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Research paper

Analysis of blood flow through a viscoelastic artery using the Cosserat continuum with the large-amplitude oscillatory shear deformation model

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ABSTRACT

In this investigation, semiempirical and numerical studies of blood flow in a viscoelastic artery were performed using the Cosserat continuum model. The large-amplitude oscillatory shear deformation model was used to quantify the nonlinear viscoelastic response of blood flow. The finite difference method was used to solve the governing equations, and the particle swarm optimization algorithm was utilized to identify the non-Newtonian coefficients (k_υ and γ_υ). The numerical results agreed well with previous experimental results.

1. Introduction

The behavior of blood in the arteries is one of the most important problems in biomechanical engineering. Accordingly, various analytical, numerical, and experimental studies of blood behavior have been performed (Monson et al., 2011; Rossmann, 2010). The investigation of blood flow parameters has a long historical background, even engaging such pioneer scientists as Aristotle, and the nonlinear behavior of blood was unknown until the second half of the last century (Schneck, 1990). From a rheological perspective, blood is a water-based solution comprised of organic and inorganic substances and various suspended cells, including mainly red cells. These properties strongly affect the dynamics of blood flow and render blood as a non-Newtonian fluid (Silber et al., 1998).

The fluctuating state and non-Newtonian characteristics of blood flow as well as the flexibility of the arterial walls make the theoretical analysis of blood very difficult. Experimental studies have revealed that the blood's viscosity

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Nomenclature

V	Velocity vector
γ_v	Non-Newtonian coefficient
ω	Rotation vector
γ	Strain
δ_{ij}	Kronecker delta
$\dot{\gamma}$	Strain rate
Γ_{ij}	Permutation tensor
$\sigma(t)$	Stress response
ε_{ij}	Cosserat deformation tensor
$\sigma'(t)$	Elastic stress
κ_{ij}	Torsion-curvature tensor
$\sigma''(t)$	Viscous stress
t_{ij}	Nonsymmetric force-stress tensor
$T_n(x)$	nth-order Chebyshev polynomial of the first kind
m_{ij}	Nonsymmetric couple stress tensor
e_n	Elastic Chebyshev coefficient
ρ	Density
v_n	Viscous Chebyshev coefficient
J	Microinertia
L	Length scale
f_i	Body force per unit mass

Subscripts

l_i	Body couple per unit mass
z	Axial
π	Thermodynamic pressure
r	Radial
R	Radius of artery
θ	Circumferential
k_v	Non-Newtonian coefficient
$i.j, k$	Coordinate axis
α_v	Non-Newtonian coefficient
β_v	Non-Newtonian coefficient.

decreases with an increase in shear rate, and that blood has a small yield stress. Constitutive models have been proposed for blood as a non-Newtonian fluid by several researchers. Casson proposed a model that later was applied successfully for the analysis of blood flow by Merill and others (Walburn and Schneck, 1976; Hodis and Zamir, in press). Later, the biviscosity model was proposed, which assumed that blood behaves as a non-Newtonian fluid under small shear rates and as a Newtonian fluid under large shear rates. This latter model was used successfully by Nakamura and Sawada (1988) and Kamali and Moayeri (1999). Because of the considerable mechanical properties embedded in the blood's microstructure, simple material theories cannot solve the problem of blood flow. Use of the more sensitive continuum theories, such as nonlocal, micropolar, multipolar, and gradient theories (Silber et al., 1998; Eringen, 2001; Atefi and Moosaie, 2005) with higher kinematic statuses, therefore are more appropriate.

The idea a material body endowed with both translational and rotational degrees of freedom stems from the work of the Cosserate and Cosserate (1909). In this so-called "micropolar continuum", the effects of couples and forces are considered independently of each other (Forest, 2001). Fluids in this continuum can support the couple stress, body couple, and nonsymmetric stress tensor. The fluids possess a rotation field that is independent of the velocity field (i.e., is no longer equal to half of the curl of the velocity vector field). Because of the assumption of infinitesimal rotations, the rotation field can be treated as a vector field. Therefore, this theory has 2 independent kinematic variables: the velocity vector **V** and the spin or microrotation vector ω.

Blood displays complex rheological behaviors and contains cells that exhibit spinning movements that affect the blood flow's velocity. Accordingly, we propose the use of the Cosserat continuum model, which considers the effects of rotational movement and can describe complex fluid flows such as non-Newtonian and turbulent flows (Eringen, 2001; Atefi and Moosaie, 2005; Moosaie and Atefi, 2007; Alexandru, 1989), as an appropriate approach for blood flow simulation.

2. Equation of motion in the Cosserat continuum

In the Cosserat continuum, both the velocity and rotation vector field are considered at any material point. To develop the relationship between the current states of the orthonormal directions attached to each material point and the initial state, we define the so-called Cossert microrotation tensor R_{ij} as

$$R_{ij} = \delta_{ij} - \Gamma_{ijk}\omega_k \tag{1}$$

where δ_{ij} and Γ_{ijk} are the Kronecker delta and permutation tensor, respectively. The associated Cosserat deformation tensor ε_{ij} and torsion-curvature tensor k_{ij} are written as

$$\varepsilon_{ij} = V_{j,i} - \Gamma_{ijk}\omega_k \tag{2}$$

$$\kappa_{ij} = \omega_{j,i} \tag{3}$$

where a comma denotes partial differentiation. In the absence of the rotation vector ω, the classical continuum mechanics is recovered.

It is assumed that the transfer of an interaction between 2 particles of the continuum through a surface element $n_i ds$ occurs by means of a traction vector $t_i ds$ and a moment vector $m_i ds$. Surface forces and couples are represented by the generally nonsymmetric force-stress and couple-stress tensors t_{ij} and m_{ij}, respectively. The balance of the linear and angular momentums requires that the following equations be satisfied:

$$t_{ij,j} + f_i = \rho \frac{DV_i}{Dt} \tag{4}$$

$$m_{ij,j} + \Gamma_{ijk}t_{ik} + l_i = J\frac{D\omega_i}{Dt} \tag{5}$$

where ρ, J, f_i and l_i are the mass density, microinertia, body force per unit mass, and body couple per unit mass, respectively. D/Dt denotes the material time derivative.

The linear constitutive equations are used to describe the material behavior. These equations can be considered to be generalization of Newtonian fluids in the classical