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THE SETTING OF CFD MODEL WITH MAGNETORHEOLOGICAL FLUID AND ITS INFLUENCE ON THE RESULTS

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Abstract: *The paper deals with the setting of the CFD model with a magnetorheological fluid and its influence on the results. The rheological behaviour of MR fluid under magnetic field was described by the Bingham constitutive equation. Two magnetorheological valves based on parallel plate simplification are presented. The influence of the number of elements and setting BIAS factor across the gap, entrance and exit losses and velocity profile development on the pressure drop is carried out. The results indicate that for accurate computation the minimum number of elements across the gap is 30 and a suitable BIAS factor is 1.5 or more. The influence of entrance and exit losses on pressure drop in the gap is more significant for conventional hydraulic oil than for MR fluid. These results were used in slit-flow rheometer developing.*

Keywords: Magnetorheological fluid, MR valve, CFD simulation of MR damper, flow model.

1. Introduction

Magnetorheological (MR) fluid is a smart material which exhibits a rapid and fast change of rheological behavior in the magnetic field. The MR fluid is composed of micro-scale ferromagnetic particles, a carrier fluid, and additives. The MR damper is a device that can benefit from the special properties of MR fluid where the yield stress is generated in tens of kPa by the magnetic field. The MR damper is used in several technical applications in automotive, civil engineering or aviation. The performance of the system with the MR damper can be increased by using fast semi-active control where the designed MR damper with a short response time is necessary (Strecker et al. 2018; Kubík et al. 2017). The flow modelling of the MR damper, namely the MR valve, is necessary for the design process. The most useful classification of MR valve flow models is: steady-state and transient. The steady-state models are further divided into the analytical models and computational fluid dynamics models. The steady-state models are usually used in the MR valve dimensioning. The transient models provide insight into the flow dynamics of the MR valve.

The steady-state analytical models are used during MR valve designing because of their fast computation and simplicity. The MR fluid non-Newtonian behavior in the magnetic field is described by rheological constitutive models such as Bingham, Herschel-Buckley, etc. The geometry of the MR valve in the damper is usually simplified in the form of two parallel plates. Most authors use models based on a non-dimensional approach involving all key geometric and material variables (Goldasz and Sapinski 2012; Phillips 1969). Phillips defined the non-dimensional approach based on dimensionless pressure P and dimensionless yield stress T (Phillips 1969). Goldasz published the approach based on pressure number G and plasticity number S (Goldasz and Sapinski 2012).

The computational fluid dynamics (CFD) models solve the more complex geometry of the MR valve, non-uniform distribution of the yield stress, and development of velocity profile, etc. However, this approach is time-consuming and a computing cluster is necessary. The significant advantage of this approach is the possibility of creating co-simulation with magnetic or thermal FEM models. The published CFD models of the MR damper are rare. Zekeriya (Zekeriya and Tahsin 2012) published the CFD model of the MR damper

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based on the Bingham model. This analysis was carried out by CFX tools of Ansys. Goldasz (Gołdasz and Sapiński 2015) described the squeeze mode of the MR damper by CFD simulation. The model was developed in software Ansys Fluent R16. However, it is not clear how to set the CFD analysis of the MR valve from available papers. The main aim of our research is to introduce the CFD model of the MR valve and determine the main parameters which significantly influence the calculation of the pressure drop.

2. Materials and methods

2.1. Analytical model of the MR valve

The frequently used flow model for the MR valve design is based on the non-dimensional group P-T. The pressure drop of the MR valve was determined by the non-dimensional group P-T and Bingham model – see equations in (Yang et al. 2002). In this model, the geometry was simplified into two parallel plates.

2.2. Geometry in CFD simulation

Two different simplified MR valve geometry are presented, specifically the parallel plates (model 1) and tubes with parallel plates (model 2). Model 1 was used for calculating the pressure drop without influence of entrance and exit losses. The influence of the elements number across the gap and BIAS factor set was studied in model 1. The entrance and exit losses or development velocity profile was studied in model 2. The gap size $g = 0.6\ mm$, gap length $L_a = 16\ mm$, gap width $w = 51\ mm$ – see Fig. 1.

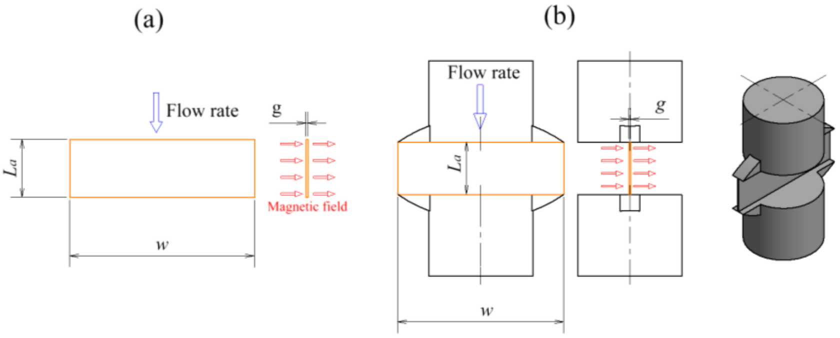


Fig. 1: (a) The simplification of MR valve geometry into two parallel plates (model 1) and (b) parallel plates with hydraulic tubes and transitional parts (model 2).

2.3. CFD simulation general settings

The software Ansys CFX 19.2 was used. The Inlet boundary condition was set on the entrance region of the flow domain, and the Outlet with relative pressure of 1 bar was set on the exit. The wall was considered with no slip flow. The Reynolds number for most of the MR damper designs is under 1000. Therefore, laminar flow can be assumed. The Reynolds number achieved a value of 490 for the presented geometry and the mean velocity in the gap was 15 m/s. In the simulation, the MR fluid is assumed as continuous fluid and its behaviour under the magnetic field is described by Bingham a constitutive model. This model was transformed into a form for apparent viscosity – see equation (1) and (2). It was necessary to set the limit of shear rate otherwise the apparent viscosity would reach an infinitely large value near the zero shear rate and convergence could be problem.

$$\eta = \eta_0 + \frac{\tau_0(H)}{\dot{\gamma}}, \qquad \dot{\gamma} > \dot{\gamma}_c, \tag{1}$$

$$\eta = \eta_0 + \tau_0(H)\frac{2-\frac{\dot{\gamma}}{\dot{\gamma}_c}}{\dot{\gamma}_c}, \qquad \dot{\gamma}_c > \dot{\gamma}, \tag{2}$$

where η is the apparent viscosity, $\dot{\gamma}$ is the shear rate in MR fluid, $\dot{\gamma}_c$ is the shear rate limit, η_0 is the Bingham viscosity, H is the magnetic flux intensity and a $\tau_0(H)$ is the yield stress of the MR fluid. The MR fluid Lord 132-DG with Bingham viscosity $\eta_0 = 0.112\ Pa.s$ at 40 °C was used. The lower limit of shear rate $\dot{\gamma}_c = 0.001\ s^{-1}$and upper limit of shear rate $\dot{\gamma}_u = 100\ 000\ s^{-1}$ were used. The presented equation was applied by script on the flow domain with magnetic field. The main advantage of this approach is the possibility of changing the MR fluid yield stress across the length and thickness of the gap. The average element size across the width and length of the gap was set to 0.2 mm. The number of elements across the gap thickness (g) was tested.

2.4. Parameter sensitivity study

The influence of the elements number across the gap thickness was tested in the range from 6 to 50 and the resulting pressure drop was evaluated for three different mean velocities in the gap (0.5, 1 and 2 m/s) and two yield stresses of MR fluid (10 and 20 kPa). The BIAS factor is the next important parameter influencing the degree of refining elements near the wall. Bias Factor is defined as the ratio of the largest edge to the smallest edge of elements. The pressure drop was again evaluated based on the varying BIAS factor for the configuration with 20 elements and the yield stress of 10 kPa. The MR fluid has a higher density (3050 kg/m^3) than hydraulic oil which significantly affects the losses of the valve on its entrance and exit. These losses were compared to an MR fluid with a 10 kPa yield stress and hydraulic oil in the valve geometry showing the same pressure drop (damping forces) at a piston velocity of 0.4 m/s. This geometry is different. For hydraulic oil, the gap size of 0.22 mm was considered. The losses were expressed as the difference between the pressured drop from model 2 and model 1. Model 1 represents pure viscous losses. For hydraulic oil, the dynamic viscosity 0.013 Pa.s at 40 °C and density 865 kg/m^3 was used.

3. Results

3.1. Number of elements across the gap

Fig. 2 shows the resulting pressure drop in dependence on the elements number across the gap. The value of the pressure drop is stabilized for 30 or more elements for both yield stresses. The flow velocity and yield stress have no influence on results. The 30 elements appear to be the minimum value for accurate CFD simulation of the valve generally. A higher number of elements can be used, but it is unnecessary and time-consuming.

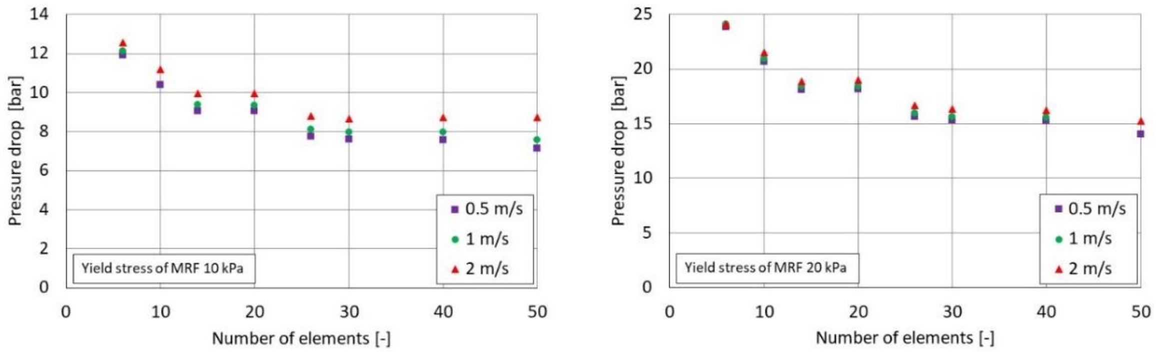


Fig. 2: Influence of the number of the elements for yield stress 10 kPa (left) and 20 kPa (right).

3.2. BIAS factor settings

The BIAS factor setting has a significant influence on the pressure drop. This parameter should be set to a minimum value of 1.5 or higher – see Fig.3 left. When this value is lower, the pressure drop is inaccurately computed.

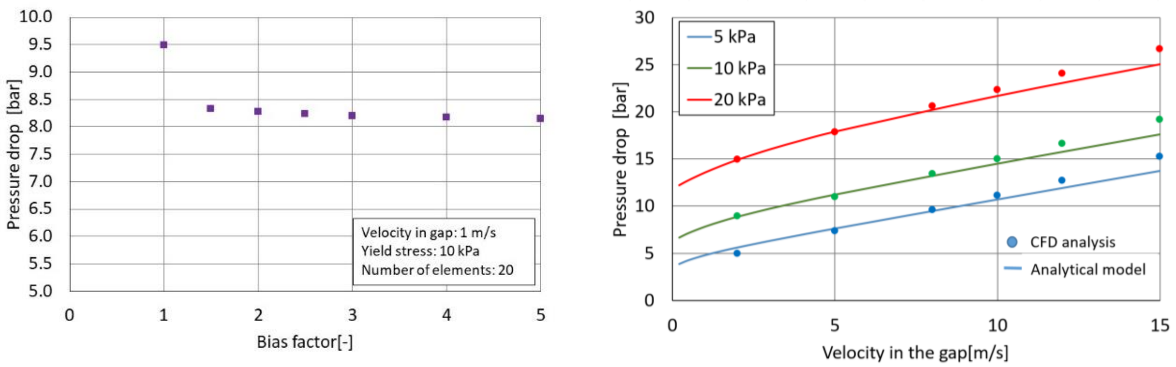


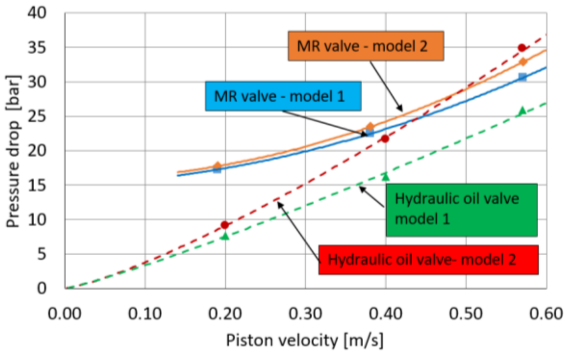
Fig. 3: Influence of the BIAS factor settings (left), comparison of CFD and analytical model (right).

3.3. Comparison of CFD analysis and analytical model

The results from the CFD simulation and analytical model in parallel plate geometry (model 1) were compared for three different yield stresses (5, 10 and 15 kPa) at a mean velocity in the gap from 2 to 15 m/s – see Fig.3 right. The CFD and analytical model are in strong agreement, thus the CFD model (model 1) is verified and this approach can be used for entrance and exit losses.

3.4. Influence of entrance and exit losses

The difference in pressure drop between model 2 and model 1 should be the effect of entrance and exit losses. The results show that the problem of entrance and exit losses is more important with common hydraulic oil than with MR fluid with yield stress 15 kPa – see Fig. 4 left. The velocity profile in the tested MR valve is fully developed after 0.5 mm. This profile developing has minimal influence on the resulting pressure drop (see Fig.4 right), which was tested on the geometry of a parallel plate (model 1), when the fully developed profile (red curve) was set as an initial condition.



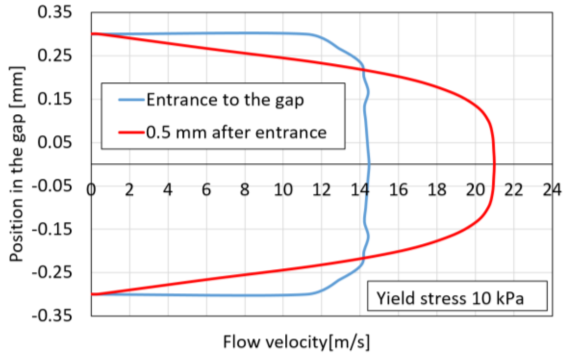


Fig. 4: Influence of entrance and exit losses (left), development velocity profile at velocity 15 m/s (right).

4. Conclusion

In this paper, the setting of CFD simulation with MR fluid and its influence on the results were presented. The results are summarized in the following points: laminar flow can be considered because the Reynolds number is low; the minimum number of elements through the thickness of the gap is 30; BIAS factor should be set to 1.5 or higher; the development of the velocity profile in the gap with MR fluid is insignificant in terms of the pressure drop of the MR valve (length 16 mm); entrance and exit losses of the MR valve are less significant than in the case of hydraulic oil.

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