Macroscopic dynamics of magnetic gels – surface waves and Rosensweig instability

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Introduction

Ferrogels are chemically cross-linked polymer networks that are generated using a ferrofluid as a solvent. While isotropic ferrogels experimentally show a superparamagnetic behavior like usual ferrofluids [1], anisotropic ones are characterized by a nonvanishing magnetization even without any external magnetic field. To produce these uniaxial gels, the cross-linking process is performed in an external magnetic field [2, 3]. In this situation the nanosized particles very likely form columns and fibers due to the necessarily lowered pH-value to get the cross-linking process started. These chains are then fixed in the network, leading to a frozen-in magnetization.

Macroscopic dynamics

Here we generalize the set of hydrodynamic equations for isotropic ferrogels [4] to uniaxial ferrogels. Ferromagnetic gels are uniaxial, if the frozen-in magnetization denotes the only preferred direction. On the one hand they show similarities to other anisotropic gels like, for example, nematic elastomers as well as to isotropic ferrofluids and ferrogels, but on the other hand the combination of preferred direction, magnetic degree of freedom and elasticity makes them unique and very special.
Prominent features [5] are the relative rotations between the magnetization and the elastic network, which couple dynamically flow, shear, and magnetic reorientation. As a result, shear flow in a plane that contains the frozen-in magnetization induces a rotation of the magnetization, not only within the shear plane, but also out of the shear plane. Another outstanding aspect of the hydrodynamics of this material is the difference between the mass current density (mass density times velocity) and the momentum density due to a nonvanishing magnetization vorticity. This difference also appears in uniaxial quantum fluids but this is the first time a macroscopic, classical system shows up that coupling. Finally an oscillating external magnetic field induces not only an oscillation of the magnetization in the direction of the external field, but also oscillating shear strains. The latter are found in planes that contain the frozen-in magnetization and either the external field or the third, perpendicular direction. In addition, the external magnetic field also induces a magnetization component perpendicular to both, the field and the frozen-in magnetization.

Rosensweig instability

It is known from usual ferrofluids, that if a magnetic field is applied normal to a free surface of that ferrofluid, an instability of the surface occurs above a certain threshold resulting in a periodic, stationary structure of spikes [6]. The threshold field depends on the surface tension and gravity, but is independent of the viscosity of the ferrofluid. Within the framework of a linear stability analysis we could show however [7], that for a uniaxial ferrogel the elasticity does influence the threshold, whereas the characteristic wavelength at onset does not change with respect to ferrofluids. We discuss also the possible influence of the viscosity of the ferrogel on the instability. In addition we derive the dispersion relation for surface waves on a uniaxial ferrogel and show how the Rosensweig instability emerges from surface waves, if the field reaches the threshold value.

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