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Magnetic particulate suspensions from the perspective of a dynamical system

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ABSTRACT

This paper focuses on the dynamic behavior of a magnetorheological fluid undergoing an unsteady oscillatory shear under the presence of an applied magnetic field. The problem is studied from a nonlinear mechanical system perspective using tools such as: analysis in the phase space, frequency response and neural networks for parameters identification. For this purpose several numerical simulations are performed to compute the motion of N magnetic rigid spheres suspendend in a Newtonian carrier liquid. The particles are neutrally buoyant and interact both hydrodynamically and magnetically throughout the process of dynamic simulation. We apply an external magnetic field together with an oscillatory shear. These two deterministic mechanisms compete with each other to align the particles in a preferential direction. The nonlinearities are introduced into the system due to particle-particle interaction. The intensity of the non-deterministic mechanisms is regulated by two physical parameters that appear in the present formulation. The numerical simulations are based on a sophisticated technique of Ewald sums that compute convergent hydrodynamic and magnetic interactions. A numerical research code developed by the authors is used for this purpose. The code is both accurate and computationally efficient. The present work intends to show that several tools, otherwise thought to be mostly applied to the dynamics of nonlinear systems, can be used to explore the physical behavior of wet suspensions in fluid mechanics. Moreover several details of the micromechanics of these complex materials are captured and physically interpreted through the use of the proposed tools.

List of symbols

N	number of particles
a	radius of a particle
η	viscosity of the carrier liquid
ρ_f	density of the fluid
ρ_p	density of the particle
H	applied magnetic field
g	gravitational acceleration vector
g	intensity of the gravitational acceleration vector
g	direction of the gravitational acceleration vector
d	dipole moment
d	intensity of the dipole moment vector
d	direction of the dipole moment vector
$\dot{\gamma}$	shear rate intensity
$\dot{\gamma}_0$	reference shear rate intensity
h	separation between the upper and lower boundaries of the calculation domain
ω	oscillatory shear rate frequency
t	time
Re_p	particle Reynolds number
u_i	velocity of particle i
z_i	height of particle i
$M^s_{i,i}$	self-mobility matrix
f_i	forces acting on particle i
$M^p_{i,j}$	pair mobility matrix
f^r_i	repulsive forces acting on particle i
f^c_i	contact forces acting on particle i
f^m_i	magnetic forces acting on particle i
f^{mf}_i	magnetic forces due to an external field acting on particle i
∇	gradient operator
ξ	Ewald summation convergence parameter
V	lattice volume
x	position of an arbitrary point in space
r	distance vector
k	wave number vector
r, r_{ij}	distance between particles i and j
$\Lambda, \mathcal{Y}, P_c$	constants of the model

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ε_{ij} distance between the surfaces of particles i and j
ψ_{ij} dipole-dipole interaction potential between particles i and j
φ_m dipole-dipole magnetic interaction parameter
St_r rotational Stokes number
ω angular velocity
$T_m{}^i$ magnetic torques acting on particle i
ψ_m field-dipole magnetic interaction parameter
$\gamma_1, \gamma_2, \gamma_3$ physical space lattice indices
$\beta_1, \beta_2, \beta_3$ reciprocal space lattice indices
l_i length of lattice i
ϕ volume fraction of particles in the central lattice
v_p volume of an arbitrary particle
U_s Stokes velocity of an isolated particle
$\bar{U}$ mean suspension velocity
M_0 equilibrium magnetization
M_d particle magnetization
M^* dimensionless magnetization
$\mathcal{R}(t)$ normalized self-correlation function of velocity fluctuations
t_m typical magnetic relaxation time scale
t_f typical shear rate time scale
$\mathcal{F}$ dimensionless magnetic relaxation time scale

1. Introduction

A ferrofluid is defined as a stable colloidal magnetic suspension of nanometric particles immersed in a carrier liquid [1]. The addition of small magnetic particles inside a carrier liquid (usually oil or water based) leads to new possibilities regarding the fluid response due to the application of an external field. In the absence of a magnetic field, a ferrofluid behaves as a Newtonian liquid, but when an external field is applied the fluid magnetizes itself and, as a consequence, several rheological properties are altered [2]. The discovery of ferrofluids in the 1960s opened the doors for several interesting applications. At first, ferrofluids were mostly used in applications where the focus was to control its motion due to the application of an external field. As years of research went by we now understand that ferrofluids can be used in a great wide of otherwise unthinkable applications. We can mention for example the use of ferrofluids to increase the efficiency of heat transfer devices [3,4], magnetic pumping [5] and drag reduction due to the magnetoviscous effect [6]. Just recently [7] have shown that the interaction between magnetic particles and the application of an external field can help to stabilize a fluidized bed.

Another interesting class of magnetic suspensions is the so called magnetorheological suspensions (M.R.S), or magnetorheological fluids. This type of fluid is a noncolloidal liquid-solid suspension made through the addition of micron-sized magnetic particles in a Newtonian carrier liquid. The primary difference between a M.R.S and a ferrofluid is the particle sensibility to thermal fluctuations induced by the liquid molecules [2,8]. In recent years some interesting studies have been done regarding the use of M.R.S in practical applications or simply exploring the physics of this complex material. Sudo et al. [9] made an interesting experimental study on the dynamics of droplets of M.R.S impacting on a flat surface under the presence of an applied field, in this study they used M.R.S drops of 2.08 mm containing micron-sized particles. Recent studies have tried to link nonlinear dynamic tools, such as neural networks and fuzzy logic to control the behavior of M.R.S in different applications [10–12].

One interesting fact about ferrofluids and M.R.S is that they tend to form self-organized patterns depending on the applied field and geometry where these fluids are confined. Since the 1980s we can observe interesting pattern formation in magnetic fluids [13–15]. For instance [16] used a 3D finite element method to identify hexagonal ferrofluid pattern formation under the presence of an applied field. Other authors have used theoretical approaches in order to understand the theory of pattern formation [17,18]. A recent experimental study shows the fingering formation of an immiscible ferrofluid drop immersed in water and subjected to a radial magnetic field [19].

Another great research field regarding ferrofluids and M.R.S is the rheology of these complex class of fluids. In order to study the rheological behavior of a complex fluid, we must apply a simple rheological flow and observe how it resists to the attempt of shearing it. The interesting feature of magnetic fluids is that their macroscopic rheological response is intrinsically related to their microstructural behavior. A great amount of experimental work has been done in recent years in order to understand the rheological response of ferrofluids [20–23]. Another possible way to study the rheology of magnetic fluids is through numerical simulations [24] in a microstructural scale.

Even though magnetic fluids present several interesting patterns under the presence of an applied field and a rich rheology due to dipolar interactions in the micro or nano scale, these two features have not been explored jointly. This works seeks to perform a numerical study using an oscillatory shear rate as a rheological flow to understand the microstructural dynamics of M.R.S under the presence of an applied field. Dipolar [25,26] and hydrodynamic [27,28,30,31] interactions between all the particles within the suspension space are also considered.

It is important to highlight that we use a numerical method developed for particulate suspensions free of fluid and particle inertia. This methodology is different from the Eulerian-Eulerian [32,33] method used in multiphase flows for arbitrary intensities of particle and fluid inertia (arbitrary Reynolds and Stokes number). Our methodology is efficient in treating liquid-solid suspensions where the inertia of the fluid is neglectable (Creeping flow limit). It is advantageous in the sense that it is as meshless method, of simple implementation and produce very accurate results when compared to experimental data obtained in the Creeping flow limit.

In the present work we use nonlinear dynamic system tools to explore the unsteady behavior of the suspension magnetization under different conditions of the problem's physical parameters. We intend to show that due to its intrinsic microstructure nonlinearity, mainly under the action of strong magnetic interactions, the output of the fluid system when excited in an harmonic way may be highly nonlinear. Several different features are explored and interpreted from a physical perspective. A neural network is also trained to identify the problem's physical parameters based on the FFT response of the excited complex fluid and its energetic dispersion area on the phase plane. Several nonlinear dynamical system tools, such as phase space analysis, FFT and neural networks are used in this work to capture the physics of magnetorheological fluids.

2. Formulation of the Problem

In this problem, we consider a suspension of N spherical magnetic particles with radius a suspended in a Newtonian liquid with viscosity η and density ρ_f. The density of the particles ρ_p is the same as the liquid density ($\rho_p = \rho_f$) so the suspension is assumed to be neutrally buoyant. An external magnetic field $\boldsymbol{H}$ is suddenly applied in the suspension space. The field is applied in the same direction but with opposite sense to the gravitational acceleration vector $\boldsymbol{g} = gg$. The particles are initially distributed in an ordered manner. Their magnetic dipole moments $\boldsymbol{d} = dd$ are set to be initially aligned transversely to gravity, so $d \cdot g = 0$. An unsteady oscillatory shear is applied at the same moment as the magnetic field. The upper boundary of our calculation domain is set to move with velocity $\dot{\gamma} \times h$, where h denotes the separation between the upper and lower boundaries of our domain. The applied shear rate $\dot{\gamma}$ is a function of time, given by $\dot{\gamma}(t) = \dot{\gamma}_0 \cos(\omega t)$, where $\dot{\gamma}_0$ is the amplitude of the applied shear, ω denotes its frequency and t is the time. A simple sketch of our problem is shown in Fig. 1.

The dimensionless expression to compute the velocity of an arbitrary ith particle in the suspension space is based on the linearity of Stokes equations (valid for $Re_p \ll 1$, where Re_p is the particle Reynolds