Paweł KOWOL, Zbigniew PILCH

Silesian University of Technology

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Analysis of the magnetorheological clutch working at full slip state

***Abstract**. In the paper the magnetorheological clutch prototype (MR clutch) is presented. The results of measurements of electromechanical parameters of the clutch are presented as curves of clutching torque vs. current of the MR clutch's coil $T_C(I)$. The results of thermal measurements of the MR clutch as heating curves are presented. On base of the thermal measurements the influence of temperature on clutching torque is obtained. The thermal field analysis of the MR clutch at full slip state is described. On the base of the thermal field analysis the operation range at full slip state for the MR clutch is determined.*

***Streszczenie.** W artykule przedstawiono prototyp sprzęgła elektromagnetycznego z cieczą magnetoreologiczną. Przedstawiono wyniki badań laboratoryjnych momentu sprzęgającego T_C w funkcji prądu sterującego. Zaprezentowano również wyniki pomiarów cieplnych sprzęgła. Ostatnia część artykułu poświęcona jest omówieniu wyników analizy cieplnej sprzęgła z wykorzystaniem metod polowych. Zidentyfikowano źródła ciepła odpowiadające pracy sprzęgła w pełnym poślizgu (s=1) i dla tego przypadku przeprowadzono obliczenia. Na podstawie wyników obliczeń określono dopuszczalny i niedopuszczalny zakres ciągłej pracy sprzęgła. (**Analiza pracy sprzęgła z cieczą magnetoreologiczną pracującego w stanie pełnego poślizgu**)*

Keywords: Magnetorheological fluid, electromagnetic clutch, electromechanical measurements, thermal measurements.
Słowa kluczowe: ciecz magnetoreologiczna, sprzęgło elektromagnetyczne, pomiary elektromechaniczne, pomiary i obliczenia cieplne

Introduction

Magnetorheological fluids (MR fluids) belong to SMART material group. Thanks to their main feature – magneto-mechanical feature consisting of MR fluid viscosity's increase in the external magnetic field – the fluids are applied in electromagnetic brakes, dampers and clutches [1], [4], [6]. In these devices, MR fluid is introduced between moving elements, which are part of magnetic circuit, and the magnetic field passes through the fluid. Because of the nonlinearity of magneto-mechanical parameters of MR fluids [2] and nonlinearity of magnetic materials constituting the magnetic circuit the main electromechanical characteristics of these devices (force or torque versus current causing magnetic field) are nonlinear.

Magnetorheological clutch

In electromagnetic clutches a MR fluid is located between discs of driving and driven members (Fig. 1).

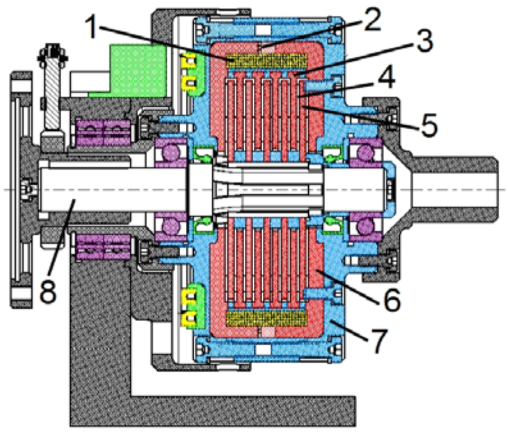

Fig.1. Axial section of magnetorheological clutch: 1 – coil of the clutch, 2 – permanent magnet, 3 – disc of driven member, 4 – MR fluid, 5 – disc of driving member, 6 – yoke of magnetic circuit, 7 – housing of the clutch, 8 – shaft of driving member

Magnetic field which changes viscosity of MR fluid is generated by the coil carrying the current I and the permanent magnet (PM) – the hybrid excitation. Thanks to two sources of magnetic field (coil and PM) the clutch generates clutching torque $T_C(I=0)$ without necessity of supplying the coil. The current I carrying the coil can decrease (I–) or increase (I+) magnetic field in the gaps with MR fluid, which results in decreasing the clutching torque $T_C(I-)$ or increasing the clutching torque $T_C(I+)$.

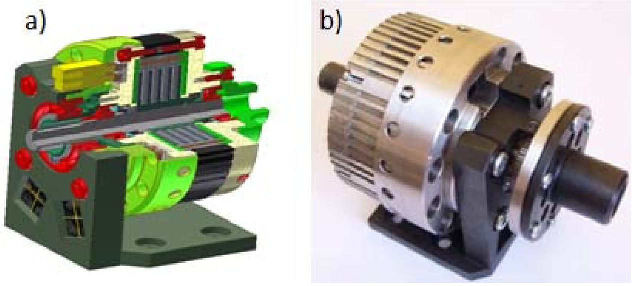

Fig.2. The magnetorheological multidisc clutch (MR clutch): a) 3D CAD model, b) the prototype [5], [8]

Measurements of electromechanical parameters of the MR clutch

For tests of MR clutch the dedicated laboratory stand (test bench) was built. The laboratory stand is shown in the Figure 3.

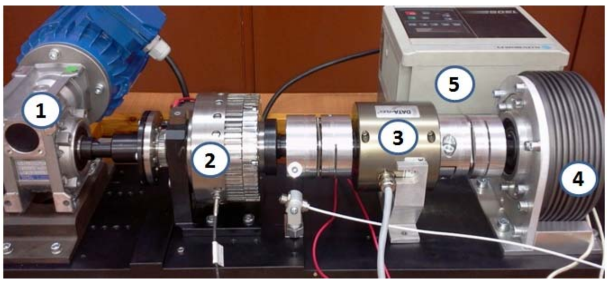

Fig.3. The test bench for the MR clutch: 1) gearmotor, 2) investigated MR clutch, 3) torquemeter, 4) load (brake), 5) inverter

Owing to supplying of gearmotor (induction motor) from inverter the clutch shaft can be driven at a speed in range 0÷200 rpm.

The torquemeter, located between investigated MR clutch and the load, measures clutching torque T_C, i.e. torque transmitted by the MR clutch.

The brake (load) can generate braking torque greater than maximum value of clutching torque, what gives rise the full slip state.

The Figure 4 shows the results of measurements as two curves of the clutching torque vs. coil current $T_C(I)$ – for two type of excitation system, which were described in previous chapter. The curves are related to the clutch filled with the fluid MRF-140CG [9].

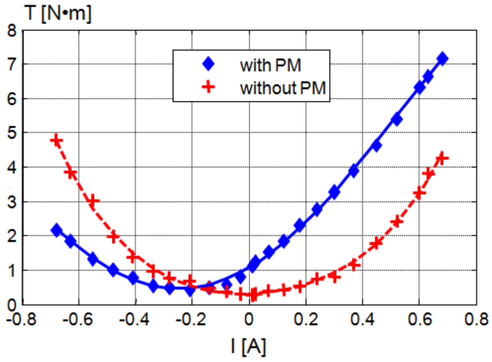

Fig.4. Clutching torque versus coil current $T_C(I)$ – results of the measurements – for two type of magnetic excitation: +– only current carrying coil (without PM), ♦ – hybrid (with PM and current carrying coil) [8] at a temperature of 22 °C

Work states of the MR clutch

The clutch work states can be described by balance of power: power transported by the clutch, difference of input and output power, and also by mechanical parameters: speed n and torque T (Fig.5).

The main loss of the transported power P_{slip} takes place when the speed of driven member n_2 differs from the speed of driving member n_1 – when a clutch operates at slip. In this state, the slip s is unequal to zero

(1) $$s = \frac{n_1 - n_2}{n_1}$$

During work of the clutch the slip s can take values $-1<s\leq 1$. The presented laboratory stand (Fig. 3) allows testing the MR clutch in three work states: the engaged state (s=0), the slip state (0<s<1) and the full slip state (s=1).

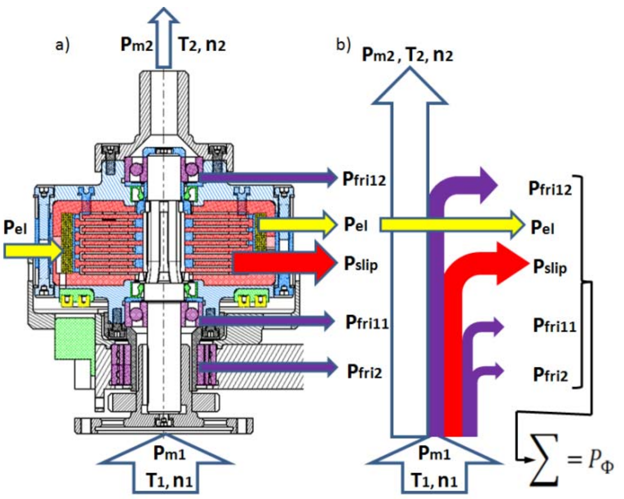

Fig.5. Diagram of power balance: a) the flow of power, b) sources of thermal power P_Φ in the clutch

The work state of the clutch when slip s<0 will be achieved in drive systems if the part of drive system connected to driven member has big moment of inertia and the motor reverses.

The electric input power P_{el} which causes changes of MR fluid viscosity, which is the control power as well, is converted into heat energy. Losses of mechanical power – power of friction in bearings P_{fri} occur in all work states. All losses of power and electric input power P_{el} are the thermal power P_Φ.

The most dangerous work state for the MR clutch is full slip state, because all input power are converted into thermal power P_Φ.

Thermal measurements of the MR clutch

Thermal measurements of the MR clutch were made in two cases: measurements of a temperature ϑ of the MR clutch during an electric heating (Fig.6) and measurements of an influence of a temperature ϑ on a clutching torque T_C made during the electric heating as well. During the electric heating the coil of the clutch was supplied with set value of current (I=0.4, 0.5, 0.6 A) and the speeds n_1,n_2=0.

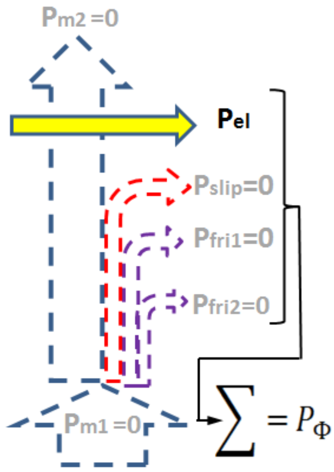

Fig.6. Source of the thermal power P_Φ in the clutch during the electric heating

A temperature ϑ of the MR clutch was measured using the infrared camera FLIR A325 connected with a computer by Ethernet (Fig.7).

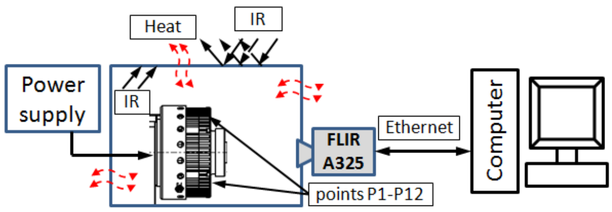

Fig.7. Schema of the thermal measurement system

The MR clutch was located under a special cover, which insulates against external infrared radiation and enables a natural heat exchange with an environment.

The image from the infrared camera (Fig.8) and heating curves of the MR clutch (Fig.9) are the examplary results of the thermal measuremets.

In the Figure 9 are shown twelve heating curves for twelve points P1÷P12 uniformly arranged on the circumference of the clutch on the front surface. There is also the heating curve, which is averaged over the point's curves.

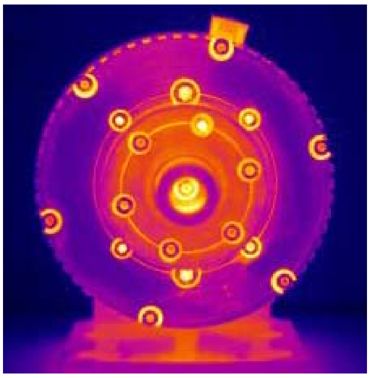

Fig.8. The image of the front surface of the MR clutch from the infrared camera recorded during the electric heating

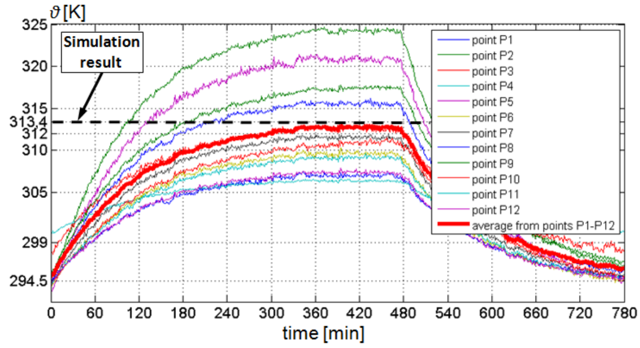

Fig.9. Results of measurements and simulation of thermal researches

The second part of thermal research – measurements of an influence of the temperature ϑ on the clutching torque T_C – was performed during electric heating. The clutching torque T_C was measured with time interval 1 hour. For the measurement of T_C the induction motor was supplied for few seconds – in this time the speed $n_1 \neq 0$. The results of the measurements are shown in the Figure 10. There is shown the clutching torque T_C versus temperature rise $\Delta\vartheta$ (2) for three value of coil current I=0.4, 0.5, 0.6 A.

$$\Delta\vartheta = \vartheta_{AV} - \vartheta_{ref} \tag{2}$$

where: ϑ_{AV} is the average of temperature ϑ measured in twelve points P1÷P12 and ϑ_{ref} is the temperature reference 295 K.

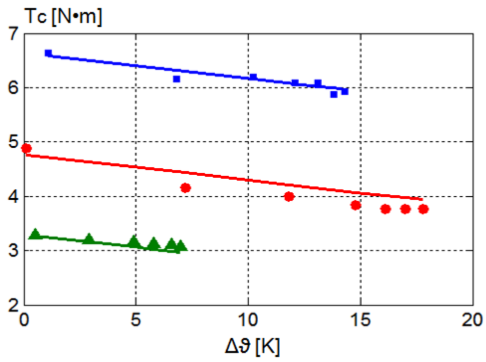

Fig.10. Results of measurements of influence of temperature ϑ on clutching torque T_C, for three coil current: ▲ – I=0.4 A, ■ – I=0.5 A, ● – I=0.6 A

The presented relation $T_C(\Delta\vartheta)$ are approximated by linear function:

$$T_C = T_{C0} - a\Delta\vartheta \tag{3}$$

where: T_{C0} is determined from curve $T_C(I)$ and a=0.047 N·m/K.

Thermal field analysis of the MR clutch at full slip state

For the analysis of the operating properties of the MR clutch in chosen work states the thermal model of the clutch was made in FEMM (Fig.11), which enables steady-state thermal analyses.

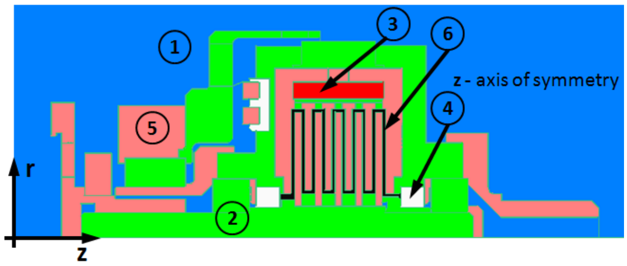

Fig.11. Axisymetrical thermal model of the clutch: 1) air, 2) stainless nonmagnetic steel, 3) copper, 4) plastic, 5) carbon steel, 6) MR fluid

The analysis was performed for the most dangerous work state– full slip state. In this state the power losses are the biggest and the clutch heats up the most. For this state the output power P_{m2} is equal to zero (T_2=0, n_2=0). The power loss P_{slip} connected with MR fluid results from the speed n_1 and the clutching torque T_C. In the model P_{slip} are assigned to "MR fluid" area assuming a uniform distribution over the entire volume. The second part of thermal power – electric power P_{el} is related to the resistance R_C of the clutch coil and to the coil current I, which is determined by $T_C(I)$ curve. The influence of the temperature on the torque T_C (3) and influence of the temperature on the coil resistance R_C (resistance of copper winding) is taken into account. In the analysis power loss in the bearings are taken into account. In the thermal model a boundary condition as natural convection was assumed. The exemplary result of the thermal calculations as temperature distribution field in MR clutch is shown in the Figure 12.

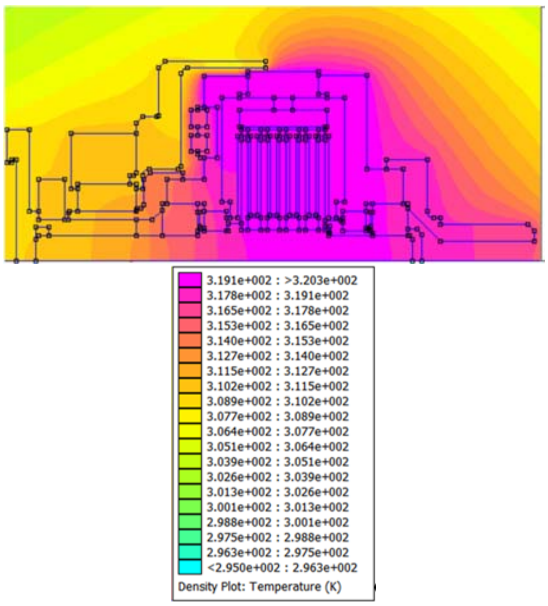

Fig.12. Result of thermal field analysis – temperature distribution field in MR clutch

The final results of the thermal calculations as operation range of the clutch is shown in the Figure 13, in which the available range is limited by maximum temperature of the clutch 400 K (127 C). The maximum temperature is limited by ignition temperature of MR fluid [9].

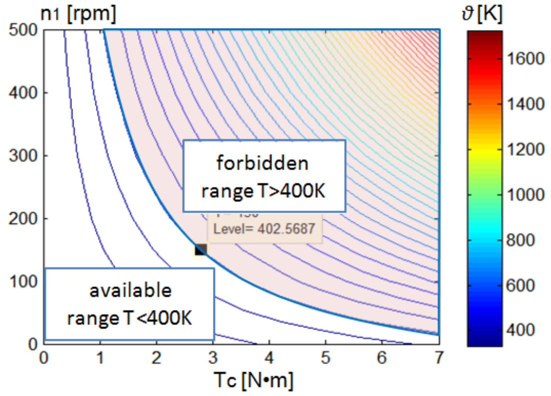

Fig.13. Available and not available operation range for MR clutch working in full slip state

Summary

The thermal analysis based on measured electromechanical $T_C(I)$ curve and measured influence of the temperature on the torque T_C and also geometric and material parameters of the MR clutch allows to determine the forbidden range of work, which is an important guideline for creating a control strategy of the MR clutch.

REFERENCES

[1] M. Benetti, E. Dragoni, Nonlinear Magnetic Analysis of Multi-plate Magnetorheological Brakes and Clutches, *Proc. of the COMSOL Users Conference*, Milano, 2006
[2] S. Chen, J. Huang, H. Shu, T. Sun, K. Jian, Analysis and Testing of Chain Characteristics and Rheological Properties for Magnetorheological Fluid, *Advances in Materials Science and Engineering*, Volume 2013
[3] H. Y. Fu, T. Zu Zhi, W. N. Nan, The Steady-state and Transient Temperature Field of a Magnetorheological Fluid Transmission Device, *International Conference on Computer, Mechatronics, Control and Electronic Engineering* (CMCE), 2010, 149-153
[4] C. Jędryczka, FE analysis of electromagnetic field coupled with fluid dynamics in a MR clutch, *COMPEL*, , Vol. 26, No. 4, (2007), 1028-1036
[5] P. Kielan, P. Kowol, Z. Pilch, Conception of the electronic controlled magneto-rheological clutch, *Electrical Review*, vol. 87, no. 3 (2011), 93–95
[6] W. Szeląg, *Przetworniki elektromagnetyczne z cieczą magnetoreologiczną,* Poznań, Wydawnictwo Politechniki Poznańskiej, 2010
[7] S. Yuliang; Y. Shaopu; P. Cunzhi, Experimental research of magneto-rheological fluid clutch, *IEEE International Conference on Vehicular Electronics and Safety*, 2005, 104-107
[8] Report from the Grant N N510 355337 sponsored by Polish Ministry of Science in years 2009-2011
[9] Bulletins of Lord Corporation: www.lord.com

Autorzy: Paweł KOWOL, Zbigniew PILCH
Silesian University of Technology
Pawel.Kowol@polsl.pl