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Modelling of Magnetorheological Fluids with Combined Lattice Boltzmann and Discrete Element Approach

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Abstract. A combined lattice Boltzmann and discrete element approach is proposed for numerical modelling of magnetorheological fluids. In its formulation, the particle dynamics is simulated by the discrete element method, while the fluid field is resolved with the lattice Boltzmann method. The coupling between the fluid and the particles are realized through the hydrodynamic interactions. Procedures for computing magnetic, contact and hydrodynamic forces are discussed in detail. The applicability of the proposed solution procedure is illustrated via a two-stage simulation of a MR fluid problem with four different particle volume fractions. At the first stage, simulations are performed for the particle chain formation upon application of an external magnetic field; and at the second stage, the rheological properties of the MR fluid under different shear loading conditions are investigated with the particle chains established at the first stage as the initial configuration.

AMS subject classifications: 65Z

Key words: Magnetorheological fluids, particle dynamics, rheological properties, magnetic interaction models, lattice Boltzmann method, discrete element method.

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1 Introduction

Since the discovery of magnetorheological fluids (MR fluids) by American inventor Jacob Rabinow [23] in the 1940s, the MR technology has found many control-based applications such as dampers, shock absorbers, brakes and clutches in automotive, aerospace and some other industries. A structure based on MR fluids might be the next generation in

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design for products where power density, accuracy and dynamic performance are the key features [21].

A MR fluid is a type of smart fluid. It consists of micron-sized magnetizable particles dispersed in a non-magnetic carrier fluid. In the absence of a magnetic field, the rheological behaviour of a MR fluid is basically that of the carrier fluid, except that the suspended magnetizable particles makes the fluid 'thicker'. When subjected to an external magnetic field, the particles become magnetized and acquire a dipole moment. Due to magnetic dipolar interactions, the particles line up and form chainlike structures in the direction of the applied field. This change in the suspension microstructure significantly alters the rheological properties of the fluid. The viscosity of the fluid is increased as the fluid motion is largely restricted by the particle chains. Also the yield stress of the fluid increases with the applied magnetic field strength and can be controlled very accurately. Besides, the response of the MR fluid to the applied magnetic field is usually rapid (in milliseconds). The MR effect is also reversible. When the magnetic field is removed, the original condition of the fluid is re-established [21].

Experimental and theoretical studies have been reported to better understand and predict the behaviour of MR fluids. Particularly from the design prospective it is important to establish the quantitative relationship between the rheological properties (viscosity, yield stress etc) and the volume concentration fraction of the particles and their magnetic properties as well as the intensity of the applied magnetic field. Due to the limitations in the experiments and over-simplifications in the theoretical analysis, numerical modelling has become increasingly important in recent years as a powerful prediction tool for modelling the rheological behavior of MR fluids.

For instance, Ly *et al.* [19] performed two-dimensional particle dynamics simulations of MR fluids, where the motion of the particles was governed by magnetic, hydrodynamic, and repulsive interactions; fluid-particle interactions were accounted for via Stokes' drag while inter-particle repulsions were modelled through approximate hard-sphere rejections; magnetostatic forces were derived from the solution of (steady) Maxwell's equations by employing a fast multipole method on a boundary integral formulation. Kang *et al.* [14] recently developed a direct numerical simulation method based on the Maxwell stress tensor and a fictitious domain method. Particles were assumed to be non-Brownian with negligible inertia. Rigid body motions of particles in two-dimensions were described by a rigid-ring description implemented by Lagrange multipliers. The magnetic force was represented by the divergence of the Maxwell stress tensor, which acted as a body force added to the momentum balance equation. Keaveny *et al.* [15] developed a new model to accelerate the calculation of many-body dipole interactions, where each particle's magnetization was represented as a finite distribution of current density. The exact solution to the two-body problem was also presented and a technique was introduced to blend this result with a many-body dipole calculation.

Numerical simulations of MR fluids require an accurate and computationally efficient approach to fully account for magnetic, hydrodynamic and contact interactions. Firstly, the scheme to be employed should be able to effectively model contact phenomena be-