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Viscometric characterization of cobalt nanoparticle-based magnetorheological fluids using genetic algorithms

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Abstract

The rheological flow curves (shear stress vs. shear rate) of a nanoparticle cobalt-based magnetorheological fluid can be modeled using Bingham-plastic and Herschel–Bulkley constitutive models. Steady-state rheological flow curves were measured using a parallel disk rheometer for constant shear rates as a function of applied magnetic field. Genetic algorithms were used to identify constitutive model parameters from the flow curve data.

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1. Introduction

Magnetorheological (MR) fluids are a class of smart materials whose rheological properties may be varied by application of a magnetic field. These fluids are suspensions of soft magnetic particles (such as iron or cobalt) in a carrier fluid. Each particle has a dipole moment, the strength of which is roughly proportional to its diameter [1]. Upon application of a magnetic field, these dipoles align parallel to the magnetic field and form

chains. A finite stress must develop in the fluid to yield these structures. The field-dependent yield stress of these fluids is continuously controllable and this controllability has been the primary reason for their use in numerous smart actuation systems [2,3].

MR fluids have been produced with different types and sizes of magnetic carrier particles. The majority of existing MR fluids are composed of micron-scale Fe particles suspended in a nonmagnetic carrier fluid [4–10]. These MR fluids have high yield stress (20–100 kPa) due to the strength of the dipoles created by the particles. The comparatively higher yield stress over electro-rheological (ER) fluids (2–5 kPa) is one major

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advantage of MR fluids. However, the density of the particles makes them susceptible to settling in the absence of frequent mixing due to predominant gravity forces. Once sedimented, the residual magnetic attraction between particles makes redispersion difficult. The large particles also lead to unwanted abrasion of the components in contact with the fluid. Ferrofluids, which are suspensions of iron particles of less than 10 nm in diameter, have also been reported [11,12]. However, these ferrofluids do not present formation of elongated chain-like microstructures under the application of a magnetic field and they are unable to provide significant magnetoviscous effect, especially significant yield stress. Nanometer-sized particles (10–100 nm) have been introduced [13,14] with an attempt to reduce settling while maintaining useful yield stress levels. The mixture is seen to overcome the settling problem due to the predominance of thermodynamic forces [15,16] but the yield stresses obtained for the same shear rates and magnetic field levels are drastically reduced in comparison to fluids containing micron-sized particles. The yield shear stresses in these fluids are comparable with those achieved in electrorheological fluids.

We use the Bingham-plastic (BP) and Herschel–Bulkley (HB) constitutive models to characterize the rheological behavior of MR fluid. In both fluid models, it is assumed that the preyield behavior is rigid, and that the fluid flows if and only if the local shear stress is greater than the yield stress. For a BP model, once the local shear stress exceeds the yield stress, the postyield behavior is linear in that the shear stress increases linearly with shear rate (linear postyield model). The BP model employs two parameters: yield stress, τ_y , and viscosity, μ . For the HB model, once the local shear stress exceeds the yield stress, the postyield behavior is nonlinear in that the shear stress increases as a power law of shear rate (nonlinear postyield model). The HB model employs three parameters: yield stress, τ_y , consistency, K , and flow index, n . The flow index n can be used to classify the fluid; $n > 1$ indicates a shear-thickening fluid and $n < 1$ indicates a shear-thinning flow. The HB model has been used to characterize the flow of MR fluids, especially where shear thickening or thinning is seen [17–19]. A key issue is to identify

model parameters from flow curve measurements, that is, the shear stress as a function of shear rate for varying levels of applied magnetic field.

Genetic algorithms (GA) have been widely used in applications where a globally optimal solution is required. In conventional estimation methods, a model structure is chosen and the parameters of that model are calculated by minimizing an objective function. Gradient descent techniques are usually used for the minimization, but these are very susceptible to initial guesses and the obtained parameters may only be locally optimal. On the other hand, GA uses a probabilistically guided search procedure that simulates genetic evolution [20,21]. Populations with stronger fitness are identified and retained, while weaker ones are discarded. The process ensures that successive generations are fitter. The algorithm cannot be trapped in local minima since it employs random mutation procedures. The overall search procedure is stable and robust and can identify globally optimal parameters of a system.

The rheological parameters of MR fluid constitutive models can be identified from flow curves measured using a parallel disk rheometer. Flow curves were measured as a function of applied field for MR fluid with a solids loading of 40 weight percent (wt%) nanometer scale cobalt particles. The particles were aspherical in shape with an equivalent diameter of 100 nm (Fig. 1). Both the BP and HB models were fitted using a simple GA to estimate model parameters. Constraints were applied within the algorithm to ensure a monotonically increasing trend of the yield stress with increase in applied magnetic field. The identified rheological parameters provided a good model fit to measured flow curves. The parameter variations with change in applied magnetic field were smooth. Comparison of estimation errors suggest that the HB model is more accurate over the entire range of measured shear rates, but the BP model is equally good for the high shear rate regime.

2. Synthesis and testing of MR fluids

A chemical precipitation technique was employed to produce cobalt nanopowders. In this

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