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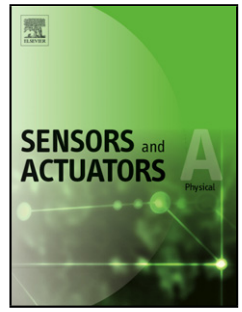

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Rheology of complex fluids with vibrating fiber-optic sensors

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Highlights

- A cost-effective, non-invasive method for rheology of complex fluids is presented.
- Method is discussed theoretically and validated experimentally with calibrated samples.
- Sensor is employed to monitor the time-evolution of a sol-gel compound across the gelation process.
- Comparative measurements with a commercial rheometer show the advantages of the presented technique.

We demonstrate a new optical rheometer where a fiber Bragg grating sensor (FBG) detects the periodical strain caused by the oscillations of a string tightened within a sample fluid. We show that the viscoelastic moduli of complex fluids can be obtained instantaneously from the FBG optical backreflection signal, without need of any current flow in the wire or magnetic field that could affect the sample chemistry. After a validation with known-viscosity solutions, the technique is employed to monitor the phase transition of a sol-gel compound. The results provide an insight in the early-stage gelation dynamics that cannot be obtained with traditional rheometers, and allow to clearly identify the gel point as the intersection of the viscoelastic moduli.

1. Introduction

Vibrating-wire instruments have been largely used to measure viscosity and density of fluids since the 60s [1]. The common principle of all these techniques is to assess the physical properties of a fluid by analyzing the motion of a wire submerged in it. In conventional wire viscometers, a tungsten wire is immersed in a magnetic field along with the sample. When an AC current is sent through the wire, the Lorentz force periodically pushes and pulls the flowing electrons. If the AC frequency coincides with a mechanical resonance of the tensioned wire, this forcing effect is greatly amplified and generates a detectable displacement oscillation measurable from the voltage across the wire ends [2-4]. Recently, it was shown that the working equations of vibrating-wire viscometers can describe the wire dynamics also in the presence of a non-Newtonian fluid, thus opening the way for vibrating-wire rheology [5]. As opposed to conventional rheology instruments, such as rotational rheometers which are limited to a few hundreds of Hz by their own inertia [6, 7], a wire can easily vibrate at 1-10KHz. This feature is particularly promising because the high-frequency viscoelastic moduli carry information on the fast-relaxation processes of the sample fluid [7-9]. In addition, a vibrating-wire rheometer can measure very small viscoelastic moduli, a task that can be hardly accomplished with conventional methods.

In this work, we demonstrate a novel fiber-optic rheological sensor (FORSe) in the KHz range. Unlike other optical viscometric techniques [10-13], the FORSe takes advantage of the exceptional strain sensitivity of a fiber Bragg Grating sensor (FBG) [14], already exploited seismology, biomedical and electrical sensing applications [15-18], to track the harmonic motion of a wire in a sample fluid. The demonstrated technique can be deployed in a simple and low-cost setup without any current flow or magnetic field, and can be easily applied to investigate the properties of complex fluids. Indeed, after validating the instrument with known viscosity water-glycerol solutions, we use it to monitor the rheological properties of a sol-gel mixture during its transition from liquid to gel. The results provide an insight in the initial phase the gelation process, when the sample viscosity is too low to be accurately measured with conventional rheometer, and allow to precisely identify the gel point owing to the extremely high time resolution of the FORSe apparatus.

2. Theory

The working equations of the FORSe derive directly from the classical tight string problem [19]. The starting point is the Newton's second law for a unit length element *dz* of a wire fixed at both ends with a tension force *T*, whose radius *R* is much smaller than its length *L*. The sum of the forces in a direction *y* orthogonal to *z* is:

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