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Lallit Anand

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A theory for non-Newtonian viscoelastic polymeric liquids

Lallit Anand*

Department of Mechanical Engineering
Massachusetts Institute of Technology
Cambridge, MA 02139, USA

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Abstract

In many existing theories for incompressible polymeric liquids the Cauchy stress is decomposed as $\mathbf{T} = -p\mathbf{1} + \mathbf{S}^v + \mathbf{S}^e$, where p is an arbitrary pressure, $\mathbf{S}^v = 2\mu_s\mathbf{D}$ a deviatoric viscous stress with μ_s a viscosity and $\mathbf{D}$ the deviatoric stretching tensor, and $\mathbf{S}^e$ is a deviatoric elastic stress which is introduced to account for stiffening arising from the alignment of long-chain polymer molecules during flow. A constitutive equation for $\mathbf{S}^e$ needs to be prescribed and there are *a large number of different proposals* in the literature, with most proposals involving a *hypoelastic* rate constitutive equation for $\mathbf{S}^e$ given in terms of a suitable frame-indifferent rate, which is usually taken as the Oldroyd or upper-convected rate. As is well-known, a hypoelastic equation for the stress is not thermodynamically consistent, in the sense that the constitutive equation for $\mathbf{S}^e$ is not derived form a free energy function.

The purpose of this paper is to present an alternative — thermodynamically-consistent and frame-indifferent — continuum theory for incompressible viscoelastic liquids. The theory is based on a Kröner-type multiplicative decomposition of the deformation gradient $\mathbf{F}$ of the form $\mathbf{F} = \mathbf{F}^e\mathbf{F}^p$. In this theory the elastic stress $\mathbf{S}^e$ is derived from a free-energy function which is prescribed in terms of a suitable measure based on the unimodular elastic distortion tensor $\mathbf{F}^e$. This relation is supplemented by an evolution equation for the unimodular plastic distortion tensor $\mathbf{F}^p$ — the plastic flow rule.

We study the response of the constitutive theory in steady simple shearing and steady extensional flows. We show: (i) that the theory qualitativley reproduces the experimentally-observed transient shear-thinning and normal stress effects during shearing flows of a polymer melt; and (ii) that it also reproduces the transient extensional response of a polymer melt.

Keywords: B. polymeric material; viscoelastic material; viscoplastic material.

1 Introduction

An accurate mathematical description of the large deformations of polymer melts and concentrated polymer solutions, both of which are viscoelastic liquids, is important for the development of a numerical simulation capability for polymer processing operations, and also for simulating the behavior of various bodily fluids in human physiology. Viscoelastic liquids are capable of accumulating large recoverable strains during flow — which puts such materials in an intermediate position between liquids and solids — and this makes their rheological behavior quite complex.

In the past four decades there has been substantial progress in formulating theories for such materials, and reviews of the literature may be found in textbooks and several review articles (cf., e.g., Giesekus, 1982; Bird et al., 1987a,b; Bird and Wiest, 1995; Leonov, 1999; Tanner, 2000; McKinley and Sridhar, 2002; Larson and Desai, 2015). For *isothermal* and *incompressible* fluid flows, most current theories are described by:

*Tel.: +1-617-253-1635; E-mail address: anand@mit.edu