Nanorheology of MR Elastomers Studied by Dynamic Speckle

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Introduction

Magnetorehological (MR) elastomers exhibit dynamic stiffness properties in an applied magnetic field. Such field-controllable response is achieved by embedding sub-micrometer magnetic particles in a cross-linked natural rubber elastomer. On application of an external magnetic field, a dipole moment is induced in each particle, and when the elastomer is cured in a magnetic field, the particles form a chainlike configuration inside the cross-linked elastomer matrix [1]. On a microscopic scale, the tethered particles in the field-cured elastomer react to application of an external field by undergoing small displacements and rotations. On a macroscopic scale, the stiffness of the material changes by a few percent. The timescale of the response is related to the nanometer-scale deformation of the matrix. The magnetic particles serve a dual role for this experiment. First, through magnetic excitation, they perturb the elastomer matrix. Second, they serve as scatterers, enabling the measurement of dynamic deformations in the matrix [2]. Understanding the dynamic response is critical to the functionality of MR elastomers in automotive applications, such as variable stiffness suspension systems and active damping components [3].

Methods and Materials

We utilize high-intensity x-ray synchrotron radiation from the MHATT-CAT sector 7 undulator beamline at the APS to make novel measurements of real-time particle dynamics in MR elastomers. Through elastic small-angle transmission scattering of transversely coherent x-rays, the phase of the wavefront will shift with the relative motion of the particles, resulting in a time-dependent speckle interference pattern. Since the samples lack periodicity, coherent illumination is essential for extracting dynamic properties. In a nonequilibrium measurement, the MR elastomer samples were excited with a 0.15-Hz square waveform with an applied magnetic flux density alternating between about 1 Tesla and zero. The dynamic speckle pattern was recorded as a movie with a 60-ms integration time by using a fast charge-coupled detector (CCD) camera operating in direct detection mode [1]. Through intensity correlation of the speckle patterns, we were able to measure the relaxation dynamics of magnetic particles embedded in the elastomer matrix upon perturbation by an applied magnetic field. The small-angle scattering configuration is shown in Fig. 1.

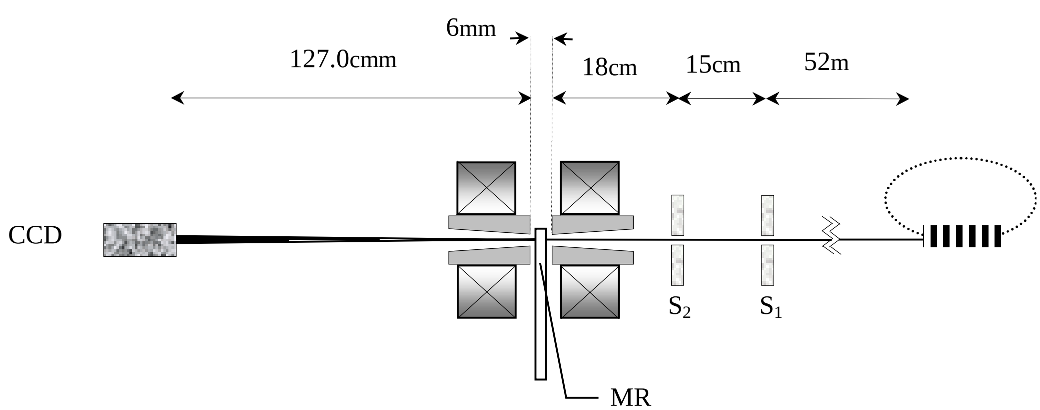

FIG. 1. Schematic arrangement for small-angle scattering measurements. The undulator was tuned to produce 7-keV x-rays, which were then filtered to deliver a pink beam with a 2.5% bandpass. The coherent beam was scattered from the MR elastomer sample in a transmission geometry. The sample (MR) is located between the pole pieces of the electromagnet. Slits (S) are used to isolate the coherent section of the beam for scattering. The coherence slit, S_1, has an aperture 8-μm square. The time-dependent speckle pattern is recorded with a CCD area detector.

The samples were molded into disks about 200-μm thick, while the elastomer was cross-linked. Magnetite particles with an average size of about 200 nm were embedded in a natural rubber, cis-polyisoprene, elastomer matrix at a 25% particulate volume fraction.

Results and Discussion

A speckle pattern recorded as one frame of a movie is shown in Fig. 2. The coherent speckle character of the small-angle scattering from the ferrite nanoparticles is clearly evident, extending beyond the shadow of the backstop (horizontal band). The intensity autocorrelation function $g_2(q,t)$ is calculated for each discrete pixel in the movie. The scattering wave vector q was also determined for each pixel. The autocorrelation functions were then averaged around a ring of constant q. These averaged correlation functions contain the relaxation information for a given length scale associated with the return to equilibrium following excitation by the external magnetic field. Initial analysis shows a relaxation time of 3 s^{-1} for q = 0.001 $Å^{-1}$, while for larger scattering vectors q = 0.005 $Å^{-1}$, the relaxation rate reduces to 1 s^{-1}. Currently analysis is underway to understand the unusual q dependence of the relaxation process. These measurements demonstrate the feasibility of using coherent undulator beams to probe relaxation dynamics in bulk, optically opaque samples of MR elastomers on short time scales and short length scales relevant to practical applications.

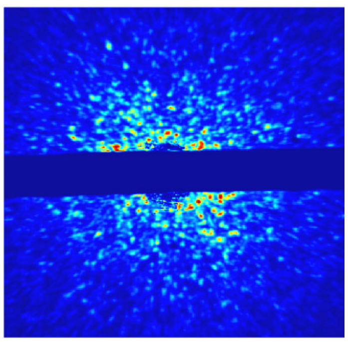

FIG. 2. Small-angle coherent beam scattering from MR elastomer material containing magnetic nanoparticles. Incident beam diameter is about 10 μm.

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