TRANSIENT THERMAL ANALYSIS OF A MAGNETORHEOLOGICAL CLUTCH

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Abstract. Magnetorheological (MR) fluids are smart materials which can have their properties controlled by an induced magnetic field. The application of MR fluids in clutches devices is increasing due the ability to control the coupling torque and velocity between two shafts, and the possibility to have a progressive coupling between axes. Despite the great properties and benefits, the MR fluid properties are strongly related to the temperature. When the fluid temperature reaches certain limit, the fluid additives begin to deteriorate and the viscosity of the carrier fluid starts to change, which can lead to irreversible changes on the MR fluid and uncontrollability of its rheological properties. This paper presents a thermal analysis of a MR clutch to address some limitations of the MR fluid with respect of working conditions. Two analyses are developed, the first one is a thermal analysis of the clutch in the full slip condition. This condition occurs when the torque required to moving a load is greater than the clutch maximum torque. Since the heat generation is high, full slip condition is the most dangerous condition for the clutch. The model proposed evaluates the time limit of the clutch on this condition before the MR fluid starts to deteriorate. The second analysis is for the clutch working for 8 hours straight. The objective of the second analysis is to determine the temperature of the MR fluid region after a long term operation. A correlation equation between the fluid shear stress and temperature is applied to evaluate the clutch output torque variation. Results show that the full slip operation must be avoided due to the higher temperatures on the fluid region. Although the long term operation analysis shows the fluid region in temperatures below the maximum MR fluid temperature, it still can significantly decrease the output torque.

Keywords: Magnetorheological clutch, transient thermal analysis, magnetorheological fluid.

1. INTRODUCTION

Magnetorheological fluid (MR) is a suspension of micro-sized of magnetizable particles mixed with insulated carrier fluid, usually mineral based or silicone-based (Chen et al., 2015). The weight percentage of particles in suspension can reach about 80% (Zipster et al., 2001). When the fluid is subjected to an external magnetic field, particles begin to form columnar structures parallel to the magnetic flux lines. This behavior changes the rheological properties of the fluid, such as viscosity, yield stress and others, the response time is in order of milliseconds (Yang, 2001). The columnar structures are deformed according the external force or pressure applied. These deformations occur in three different modes as shown in Fig. 1. In shear mode, the chain has to resist the bordering plates displacement. The flow mode or valve mode is thee resistance to the perpendicular pressure applied on the chain. The MR fluid is on the squeeze mode when an axial force is applied on the plate and the columnar structure tries to resist a buckling (Zipster et al., 2001).

Due to these characteristics, MR fluids have been used in dampers, allowing modulate the damping level imposed by the magnetic field, and in power transmission systems that require adjustment of the output torque, as clutches. MR devices are used in various applications in engineering and industry: vehicle suspensions (Sung and Choi, 2008), clutches (Kavlicoglu et al., 2006), brakes (Nguyen and Choi, 2010), intelligent prosthesis (Andrade et al., 2015), (Dong et al., 2006), and others.
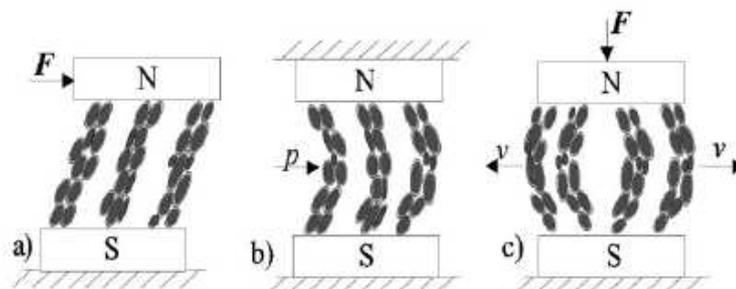

Figure 1. Stress modes of MR fluid. (a) Shear mode, (b) Flow mode, (c) Squeeze mode (Zipster et al, 2001).

The properties of the MR fluid strongly depends on temperature, for this reason, the fluid shows different performances with the temperature variation (Chen et al., 2015). The main reason for this variation is the temperature sensitivity of the carrier fluid. The viscosity of the carrier fluid changes with the temperature variation, which results in variation of the MR fluid shear stress. Additives are applied in the MR fluid to decrease the sedimentation rate and increase the particles dispersion on carrier fluid (Wang et al., 2014). However these additives are also sensitive to temperature variation, some are decomposed at about 100 °C. The cyclic operation under high and low temperature can lead to irreversible changes on the MR fluid. It can cause the reduction of the rheological properties and uncontrollability of the shear stress by the influence of the chaining of the material under magnetic field (Chen et al., 2015). To account these properties changes with the temperature, Chen et al. (2015) proposed an experimental setup for evaluation of a MR transmission (which works on the shear mode of the MR fluid) under different temperatures, obtaining a set of curves for torque and temperature with different current inputs. Zipster et al (2001) proposed an experimental setup which analyzes the MR fluid in the flow mode under different temperatures. Wang et al (2014) made a complete characterization of the MR fluid under different temperatures. Lee et al (2015) accounted the temperature rise of the variable inductor for magnetorheological fluid under high-frequency pulsed voltage source. The variation, mainly due the eddy current, has an influence on the MR fluid temperature rise.

Since the MR fluid has limited temperature of operation, the thermal analysis of the MR component has a great importance in almost all applications. Kowol and Pilch (2015) analyzed the temperature rise on a MR clutch on the full slip state, which is the most dangerous state for the MR fluid in shear mode. Wang et al (2013) proposed a cooling water method for dissipation for a high torque MR brake. An extensive investigation of the MR brake temperature distribution and fluid irreversible changes caused by excessive heat are made in Wang et al (2015). Although it is a very important analysis for the MR fluid device implementation in a real environment, any transient analysis were made on a MR fluid device to evaluate the time limit of operation under full slip state or under certain temperature condition.

In this paper, a low torque MR clutch temperature distribution and torque performance are analyzed under the full slip state and for a typical summer day in a tropical south hemisphere region temperature condition. This paper is organized as follows: Section 2 presents the MR clutch applied for analysis. Section 3 presents the thermal analysis and torque performance for the full slip condition. Section 4 presents the thermal analysis and torque performance for the operation in a typical summer day in a tropical south hemisphere region. Final remarks and future works are presented in Section 5.

2. MR CLUTCH DESIGN

The MR clutch developed can couple two axles in a soft and progressive manner taking advantage of the shear mode of the MR fluid. Therefore it reduces the gear reduction backlash and provides a safer operation. This clutch has many applications in industry and robotics. It has two ways to be mounted. It can be mounted between the motor and gear reduction to decrease the gear reduction backlash or it can be mounted on the output of the gear reduction to increase the back drivability of the system.

The clutch comprises an input shaft that connects the driveshaft. This axis supports the discs that have relative motion between them. The MR fluid is placed in the spaces between the discs. As the MR fluid undergoes the action of an external magnetic field produced by a solenoid coil, particles begin to form columnar structures parallel to the lines of magnetic flux. With the application of the magnetic field in the fluid, it begins to behave like a semi-solid and there is increased friction between the fluid and disc.

Figure 2 shows the CAD model of the MR clutch. The input shaft (1) has slots in its outer diameter for mounting and motion transmission to the inner discs (6), (10). The end disc (4) are connected to the end ring (5), this ring is made of nylon its function is to position the end disc (4) which has freedom of movement in relation to the input shaft (1). The spacer rings (7), (9) position the discs (6), (8), (10), guaranteeing the necessary distance between the all the discs.

Bearings (2) and (15) ensure the outer discs (4), (8), (11) have freedom of movement relative to the inner disc (6), (10). The bearings also ensure that the coil (16) and its core (13) and (17) do not have rotational movement. The output shaft connection (18) is held by a screwed connection wherein the output shaft is connected to the support ring (3) and the lateral shaft output (12). The output shaft (18) also has a bearing (19) which add freedom of movement to the encapsulation (14) which is mounted via a screwed connection (21) at the side of the encapsulation (20).

The clutch operation comprises on apply current in the coil which generates a magnetic field. The coil core and discs directs the magnetic field to the MR fluid and the coil time constant accounts the time required for the magnetic field construction. Under the magnetic field, the fluid begins to behave as a semi-solid. This behavior leads to an increase in the friction discs, so with a sufficiently high magnetic field, the inner and outer discs rotate together with the same speed. Therefore, the output shaft which rotates together with the outer discs rotates with the same speed and the same torque of the input shaft. In the MR clutch dynamic model, the current input is converted into magnetic field force on the MR fluid region. Magnetic field relates with the MR fluid yield stress through the experimental curve provided by the manufacturer. MR fluid yield stress and output torque are related through Eq. (1).
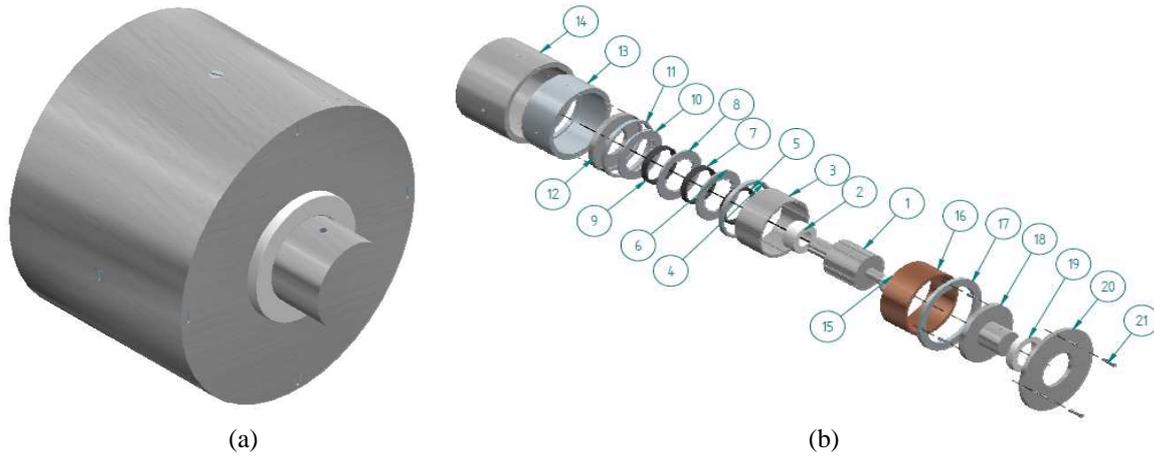
Figure 2. MR clutch CAD model. (a) Isometric view. (b) Exploded view.

$$T = N\pi \int_{ri}^{ro} (\tau_Y + \eta\dot{\gamma}) r_D (r_D dr_D) = N\pi \left[\frac{\tau_Y}{3} \left(r_o^3 - r_i^3 \right) + \frac{\omega\eta}{4g_D} \left(r_o^4 - r_i^4 \right) \right] \tag{1}$$

Where τ_Y is the yield stress related to the applied magnetic flux density obtained by consulting the MR fluid datasheet provided by the manufacturer, η is the off-field viscosity and $\dot{\gamma}$ is the shear rate as a function of the radius, the length of the working gap (g_D) and the angular velocity (ω).

3. THERMAL ANALYSIS ON FULL SLIP CONDITION

The full slip condition is the most critical condition in the MR clutch operation. It occurs when the maximum output torque of the clutch is not capable of move the load. Therefore, the coil has its maximum current which leads to a higher heat generation. Moreover, almost all input power on the MR fluid is converted into thermal power (Kowol and Pilch, 2015). When the MR clutch is on the full slip condition, its temperatures rise in higher rate. Hence, this condition should be avoided. Nevertheless, it is important to know for how much time the MR clutch can keep a full slip condition. The time limit evaluation is made through a finite element analysis of the MR clutch. Ansys Workbench 15.0 is employed for the transient thermal analysis with the Mechanical APDL solver.

As the clutch an assembly of many components with different sizes and masses, the mesh has different sizes to increase computation efficiency and solution accuracy. Several components are responsible for the heat generation on the full slip condition. Equation (2) presents the slip power loss, all the slip power loss is converted to heat generation (Wang et al., 2015).

$$\dot{\Phi} = \frac{T\Delta\omega}{V} \tag{2}$$

Where $\dot{\Phi}$ is the volumetric heat generation rate on the full slip condition, $\Delta\omega$ is the angular velocity, T is the MR clutch torque and V is the MR fluid volume.

The electric power loss is applied to the model through the Joule effect on the coil. Since the MR clutch works with direct current, the effects of eddy current are neglected. Thus, Eq. (3) presents the electric power loss, which is converted to heat generation.

$$\dot{\Phi}_C = \frac{I^2 R_C}{V_C} \tag{3}$$

The $\dot{\Phi}_C$ is the coil volumetric heat generation rate, I is the coil current, R_C is the coil wire resistance and V_C is the coil volume.

Bearings friction is another source of heat in the clutch. Referring to Fig. 2, heat generation occurs on bearings (2) and (15) when the clutch is on the full slip operation. Equation (4) shows the heat generation applied on bearings.

$$\dot{\Phi}_B = \frac{0.105 \times 10^{-3} \mu P d \Delta \omega}{2V_B} \qquad (4)$$

Where $\dot{\Phi}_B$ is the bearing volumetric heat generation, μ is the bearing friction coefficient which can be obtained on manufacturer datasheet, P is the bearing load, d is the bearing bore diameter, $\Delta \omega$ is the angular velocity and V_B is the bearing volume.

Solar radiation and natural convection are also considered in the model. Another heat exchange occurs on the shaft surface during high speed rotation which generates axial and tangential airflows. The heat exchange coefficient for this case is obtained in Eq. (5) (Wang et al., 2015).

$$h_s = 28(1 + \sqrt{\frac{3\pi n_s d_s}{40}}) \qquad (5)$$

Heat exchange coefficient is represented by h_s, n_s is the shaft angular velocity, d_s is the average diameter of the rotating surface.

Initial temperature and ambient temperature are 25ºC. Since all mechanical parts of the clutch are made of metal (SAE 1020 steel, aluminum alloy, copper), the time of full slip condition is limited by the MR fluid temperature. The MRF-132LD which is applied in the MR clutch has the maximum operation temperature of 150ºC. Therefore the temperature on the fluid region cannot exceed this value. Once the maximum temperature is exceeded the MR fluid suffers from irreversible changes which lead to uncontrollability of the fluid properties such as the shear stress (Chen et al., 2015). Figure 3 shows the results of the simulation and temperature variation on the MR fluid region with time.

Referring to Fig. 3 the region with the greater temperature is the fluid-disc interface. This is expected since the greater heat generation occurs in this region. The maximum temperature is 321.27ºC which is not shown in the figure since it occurs on the bolts that connects the output shaft. The bolts are not shown in the section view. Figure 3 (b) shows the MR fluid temperature variation with time. As aforementioned, the maximum temperature for the MR fluid employed on the clutch is 150ºC. This maximum temperature is surpassed in about 80 seconds. Although the MR fluid datasheet suggest a temperature range from -40ºC to 150ºC, in many cases the MR fluid decrease its shear stress under magnetic field in temperatures about 100ºC due the additive deterioration (Chen et al., 2015). For this reason is safer to limit the MR fluid temperature to 100ºC. Therefore, the MR fluid has its recommended temperature surpassed in about 15 seconds.
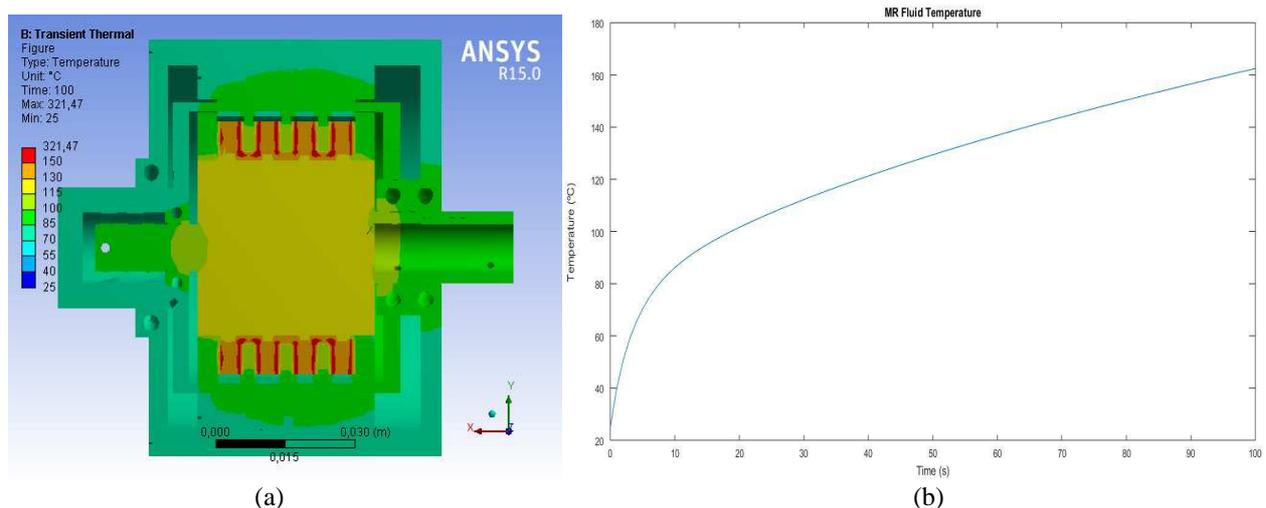

Figure 3. MR clutch results for full slip condition. (a) Temperature distribution after 100 seconds. (b) MR fluid temperature variation with time.

4. THERMAL ANALYSIS ON 8 HOUR OPERATION

The following analysis is made for 8 hour operation of the MR clutch in a typical summer day. According the meteorological information the average temperature between 9 and 17 o'clock is 30ºC (AccuWeather Inc.). In this case there is no slip between inner and outer discs. Therefore the Joule effect on the coil and the friction in the bearings are the only responsible for the heat generation in this model. The same methodology applied for the previous analysis is employed on this analysis. However some differences between both models have to be addressed. The main difference between these models is the absence of slip on the 8 hour operation condition. Moreover, for 8 hour operation condition the heat generation due bearing friction is applied in all bearings. Referring to Fig. 2, the bearings which have heat generation are (2), (15), (19).

Figure 4 shows the results for the 8 hour operation condition. The ambient temperature is 30ºC and components initial temperature is also 30ºC. Figure 4 (a) shows the temperature distribution after 8 hour operation and Fig. 4 (b) shows the variation of the temperature in the MR fluid region with time. Figure 3 shows higher temperatures on the coil and nearby regions which are expected since the greater heat generation occurs on the coil. Regarding the MR fluid temperature, the figure shows a steady state temperature of 52.76ºC which is achieved after 40 minutes operation.

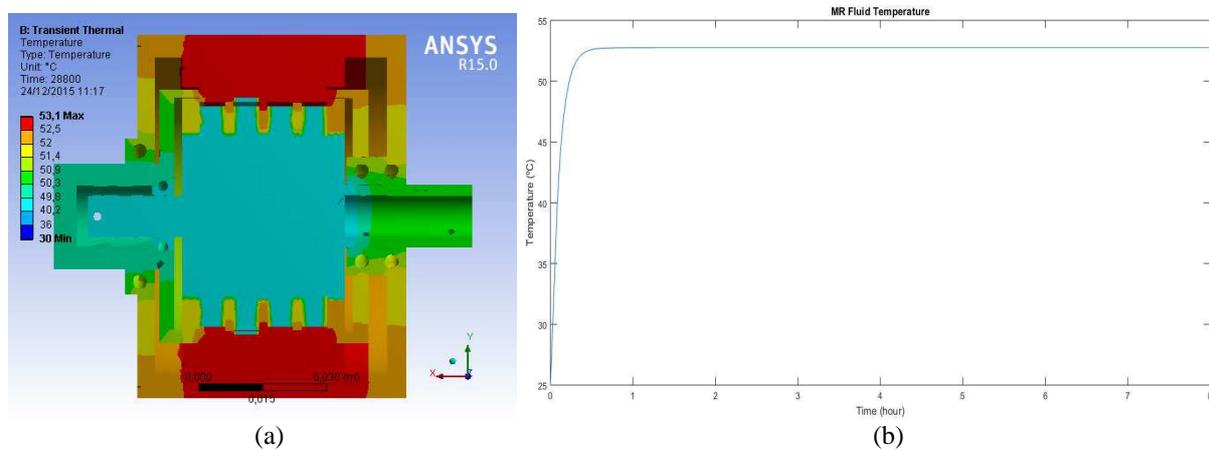(a)   (b)

Figure 4. MR clutch results for 8 hour operation condition. (a) Temperature distribution after 8 hour. (b) MR fluid temperature variation with time.

Although the steady state temperature is below the recommended temperature for the MR fluid, the temperature rise can modify MR fluid properties, especially the MR fluid shear stress under magnetic field. Zipster et al. (2001) performed experiments with the MRF-132LD fluid to obtain the temperature and shear stress correlation. The points obtained by experiments are approximated by a regression line. The line equation is presented in Eq. (6).

$$\tau_y = 145B - 0.304BT \tag{6}$$

Referring to Eq. (6), τ_y is shear stress, B is the magnetic field density and T is the absolute temperature.

It is possible to determine the output torque of the clutch under temperature variation. The shear stress is calculated through Eq. (6) and is substituted in Eq. (1). The results of the finite element analysis on the MR fluid region is exported to a Simulink model, which comprises the MR clutch dynamic equations, including Eq. (1) and Eq. (6). Figure 5 shows the MR clutch torque until the system reaches the steady state temperature.

The MR clutch torque on 25ºC is about 6.5 Nm, as the temperature raises this output torque decreases. When the clutch reaches the steady state temperature, the torque is 5.7 Nm. This considerable difference between the output torque on 25ºC and 52ºC have to be considered in the MR clutch operation. The lack of knowledge of this difference can lead to undesirable slippage between inner and outer discs, which represent a power loss. Moreover, it can make the clutch work in the full slip condition.
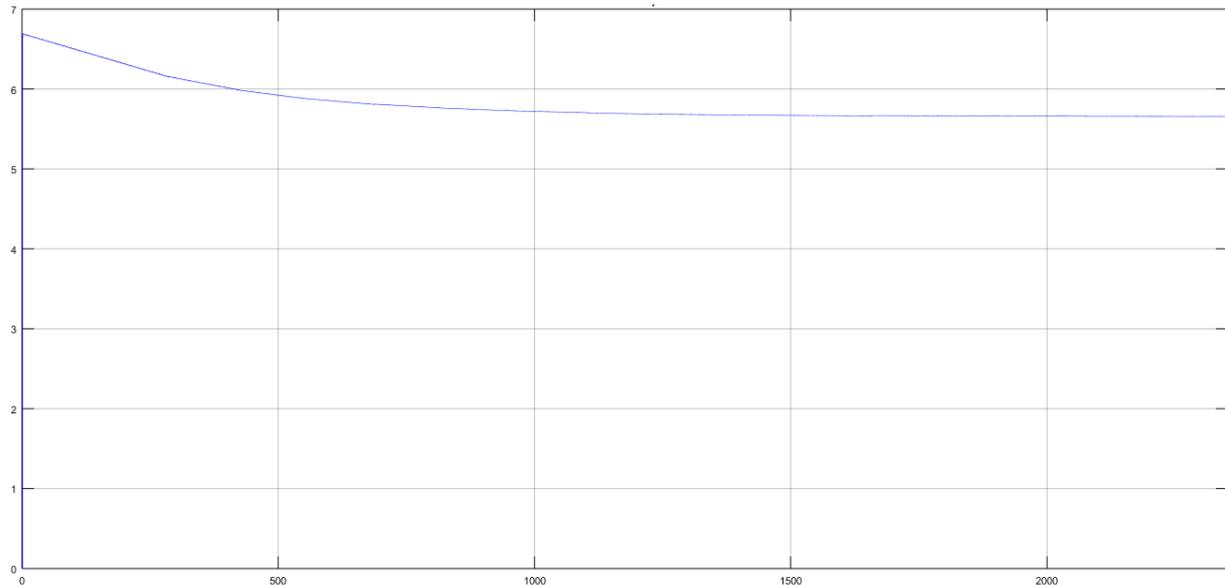
Figure 5. MR clutch torque. Horizontal axis has time in seconds and Torque in Nm on the vertical axis.

5. FINAL REMARKS

This paper presents a thermal analysis of a MR clutch for a full slip condition and a long term operation in a typical summer day in a tropical region and output torque analysis. Results show that the full slip condition must be avoided. The time limit to a full slip condition is about 1 minute, after that the MR fluid suffers for irreversible changes and loses its functionality. Although the 8 hour operation does not lead to temperatures above 100ºC, the rise of temperature of 25ºC to 52ºC is sufficient to decrease the output torque in 12.3%. The thermal analysis is very important and has to be made before submit the clutch to a certain operation condition. If the clutch is submitted to a load close to its maximum capacity for a long term operation, the torque should decrease with the temperature raise and it can lead to a full slip condition.

Future works include the experimental validation of the thermal model and experiments with the MR fluid applied on the clutch to evaluate the regression line obtained in reference works.

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