The evolution of bending chains in magnetorheological fluid at external field

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Abstract

The behavior of bending chains in magnetorheological (MR) fluid are observed by applying a vertical magnetic field. This novel structure is stable and controllable with various magnitude of the field. The energy minimization calculation has been carried out to support our observation and to demonstrate the structure stability of the bending chain with the existing of gravity. © 2001 Published by Elsevier Science B.V.

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The key to understand and controlling the rheology of colloidal system lies in characterizing the microstructure and its response to perturbation [1]. Magnetorheological (MR) fluid, generally consisting of small magnetic particles in a liquid, offers a very clear picture that its microstructures and rheological properties are controllable through the application of an external magnetic field [2–14]. These field-induced structures can dramatically modify the rheological properties of the suspension leading to many potential applications. Under an external magnetic field, the particles in a MR suspension acquire dipole moments and aggregate to form chains in the field direction [15–18]. If the particles bear permanent dipoles, they induce stresses in the liquid phase during their reorientation process even in the single-particle domain when the dipoles are induced, in this case, the presence of permanent dipole moments leads to the formation of complex one-dimensional structures, which are stable at moderate applied fields. One of our authors and his co-authors have studied chain, ring, network, and even crystal structures formed by the microspheres in MR fluids in the previous work [8,19,20].

In this Letter, we report the new MR fluid structure with bending chains induced by the gravity field and a vertically applied magnetic field, which has not yet been observed in previous reports. We focus on the evolution of a single bending chain which is an elemental unit of the structure and calculate the internal rotations (particle rotating relative to their surrounding fluid) of the particles at various magnitudes of external magnetic field. The stable bending chain patterns we obtained based on the minimization of the total energy of the system are in excellent agreement with our experimental results.

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For the purpose of the experiments, the microspheres have been produced as described in Refs. [19, 20]. The moment-controllable magnetic particles were fabricated by selecting uniform glass microspheres with average diameter of 47 µm as an initial core, and coating a layer of nickel of thickness between 2.5 and 4 µm using chemical coating process [21]. The coated microspheres possess a small magnetic moment \( \vec{\mu} = M(\pi D^3/6)\hat{\mu} \), on the order of \( 10^{-6} \) emu, the same as that in Ref. [20], where \( D \) is the diameter of a particle and \( \hat{\mu} \) is the direction unit vector. In Ref. [19], we pointed out that the formation of circularly shaped rings in MR fluids is due to the large size of the particles, which hinders the Brownian motion of the particles at room temperature and provides a relatively strong magnetic coupling at a moderate level of magnetization. In the experiments the optical side of a two-inch Si wafer was used as the bottom plate on which four plastic barriers are mounted to form a container filled with silicone oil of viscosity \( \eta = 5.17.68 \) mPa s. The container was horizontally placed in the center region of a pair of Helmholz coil, where the magnetic strength of coil was controlled by a current amplifier. The evolution of bending chains in

Fig. 1. The evolution of the MR fluid structure with two/three bending chains involved at various magnitude of applied field \( B \).
the container was monitored in situ by a CCD camera and a video recorder.

First, we applied an magnetic field to the nickel-coated microspheres in a horizontal direction. During the application of an external magnetic field to the MR fluid, the particles aggregate into chains of dipoles aligned in the field direction onto the container. In the absence of the external magnetic field, the chains can also exist stably due to the permanent dipole moment. In the next stage of the experiment, distinguishing from our previous studies, the external magnetic field was switched on such that its direction was fixed to be vertical. As the magnitude $B$ of the field was slowly increased linearly, each chain was dramatically bent up with the particles at one end being lifted one by one. In Fig. 1, we show the picture of the formation and transformation of this structure in a scale of two/three bending chains involved. In Fig. 2, we focus on the behavior of a single dipolar chain with slowly increasing magnetic field $B$. These structures were obtained at low concentration where the interactions between chains are too small to affect the pattern.

Fig. 2. A single chain behavior under the vertically applied magnetic field with slowly increasing magnitude $B$. 
To understand our observations and gain deeper insight into the bending chain structures, the calculation of the stability of a single bending chain at gravity field and the external magnetic field has been carried out in this work. We consider a dipolar model of the MR fluids and use energy minimization to derive the chain pattern and its behavior at various magnitude of the vertical field.

For a static up bending chain with \( n \) particles and \( l \) particles being lifted by an externally magnetic field \((l \leq n)\), the total potential energy \( U \) of the system of paramagnetic particles with a magnetic moment \( \vec{\mu}_i \) in an externally applied magnetic field \( B \) consists of the interaction between each particle and the applied field, and the gravity potential of those particles having been pulled up. This can be expressed as

\[
U = \sum_{i=1}^{n} -\vec{\mu}_i \cdot \vec{B} - \sum_{i \neq j} u_{ij} + \sum_{i} U_i^g. \tag{1}
\]

The dipole–dipole interaction \( u_{ij} \) between two identical particles, separated by \(|\vec{r}_{ij}| = |\vec{r}_j - \vec{r}_i|\) which is equal to the particle diameter \( D \) and carrying the magnetic moment \( \vec{\mu}_i = \mu_0 \hat{\mu}_i \), has the form [22]

\[
u_{ij} = (\mu_0^2/|\vec{r}_{ij}|^3)[\vec{\mu}_i \cdot \vec{\mu}_j - 3(\vec{\mu}_i \cdot \hat{\vec{r}}_{ij})(\vec{\mu}_j \cdot \hat{\vec{r}}_{ij})] = -\left(\frac{\mu_0^2}{D^3}\right)(1 + \cos^2 \beta_i), \tag{2}
\]

where \( \beta_i \) as shown in Fig. 3 denotes the angle of the direction of the dipole \( i \) (or \( i + 1 \)) with respect to the direction from dipole \( i \) (or \( i + 1 \)) to \( i + 1 \) (or \( i \)) in the assumption that there is no sliding between two particles. This assumption is identical with what we observed in experimental processes. All interparticle interactions here are restricted to nearest neighbors only, which is similar as the approximation made in Ref. [18]. The other two terms in above equation can be written as

\[
\vec{\mu}_i \cdot \vec{B} = \mu_0 B \sin \phi_i, \tag{3}
\]

and the gravity potential of the system

\[
U_i^g = (m - \rho V)gD \times \left[ \sin(\phi_i - \beta_i) + \sin(\phi_{i+1} - \beta_{i+1}) + \cdots + \sin(\phi_l - \beta_l) \right], \tag{4}
\]

where

\[
\phi_i = 2\beta_i + 2\beta_{i+1} + \cdots + 2\beta_l, \tag{5}
\]

and \( m, V \) are the mass and volume of each particle, respectively, and \( \rho \) is the density of fluid in above equations.

In the equilibrium system with stable pattern at a certain external magnetic field \( B \), it should satisfy to following conditions:

\[
\begin{align*}
\frac{\partial U}{\partial \beta_i} &= 0, \\
\frac{\partial ^2 U}{\partial \beta_i^2} &> 0, \\
\frac{\partial ^3 U}{\partial \beta_i^3} &> 0, \\
&\vdots
\end{align*}
\tag{6}
\]

By solving above equation group numerically, we can obtain each angle \( \beta_i \) with \( i = 1, 2, \ldots, l \). For those particles lying on the surface, \( i = l + 1, \ldots, n \), \( \beta_i = 0 \). The coordinates of each particle can be obtained from these angles. Thus, stable bending chain structures with the existing of gravity can be obtained for various applied field values of \( B \), which are shown in Figs. 4(a)–(e). The magnetization \( M \) of microspheres used in our calculation is about 6.162 emu/cm\(^3\), which is identical with the experiments. The total energies of the single bending chain \( U \) at various \( B \) can also be obtained by solving the equation group (6). It has been found that the total energy \( U \) decreases with increasing the magnetic field \( B \) as what we expected. This result indicates that the interaction between the
applied field and particles play a dominate role instead of the gravity of those particles. The corresponding results are shown in Fig. 5. A slight discrepancy between the theoretical and experimental results in the bending shapes is due to the ignoring of the interactions from beyond-nearest neighbors as what we have mentioned above.

In summary, we report a novel MR fluid structure with bending chains. Our calculation based on the total energy minimization shows that the competition between the gravity field and vertically applied magnetic field are the reason for the formation and transformation of bending chains. The excellent agreement of the theoretical calculation with the observations at various magnitudes of the field clearly demonstrates that the structures are stable with the existing fields. The further study on the MR effect of this new microstructure is expected.

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Fig. 5. The corresponding total energy of the chain in Fig. 4 as the function of magnetic field $B$.

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