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Langevin equations for suspended magnetic particles drifting under the Magnus force

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The Magnus effect, i.e., dependence of the trajectory of a body on its rotation, is widely used in sport, science and technical applications. Recently we have shown [1, 2] that due to the Magnus force the single-domain ferromagnetic particles, which are suspended in a viscous fluid and subjected to a harmonic driving force and a non-uniformly rotating magnetic field, can perform drift in a preferred direction. This result has been obtained within the deterministic approach when thermal fluctuations, leading to translational and rotational Brownian motion of particles, are ignored. Our estimations show [2] that it is possible for relatively large particles ($> 10^2$ nm). Therefore, to study the drift phenomenon for smaller particles, it is necessary to account for these fluctuations in basic equations.

To this end, we added the random force and torque into the force and torque balance equations, respectively. Assuming that these equations contain the driving, friction and Magnus forces and the magnetic field and friction torques, we derived the following system of Langevin equations:

$$\mathbf{u} = [\mathbf{e}_x - \gamma \mathbf{e}_x \times (\mathbf{m} \times \mathbf{h})] \sin(2\pi\tau) + \mathbf{f}_r, \tag{1}$$

$$\dot{\mathbf{m}} = -\alpha \mathbf{m} \times (\mathbf{m} \times \mathbf{h}) - \alpha \mathbf{m} \times \mathbf{t}_r, \tag{2}$$

which describes the stochastic dynamics of suspended magnetic particles in dimensionless variables. Here, $\mathbf{u}$ and $\mathbf{m}$ are the particle velocity and magnetization, $\mathbf{h}$ is the time-dependent magnetic field, the overdot denotes the derivative with respect to time τ, the sign $\times$ denotes the vector product, $\mathbf{e}_x$ is the unit vector along the driving force, α and γ are the dimensionless parameters [2], and the components of the random force $\mathbf{f}_r$ and torque $\mathbf{t}_r$ are independent Gaussian white noises. We used Eqs. (1) and (2) for describing the stochastic dynamics of particles within the Fokker-Planck approach and for finding the temperature dependence of their drift velocity.

1. S.I. Denisov, et al., *J. Nano- Electron Phys* **8**, 04087 (2016).
2. S.I. Denisov, B.O. Pedchenko, *J. Appl. Phys.* **121**, 043912 (2017).