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On-state Torque Optimization for Synthesized MR Fluid

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ABSTRACT
Magneto-Rheological (MR) fluids are the suspension of magnetizable particles in a carrier fluids and their rheological properties viscosity etc. can be changed by varying the magnetic field applied to it. Due to such variable characteristics, these MR fluids find wide application in various automotive industries devices e.g. MR brakes and MR clutches etc. In MR brakes, the MR fluids generate a resisting torque (between housing and rotor) within milliseconds on the application of magnetic field. In the present work, the optimal values of MR fluid constituents is obtain which give the high values of on-state torque. For this, 18 samples of MR fluids are prepared and their compositions are selected using L-18 orthogonal array. Further, an experimental approach is used to determine and validate the torque generated by the MR fluid samples. For this purpose, experimental setup is designed and fabricated in-house. ANOVA is used to statistically analyze the significant factors which affect the on-state torque which in-turn gives the optimal composition of MR fluid. For this optimal composition, on-state torque of the MR fluid sample came out to be 0.887587 N-m.

***Keywords* -** ANOVA technique, High on-state torque, Magneto-Rheological, Orthogonal Array,

I. INTRODUCTION

Materials which are having the ability to bring the change in their shape, size and physical characteristics under the influence of particular condition are usually referred as smart materials. Magneto–rheological fluid belongs to this class of smart materials. Rheological properties *e.g.* viscosity etc. can be easily varied by applying magnetic field for these fluids. These MR fluids mainly consists of three components *i.e.* micron size magnetizable particles, non-magnetic carrier liquid and some additives. The MR particles are typically in the range of 0.1 to 10μm [1 & 2]. The carrier liquid serves as dispersed medium and magnetizable particles are suspended in it. The carrier liquid may be oil, water and some synthetic liquid depending upon the particular requirement [3]. When no magnetic field is applied, the rheological behavior of these MR fluids is almost similar to low viscosity Newtonian fluids. But under the application of magnetic field, suspended magnetizable particles acquire dipole-dipole interaction and starts attracting towards each other to form chain like structure. This chain of magnetizable particles formed in a direction parallel to the direction of applied magnetic field and restricts the flow of the fluid. This leads to an increase in the viscosity and the yield strength of MR fluids which in-turn increases the resisting torque. The increase of these parameters depend on the magnitude of magnetic field applied [4]. Mangal and Kataria [5] prepared four different MR fluid samples using different weight percentage of iron particles, silicon oil and lithium grease. These samples were analyzed and tested for rheological characteristics under off-state condition. It was found that the viscosity of the MR fluid varied between 0.244-0.42 Pa-s for all the fluid samples prepared. It has been observed that the MR fluid consisting of larger particle size gives better yield strength as compared to the smaller particles size [6].

MR fluids with excellent rheological properties can be applied in various fields of civil engineering, safety engineering, automotive industry *etc*. Due to their variable viscosity characteristic, the MR fluid finds wide and diverge application in different magnetically controlled devices *e.g.* MR brakes, MR clutches etc. The MR brakes operate in direct shear mode in which MR fluid is filled between the two surfaces *i.e.* housing and rotor moving with respect to each other. On an application of magnetic field, MRF changes its state from liquid to semi-solid and develops the resisting torque. Torque generated by the MR fluid depends on the change in its apparent viscosity with the change in applied magnetic field. MR fluids generate this torque within milliseconds [7] and regain its original structure immediately after the removal of magnetic field. Sarkar and Hirani [8] investigates that resisting torque decreases with an increase in film thickness of MR fluid between the two surfaces. Jae-Hoon Lee *et al*. [9] have calculated the resisting torque of Lord MRF-140CG fluid by rotating the fluid inside a rotational damper and reported a maximum torque of 475 Nm at a rotating speed of 10 rpm. Sukhwani and Hirani [10] experimentally evaluated MRB performance parameters at high speed braking application and advocated a MR gap of 1 mm. Sarkar and Hirani [11] have prepared MR fluid samples using carbonyl iron powder (80% by weight), silicon oil (19.5% by weight), oleic acid and tetra-methyl-ammonium-hydroxide as additives and found that this MR fluid develops better resisting toque as compared to commercial available MRF 241ES and it also gives better particle stability.

Sedimentation of MR particles makes the MR fluid unstable [7]. Sedimentation phenomenon reduces the MR effect where the particles in the MRF are settled down and form a hard *cake* [6]. Variety of additives (*i.e.* surfactants, stabilizers and coated particles) are mixed in the composition of MR fluids to prevent the settling down of these suspended particles and to increase the stability of the composition. Fang [12] introduced the single walled carbon nano-tube in the carbonyl iron based MR fluids to reduce the sedimentation of particles. Zhao *et al.* [13] prepared MR fluids using the guar gum coated carbonyl iron particles. It was found that guar gum coating not only improves the sedimentation stability but also helps in increasing the yield strength of MR fluids. In the present work, the torque characteristic of the MR fluid under the externally applied magnetic field is evaluated and optimized using ANOVA technique. For this, different MR fluid samples are synthesized using Taguchi’s Design of Experiment technique. An L-18 orthogonal array approach is used in which carrier fluid has given two levels while other parameters/factors are taken at three levels. An experimental approach is used to determine the torque generated by the MR fluid samples using the in-house developed experimental setup.

II. SYNTHESIS OF MAGNETO-RHEOLOGICAL FLUID

In the present work, synthesis and on-state rheological characterization of in-house developed MR fluids is carried out to obtain high values of torque. For this, different MR fluid samples are prepared in-house by using the following procedure.

1. Firstly, the iron particles are mixed with the oleic acid using a stirrer at 400 rpm for 30 minutes.
2. The tetra-methyl-ammonium-hydroxide is poured next and again the mixture is stirred for 30 minutes at 400 rpm.
3. Finally the carrier liquid *i.e.* silicon/mineral oil is poured gradually in the above mixture and it is stirred another one hour at 400 rpm.

The MR fluids are prepared by using 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). The carrier fluid is taken as residual component for the MR fluid formulation. The factors and levels selected for the particular components are summarized in Table 1.Taguchi’s experimental design is used for designing the experiments. Orthogonal array (OA) L18 with 17 degree of freedom is found to be the most suitable array for the combination of levels and factors taken in the experimental designs. The various parameters assigned under the columns of L-18 orthogonal array are shown in Table 2.

Table 1 Input parameters and their levels

Parameter	Parameter Name	Levels		
		1	2	3
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

III. DESIGN OF EXPERIMENTAL SET UP

The experimental set-up used to determine the yield stress of the above MR fluid samples is designed, developed and fabricated in-house and consists mainly the following five parts-

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

Table 2 L-18 Assigned orthogonal array matrix with input parameters

A	B	A×B	C	D	E	A×C	A×E
Col 1	Col 2	Col 3	Col 4	Col 5	Col 6	Col 7	Col 8
1	1	1	1	1	1	1	1
1	1	2	2	2	2	2	2
1	1	3	3	3	3	3	3
1	2	1	1	2	2	3	3
1	2	2	2	3	3	1	1
1	2	3	3	1	1	2	2
1	3	1	2	1	3	2	3
1	3	2	3	2	1	3	1
1	3	3	1	3	2	1	2
2	1	1	3	3	2	2	1
2	1	2	1	1	3	3	2
2	1	3	2	2	1	1	3

2	2	1	2	3	1	3	2
2	2	2	3	1	2	1	3
2	2	3	1	2	3	2	1
2	3	1	3	2	3	1	2
2	3	2	1	3	1	2	3
2	3	3	2	1	2	3	1

The developed electromagnet has 1800 turns of copper wire of 18 SWG and generates magnetic field up to 2.0 Tesla for an air gap of 18 mm. The electromagnet is made of soft iron poles with an input current capacity up to 6 A. The 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 between the poles of the electromagnet. The different values of magnetic field retained by the on-state activated MR fluid are measured using the gauss meter. The servo motor rotates inside the on state activated fluid and can be used to measure the torque of the MR fluid. The test set up used for measuring torque of MR fluid can be seen in Fig. 1.

In this experimental approach, the cylindrical tube of 18 mm diameter is placed vertically and constricted between the poles of an electromagnet. The tube is filled with the prepared MR fluid samples. After this, the servo motor's shaft of 13 mm in diameter is immersed vertically in MR fluid of 68 mm length. The shaft attached to servo motor is rotated at a very low speed of 10 rpm initially so that particles get mixed properly and sedimentation is halted/ minimized.

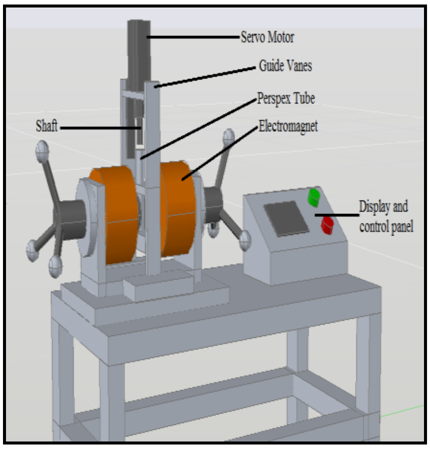

Fig. 1 (a) Schematic Diagram of Test Setup

Fig.1 (b) Original Test Setup

Now, the D.C. current is supplied to electromagnet ranging from 0.2 A to 5.6 A using DC regulated power supply. This current induces a magnetic field between the poles of the electromagnet which activates the MR fluid of the tube. This on-state activated MR fluid exerts a resisting torque on the shaft of the servo motor (rotating at 10 rpm). The on-state resisting torque on the shaft of servo motor is measured by torque sensor fitted on the servo motor. The final L18 OA listing the 18 experimental set of parameters along with torque as an output response is shown in Table 3.

Table 3 Response parameter for experimental L-18 orthogonal array

xpt. no.	Parameter 1	Parameter 2	Parameter 3	Parameter 4	Parameter 5	Response	S/N ratio
	A:Type of carrier fluid	B:Size of Iron Particles	C: Iron Particle (vol %)	D: Oleic acid (vol %)	E: Tetra Methyl ammonium hydroxide (vol %)	Torque (N-m)	
1	Mineral oil	Fe 500 mesh	22	0.5	0.6	0.502194602184343	-5.98256
2	Mineral oil	Fe 500 mesh	27	0.6	0.7	0.68536028990845	-3.28162
3	Mineral oil	Fe 500 mesh	32	0.7	0.8	0.88720580528335	-1.03951
4	Mineral oil	Fe 400 mesh	22	0.6	0.7	0.501846782536394	-5.98858
5	Mineral oil	Fe 400 mesh	27	0.7	0.8	0.678016253408927	-3.37520
6	Mineral oil	Fe 400 mesh	32	0.5	0.6	0.884246275014654	-1.06854

7	Mineral oil	Fe 300 mesh	27	0.5	0.8	0.686134658572968	-3.27181
8	Mineral oil	Fe 300 mesh	32	0.6	0.6	0.887586562914417	-1.03579
9	Mineral oil	Fe 300 mesh	22	0.7	0.7	0.506723789388231	-5.90457
10	Silicon oil	Fe 500 mesh	32	0.7	0.7	0.844453566693586	-1.46848
11	Silicon oil	Fe 500 mesh	22	0.5	0.8	0.476622293982176	-6.43651
12	Silicon oil	Fe 500 mesh	27	0.6	0.6	0.651827925644319	-3.71734
13	Silicon oil	Fe 400 mesh	27	0.7	0.6	0.622625724699355	-4.11546
14	Silicon oil	Fe 400 mesh	32	0.5	0.7	0.839456719747276	-1.52003
15	Silicon oil	Fe 400 mesh	22	0.6	0.8	0.480062269364863	-6.37405
16	Silicon oil	Fe 300 mesh	32	0.6	0.8	0.820045610695672	-1.72324
17	Silicon oil	Fe 300 mesh	22	0.7	0.6	0.473208201089268	-6.49895
18	Silicon oil	Fe 300 mesh	27	0.5	0.7	0.695061475154445	-3.15954

IV. CALCULATION OF SIGNAL TO NOISE (S/N) RATIO

The values of torque are taken for each experimental run and their signal to noise ratio are given in Table 3. Now the aim is to find out optimal combination of parameters that can provide maximum torque values. Based on the Taguchi method, the S/N calculation is decided as "Larger the better" characteristic and is calculated using the following equation.

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

where n refers to number of experiments, y_i is the observed value of torque for i^{th} experiment. Further the response table for S/N ratios and means is calculated using Eq. (1) which are shown in Table (4 & 5). The main effect plots for S/N ratio and means are shown in Figs. (2 & 3). From these two figures, one can interpret that factor C (Iron Particle (vol %)) and factor A (Type of carrier fluid) are the most significant parameters/constituents of the MR fluid.

Table 4 Response table for S/N ratios

LEVEL	A	B	C	D	E
1	-3.439	-3.599	-6.198	-3.573	-3.736
2	-3.890	-3.740	-3.487	-3.687	-3.554
3		-3.654	-1.309	-3.734	-3.703
DELTA	0.452	0.141	4.888	0.161	0.183
RANK	2	5	1	4	3

Table 5 Response table for Means

LEVEL	A	B	C	D	E
1	0.6910	0.6781	0.4901	0.6806	0.6703
2	0.6559	0.6677	0.6698	0.6711	0.6788
3		0.6746	0.8605	0.6687	0.6713
DELTA	0.0351	0.0104	0.3704	0.0119	0.0085
RANK	2	4	1	3	5

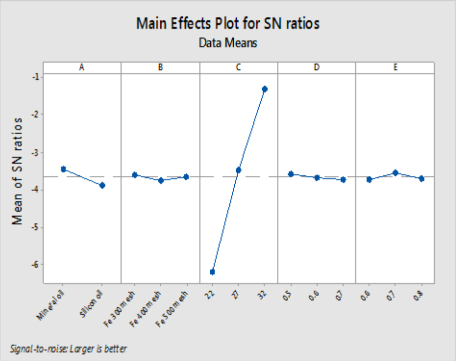

Fig. 2 Main Effects plot for signal to noise ratio

Fig. 3 Main Effects plot for means

V. ANOVA RESULTS

The Analysis of Variance (ANOVA) of the experimental data is done to statistically analyze the relative significance of the input factors such as type of carrier fluid, size of iron particles, iron particle (vol%), oleic acid (vol %) and tetra-methyl-ammonium-hydroxide (vol %) on the response variable *i.e.* torque. The ANOVA results as shown in Table 6 are developed for 95% level of confidence. Values of "Prob > F" less than 0.0500 indicate model is significant. Its values greater than 0.1000 indicate the model terms (parameters) are not significant. From the F and P values, the Factor C (iron particle vol %) and Factor A (type of carrier fluid) have come out to be the most significant input parameters. The same results are also obtainable on the basis of S/N ratios plots.

Table 6 Analysis of Variance

Source	DF	S eq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
A	1	0.005546	1.32%	0.005546	0.005546	74.68	0.013
B	2	0.000337	0.08%	0.000337	0.000169	2.27	0.306
C	2	0.411685	97.81%	0.189195	0.094597	1273.81	0.001
D	2	0.000476	0.11%	0.000145	0.000072	0.97	0.507
E	2	0.00026	0.06%	0.001333	0.000667	8.98	0.1
A*B	2	0.000077	0.02%	0.000077	0.000039	0.52	0.658
A*C	2	0.001693	0.40%	0.001693	0.000846	11.4	0.081
A*E	2	0.000702	0.17%	0.000702	0.000351	4.73	0.175
Error	2	0.000149	0.04%	0.000149	0.000074		
Total	17	0.420924	100.00%				

VI. OPTIMIZATION OF TORQUE FOR MR FLUID

In the present study, the main aim is to obtain the optimal values of MR fluid constituents which gives the high values of on-state torque. The constraints used during the optimization process are summarized in Table 6. The optimal solutions are reported in Table 7. The optimal combination of input parameters for maximizing the torque of MR fluid (as inferred from the Table 7) is shown in Table 8.

Table 6 Parameters with goals and limits

Constraints			
No.	**Goal**	**Lower limit**	**Upper limit**
A	is in range	Mineral	Silicon
B	is in range	Fe500Mesh	Fe300Mesh
C	is in range	22	32
D	is in range	0.5	0.7
E	is in range	0.6	0.8
Torque	Maximize	0.473208201	0.887586563

Table 7 Solutions for various combinations of categorical factor levels

Number	A	B	C	D	E	Torque	Desirability
1	Mineral	Fe300Mesh	32	0.6	0.6	0.887587	1Selected
2	Mineral	Fe500Mesh	32	0.6	0.6	0.885692	0.995427437
3	Mineral	Fe300Mesh	32	0.7	0.6	0.88323	0.989485312
4	Mineral	Fe400Mesh	32	0.6	0.6	0.882141	0.986859272
5	Mineral	Fe300Mesh	32	0.6	0.8	0.881994	0.986504264
6	Mineral	Fe500Mesh	32	0.7	0.6	0.881335	0.984912749
7	Mineral	Fe500Mesh	32	0.6	0.8	0.880099	0.981931701
8	Mineral	Fe400Mesh	32	0.7	0.6	0.877784	0.976344584
9	Mineral	Fe300Mesh	32	0.7	0.8	0.877637	0.975989576
10	Mineral	Fe400Mesh	32	0.6	0.8	0.876549	0.973363536
11	Mineral	Fe500Mesh	32	0.7	0.8	0.875742	0.971417013
12	Mineral	Fe300Mesh	32	0.5	0.6	0.874439	0.968272231
13	Mineral	Fe500Mesh	32	0.5	0.6	0.872544	0.963699668

Table 8 Optimized values for obtaining high value of torque

A	B	C	D	E	Torque	Desirability
Mineral	Fe300Mesh	32	0.6	0.6	0.887587	1

VII. CONCLUSION

In present work, the torque of the MR fluid under the externally applied magnetic field is evaluated and is optimized with respect to its components composition. An experimental design is performed using the Taguchi method with parameters such as type of carrier fluid, size of iron particles, iron particle (vol %), oleic acid (vol %), tetra-methyl-ammonium-hydroxide (vol %). For this work, different MR fluid samples are synthesized in-house. An L-18 orthogonal array approach is used in which carrier fluid is taken as two level factors while other parameters/factors are taken at three levels. Torque generated by the MR fluid samples is determined using the in-house developed experimental setup. By statistically analyzing the experimental data using the ANOVA, It is determined that torque characteristic of MR fluids mainly depends on the volume percentage of the iron particles and type of carrier fluid used in its formulation. ANOVA has given the optimal combination of input parameters for which MR fluid gives higher value of torque which are 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 0.6% and tetra-methyl-ammonium-hydroxide with a volume percentage of 0.6%. The optimal combination of these input Parameters has given on-state torque of 0.887587 N-m. It is recommended to use mineral oil rather than silicon oil as carrier liquid in MR fluids samples to obtain high value of torque. The above inferences can be used for the development of an effective MR fluid related device

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