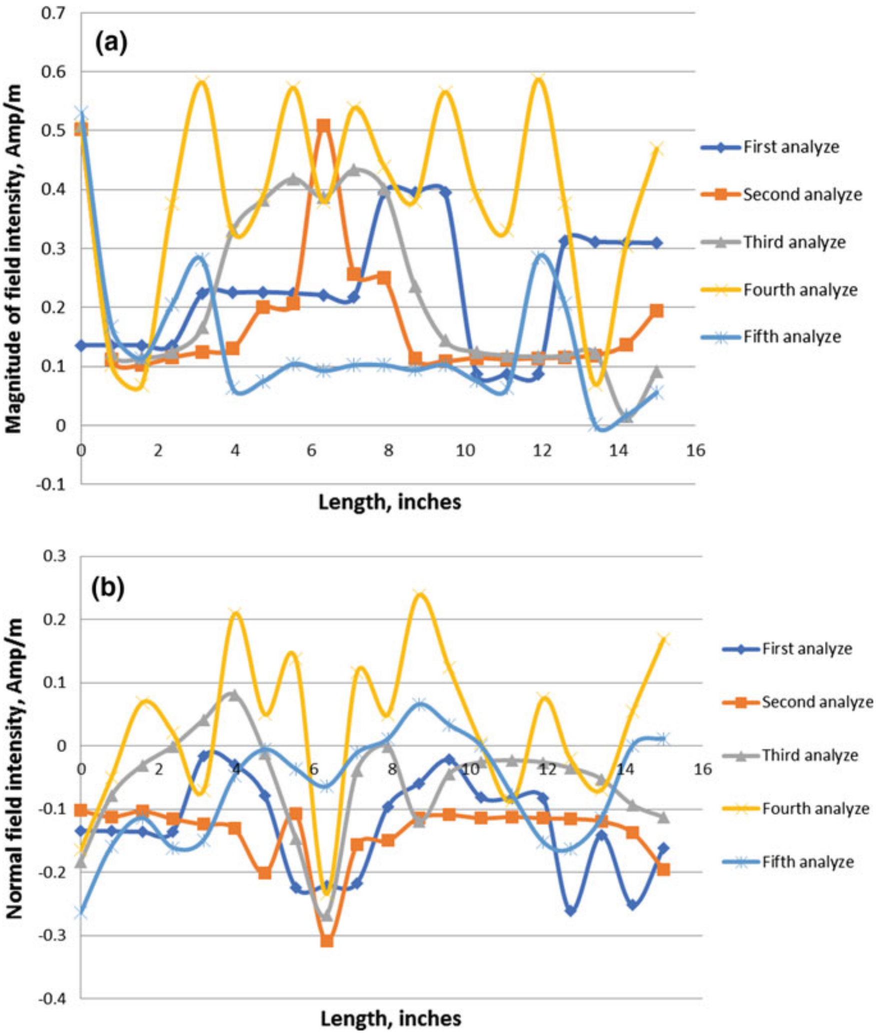

Fig. 7 **a** Analysis result comparison of magnitude of filed intensity; **b** analysis result comparison of normal field intensity

From the comparison of all results, the fourth analysis shows the best results compared to the other. This is evidenced by the value of the flux density and intensity generated from the simulation. The fourth analysis shows the highest value and a stable graph. From the simulation, the best choice of design is the fourth analysis to fabricate the prototype compared with other analyses.

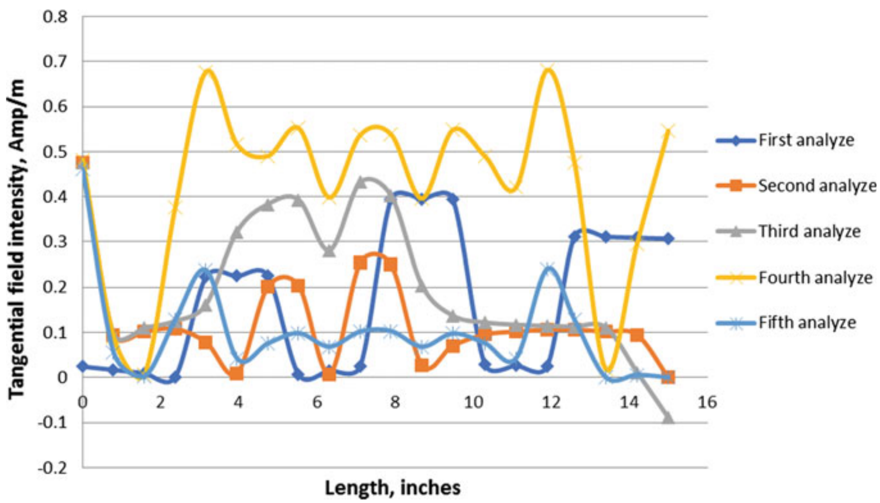

Fig. 8 Analysis result comparison of tangential field intensity

4 Conclusion

A new magneto-rheological fluid in MRF torque sensor simulation has been conducting. The software of magnetic FEMM (Finite Element Method Magnetics) was used to analyze the magnetic distribution in the torque sensor structure and to characterized the fatigue behavior in the torque sensor structure with the presence of various load amplitudes. The software is used because it contains the contour function. The steps of this project has been shown in the methodology. The result of the simulation shows the difference of behavior in the MRF.

From the result, several conclusions can be drawn. The magnetic flow rate increased in the MRF container where several factors influenced the amount of flux density and intensity of magnetic. The magnetic metal is capable of influencing the magnetic field generated by the electro-magnetivity, resulting in the randomized distribution of magnetic flux and field, where a portion of the magnetivity is guided to the magnetic parts.

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