DESIGN OF MAGNETO-RHEOLOGICAL FLUID CLUTCH

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Abstract: This paper presents the study of MR fluids and the design of the MR clutch which should be able to transmit the torque between input and output shaft. The study is carried on the basis of the torque transmission capacity of light duty motorcycles available in the market currently. Instead of conventional friction material MR fluid is used to check the effectiveness of the clutch with torque transmission. This type of magneto-rheological (MR) clutches have the quick response time of about 15-25 milliseconds, which will ensure quick and smooth operation of clutch. Depending upon the torque requirement in the light weight motorcycles the design of the magneto-rheological (MR) clutch has been carried out.

Index Terms **- MR fluid, Magneto-rheological (MR) clutch, Design procedure**

I. INTRODUCTION

The clutches are widely used in automotive vehicles for engaging and disengaging the input and output shafts. The clutch is place in between the engine and the gearbox. The main function of the clutch is to transmit the torque. There are various types of clutches like single plate clutch, multiplate clutch, and centrifugal clutches. The main drawback in all these conventional type of clutches was the wear. This wear was also causing pollution as burning of friction material can produce carbon monoxide gas. Also the response time of clutch actuation was more. So to address all these problems the magneto-rheological (MR) clutches have been introduced. During the recent years many attempts have been carried out to design the MR clutches for cars with improved torque transmission capacities. In this paper the design of MR clutch has been carried out for the purpose of light weight two wheeler.

The fluids which have the ability to change their physical form under the influence of the external electric or magnetic field are called as the smart fluids. Magneto-rheological (MR) fluid is also a smart fluid. Rheology means the branch of physics that deals with the deformation and flow of matter, especially the non-Newtonian flow of liquids and the plastic flow of solids. Whenever external electric or magnetic field is applied to smart fluids their rheology is changed from Newtonian to non-Newtonian fluids.

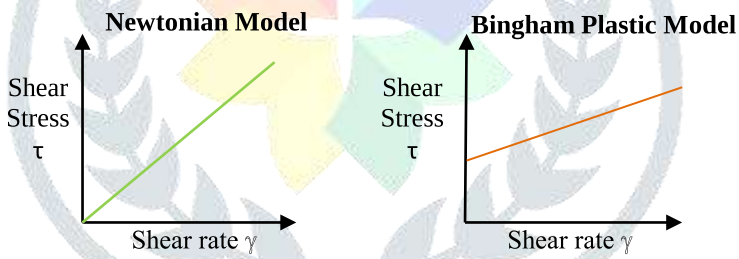


Fig. 1: Shear stress vs. shear rate for Newtonian fluid and Bingham plastic (non-Newtonian fluids)

A Newtonian fluid is represented by the following equation:

$$\tau = \eta \frac{dv}{dz} \quad (1.1)$$

Where $\frac{dv}{dz}$ is the velocity gradient in the z direction, τ is the shear stress, η is the Newtonian viscosity i.e. the viscosity during the off state.

A non Newtonian fluid is represented by the following equation:

$$\tau = \tau_y(\mathrm{H}) + \eta \frac{dv}{dz} \quad (1.2)$$

The first part of the right hand side of Eq. (1.2) produces a torque dependent on the magnetic field, T_{MR}, and the second term generates a viscous torque, Tvis. Therefore, the total output torque can be expressed as,

$$\mathrm{Tout} = \mathrm{TMR} + \mathrm{Tvis} \quad (1.3)$$

II. FORMULATION OF TORQUE EQUATION FOR MR CLUTCH

In case of the uniform pressure theory the pressure is assumed to be constant. Similarly in case of MR clutch the shear stress formed in the fluid gap and acting on the plate is assumed to be constant.

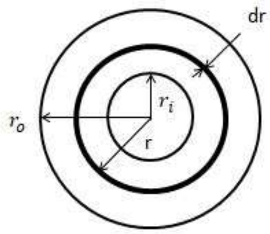


Fig. 2: Radial variation of MR gap

r_o = outer diameter of friction disk (mm)
r_i = inner diameter of friction disk (mm)
dr = thickness of element
dA = elemental area = (2πr. dr)
dF = elemental force
dT = elemental torque
T = torque transmitted by the clutch (N-mm)

Elemental force is given as,

$$dF = \tau \times dA \tag{2.1}$$

Now the elemental torque can be given as,

$$dT = dF \,.\, r \tag{2.2}$$

$$dT = \tau\,(\,2\pi r.\, dr\,)\, r \tag{2.3}$$

In order to estimate the torque output of the MR fluid clutch, a theoretical analysis is performed. The first step in theoretical torque transfer model is to define the MR fluid's behaviour. The Bingham-Plastic constitutive model is utilized for MR fluid in this study.

$$\tau = \tau_y(H) + \eta \frac{\partial v}{\partial z} \tag{2.4}$$

To predict the transmitted torque by a single MR fluid gap, one can use the shear yield stress relation in Eq. (2.4) and integrate elemental torque due to MR and viscosity over the surface of the plates, as follows.

$$T_{OUT} = \int_{r_i}^{r_o} \left[\tau_y(H) + \eta \frac{\partial v}{\partial z}\right] 2\pi r \cdot r\, dr \quad [1]$$

However, it is observed that the viscous torque, $\boldsymbol{T}_{vis}$ is very small compared to the magneto-rheological torque, $\boldsymbol{T}_{MR}$. Hence the $\boldsymbol{T}_{vis}$ is neglected.

Then, the total output torque can be written as,

$$T_{OUT} = \sum_{j=1}^{n} \int_{r_i}^{r_o} \left[\tau_y(H)\right] 2\pi r \cdot r dr \tag{2.5}$$

Therefore the total torque is given as,

$$T = 2\pi.\, \tau\, .\, \int_{r_i}^{r_o} r^2\, dr \tag{2.6}$$

$$T = \frac{2}{3}\, .\, \pi.\, \tau\, .\, (r_o{}^3 - r_i{}^3) \quad [1] \tag{2.7}$$

For 'N' discs (both input and output), the number of pairs of torque transmitting surfaces is (N+1). Therefore the total torque is given by,

$$T = \frac{2}{3}\, .\, \pi.\, \tau\, .\, (r_o{}^3 - r_i{}^3) \times (N+1) \tag{2.8}$$

From the survey conducted it has been noticed that rated torque (Tr) of 12 Nm is to be maintained for 125 cc motorcycles.
Therefore the maximum torque can be given as

T = SF x Tr

The service factor is considered as 1.5

T = 1.5 x 12 Nm
T = 18 Nm (2.9)

III. Selection of optimum vertical MR gap

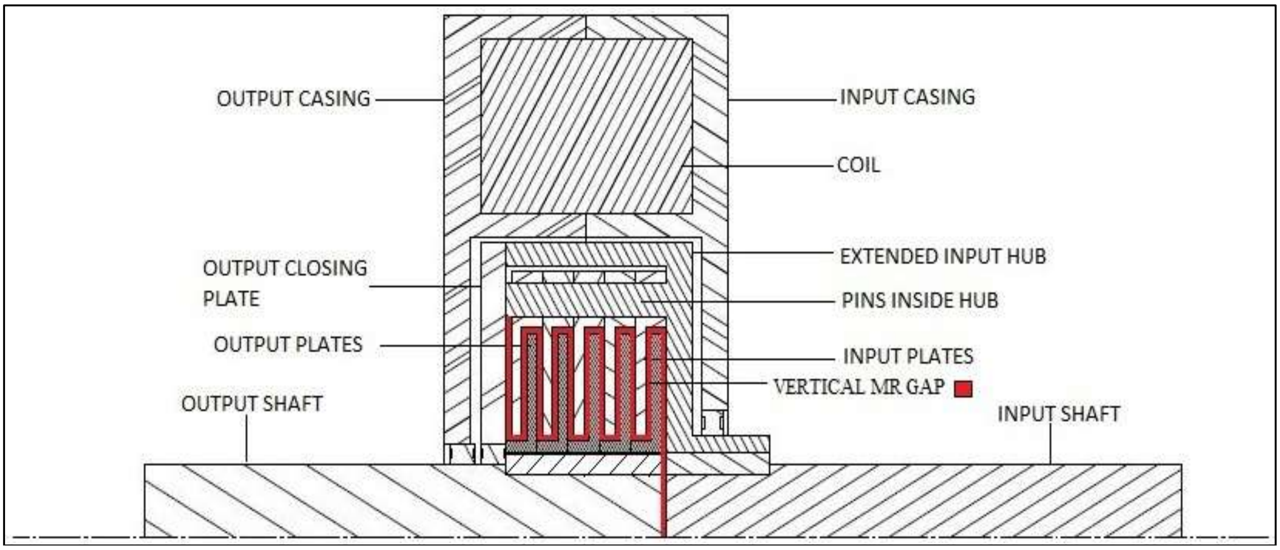


Fig. 3: Representation of vertical MR gap

In order to find the optimum MR gap which will be best suited for the MR clutch, firstly it is needed to define the criteria based on which the optimization will be carried out. There are five criteria on the basis of which the optimum vertical MR gap is to be selected.

For the selection of the optimum vertical MR gap, the graphs has been plotted for all the varying vertical MR gaps corresponding to each criteria with the help of all the formulas putting in the excel sheet. On the basis of the graphs the the vertical MR gaps are eliminated which are not suitable for the MR clutch operation.

Following table shows the table containing the vertical MR gaps that are eliminated based on the requirements from the criteria.

Table No 1.Selection of optimum vertical MR gap

Sr. No.	Criteria for MR gap selection	MR gaps eliminated on the basis of corresponding criteria of MR gap selection.		
		MR gaps for 8 plates (1 to 24) mm	MR gaps for 10 plates (1 to 24) mm	MR gaps for 12 plates (1 to 24) mm
1)	Shear stress more than 46 KPa cannot be selected.	1 mm to 12 mm	1 mm to 11 mm	1 mm to 10 mm
2)	Wire should be able to carry current of 3 A.	23, 24	24	24
3)	Coil height above 35 mm cannot be selected (smaller the better)	13 to 20	12 to 19	11 to 18
4)	As Core length increases the width of clutch also increases. Hence MR gaps with higher core length are neglected.	-	-	19 to 23
5)	From the remaining MR gaps, MR gap with higher no of turns has to be selected.	21, 22	21, 22, 23	-
*	Remaining MR gap	-	20	-

By comparing all the MR gaps in 5 different types of criteria for the selection of best suitable MR gaps, it can be seen that MR gap of 20 mm with 10 no of plates will be best suited for the clutch operation.

IV. Calculations for Optimum vertical MR gap

Inner radius of the radial MR gap = 16.5 mm
Outer radius of the radial MR gap = 36.5 mm
Actual MR gap = 20 mm
Select no of plates as 10 (5 input & 5 output)
Input and output closing plates = 5 mm each
Thickness of the plates inside = 2 mm
Current supplied = 3 A
Bobbin diameter = 114 mm

4.1 Shear stress calculations

We have torque equation as follows,

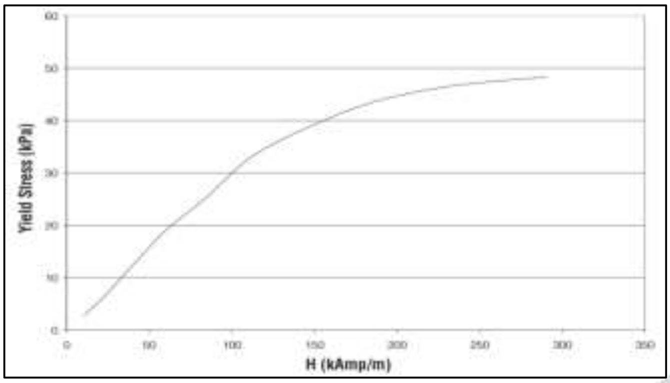
$$T = \frac{2}{3} \,.\, \pi \,.\, \tau \,.\, (r_o{}^3 - r_i{}^3) \times (N+1). \qquad (4.1)$$

By rearranging above equation we get,

$$\tau = \frac{3\,T_f}{2\,.\,\pi\,.\,(N+1).\,(R^3 - r^3)} \tag{4.2}$$

4.2 Magnetic field intensity and magnetic flux density calculations

For the proper working of the MR clutch the MRF-132DG is selected as the working magneto-rheological fluid. Now for this calculated value of shear stress it is needed to find the corresponding magnetic field intensity and magnetic flux density.
Following graphs shows the variation of shear stress (τ) corresponding to magnetic field intensity (H) and the variation of magnetic flux density (B) corresponds to magnetic field intensity (H).



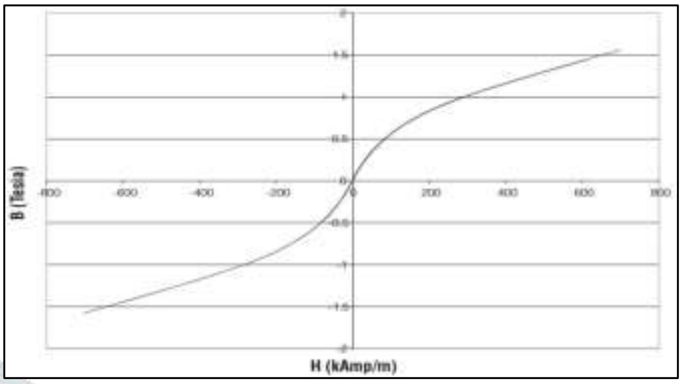


Fig. 4: τ vs H variation for MRF-132DG **Fig. 5: H vs B variation for MRF-132DG**

Above graphs are plotted in MATLAB by using the following equations,

$$\tau = -0.0007\,H^2 + 0.3574\,H + 0.01 \tag{4.3}$$

$$B = -2.127\,E^{-11}\,H^4 + 3.73\,E^{-8}\,H^3 - 2.34\,E^{-5}\,H^2 + 0.007585\,H \tag{4.4}$$

By putting the value of the calculated shear stress in the above equations, corresponding magnetic field intensity and magnetic flux density values can be obtained as follows.

H = 55.5214 kAmp/m B = 0.36 T

4.3 Core length calculations

Core length is the length of the slot in which the electromagnetic coil is to be adjusted.

Core length = input and output closing plates thickness + 10 plates thickness + axial gap between 10 plates
= (5+5) + (10 x 2) + (10 + 1)

Core length (l) = 41 mm

4.4 No of turns

By using Ampere's law for magnetic circuits, the required no of turns for magnetic coil can be determined as,

$$NI = H \times l \tag{4.5}$$

Putting all the values in equation (4.5) we can get the number of turns as 759.

4.6 Wire gauge calculations

A = Cross sectional area of wire
ρ = resistivity of copper (ohm-meter)
$= 1.71 \times 10^{-8}$

L = Total length of wire
= (2 π r) × 759
= (2 π × 0.057) × 759
= 271.82 m

Now we know that resistance is given as,

$$R = \frac{V}{I} = \frac{12}{3} = 4 \tag{4.6}$$

$$R = \frac{\rho \times L}{A} \quad \text{gives, } A = \frac{\rho \times L}{R} \tag{4.7}$$

Putting all the values in equation (4.7) we can get the wire diameter as d = 1.216 mm
There are two standards of wire gauges are used AWG and SWG. Mostly the manufactures prefer to use SWG in India. Hence we can select AWG 16 wire / SWG 18. For SWG 18 the given diameter in chart is 1.22 mm.

$$\text{No of turns per layer} = \frac{\text{length of the coil}}{\text{diameter of the wire}}$$

$$= \frac{41}{1.22}$$

No of turns per layer = 33.63 turns

Now no of layers can be calculated as,

$$\text{No of layers} = \frac{\text{no of turns}}{\text{no of turns per layer}}$$

$$= \frac{759}{33.63}$$

No of layers = 22.57

Now the height of the coil can be calculated as,

Height of the coil = No of layers × diameter of wire

= 22.57× 1.22

Height of the coil = 27.53 mm

4.7 Coil compensation

For compensating the required no of turns in small size slot, considering the spring back by wire and air voids present between the winding, we need to consider a small size of wire than SWG 18. Following tables gives the information about the fill factor.

$$Fill\ Factor = \frac{Total\ conducting\ area}{Total\ slot\ area}$$

Table No. 2: Comparison between SWG 18 and SWG 19

Sr. No.	Specifications	SWG 18	SWG 19
1.	Wire diameter	1.22 mm	1.016 mm
2.	No. of turns/ layer	33.63	40.35
3.	No of layers	22.57	18.81
4.	Height of coil	27.53 mm	19.11 mm
5.	Fill factor without bobbin	88.88 %	61.63 %
6.	Fill factor with bobbin	105 %	73 %

As shown in above table, fill factor cannot be greater than 100 %, hence the SWG 19 will be best suited for the operation.

V. CROSS-SECTIONAL VIEW OF THE CLUTCH

Following figure shows the actual cross section of the magneto-rheological clutch. Input and output plates are of electrical steel for increasing flux density. Shaft is made of stainless steel 304 for avoiding problems while disengagement. All other parts are to made of mild steel to reduce cost.

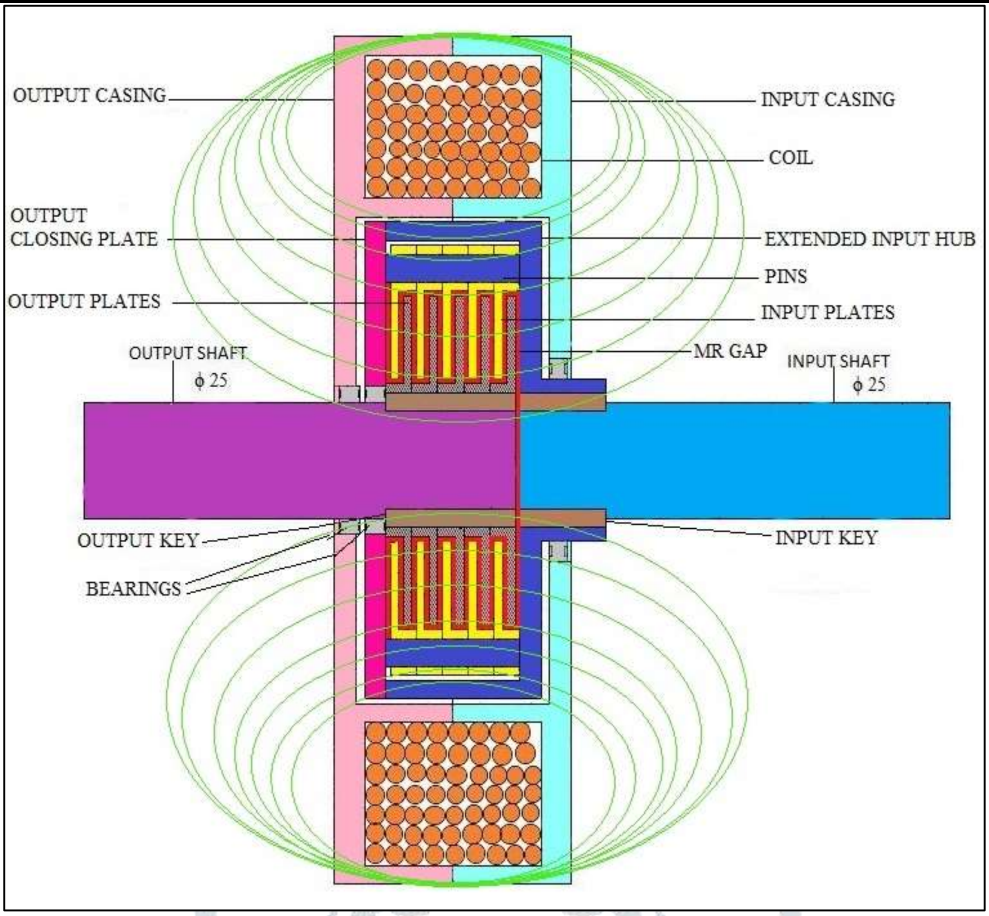


Fig. 6: Cross-sectional view of the Magneto-rheological clutch

VI. RESULTS AND DISCUSSION

An attempt is made to design the magneto-rheological fluid clutch. As per the theoretical calculations the clutch should be able to transmit the 18 Nm of torque which is sufficient to be used in light weight two wheeler motorcycles in India upto 125 cc. The volume of clutch may increase upto 30% than conventional clutch, which can be further reduced by increasing the no of plates. As the clutch can be controlled on the basis of the current supply variation, working of the clutch is smooth and offers increased control over operation. Reliability is high as no wear takes place and hence no pollution caused by the burning of friction materials.

VII. Acknowledgment

I would like to offer my special thanks to the institute, Walchand College of Engineering, Sangli. I would like to extend my appreciation to all who directly or indirectly help me in completion of this work.

VIII. REFERENCES

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