Universität Bielefeld
Condensed
Matter
Theory

Ferrofluids as thermal ratchets

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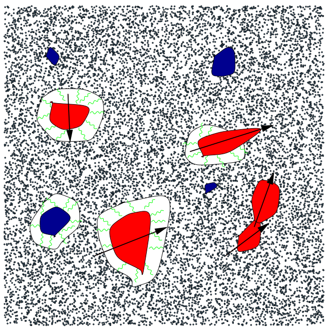
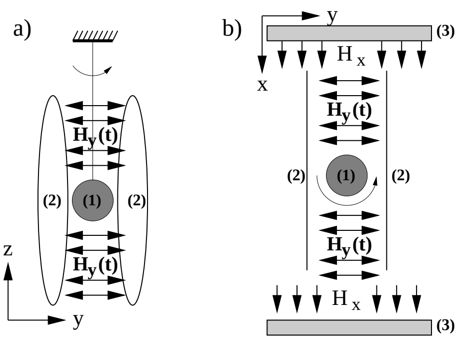
Colloidal suspensions of ferromagnetic nano-particles, so-called ferrofluids, are shown to be ideal systems to demonstrate and investigate thermal *ratchet* behavior: By rectifying thermal fluctuations, angular momentum is transferred to a resting ferrofluid from an oscillating magnetic field without net rotating component. Via viscous coupling the noise driven rotation of the *microscopic* ferromagnetic grains is transmitted to the carrier liquid to yield a *macroscopic* torque.

System



Ferrofluid: colloidal suspensions of ferromagnetic grains of ~ 10nm size.



(a) side view, (b) top view of the setup: The main ingredient is a torsion balance similar to those used in string galvanometers. A hollow plastic sphere (1) is filled with ferrofluid and suspended on a thin Kevlar fiber. A static magnetic field H_x acts along the x-direction. A time dependent magnetic field $H_y(t)$ in y-direction is generated with a pair of Helmholtz coils (2) via a computer generated signal of the form

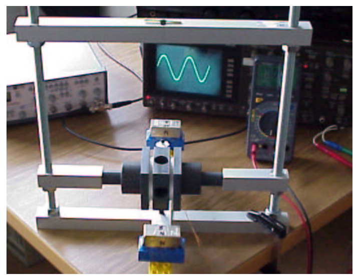
$$H_y(t) = h\left[\cos(\omega t) + a\sin(2\,\omega t + \beta)\right] . \qquad (1)$$

An alternative time dependence is

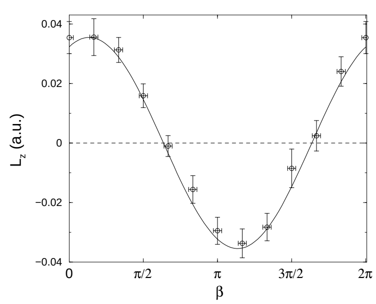
$$H_y(t) = h\left[\cos(\omega t) + a\sin(3\,\omega t + \beta)\right] . \qquad (2)$$

In either case, the resulting total magnetic field is rocking back and forth in the horizontal plane **without a net rotating component**.

Experiment



A hollow plastic sphere (inner diameter 16 mm) is filled with a ferrofluid (APG 933 (Ferro-Tec), density $\rho = 1,100$ kg/m^3, susceptibility $\chi = 1.09$, saturation magnetization $M_s = 18$ kA/m, dynamic viscosity $\eta = 0.1$ Pas). Kevlar fiber: length 20 cm, diameter $10\,\mu$m. Magnetic fields: $h \simeq 4$ kA/m, $H_x \simeq 1.2$ kA/m. Parameters in Eq. (1): $\nu = \omega/(2\pi) = 200$ Hz, $a = 1$.



Symbols: Magnetic torque transferred to the ferrofluid as function of the phase angle β in Eq. (1). Solid line: fit to the analytical approximation (3), $L_z = A(\omega\cos\beta + 2\sin\beta)$ with the amplitude A and the frequency ω as fit parameters. The obtained value $\omega \simeq 4.41$ in dimensionless units translates into a fit for the Brownian relaxation time of $\tau_B \simeq 1.8$ ms.

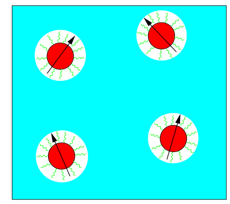
No rotation is observes without static field ($H_x = 0$), or for a purely sinusoidal driving ($a = 0$), or if the driving (1) is replaced by (2).

References

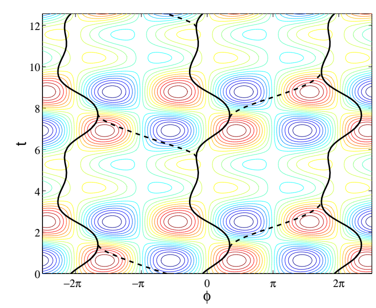
[1] A. Engel, H. W. Müller, P. Reimann, A. Jung, Phys. Rev. Lett. **91**, 060602 (2003)

[2] H. Linke, Brennpunkt "Brownsche Motoren: gemeinsam stark", Phys. J. **2**(10), 18 (2003)

Theory



Model: non-interacting, identical spherical dipoles of volume V and magnetic moment $\mathbf{m}$. Potential energy $U = -\mathbf{m}\cdot\mathbf{H}$ governs orientation $\mathbf{e} = \mathbf{m}/m = (\sin\theta\cos\phi, \sin\theta\sin\phi, \cos\theta)$. A reorientation of the magnetic moment requires a rotation of the particle against the viscosity η of the carrier liquid characterized by the Brownian relaxation time $\tau_B = 3\eta V/k_BT$.
Dimensionless units: magnetic field $\alpha_{x,y} := mH_{x,y}/k_BT$, rescaled time$:= t/2\tau_B$.



Space-time contour plot of the potential $U(\theta = \pi/2, \phi, t)$ for $\alpha_x = 0.3$, $\alpha_y = 1$, $a = 1$, $\beta = 0$. In the long-time limit, the deterministic dynamics (no thermal noise) approaches $\theta(t) = \pi/2$ and a periodic $\phi(t)$, represented by either of the full black lines. In the presence of thermal noise, transitions ("2π-phase slips") between these deterministic solutions become possible schematically indicated by the dashed lines. The spatial asymmetry and temporal anharmonicity of the potential results in slightly different rates for noise induced increments and decrements of ϕ respectively. As a result a noise driven rotation of the particles arises. Noise assisted transfer of angular momentum from the magnetic field to the ferrofluid manifests itself in a rotation of the sphere. Analytical approximation for the angular momentum [1]:

$$L_z = \frac{\mu_0 M_s^2}{90\chi}\,\alpha_y^3\,\alpha_x\,a\,\frac{\omega^2\,(\omega\cos\beta + 2\sin\beta)}{(1+\omega^2)(4+\omega^2)^2} \qquad (3)$$

for driving (1), $L_z = 0$ for driving (2).