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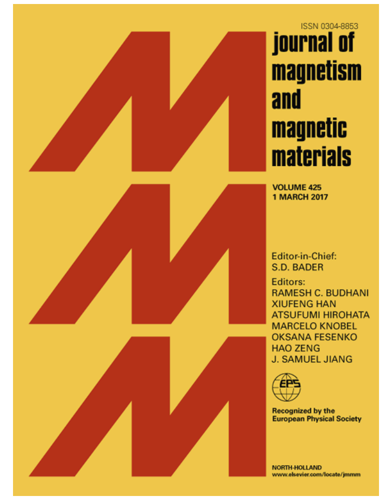

Research articles

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Magnetic and Hydrodynamic Torques: Dynamics of Superparamagnetic Bead Doublets

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Abstract

Rotating chains of magnetic microparticles have many applications in lab-on-a-chip technologies. The simplest such chain is the fluid-borne doublet, where two beads are in close contact, but remain unattached, allowing each bead to freely rotate. These beads typically have two components contributing to their net magnetic moment: (i) a superparamagnetic moment and (ii) a field-independent permanent moment. In a rotating magnetic field, there are magnetic torques that separately rotate the doublet and its constituent beads as well as a hydrodynamic torque from the bead-doublet coupling. This study investigates, through experiments and simulations, the dynamics of field-driven doublets. New dynamics were found for the case where the dominant torque stems from the hydrodynamic coupling.

Keywords: Magnetic Beads, Magnetic Fields, Hydrodynamics

1. Introduction

Actuating magnetic micro- and nano-particles has become important to the development of several lab-on-a-chip technologies becaue of their translation and rotation in applied external fields, capability for multiplexing, biocompatibility, and cellular-relevant length scale. They have been investigated in many systems such as ferrofluids [1–3], magnetic chains [4–10], magnetotactic bacteria [11, 12] and clusters [13, 14]. The ensuing applications are broad. They include fluid mixers [2, 4, 8, 9, 15–18], micro-swimmers [19, 20], sorting [21–25], drug delivery [20, 26, 27], micro-surgery [20, 28], cell detection [29, 30], as well as stiffness-, bio- and rheological-sensing [10, 31–40]. To optimize these applications, the interplay between the hydrodynamic and magnetic forces affecting their dynamics must be understood. One of the simplest constructs that displays this interplay is the detached doublet consisting of two adjacent, but unattached, fluid-borne magnetic beads rotating in a magnetic field.

Magnetic microbeads that are typically used in lab-on-a-chip devices are created by embedding magnetic nanoparticles within a polymer matrix [41]. Two components contribute to their net magnetic moment: (i) a superparamagnetic Néel dipole m_H that rapidly aligns with an external field H due to the fast stochastic reorientation of the nanoparticle magnetic domains and (ii) a Brownian field-independent permanent moment m_P arising from the slow relaxation of the magnetization of the larger nanoparticles within the bead [33, 42]. Studies have investigated how magnetic torques arising from the interaction between m_p and H (dipole-field interaction) affects the rotation of individual beads [33] as well as chemically attached [43] and detached [44] doublets. Detached doublets present an interesting case where the dipole-field torque directly rotates the individual beads in the presence of a time varying magnetic field and consequently affects the doublet's rotation through the hydrodynamic coupling of the beads' and doublet's rotation.

Detached magnetic particles have previously been studied without including the hydrodynamic bead-doublet coupling [10, 36]. With only the magnetic torque, the doublets rotate at the same rate as the external field up to some critical frequency, above which the doublet on average begins to slow down. Coughlan et. al. [44] found that the hydrodynamic bead-doublet coupling had a small perturbation on the rotation rate of detached doublets. The perturbation was small in this case because of the relative weakness of m_P and the dipole-field torque on their beads.

The present study finds new dynamics in the rotation rate of the doublets when the hydrodynamic bead-doublet coupling is the strongest torque. This previously unreported response arises from separate critical frequencies caused by the moments m_H and m_P. Simulations reveal that the hydrodynamic torque τ_D^{Hyd} on the doublet is linear with respect to the rotation rate of the doublet (ω_D) and of the individual beads (ω_B), $\tau_D^{Hyd} = \gamma_D^D \omega_D - \gamma_D^B \omega_B$. The coefficients γ_D^D and γ_D^B represent the strength of the drag torque on the doublet and the hydrodynamic bead-doublet coupling respectively and are determined from the simulations. Analytical models based on these results compare favorably with measurements of the average doublet rotation rate $\bar{\omega}_D$ for beads with different strengths of superparamagnetic (m_H) and ferromagnetic (m_P) moments.

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