doi: 10.21495/71-0-323

25th International Conference
ENGINEERING MECHANICS 2019
Svratka, Czech Republic, 13 – 16 May 2019

STRIBECK CURVES OF SELECTED MAGNETORHEOLOGICAL FLUIDS

J. Roupec*, Z. Strecker*, M. Kubík*, O. Macháček*, J. Smilek, M. Smilková****

Abstract: *The papers deals with the measurement of Stribeck curves of magnetorheological (MR) fluids and it compares them with common hydraulic oil Paramo HM 32 and synthetic liquid hydrocarbon PAO4 using as a base oil for many products. The MR fluid MRF-122ED, MRF-132DG and MRF-140CG by Lord Corporation were tested. The results show that all fluids behave identical at boundary lubrication, but EHD regime comes on for MR fluid at significantly higher COF (0.08) than at HM 32 (0,045) or PAO4 (0,03). Such description of lubricating features of MR fluids, has never been published before. This contribution also describes in detail the settings of measurement and nears details of data analysis.*

Keywords: coefficient of friction, Stribeck curve, magnetorheological fluid, pin on plate, MR damper

1. Introduction

Adaptive or semi-active dampers are being used in a variety of technical applications, if the more sophisticated or smart damping is required. These dampers enable a change in damping forces, as the control system demands. Magnetorheological (MR) dampers belong into the group of smart damping elements. They enable a change of damping force in the great range and the switching between two damping curves can be reached within 1 ms (Strecker et al., 2018). These dampers are filled with MR fluid instead of hydraulic oil. MR fluid is the suspension of micron-sized particles, which are usually made of pure iron because of magnetic properties. These particles are suspended in the carrier fluid, for instance water, silicon oil or, in most cases, synthetic hydrocarbon as polyalphaolefin showing high viscosity index and very good oxidation resistance. When the magnetic field is applied, the ferromagnetic particles are concatenated into chain formation along the magnetic flux lines and cohesion of these formation causes the increase in apparent viscosity of MR fluid (Pappas and Klingenberg, 2006), which leads to increase in the hydraulic resistance of the piston in the MR damper, and subsequently an increase in damping forces.

The applicability of these dampers has several limitations. The main issue is the sedimentation stability of MR fluid (Roupec et al., 2017), increase of MR fluid consistency during the loading called as an In-Use-Thickening (Mazůrek et al., 2013) and the last one is the high abrasiveness and bad lubricating properties of MR fluid. Lubricating properties can be described by coefficient of friction (COF). Jolly (1999), Sohn (2009), Song (2013), Wong (2001) or Zhang (2014) measured COF of Lord MRF-132DG. They used various tester configuration and they measured COF at various sliding speeds, but every time only for one value of sliding speed. However, the COF has not been measured for wide sliding speed interval.

The main aim is to provide a trend of COF in a wide range of lubrication condition as a boundary, mixed film, elastohydrodynamic and hydrodynamic lubrication. This results can be described by a Stribeck curve.

2. Materials and Methods

Tests were performed on tribometer Bruker UMT TriboLab (fig. 2a) with a pin-on-disc configuration (fig. 2b). A hardened ball bearing with a diameter of 6.35 mm was used as a pin and a hardened tool steel

* Faculty of Mechanical Engineering, Brno University of Technology, Technická 2;616 69, Brno; CZ, roupec.j@fme.vutbr.cz

** Faculty of Chemistry, Brno University of Technology, Purkyňova 118, 612 00, Brno; CZ

as a disc. The disc had to be gently grinded and polished up to less than Ra 0.025 μm to avoiding the seizure at high speed (see fig.1a).

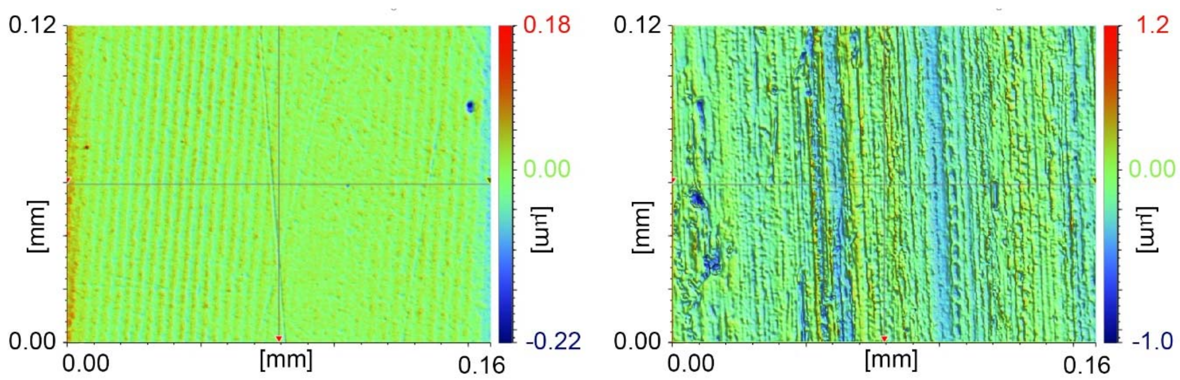

Fig. 1: (a) polished disc – Ra 0.014 μm; (b) track roughness after test – Ra 0.110 μm.

The measurement was carried out for temperatures of 40 °C. The normal force was altered from 1 to 20 N in dependence on sliding speed. The revolution of rotary test module was set according to required sliding speed and radius of the pin. To measure of Stribeck curve, the sliding speed was changed from 5 to 5,000 mm/s in 24 steps, which approximately corresponds to 2,400 rpm for maximal sliding speed. During this procedure, the hardened ball as a pin was twice turned to avoiding of contact seizure because of pin wear and high rotational speed. The measurement was repeated two times for each sample and for each measurement, the new radius, new pin and new tested fluid were used.

a) b)

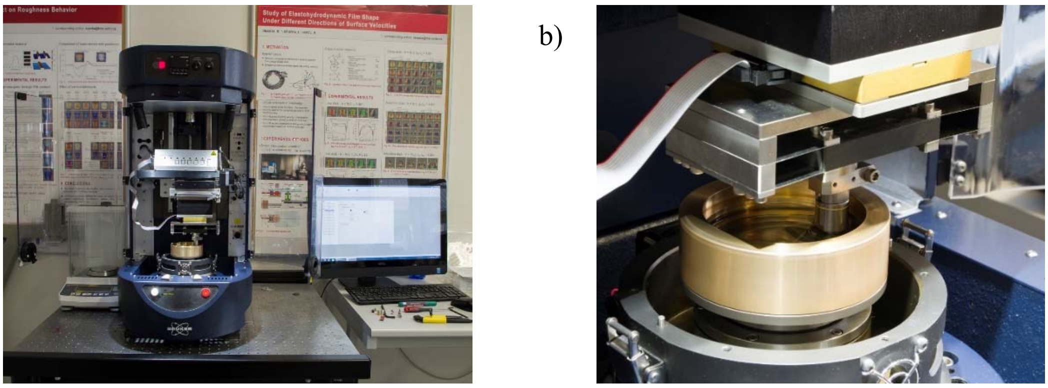

Fig. 2: (a) Tribometer UMT Bruker; (b) pin-on-disc configuration with heating module.

Three Lord MR fluids (MRF-122EG, MRF-132DG and MRF-140CG) were compared with base oil from the group of synthetic liquid hydrocarbons (poly-alpha-olefin) and with common hydraulic oil Paramo HM32. The tested MR fluids differ in iron particles concentration from 22 to 40 vol. %. The particle size and distribution was measured by scanning electron microscope FEG SEM ZEISS Ultra Plus and analyzed by own script using tools for picture analysis in Matlab. The average size (2.02 μm) and distribution (according Q3) is identical for all MR fluids (fig. 3).

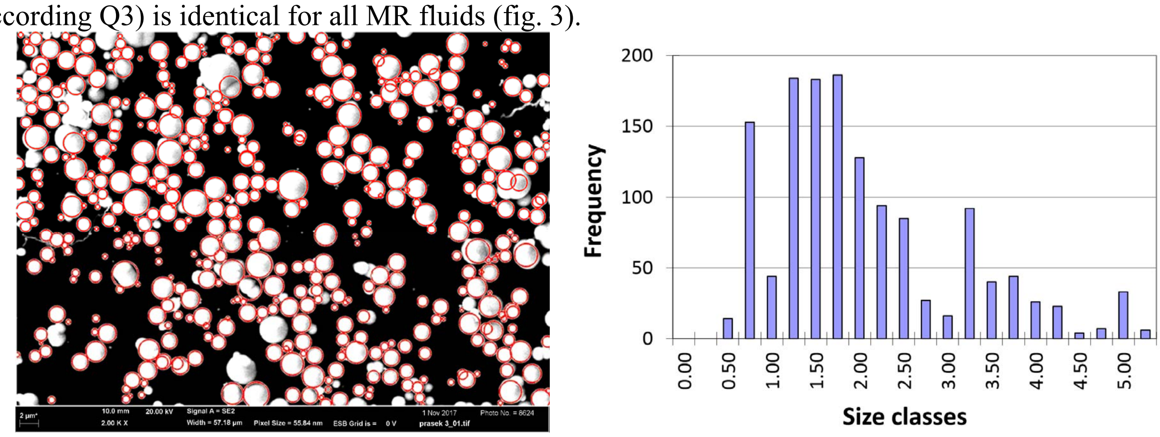

Fig. 3: (a) SEM picture of centrifuging particles; (b) histogram for 1,399 detected particles.

For each step (one step = one speed), the 16 change in direction of rotation was programmed for better flooded of contact (see fig. 4). Sometimes, the data included four types of instabilities: (i) high level of noise probably caused by resonance of metal strip keeping the holder of pin (see fig. 2b); (ii) unsymmetrical friction force for one and other direction probably caused by seizure or bad flooding of contact; (iii) increase in friction force during one step caused by seizure, (iv) peak in friction force caused by static friction when the direction is changing. The delivered SW with tribometer cannot recognize these phenomena and use them into the evaluation, which leads to misleading results. Therefore, the new software for data evaluation was created.

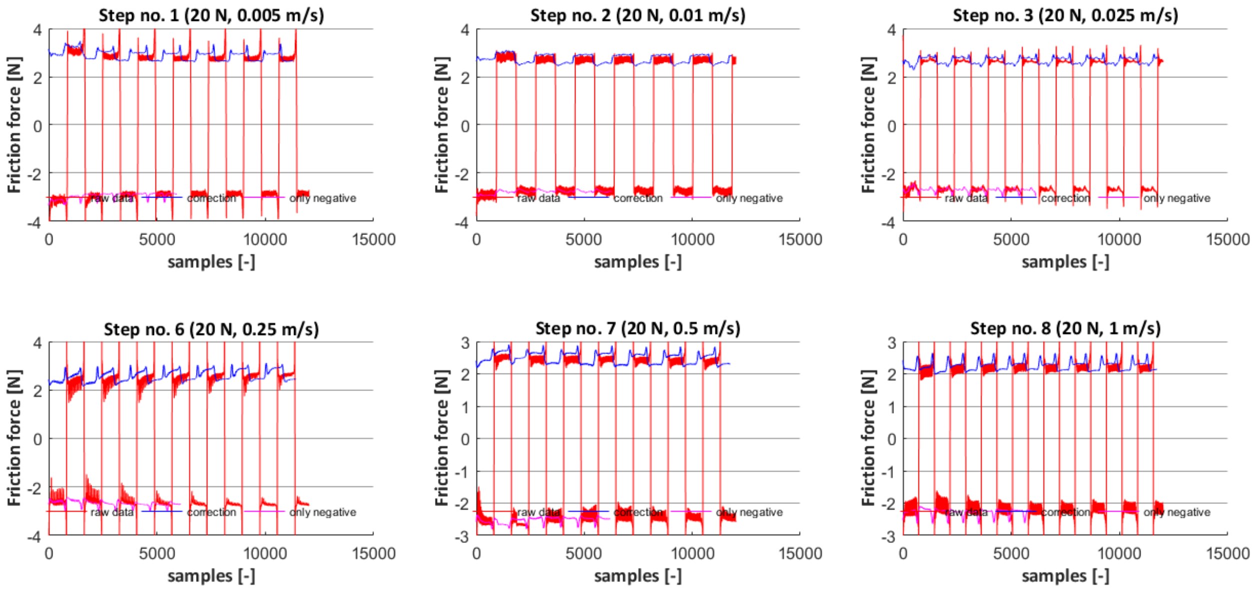

Fig. 4: Detail of selected steps after evaluation.

The delivered SW does not enable to calculate a relation among relative sliding speed of surfaces in contact v, normal force F_z and dynamic fluid viscosity η and draw it on x-axis. This relation is given by (1):

$$x\ axis\ value\ = \frac{\eta \cdot v}{F_z} \tag{1}$$

Dynamic viscosity was measured on viscometer Haake RotoVisco 1 with sensor DG41 (see fig.5). When the measured COF was not identical, the corresponding step was missed, see fig.5b.

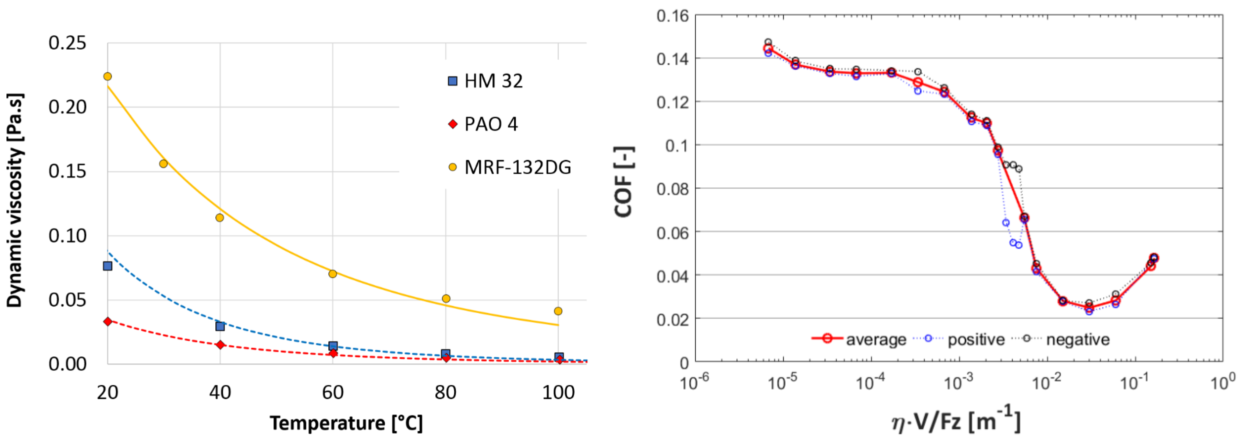

Fig. 5: (a) dynamic viscosity used for Stribeck curve calculation; (b) Stribeck curve analysis of PAO 4.

3. Results

The fig. 6 compares the Stribeck curves of measured fluid (PAO4, HM32 and MRF-132DG) for temperature of 40 °C and contact pair hardened steel-on-hardened steel. It can be seen, that boundary, mixed, elastohydrodynamic and hydrodynamic regime of lubrication is measured. It is surprising, that the

COF in boundary lubrication regime is almost identical for all fluids, despite of present of iron particles in MR fluid. However, EHD regime comes on at significantly higher COF and then it rapidly rises.

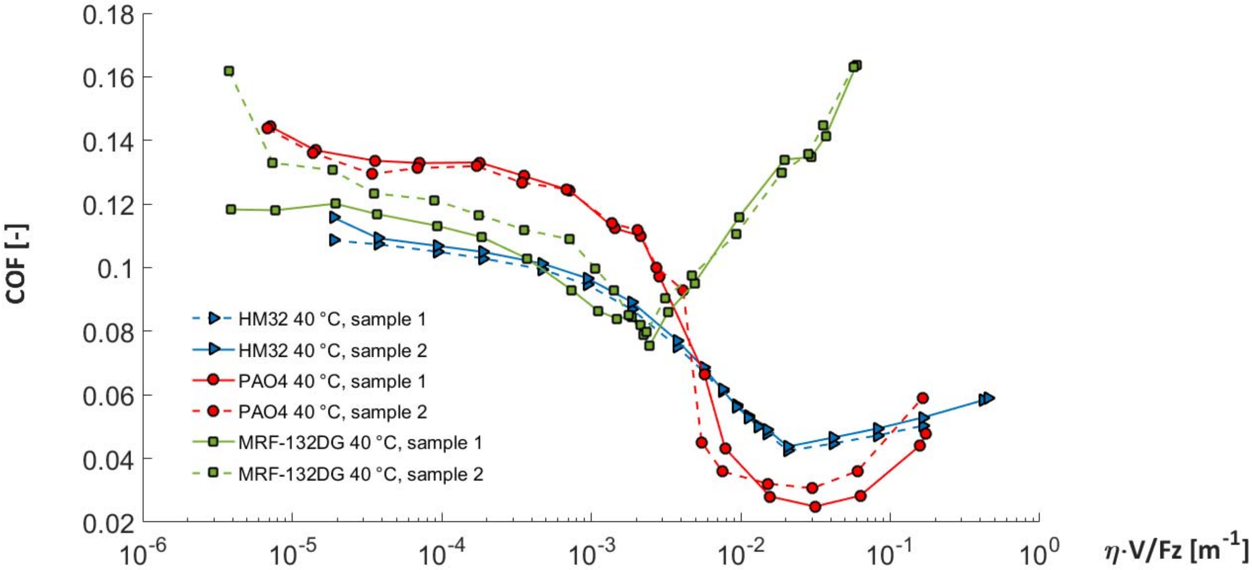

Fig. 6: Stribeck curves comparison of PAO 4, HM 32 and magnetorheological fluid MRF-132DG.

4. Conclusion

Within solution the international project with INHA University, the Stribeck curves for MR fluid were measured for the first time. The results in boundary correspond with results of Jolly (1999), Song (2013) and Wong (2001), but they are in sharp contrast to the results of Zhang (2014) and Sohn (2009). This research will be continue with testing of various material contact pairs and various operating conditions.

Acknowledgement

We highly appreciate the kind sponsorship of the Grant Agency, which granted as much as they could. The research leading to these results has received funding from GAČR 17-10660J.

References

Jolly, M.R., Bender, J.W. and Carlson, J.D. (1999) Properties and Applications of Commercial Magnetorheological Fluids. *Journal of Intelligent Material Systems and Structures*, 10, 1, pp 5–13.

Mazůrek, I., Roupec, J., Klapka, M. and Strecker, Z. (2013) Load and rheometric unit for the test of magnetorheological fluid. *Meccanica*, 48, 3, pp 631–641.

Pappas, Y. and Klingenberg, D.J. (2006) Simulations of magnetorheological suspensions in Poiseuille flow. *Rheologica Acta*, 45, 5, pp 621–629.

Roupec, J., Berka, P., Mazůrek, I., Strecker, Z., Kubík, M., Macháček, O. and Andani, M.T. (2017) A novel method for measurement of MR fluid sedimentation and its experimental verification. *Smart Materials and Structures*, 26, 10, p 107001.

Sohn, J.W., Choi, S.B., Lee, C.H. and Cho, M.W. (2009) Wear Characteristics of Magnetorheological Fluid under Boundary Lubrication. *Advanced Materials Research*, 79–82, pp 83–86.

Song, W.L., Lee, C.H. and Choi, S.-B. (2013) Sliding wear behavior of magnetorheological fluid for brass with and without magnetic field. *The Nonferrous Metals Society of China*, 23, 2, pp 400–405.

Strecker, Z., Kubík, M., Vítek, P., Roupec, J., Paloušek, D. and Šreibr, V. (2019) Structured magnetic circuit for magnetorheological damper made by selective laser melting technology. *Smart Materials and Structures*, 28, 4.

Strecker, Z., Roupec, J., Mazůrek, I., Macháček, O. and Kubík, M. (2018) Influence of response time of magnetorheological valve in Skyhook controlled three-parameter damping system. *Advances in Mechanical Engineering*, 10, 11, p 168781401881119.

Wong, P., Bullough, W., Feng, C. and Lingard, S. (2001) Tribological performance of a magneto-rheological suspension. *Wear*, 247, 1, pp 33–40.

Zhang, G, P., Lee, K.H. and Lee, C.H. (2014) Reciprocating friction characteristics of magneto-rheological fluid for aluminum under magnetic field. *The Nonferrous Metals Society of China*, 24, 1, pp 171–176.