A MICRO-MACRO DESCRIPTION FOR MAGNETORHEOLOGICAL FLUIDS BASED ON ENHANCED MAGNETIC DIPOLE MODEL

Chunwei Zhao[*], Xianghe Peng [*a)]
[*] *Department of Engineering Mechanics, Chongqing University, Chongqing 400044, China.*

Summary An enhanced dipole model is suggested by taking into account the effect of the magnetized particles on a magnetic field and verified with FE simulation, based on which and making use of a statistical approach a micro-macro description for magnetorheological fluids (MRFs) is formulated. It can consider the effects of all the main influencing factors, and can well replicate the main characteristics of the constitutive behavior of MRFs.

INTRODUCTION

Yield shear stress is one of the most important indexes of magnetorheological fluids (MRFs), which can be attributed to the interaction between magnetized particles. In analysis a magnetized particle is usually assumed approximately as a magnetic dipole and the additional magnetization of a dipole induced by the other magnetic dipoles is often neglected [1,2], which may lead to an incorrect estimation. The comparison between the results with the conventional dipole model and that with FE simulation shows that in the particle chain in an MRF, such kind of additional magnetization may play a significant role. An enhanced dipole model is suggested, based on which and making use of a statistical approach a micro-macro description for the yield shear stress of MRFs is formulated. The results obtained with this model agree well with those obtained with FE simulation and experiment.

AN ENHANCE DIPOLE MODEL FOR MRFs

In an applied uniform magnetic field $\mathbf{H}_0$, the additional magnetic field intensity at point i induced by dipolar j can be expressed as

$$\overset{(i)}{\mathbf{H}}_j = \chi R^3\left[\frac{(\mathbf{H}_0\cdot\mathbf{r}_{ij})\mathbf{r}_{ij}}{r_{ij}^5}-\frac{\mathbf{H}_0}{3r_{ij}^3}\right] \tag{1}$$

where R is the radius of particle, $\mathbf{r}_{ij}$ is the vector from particle i to particle j and χ is the susceptibility.

The total magnetic field at particle i is

$$\mathbf{H}_i = \mathbf{H}_0+\sum_{j\neq i}\overset{(i)}{\mathbf{H}}_j = \mathbf{H}_0+\chi R^3\sum_{j\neq i}\left[\frac{(\mathbf{H}_0\cdot\mathbf{r}_{ij})\mathbf{r}_{ij}}{r_{ij}^5}-\frac{\mathbf{H}_0}{3r_{ij}^3}\right], \tag{2}$$

The magnetic induction intensity $\mathbf{B}_j$ of particle i is $\mathbf{B}_i=\mu_0\mathbf{H}_i$, where $\mu_0=4\pi\times10^{-7}\mathrm{Hm}^{-1}$ is the permeability in free space, and the magnetic moment of a particle of radius R is $\mathbf{m}_i=(4/3)\chi\pi R^3\mathbf{H}_i$. The potential of a dipoles-system can be expressed as

$$U=-\frac{1}{2}\sum_i\mathbf{m}_i\cdot\mathbf{B}_i \tag{3}$$

The magnetic force on particle i can be derived as

$$\mathbf{F}_i=-\overset{(i)}{\nabla}U=\sum_{j\neq i}\frac{4\mu_0\pi H^2\chi^2R^6}{3r_{ij}^5}\left\{\left[\left(1-5\cos^2\theta\right)-\frac{\chi R^3}{3r_{ij}^3}\left(1+4\cos^2\theta\right)\right]\mathbf{r}_{ij}+2r_{ij}\cos\theta\left[1+\frac{\chi R^3}{6r_{ij}^3}\right]\mathbf{k}\right\} \tag{4}$$

where $\mathbf{k}$ denotes the direction of $\mathbf{H}_0$. Making use of Eq. (4) the contribution of the chain inclined with θ_i from $\mathbf{H}_0$ (Fig.1) to the resistance against the shear deformation of an MRF can be obtained as

$$T_i=\sum_{j=1}^{n-1}\frac{4\mu_0\pi H^2\chi^2R^6}{3r_j^4}\left[\left(1-5\cos^2\theta_i\right)-\frac{\chi R^3}{3r_j^3}\left(1+4\cos^2\theta_i\right)\right]\sin\theta_i \tag{5}$$

where n is the number of the particles in the chain. If the macroscopic yield shear stress of an MRF $\tau=\tau_0+\overline{\tau}$, where τ_0 is the shear stress without applying a magnetic field and the normal distribution of θ_i is assumed [2,3], one has

$$\overline{\tau}=\sum_{j=1}^{n-1}\frac{2\mu_0\varphi H^2\chi^2R^3(R+t)}{r_j^4}\int_{-\frac{\pi}{2}}^{\frac{\pi}{2}}\left[\left(1-5\cos^2\theta\right)-\frac{\chi R^3}{3r_j^3}\left(1+4\cos^2\theta\right)\right]\sin\theta\times\frac{1}{\sqrt{2\pi}\sigma}e^{\frac{(\theta-\mu)^2}{2\sigma^2}}d\theta \tag{6}$$

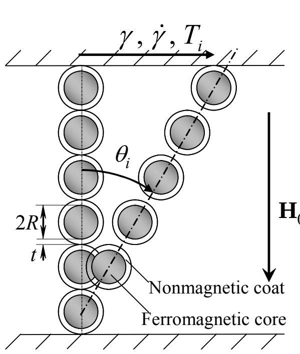

Fig.1 Deformed single chain

a) Corresponding author. Email: xhpeng@cqu.edu.cn.

where φ is the particle volume fraction, μ and σ are the mean and standard error, respectively, related to shear strain and its rate. It can be seen that the effects of H, χ, R, t (the thickness of nonferromagnetic coating), strain and strain rate on the yield shear stress can be considered in the modeling, which should be significant for the evaluation of the yield shear stress and the design if high-performance MRF. It can be shown that $n\geqslant 5$ can provide sufficient accuracy.

APPLICATION AND DISCUSSION

The variations of T against θ are shown in Fig. 2, and the variations of $\bar{\tau}$ against γ are shown in Fig. 3. It can be seen that, compared with the results obtained with the previous dipole model (DM), the results with the proposed enhanced dipole model (EDM) better match the results obtained with finite element method (FEM), implying the reasonability for EDM to be applied in the analysis of the mechanical properties of MRFs. The variations of τ against B, obtained with DM and EDM, are shown respectively in Fig. 4, it can be seen that τ increases with the increase of B, but the slope decreases as the magnetization of the particles tends to its saturation state. The variations of τ against $\dot{\gamma}$ are shown in Fig. 5, where it can be seen that τ increases with the increase of shear strain rate $\dot{\gamma}$, when it is relatively small, but it decreases when $\dot{\gamma}$ is very large. The results in Figs. 4 and 5 agree reasonably with the experimental results (EXP) [3,4].

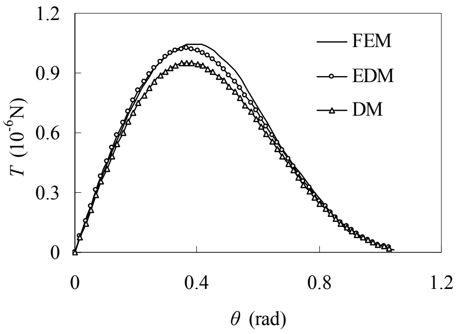

Fig. 2 Variation of T_i versus θ of a single chain

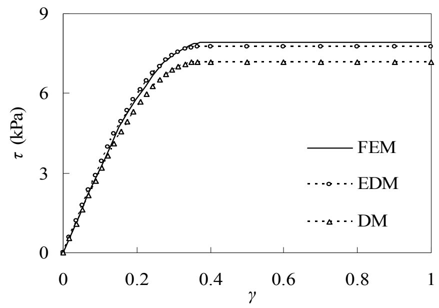

Fig. 3 Variation of τ versus γ of an MRF

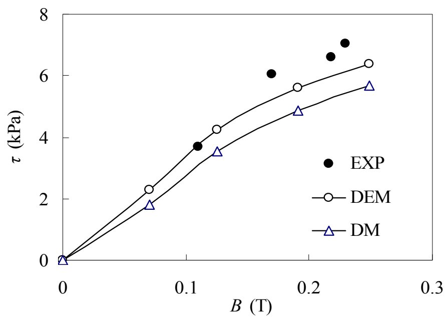

Fig. 4 Variation of τ versus B of an MRF

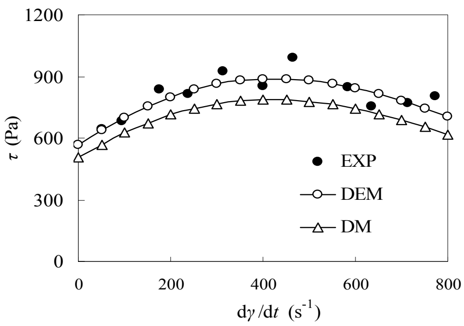

Fig. 5 Variation of τ versus dγ/dt of an MRF

CONCLUSIONS

A micro-macro analysis is developed for evaluation of the yield shear stress of magnetorheological fluids (MRFs). Starting from the FE simulation and an enhanced model for the interaction between two magnetic dipoles, the resistance of a deformed particle-chain to the shear deformation of an MRF is obtained, and the yield shear stress of the MRF is finally obtained with a statistical approach. The model can take into account the effects of the main influencing factors, and can well replicate the main characteristics of the constitutive behavior of MRFs observed in experiments.

ACKNOWLEGEMENT

The authors gratefully acknowledge the financial support to this work from NSFC under Grant Number 10872220.

References

[1] Bossis G and Lemaire E: Yield stresses in magnetic suspensions. *J. Rheol*. **35**: 1345-7,1991.

[2] Peng X, Li H.:Analysis of the magnetomechanical behavior of MRFs based on micromechanics incorporating a statistical approach. *J. Smart Materials and Structures*. **16**: 2477-2485, 2007.

[3] Jin Y and Zhou G.Y: Comparison of two Experimental Apparatuses used in Magnetorological Fluids Test. *Exp. Mechanics.* **13:** 288-293,1999.

[4] Gong R. Z., Guan J. G. and Yuan R. Z.: Properties of magnetorheological suspension for filled clusters of Cobalt-Phthalocyanine/Iron nanoparticles *Chin. Chem. Phys*. **13**: 508–12, 2000 (in Chinese).