Optimization of MR fluid Yield stress using Taguchi Method and Response Surface Methodology Techniques

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Abstract. Magneto rheological fluids belong to a class of smart materials whose rheological characteristics such as yield stress, viscosity etc. changes in the presence of applied magnetic field. In this paper, optimization of MR fluid constituents is obtained with on-state yield stress as response parameter. For this, 18 samples of MR fluids are prepared using L-18 Orthogonal Array. These samples are experimentally tested on a developed & fabricated electromagnet setup. It has been found that the yield stress of MR fluid mainly depends on the volume fraction of the iron particles and type of carrier fluid used in it. The optimal combination of the input parameters for the fluid are found to be as Mineral oil with a volume percentage of 67%, iron powder of 300 mesh size with a volume percentage of 32%, oleic acid with a volume percentage of 0.5% and tetra-methyl- ammonium-hydroxide with a volume percentage of 0.7%. This optimal combination of input parameters has given the on-state yield stress as 48.197 kPa numerically. An experimental confirmation test on the optimized MR fluid sample has been then carried out and the response parameter thus obtained has found matching quite well (less than 1% error) with the numerically obtained values.

Key words: MR fluid, yield stress, optimization, Taguchi method, RSM methodology

1. Introduction

Smart materials have the ability to change their rheological characteristics under the influence of some external field. A magneto rheological (MR) fluid belongs to this category of the materials and is generally known as smart fluids. These fluids have capability of altering their yield strength with a change in magnetic field. A typical MR fluid consists of micron sized iron particles suspended in a non-magnetic carrier fluid with some additives. Under the application of high magnetic field, these iron particles align themselves along the lines of magnetic flux. This leads to the formation of strong chains comprising of the iron particles [1] and in turn it generates high yield stress \( \tau_y \) [2]. The yield stress is defined as the stress required in rupturing the chain like arrangement of the particles [3] which in turn indicate the maximum achievable variable damping (force) from a MR based damper devices. For the synthesis of the MR fluids, various researchers have used iron powder of 300-500 mesh size in a carrier fluid mainly consisting of oils, e.g. silicon oil, hydrocarbon oil and mineral oil. The silicon oil has been proved to exhibit a good temperature stability and better heat transfer characteristics [4].
while the mineral oil have shown high flash point and low vapor pressure. These carrier fluids must be ideally non-magnetic in nature and should not react with particles being used in the preparation of the fluid. Being chemically inert, these carrier fluids can be used as an effective dispersion medium for the iron particles. Overall the silicon oil has been proved better carrier fluid in comparison to mineral oil in MR fluid synthesis. Besides the above two constituents of the MR fluid, presence of small amount of additives e.g. tetra-methyl-ammonium-hydroxide and oleic acid helps greatly in maintaining better stability of the fluids by preventing and/or minimizing the settling down characteristics of the iron particles in the carrier liquid. The tendency of settling down of the particles has found reducing with the increase in the percentage of additives in the fluid [5]. Synthesis and rheological characterization of MR fluids has been done by various researchers. Mangal and Kataria [6] prepared four different MR fluid samples using different weight percentage of the iron particles, silicon oil and lithium grease as its constituents. These samples were analyzed and tested for stability characteristics under an off-state condition. It was proved in the research that an increase in the percentage of additives (lithium grease) has provided better stability of the synthesized fluid. Mangal and Kumar [7] studied the rheological characteristics of MR fluids and concluded that the apparent yield strength of these fluids can be changed significantly on the application of an external magnetic field. Further the yield strength of MR fluids is controllable with the change in the applied magnetic field magnitude. Kumbar et al. [8] synthesized MR fluids by mixing the iron particles with grease, oleic acid and gaur gum powder and were able to generate yield strength of 32 kPa in the fluid at a magnetic field of 0.80 Tesla. Zhao et al. [9] have prepared MR fluids using the guar gum coated carbonyl iron particles. It was observed that guar gum coating not only improves the sedimentation stability but also helps in increasing the yield strength of MR fluids. Dang et al. [10] measured the yield stress of MR fluids using a pressure driven apparatus. The MR fluids were found to have the yield stress of 1.9 kPa at a magnetic field of 0.22 Tesla.

The MR fluid has found very wide applications in the industrial environment where variable damping is an utmost requirement. The applications of the fluid may be seen in automotive sector, landing gears of the aircrafts, seismic control devices etc. The objective of the present research is to develop a MR fluid capable of high yield stress i.e. more than 40 kPa. After a literature review, various parameters that are affecting the yield strength of a MR fluid were identified which are namely type of iron particle, iron volume percentage, type of carrier fluid, volume percentage of additives like oleic acid and tetra methyl ammonium hydroxide. Taguchi L-18 orthogonal array is utilized to synthesize 18 different MR fluids samples with the above as input parameters while the yield stress is considered as a response parameter. To determine the yield stress of MR fluids, an experimental set up has been designed and developed which is capable of generating a magnetic field of 1.50 Tesla. The experimental data has been analyzed by combination of statistical software of Design expert 9.0 and Minitab 17.1. From the experimental studies on MR fluid, it is concluded that yield stress of MR fluids mainly depends on volume percentage of the iron particles and type of carrier fluid. An optimal combination of input parameters based on ANOVA techniques and Response Surface Methodology has been determined which has given a yield stress of 48.197 kPa for the synthesized MR fluid. The high yield stress of the fluid thus synthesized will increase the applicability of MR fluid based damping devices requiring large variation in the damping force like seismic control devices, landing gears of the aircraft etc.

2. Design and Development of the electromagnet

2.1. Design of Electromagnet

Ampere law is used to design the electromagnet which is a relationship between the current passing through a conductor and the resulting magnetic field \( (H) \, [A/m] \) induced. The law states that the line integral of the tangential component of the magnetic field strength around a closed path is equal to the total current enclosed by the path (Figure1). Furthermore, it is important to note that magnetic field
\( (H) \) is independent of the properties of the medium (e.g. air, steel, MR-fluid). For a single conductor, line integral of \( H \) gives:
\[
\oint H \, dl = I
\]
(1)
where, \( I \) represent the current passing through the conductor. While for \( N \) conductors, line integral of \( H \) gives:
\[
\oint H \, dl = NI
\]
(2)
where, \( NI \) is called the magneto motive force and can be represented by \( F \). It is expressed in ampere-turns.

\[
\text{Figure.1 Magnetic field generated by (a) a single conductor and (b) } N \text{ conductors}
\]

In order to design an electromagnet, the Eq. (2) can be written as:
\[
NI = \oint H \, I = H_g L_g + H_s L_s
\]
(3)
where, \( N \) represents the number of turns, \( I \) denote the magnitude of current passing through coils, \( H_g \) represents the magnetic field intensity of the air gap (between the poles of the electromagnet) and \( L_g \) represents the length of the air gap, \( H_s \) denote the magnetic field intensity of the steel and \( L_s \) denotes the length of the steel path. Further the relationship between the magnetic field density \( B \) and magnetic field intensity \( (H) \) in a medium (e.g. air) can be given as:
\[
B = \mu_o \mu_r H
\]
(4)
where, \( \mu_r \) represents the relative permeability of the air gap and is equal to one, \( \mu_o \) represents the permeability of the vacuum and is equal to \( 4\pi \times 10^{-7} \text{ H/m} \). Using Eq. (4) in the Eq. (3) gives:
\[
NI = \frac{B_g L_g}{\mu_o \mu_r} + \frac{B_s L_s}{\mu_o \mu_s}
\]
(5)
where, \( B_g \) and \( B_s \) denote the magnetic field density of the air and steel respectively, \( \mu_r \) and \( \mu_s \) represents the relative permeability of air and steel respectively. Further, the permeability of the mild steel is 1000 times that of air i.e. \( \mu_s = 1000 \mu_r \).

Assuming length of steel \( (L_s) \) and air gap \( (L_g) \) are of the same order, the first term of Eq. (5) becomes prominent in comparison to second one. Therefore, Eq. (5) reduces to:
\[
NI = \frac{B_g L_g}{\mu_o \mu_r}
\]
(6)
As the value of the relative permeability of air \( (\mu_r) \) is equals to one. The above reduces to:
\[
NI = \frac{B_g L_g}{\mu_o}
\]
(7)
The electromagnet can be designed based on the above equation. In order to achieve maximum magnetic field of the order of 1.5 Tesla at maximum input current of 6.0 A to the coils by the electromagnet, designed parameters as tabulated in Table 1 are selected for the fabrication of the electromagnet.
Table 1 Input parameters and their desired values for the Electromagnet

| Input Parameters for developed electromagnet | Desired value |
|---------------------------------------------|---------------|
| Maximum current supplied to the coil (I)    | 6.0 Amp       |
| $L_g$ (Length of the air gap)               | 18 mm         |
| $\mu_0$ (Permeability of the vacuum)        | $4\pi \times 10^{-7}$ H/m |
| Number of turns                             | 3600          |

2.2. Development of the Experimental Set up

The experimental set-up is designed and fabricated in-house which is based on the principle as discussed in section 2.1. The setup mainly consists of five parts:

- Electromagnets
- DC regulated power supply
- Perspex tube
- Gauss meter
- Servo motor

As per our objective, the electromagnet is fabricated to produce a magnetic flux density ($B$) up of the order of 1.5 Tesla for an intended air gap of 18 mm (between the poles of the electromagnet). In order to generate such a high value of magnetic field density, two multilayered copper coils each with 3600 turns of copper wire of 18 SWG are used which are connected in series. These two coils can carry current up to 6.0 A safely. This current is supplied to electromagnet through a DC regulated power supply. The Perspex tube with external diameter of 18 mm is filled with the MR fluid and constricted vertically between the poles of the electromagnet (air gap). The servo motor is employed to rotate a shaft inside the (on-state) activated fluid. The Gauss meter is used to measure the developed magnetic flux density during the experimentation. The final test setup thus designed, developed and fabricated to determine the yield stress of the MR fluid samples is shown in Figure 2.

Figure 2 Experimental test setup (a) Schematic Diagram and (b) Actual
2.3. Determination of Yield Stress Experimentally

A cylindrical tube of 18 mm external diameter is placed vertically and constricted between the poles of the electromagnet to measure the on state yield stress of MR fluids experimentally. The tube is filled with the prepared MR fluid samples up to 70 mm length. The fluid is rotated by a of 13 mm diameter shaft under off state condition. The shaft is attached to servo motor which rotates at a very low speed of 10 rpm initially so that particles get mixed properly and sedimentation is halted/ minimized. Now, the D.C. current is supplied to electromagnet ranging from 0.2 to 6.0 Amp using DC regulated power supply. This current induces a magnetic field between the poles of electromagnet and activates the MR fluid in the tube. This on-state activated MR fluid exerts a resisting torque on the shaft. This resisting torque (T) is measured by torque sensor fitted on the servo motor. Theoretically, the resisting torque on the shaft of the servo motor by MR fluid is given as:

\[ T = \int_0^{2\pi} \int_0^L \tau_y r \, L \, dr \, \theta = 2\pi \, \tau_y \, R^2 \, L \]  

(8)

where, \( \tau_y \) represents the yield stress of the MR fluid, \( R \) is the radius of shaft (= 6.5 mm), \( L \) is the length up to which the MR fluid is filled in cylindrical tube (= 70 mm). The Eq. (8) can be rewritten as:

\[ \tau_y = \frac{T}{2\pi R^2 L} \]  

(9)

From Eq. (9), one can calculate yield stress of the MR fluid in the on-state condition from the measured value of torque.

3. Synthesis and Analysis of MR fluid

After a literature review on the formulation of MR fluids, five parameters which affect the yield stress significantly were selected and are type of carrier fluid, size of iron particles, iron particle (vol %), oleic acid (vol %) and tetra-methyl-ammonium-hydroxide (vol %). Synthesis and on-state rheological characterization for the yield stress of in-house developed MR fluids is carried out with the five critical constituents. The density of these five constituents is shown in Table 2.

| Table 2 Components used for preparation of MRF samples |
|---------------------------------|-----------------|
| Material                       | Density (g/cm³) |
| Iron powder varying mesh size from 300 to 500 mesh | 7.86 |
| Silicon oil / mineral oil       | 0.967/0.970     |
| Oleic acid                     | 0.890           |
| Tetra methyl ammonium hydroxide| 0.866           |

Table 3 shows the values of various levels of the five parameters selected for MR fluid samples preparation which is based on the literature survey. In this research, MR fluids were prepared by mechanical mixing of silicon/mineral oil, iron powder (22 -32% by volume), oleic acid (0.5-0.7 % by volume) and Tetra-methyl-ammonium-hydroxide (0.6-0.8 % by volume). These chemicals were procured from Moly-Chem industries, Mumbai. The MR fluids samples were prepared in-house using the following procedure:

- Firstly, the iron particles were mixed with the oleic acid using a stirrer running at 400 rpm for 30 minutes.
- The tetra-methyl-ammonium-hydroxide was poured next and mixed for next 30 minutes at 400 rpm.
• Finally the carrier liquid i.e. silicon/mineral oil was poured gradually in the above mixture and stirred for another 1 hour at 400 rpm.

In the present work; experiments were conducted on the in-house developed MR fluid samples on the developed experimental setup to determine its yield stress as discussed in sections 2.0 and 3.0.

### Table 3 Input parameter and their levels

| Parameter | Parameter Name                  | Levels       |
|-----------|---------------------------------|--------------|
| A         | Type of carrier fluid           | Mineral oil  |
|           |                                 | Silicon oil  |
| B         | Size of Iron Particles          | Fe500 mesh   |
|           |                                 | Fe400 mesh   |
|           |                                 | Fe300 mesh   |
| C         | Iron Particle (vol %)           | 22           |
|           |                                 | 27           |
|           |                                 | 32           |
| D         | Oleic acid (vol %)              | 0.5          |
|           |                                 | 0.6          |
|           |                                 | 0.7          |
| E         | Tetra Methyl ammonium hydroxide (vol %) | 0.6 |
|           |                                 | 0.7          |
|           |                                 | 0.8          |

In Taguchi experimental design [11], orthogonal L-18 array is found to be most suitable for parameters with two or three levels. For this, a mixed level of Taguchi design is selected with Parameter (A) i.e. type of carrier fluid having two levels while other input parameters have three levels. The main aim of the present work is to find an optimal combination of input parameters to have maximum value of its yield stress. The above five parameters are assigned under various columns in an L-18 Orthogonal Array (OA) design and are shown in Table 4. The yield stress of the on-state activated MR fluids is taken as response parameter for the OA design.

### Table 4 Response parameter for experimental L-18 Orthogonal Array

| Expt. | Parameter 1 | Parameter 2 | Parameter 3 | Parameter 4 | Parameter 5 | Response (kPa) | S/N ratio |
|--------|-------------|-------------|-------------|-------------|-------------|----------------|-----------|
| 1      | Mineral oil | Fe 500 mesh | 22          | 0.5         | 0.6         | 27.0388        | 28.6398   |
| 2      | Mineral oil | Fe 500 mesh | 27          | 0.6         | 0.7         | 36.9007        | 31.3407   |
| 3      | Mineral oil | Fe 500 mesh | 32          | 0.7         | 0.8         | 47.7683        | 33.5828   |
| 4      | Mineral oil | Fe 400 mesh | 22          | 0.6         | 0.7         | 27.0201        | 28.6337   |
| 5      | Mineral oil | Fe 400 mesh | 27          | 0.7         | 0.8         | 36.5053        | 31.2471   |
| 6      | Mineral oil | Fe 400 mesh | 32          | 0.5         | 0.6         | 47.6090        | 33.5865   |
| 7      | Mineral oil | Fe 300 mesh | 27          | 0.5         | 0.8         | 46.9424        | 31.3505   |
| 8      | Mineral oil | Fe 300 mesh | 32          | 0.6         | 0.8         | 47.7888        | 33.5865   |
| 9      | Mineral oil | Fe 300 mesh | 22          | 0.7         | 0.7         | 27.2827        | 28.7177   |
| 10     | Silicon oil | Fe 500 mesh | 32          | 0.7         | 0.7         | 45.4665        | 33.1538   |
| 11     | Silicon oil | Fe 500 mesh | 22          | 0.5         | 0.7         | 25.6620        | 28.1858   |
| 12     | Silicon oil | Fe 500 mesh | 27          | 0.6         | 0.6         | 35.0953        | 30.9050   |
| 13     | Silicon oil | Fe 500 mesh | 27          | 0.7         | 0.6         | 33.5230        | 30.5069   |
| 14     | Silicon oil | Fe 400 mesh | 32          | 0.5         | 0.7         | 45.1974        | 33.1023   |
| 15     | Silicon oil | Fe 400 mesh | 22          | 0.6         | 0.8         | 25.8472        | 28.2483   |
| 16     | Silicon oil | Fe 300 mesh | 32          | 0.6         | 0.8         | 44.1523        | 32.8991   |
| 17     | Silicon oil | Fe 300 mesh | 27          | 0.7         | 0.6         | 25.4781        | 28.1234   |
| 18     | Silicon oil | Fe 300 mesh | 27          | 0.5         | 0.7         | 37.4230        | 31.4628   |
4. Calculation of Signal to Noise ratio (S/N)

The design expert 9.0.6 from Stat Ease and Minitab 16.0 software are used for analyzing the response characteristic and to procure vital information of the designed model. The Taguchi suggests the concept of S/N ratio for measuring the deviation of quality characteristic from its desired value. The yield stress of the MR fluids should be high enough for its effective and wider application in MR fluid based dampers, brakes and other devices. The S/N ratio for yield stress is calculated using Larger is better criteria using the following equation:

\[
S/N = -10 \log \left( \frac{1}{n} \sum_{i=1}^{n} \frac{1}{y_i^2} \right)
\]  

[10]

where \( n \) refers to number of experiments, \( y_i \) is the observed value of yield stress for \( i^{th} \) experiment. The response table for S/N ratio is given in Table 5 and is also shown in Figure 3. These data show the maximum difference in the response parameter by a given input parameter. The optimal combination of parameters is then selected using the response table for S/N ratios. The combinations of input parameters for the optimal value of on-state yield stress are found by locating the highest value of that parameter among its level. The optimal combination of input parameters come out as A1B3C3D1E2 and is shown in Table 6.

**Table 5** Response Table for S/N Ratios

| Level | Parameters | A   | B   | C   | D   | E   |
|-------|------------|-----|-----|-----|-----|-----|
| 1     |            | 31.18* | 30.97 | 28.42 | 31.05* | 30.89 |
| 2     |            | 30.73 | 30.88 | 31.14 | 30.94 | 31.07* |
| 3     |            | 31.02* | 33.31* | 30.89 | 30.92 |

* Optimized values

**Figure 3** Main Effects plot for signal to noise ratio for on-state yield shear stress of MR fluid

**Table 6** Input Parameters levels for prediction of optimal response from S/N ratio and mean

| Parameter Name | A   | B   | C   | D   | E   |
|----------------|-----|-----|-----|-----|-----|
| Level Code     | 1   | 3   | 3   | 1   | 2   |
| Parameter Value| Mineral oil | Fe300 mesh | 32% | 0.5 | 0.7 |
As the above optimum combination of input parameters predicted by the S/N ratio is not found in OA table (design) of L-18 (shown in Table 4), therefore a confirmation test is required to validate the results.

5. ANOVA Results
The ANOVA is a statistical tool used to determine the significance of various input parameters along with their contribution towards the chosen response characteristic i.e. on-state yield stress of the MR fluid. The ANOVA results for yield stress are shown in Table 7. These results are developed for 95% level of confidence. In this work, f test is applied to analyze the data for its significance. The Model F-value obtained for this model come out to be 89.73 which implies that the model is significant. The most important statistic in the ANOVA (analysis of variance) table is the p-value. There is a p-value for each term of the model. The p-value for a term also determines whether the effect for that term is significant or not. The F values corresponding to p values less than 0.05000 are used to determine the significance of each process parameter towards output response. If p is less than or equal to 0.05 then the effect for the term on the response parameter i.e. (yield stress) is significant one. The ANOVA table with on-state yield stress of MR fluid as response parameter shows that the parameter C (Iron Particle (vol. %)) is the most significant factor having 485.59 as F-value. The other significant factor came out as parameter A (type of carrier fluid) having 13.08 as F-value. The same results are also obtained on the basis of S/N ratio plots. The "Pred R-Squared" of 0.9456 is in reasonable agreement with the "Adj R-Squared" of 0.9829; i.e. the difference is less than 0.2. The p-value (0.9142) for the interaction term A (Type of oil) and B (Type of iron) is greater than 0.05. Thus, the interaction between these parameters is not significant. It can be seen that the values are matching quite well within a error of less than 3%.

Table 7 Analysis of Variance (ANOVA) for response parameter (on-state yield stress)

| Source               | Sum of Squares | Degree of freedom | Mean Square | Contribution | F Value | p-value | Prob> F | Remark          |
|----------------------|----------------|-------------------|-------------|--------------|---------|---------|---------|-----------------|
| Model                | 1212.83        | 11                | 110.26      |              | 89.73   | < 0.0001| Significant|
| A-Type of oil        | 16.08          | 1                 | 16.08       | 1.32%        | 13.08   | 0.0111  |         |                 |
| B-Iron Type          | 0.98           | 2                 | 0.49        | 0.08%        | 0.40    | 0.6884  |         |                 |
| C-Iron Vol %         | 1193.42        | 2                 | 596.71      | 97.81%       | 485.59  | < 0.0001| Significant|
| D-Oleic Vol %        | 1.38           | 2                 | 0.69        | 0.11%        | 0.56    | 0.5977  |         |                 |
| E-Tetra Vol %        | 0.75           | 2                 | 0.38        | 0.06%        | 0.31    | 0.7471  |         |                 |
| A*B (Type of oil *iron type) | 0.22      | 2                 | 0.11        | 0.02%        | 0.091   | 0.9142  |         |                 |
| Residual             | 7.37           | 6                 | 1.23        | 0.60%        | 89.73   | < 0.0001|         |                 |
| Cor Total            | 1220.21        | 17                | 100%        |              |         |         |         |                 |

Std. Dev. = 1.11; Pred R-Squared = 0.9456; Adj R-Squared = 0.9829

6. Optimization of Yield Stress
The objective of the present work is to develop a MR fluid having sufficiently high yield strength. The concept of numerical optimization using response surface methodology is employed to obtain the optimal combination of input parameters that can provide us higher yield stress for the MR fluid. For this, the numerical optimization module of design expert software is used. Initially, a goal setting for every input parameter was done in design expert software (as shown in Table 8). After assigning different goals to the various input parameters, the optimal combination of these parameters which provide a high value of on-state yield stress (for MR fluid) is determined. The various solutions showing different combinations of input parameters with their yield stress value can be seen in Table...
9. The desirability value for each solution was taken close to one in order to obtain the significant results. From the numerical optimization technique, an optimal combination of input parameters with Fe 300 mesh (32 % by volume) as an iron particle, Oleic acid (0.5% by volume) and Tetra methyl ammonium hydroxide (0.7% by volume) was selected. This combination of input parameters gave the maximum value of yield stress as 48.197 kPa as shown in Table 10.

Table 8 Goals settings for various input parameters

| Name                | Goal             | Lower Limit | Upper Limit | Lower Weight | Upper Weight |
|---------------------|------------------|-------------|-------------|--------------|--------------|
| A: Type of oil      | is in range      | Mineral Oil | Silicon Oil | 1            | 1            |
| B: Iron Type        | is in range      | Fe 500 Mesh | Fe 300 Mesh | 1            | 1            |
| C: Iron Volume%     | is in range      | 22          | 32          | 1            | 1            |
| D: Oleic Volume %   | is in range      | 0.5         | 0.7         | 1            | 1            |
| E: Tetra Volume %   | is in range      | 0.6         | 0.8         | 1            | 1            |
| Yield Stress        | Maximize         | 25.478      | 47.789      | 1            | 1            |

Table 9 Predictions for maximizing the on-state yield stress of MR fluid

| A          | B            | C  | D  | E            | Yield stress | Desirability |
|------------|--------------|----|----|--------------|--------------|--------------|
| Mineral oil| Fe 300 mesh  | 32 | 0.5| 0.7          | 48.197       | 1            |
| Mineral oil| Fe 300 mesh  | 32 | 0.5| 0.8          | 47.7949      | 1            |
| Mineral oil| Fe 300 mesh  | 32 | 0.5| 0.6          | 47.7375      | 0.9977       |
| Mineral oil| Fe 300 mesh  | 32 | 0.6| 0.7          | 47.6857      | 0.99538      |

Table 10 Optimal combination of input parameters for maximizing the response parameter (on-state yield stress) of MR fluid

| Input/response parameter code and name | Optimal parameter setting |
|---------------------------------------|---------------------------|
| A (Type of carrier fluid)             | Mineral                   |
| B (Size of Iron Particles)            | Fe 300 mesh               |
| C (Iron Particle (vol %))             | 32%                       |
| D (Oleic acid (vol %))                | 0.5%                      |
| E (Tetra methyl ammonium hydroxide (vol %)) | 0.7%                   |
| \( \tau_y \) (Yield stress of the MR fluid) | 48.197 kPa               |

7. Experimental confirmation of results on optimized MR fluid sample
In order to determine the value of yield stress using optimal combination of input parameters as outlined above, a sample MR fluid is prepared and experimentally tested to determine for its on-state yield stress on the experimental set up. The yield stress for the MR fluid sample came out as 47.853 kPa at a magnetic field of 1.45 Tesla. The experimental value of yield stress (47.853 kPa) for optimized MR fluid sample is matching quite well with the calculated value as (48.197 kPa) with a percentage error of less than 1.0%. It, thus, has validated the experimental methodology adopted in this research and also the results obtained for on-state yield stress as a response parameter for a given MR fluid.

8. Conclusions
Magneto Rheological (MR) fluid is one of the smart materials which have the ability to change their rheological characteristics under the influence of external magnetic field. These fluids have the capability of altering their yield strength with a change in the applied magnetic field. Various input
parameters that affect the yield strength of a MR fluid are identified in this paper and are type of iron particle, iron volume percentage, type of carrier fluid, volume percentage of additives like oleic acid and tetra methyl ammonium hydroxide. From the present work, it can be concluded that the yield stress of MR fluids mainly depends on the volume percentage of iron particles and type of carrier fluid used in the MR fluid. In the present work, an optimal combination of input parameters for maximizing the on-state yield stress of MR fluids is also carried out using Taguchi and RSM technique. For this, a Taguchi L-18 orthogonal array is utilized to develop 18 different MR fluids formulations with on-state yield stress as response parameter. An optimal combination of these input parameters with mineral oil as a carrier fluid, Fe 300 mesh (32 % by volume) as an iron particle, oleic acid (0.5% by volume) and tetra- methyl-ammonium-hydroxide (0.7% by volume) has given the maximum on-state yield stress of the synthesized MR fluid sample as 48.197 kPa. This high value of the yield stress can be used more effectively in the formulation and designing of MR devices which can be used on those places requiring large variation in the damping force like seismic control devices, landing gears of the aircraft etc. This research work will further help the design engineer in preparation of MR fluid for a designated on-state yield stress values.

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