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SOME DESIGN ISSUES OF MULTI-PLATE MAGNETORHEOLOGICAL CLUTCHES

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Magnetorheological (MR) devices gain more and more importance nowadays. It is especially true for MR clutches, whose transmissible torque is now getting close to industrial needs. This paper gives introduction to MR basics and deals with ways how to increase transmissible torque of MR clutches. The survey is based on a simulation process, carried out by COMSOL package. Special aspect of investigation is the calculation of power consumption of MR clutches. As a result, optimal number of plates has been determined.

Keywords: Magnetic flux density, number of plates, magnetic resistance, torque, power consumption

Introduction

In the past MR fluid was mostly applied in shock absorbers of active or semi-active car suspension systems. Due to the following beneficial features: easy electronic controllability with short response time and simple mechanical construction without moving parts, MR fluid is gaining importance in MR clutches to. Initially, only double plate prototype clutches were built [1, 2]. It has become clear that the transmissible torque is very moderate and unsuitable for direct industrial application. The raise of the transmissible torque can be found in the focus of the further research activities. Dratzer et al. at MAGNA [3] prepared a multi-cylindrical MR clutch of 700 Nm torque. The construction of a multi-cylindrical MR clutch is complicated. This paper focuses exclusively on the behaviour of a multi-plate clutch. After summarizing MR basics, the influence of both the geometric buildup of the magnetic circuit and the number of the plates on the transmissible torque will be studied. Different numbers of plates from 1 to 51 are chosen to each of the three magnetic geometries with different flux-guide thickness (A, B, C) and transmissible torque is calculated with these data. Finally, the power consumption of magnetization is studied.

Magnetorheological fluid (MRF)

In magnetorheological clutches torque transmission is produced by a special kind of fluid. The fluid contains carbonyl iron powder, which is suspended in oil with additives. The major role of using additives is to prevent the precipitation of the iron powder in the suspension. The diameters of the iron powder particles are 1–10 μm in size. Due to the size and the spheroid shape of the particles, the fluid has low viscosity resulting small idling waste. Its shape also indicates that the fluid has a small wear out effect on the surfaces to be joined. In the absence of an applied magnetic field the particles are in a disordered position in the fluid.

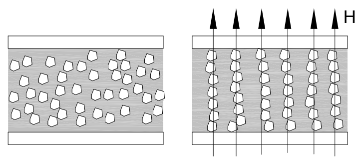

Figure 1: Behaviour of MRF in a magnetic field

With the application of such a field in the fluid the iron particles become polarized and form net-like chains in the direction of flux lines *(Fig. 1)*. The enhancement of the electro-magnetic excitation modifies the viscosity of the fluid. Initially, its density is similar to water's but increasing the excitation parallelly enhances its apparent viscosity up to the point it reaches the required excitation to show the features of solids. This state is appropriate for joining the two plates of a clutch like a solid body.

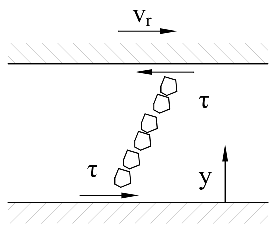

Figure 2: Shear stress in the MRF

The shear stress occurring in fluids when you put load under magnetization *(Fig. 2)* can be calculated by the following formula:

$$\tau = \tau_0(B) + \eta \frac{dv}{dy} \quad (1)$$

where:

τ_0 – Shear stress depending on the induction of the MR fluid

η – The dynamic viscosity of the fluid

dv/dy – The speed gradient in the gap

The second part of the formula originates from the behaviour of the Newtonian-fluid and its effect is neglectable (torque without magnetization).

Features of MR-clutches

Automotive industry is one of the possible applications of magnetorheological clutches. The 700 Nm torque of a MAGNA Powertrain clutch used for four-wheel drive can even be enhanced up to 1300 Nm with using a planetary gearing [3]. During the planning phase certain preliminary directives – such as smallness in size, weight, production costs and large transmittable torque - need to be complied. On the ground of the optimal usage of the maximum yield stress, it is the most effective to place the torque transmission provided by the fluid onto the largest possible diameter. Magnetic circuits are to be created with the shortest possible magnetic field lines to decrease the magnetic resistance, which results larger inductance and larger transmittable torque. Similar effects can be achieved by increasing the cross-section of the magnetic circuit avoiding the impregnation of the material.

As for their constructivity, clutches have two types: centrifugal and plate clutches *(Fig. 3)*. The basic distinctive feature between the two alternatives lays in the magnitude of the transmittable and idle torque.

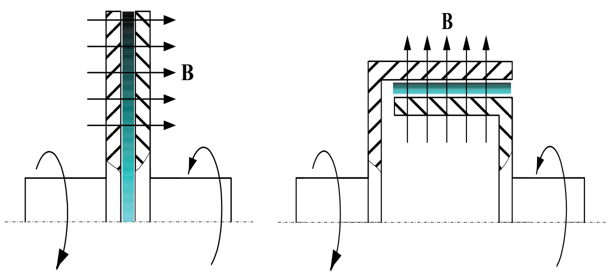

Figure 3: MR-clutch constructions

In the case of plate clutches (Fig. 3a) the effect of the centrifugal force creates a stream of particles between the inner and the outer part of the fluid. This effect grows with increasing revolution and even 1000 1/min creates a remarkable flux in the fluid. On the effect of the larger viscosity caused by the augmented number of particles on the outer diameter the idling waste of the clutch increases. Outer diameters play a big part in transmitting torque while the effect of the inner ones is insignificant.

In the case of cylindrical clutches (Fig. 3b) there is no significant particle stream which results alike fluid viscosity in the clutch. Since the fluid does not congeal even on the larger diameter, the idle waste is low. Expanding on a large surface is a very beneficial feature of the MR fluid because it improves the value of the transmittable torque.

Induction needs inductors which can occur in two possible ways: standing or rotating with the shaft.

Torque calculation of plate type MR clutches

We restricted our research to examine a plate clutch with a fixed inductor. In *Fig. 6* the design of a one-plate clutch can be seen. The radius of the plate is 45 mm. Depending on the induction this construction is able to transmit 10–20 Nm.

When calculating torque we presuppose a constant induction distribution in the fluid among the disc gaps. This presupposition was also supported by the simulation made in a program called Comsol where we used an MR 132 LD type fluid produced by LORD Corp. The outstanding ferromagnetic material C10 (AISI1010) was used for flux guide parts.

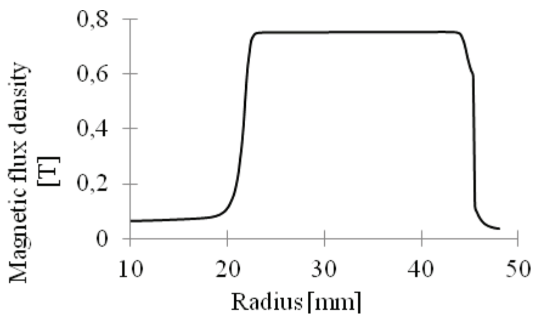

Figure 4: Magnetic flux density in the first gap

The yield stress of MR fluid can be calculated from the next formula: [4]

$$\begin{aligned}\tau(B) &= -2.774B_{ax} + 206.1B_{ax}^2 = \\ &= -204.1B_{ax}^3 + 53.55B_{ax}^4\end{aligned} \quad (2)$$

Having calculated the magnitude of the yield stress in the fluid, the torque can be given by the following formula: (in one gap)

$$M = 2\pi \int_{r1}^{r2} \tau(B(r)) r^2 dr \quad (3)$$

Applying more plates, magnetic flux density in the MR fluid gaps differs only slightly from each other. For example, magnetic flux density in gaps of 11-number of plates MR clutch measured at r=32 mm radius can be seen in *Fig. 5*.

Magnetic flux density can be regarded constant apart from the third plate. The difference is only 0.3%.

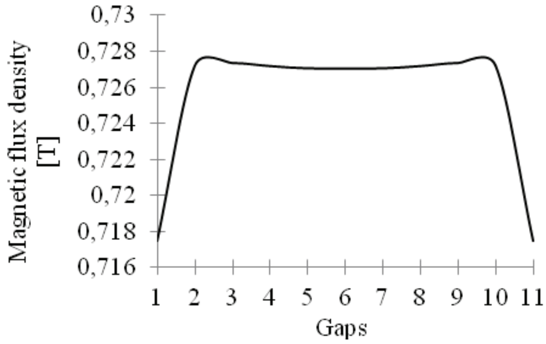

Figure 5: Magnetic flux density in the gaps

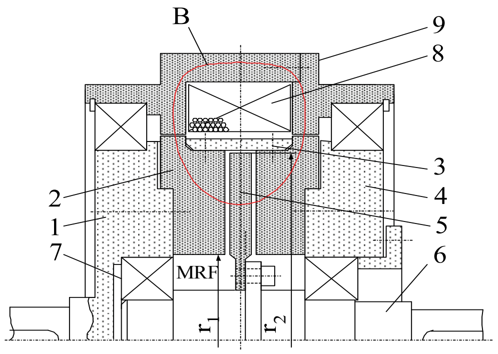

Figure 6: MR-clutch construction

The clutch developed consists of three well distinguishable units.

The first one:

- (1) the driving shaft
- (2) two ferromagnetic flux guide rings
- (3) copper tube
- (4) right hand side cap
- (6) the driven shaft

The second one:

- (7) deep groove ball bearings
- (5) the ferromagnetic plate

The third one:

- (8) electromagnetic coil
- (9) ferromagnetic casing

With this construction slip rings are not needed to activate the coil.

In case of applying a multi-plate clutch, an odd number of plates is required to be disposed in the clutch. Every second plate is to be fixed to the external rotating part (copper tube).

Result of simulation

The fixed part of the examined clutches has different magnetic resistance which can be achieved by the increase of the cross-section of the magnetic conductor.

Better conductance results in larger induction in magnetic fluids increasing the torque to be transmitted. Having a small number of discs, this difference is significant. The dimensions of the examined geometries were:

Table 1: Geometry of the magnetic circuit

Geometry	L1=L2
A	8 mm
B	10 mm
C	20 mm

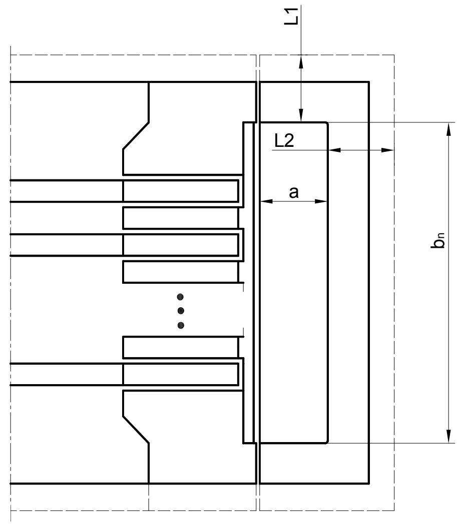

Figure 7: Geometry of the magnetic circuit

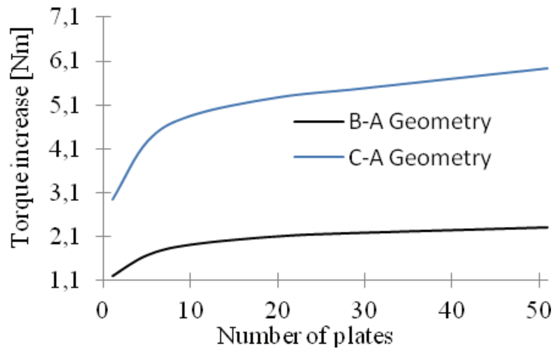

Figure 8: Torque increase at B and C geometry relative to A

We can state that the torque difference among the examined geometries was approximately constant after 10-15 discs.

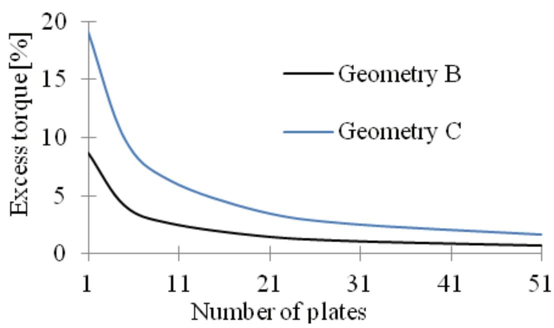

Figure 9: Relative torque increase

Enhancing L1 and L2 from 8 mm to 10 mm resulted 1.2 Nm torque increase per disc, which means nearly an increase of 9%. However, in the case of 51 discs, the excess is only 0.6%. Increasing the fixed part from

8 mm to 20 mm causes a much larger excess torque per disc. In this case it is 3 Nm, which means a 20 % growth.

Power consumption

For magnetization J=2·10^6 A/m^2 (i=1 A) current density was applied to the winding area of width a=13.8 mm and of variable length b. The length of winding is approximately proportional to the number of plates n and consists of N turns. Limiting the current of winding to i_{max}=3 A, copper wire of diameter d_w=0.8 mm will be sufficient to avoid overheating. If the mean radius of winding is r_m=0.07 m, the resistance of a single turn can be calculated as

$$R_1 = \rho \frac{2 r_m \pi}{\frac{d^2{}_w \pi}{4}} = 0.018 \frac{8*0.07}{0.8^2} = 0.0157\Omega \qquad (4)$$

The magnetizing power is then P = i^2·NR_1. *Table 2* contains data of magnetization in term of the number of plates (n).

Table 2: Power consumption

n	b [mm]	A [mm^2	N	P [W]	T [Nm]
1	25.5	351.9	700	11.1	13.7
3	35.5	489.9	975	15.5	27.0
5	45.5	627.9	1250	19.8	40.2
11	70.5	972.9	1937	30.7	73.3
21	120.5	1662.9	3310	52.5	139.2
31	170.5	2352.9	4683	74.2	205.1
51	275.5	3801.9	7567	120	343.3

It can be concluded that the increasing number of plates results higher transmissible torque, but also higher energy consumption. It is worth considering the limit of an acceptable power consumption as well. A practical point of view may be the specific torque (e.g. transmissible torque divided by power consumption) in term of number of plates that can be seen in *Fig. 10.* The graph tends monotonously to 3 Nm/W.

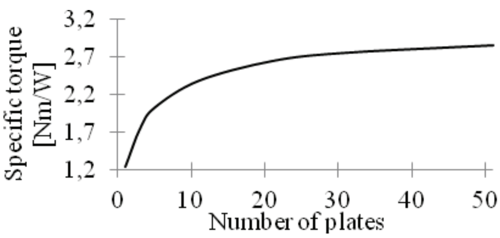

Figure 10: Specific torque

Conclusion

This paper dealt with optimization of geometric buildup of a multi-plate MR clutch. The simulation process showed that the transmissible torque of an MR clutch can be enhanced by reducing the magnetic resistance of flux-guide parts with using only small numbers of plates. Increasing the number of plates, the previously mentioned effect is getting negligible because the high magnetic resistance of the several gaps filled with MR fluid. Increasing the number of the plates is a more efficient way to enhance the transmissible torque. To conclude, the transmissible torque is approximately proportional to the number of plates, but because of power consumption of magnetization, the number of plates cannot be raised unlimitedly.

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