Preface

First Edition This book presents an introduction to viscoelasticity; in particular, to the theories of dilute polymer solutions and dilute suspensions of rigid particles in viscous and incompressible fluids. These theories are important, not just because they apply to practical problems of industrial interest, but because they form a solid theoretical base upon which mathematical techniques can be built, from which more complex theories can be constructed, to better mimic material behavior. The emphasis is not on the voluminous current topical research, but on the necessary tools to understand viscoelasticity at a first year graduate level.

The logo of the Society of Rheology

Viscoelasticity, or Continuum Mechanics, or Rheology[1] (certainly not to be confused with Theology) is *the science of deformation and flow*. This definition of was due to Bingham, who, together with Scott Blair[2] and Reiner,[3] helped form The Society of Rheology in 1929. Rheology has a distinguished history involving high-profile scientists. The idea that everything has a time scale, and that if we are

[1]This word was coined by E.C. Bingham (1878–1946), Professor of Chemistry at Lafayette College, Pennsylvania. The Bingham fluid is named after him.

[2]G.W. Scott Blair (1902–1987), Professor of Chemistry at the University of Reading. His main contributions were in biorheology.

[3]M. Reiner (1886–1976), Professor of Mathematics at the Technion University of Haifa, Israel. He is remembered for contributing to the Reiner–Rivlin fluid.

prepared to wait long enough then everything will flow was known to the Greek philosopher Heraclitus, and prior to him, to the Prophetess Deborah—*The Mountains Flowed Before The Lord*.[4] Not surprisingly, the motto of the Society of Rheology is $\pi\alpha\nu\tau\alpha\ \rho\varepsilon\iota$ (everything flows), a saying attributed to Heraclitus.

From the rheological viewpoint, there is no clear distinction between solid and liquid, it is a matter between the relative time scale T of the experiment to the time scale τ of the material concerned. The time scale ratio, $De = \tau/T$ is called the *Deborah number*. If this ratio is negligibly small, then one has a viscous fluid (more precise definition later), if it is large, a solid, and in-between, a viscoelastic liquid. The time scale of the fluid varies considerably, from 10^{-13} s for water, to a few milliseconds for automotive oils, to minutes for polymer solutions, to hours for melts and soft solids.

Graduate students of Rheology naturally have the unenviable task of walking the bridge between solid mechanics and fluid mechanics, and at the same time trying to grasp the more significant and relevant concepts. They often find it hard (at least for me) to piece together useful information from several comprehensive monographs and published articles on this subject. This set of lectures is an attempt to address this problem—it contains the necessary tools to understand viscoelasticity but does not insist on giving the latest piece of information on the topic.

The book starts with an introduction to the basic tools from tensor and dyadic analysis. Some authors prefer Cartesian tensor notation, others, dyadic notation. We use both notations and they will be summarized here. Chapter 2 is a review of non-Newtonian behavior in flows; here the elasticity of the liquid and its ability to support large tension in stretching can be responsible for variety of phenomena, sometimes counter-intuitive. Kinematics and the equations of balance are discussed in details in Chap. 3, including the finite strain and Rivlin–Ericksen tensors. In Chap. 4 some classical constitutive equations are reviewed, and the general principles governing the constitutive modeling are outlined. In this chapter, the order fluid models are also discussed, leading to the well-known result that the Newtonian velocity field is admissible to a second-order fluid in plane flow. Chapter 5 describes some of the popular engineering inelastic and the linear elastic models. The inelastic models are very useful in shear-like flows where viscosity/shear rate relation plays a dominant role. The linear viscoelastic model is a limit of the simple fluid at small strain—any model must reduce to this limit when the strain amplitude is small enough. In Chap. 6, we discuss a special class of flows known as viscometric flows in which both the kinematics and the stress are fully determined by the flow, irrespective of the constitutive equations. This class of flows is equivalent to the simple shearing flow. Modeling techniques for polymer solutions are discussed next in Chap. 7. Here one has a set of stochastic differential equations for the motion of the particles; the random excitations come from a white noise model of the collisions between the solvent molecules and the particles. It is our belief that a relevant model should come from the microstructure; however, when the microstructure is so

[4] The Book of Judges.

complex that a detailed model is not tractable, elements of continuum model should be brought in. Finally, an introduction to suspension mechanics is given in Chap. 8. I have deliberately left out a number of topics: instability, processing flows, electrorheological fluids, magnetized fluids, and viscoelastic computational mechanics. It is hoped that the book forms a good foundation for those who wish to embark on the Rheology path.

This has been tested out in a one-semester course in Viscoelasticity at the National University of Singapore. It is entirely continuous-assessment based, with the assignments graded at different difficulty levels to be attempted—solving problems is an indispensable part of the education process. A good knowledge of fluid mechanics is helpful, but it is more important to have a solid foundation in Mathematics and Physics (Calculus, Linear Algebra, Partial Differential Equations), of a standard that every one gets in the first two years in an undergraduate Engineering curriculum.

I have greatly benefited from numerous correspondence with my academic brother, Prof. Raj Huilgol and my mentor, Prof. Roger Tanner. Prof. Jeff Giacomin read the first draft of this; his help is gratefully acknowledged.

Singapore, February 2002 Nhan Phan-Thien

Second Edition In this second edition, typographical errors brought about by the conversion process to LaTeX were corrected; my gratitude went to Brittany Bannish (University of Utah) for painstakingly going through the first edition. My main aim in revising this is to produce a still compact book, sufficient at the level of first year graduate course for those who wish to understand viscoelasticity, and to embark in modeling viscoelastic multiphase fluids. To this end, I have decided to introduce a new chapter on Dissipative Particle Dynamics (DPD), which I believe is relevant in modeling complex-structured fluids. All the basic ideas in DPD are reviewed, with some sample problems to illustrate the methodology. My gratitude goes to A*STAR, the Agency for Science, Technology and Research, for funding Multiphase Modeling Projects, and Prof. Khoo Boo Cheong, a colleague and above all a friend, for his support, which made the writing of Chap. 9 possible. I wish to acknowledge Prof. Mai-Duy Nam and Dr. Pan Dingyi, for their contributions to the DPD research, and Prof. Yu Shaozheng, for his comments on the revised book. Lastly, my humble thanks to the continuing support and constant encouragement of my wife, Kim-Thoa—without her capable hands, normal daily tasks would be impossible, let alone revising this book! It has been good for me to go through this revision, and I sincerely hope that the readers find the book useful in their research works.

Singapore, June 2012 Nhan Phan-Thien

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