Evaluation of Stretched Thread Lengths in Spinnability Simulations

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ABSTRACT

In this paper, we report evaluation of thin stretched thread lengths in spinnability simulations. There are many previous studies related to viscoelastic fluid, however, there are few studies that represent "spinnability", which is a feature that the material is stretched thin and long. Although some studies represented thread-forming property, they did not evaluate the stretched length of the material. We also tried to represent spinnability of viscoelastic fluid, however, the simulation results were not similar to a real material. Therefore, we try to perform spinnability simulations with three kinds of models, and evaluate stretched thread lengths by comparison of simulation results with a literature datum.

CCS CONCEPTS

• **Computing methodologies** → *Model verification and validation*;

KEYWORDS

Particle method, Viscoelastic fluid, Spinnability, Constitutive equation, Surface tension

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1 INTRODUCTION

One of the most challenging issues is to simulate and visualize liquid behavior since its shape changes dynamically. Simulation of Newton fluid such as water is comparatively simple because the relation between shearing stress and velocity gradient is linear. However, materials such as plastic and rubber are called viscoelastic substance and they have both features of viscosity and elasticity. The relation between shearing stress and velocity gradient is not linear and the behavior is complex. Then, there are many studies related to viscoelastic fluid. [Ram et al. 2015] proposed a new method called "Material Point Method" to simulate viscoelastic fluids, foams, and sponges, and [Barreiro et al. 2017] proposed a constraint based model of viscoelasticity to represent spanning elastoplastic and inviscid liquid behavior. These studies presented viscoelastic fluid behavior, however, thin thread property called "spinnability", which appears in synthetic fiber, was not evaluated. [Wojtan and Turk 2008] presented thin feature of viscoelastic fluid by combining surface mesh and tetrahedral finite element. Although they showed several thin strands of slime, they did not evaluate elongated lengths of threads by comparison of simulation results with a literature datum. [Mukai et al. 2010] and [Nishikawa et al. 2016] also performed spinnability simulations. However, the stretched length of viscoelastic fluid was not so long. Therefore, in this paper, we perform three kinds of spinnability simulations, and evaluate stretched lengths by comparison of simulation results with a literature datum.

2 SIMULATION METHOD

We employ MPS (Moving Particle Semi-implicit) method, which is a particle method that has been developed for incompressible fluid, for the simulations, and the governing equations are as follows.
Equation of continuity:

$$\frac{d\rho}{dt} = 0 \tag{1}$$

Cauchy's equations of motion with surface tension:

$$\rho\frac{d\boldsymbol{v}}{dt} = \nabla\cdot\boldsymbol{\sigma} + \boldsymbol{g} + \boldsymbol{f} = (-\nabla p\boldsymbol{I} + \nabla\cdot\boldsymbol{\tau}) + \boldsymbol{g} + \boldsymbol{f} \tag{2}$$

where, ρ is density, t is time, $\boldsymbol{v}$ is velocity, $\boldsymbol{\sigma}$ is stress tensor, $\boldsymbol{g}$ is gravity, $\boldsymbol{f}$ is external force, p is pressure, $\boldsymbol{I}$ is unit matrix, and $\boldsymbol{\tau}$ is deviation stress. Here, we employ two approaches used in the previous research [Mukai et al. 2010][Nishikawa et al. 2016] to solve the deviation stress. One is linear combination of viscous and elastic stresses, and the other uses Giesekus model [Giesekus 1982]. The linear combination approach considers that the deviation stress $\boldsymbol{\tau}$ is composed of viscous stress $\boldsymbol{\tau_v}$ and elastic stress $\boldsymbol{\tau_e}$ as follows [Nishikawa et al. 2016].

$$\boldsymbol{\tau} = \alpha\boldsymbol{\tau_v} + (1-\alpha)\boldsymbol{\tau_e} \tag{3}$$

$$\boldsymbol{\tau_e} = 2\mu\boldsymbol{\epsilon}, \mu = \frac{E}{2(1+\nu)} \tag{4}$$

where, $\boldsymbol{\epsilon}$ is distortion tensor, E is Young's modulus and ν is Poisson's ratio. α is the coefficient that decides the mixture ratio between viscosity and elasticity, and calculated with the following equation, which is derived from a figure that shows the relation between shearing velocity and viscosity [Nishikawa et al. 2016].

$$\alpha = 3.887\times10^{-4}\,\dot{\boldsymbol{\gamma}}^2 - 2.858\times10^{-2}\,\dot{\boldsymbol{\gamma}} + 1 \tag{5}$$

where, $\dot{\boldsymbol{\gamma}}$ is shearing velocity, and the above equation is normalized so that $\alpha = 1$ for $\dot{\gamma} = 0$. On the other hand, Giesekus model

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considers that deviation stress $\boldsymbol{\tau}$ is divided into two: solvent stress $\boldsymbol{\tau_s}$ and viscoelastic fluid stress $\boldsymbol{\tau_f}$, and these stresses are solved as the following.

$$\boldsymbol{\tau} = \boldsymbol{\tau_s} + \boldsymbol{\tau_f} \tag{6}$$

$$\boldsymbol{\tau_s} = 2\eta_s \boldsymbol{D} \tag{7}$$

$$\boldsymbol{\tau_f} + \lambda \overset{\nabla}{\boldsymbol{\tau_f}} + C_f \frac{\lambda}{\eta_f} \boldsymbol{\tau_f} \cdot \boldsymbol{\tau_f} = 2\eta_f \boldsymbol{D} \tag{8}$$

$$\overset{\nabla}{\boldsymbol{\tau_f}} = \frac{d\boldsymbol{\tau_f}}{dt} - \boldsymbol{L} \cdot \boldsymbol{\tau_f} - \boldsymbol{\tau_f} \cdot \boldsymbol{L^t} \tag{9}$$

$$\boldsymbol{L} = \nabla \boldsymbol{v}, \boldsymbol{D} = \frac{1}{2}(\boldsymbol{L} + \boldsymbol{L^t}) \tag{10}$$

where, η_s and η_f are solvent and viscoelastic viscosities, respectively. $\boldsymbol{D}$ is velocity tensor by deformation, λ is relaxation time, and C_f is constant. Here, ∇ means top convection differential. In addition, we have to consider surface tension as the external force $\boldsymbol{f}$. In the previous method, surface tension $\boldsymbol{f}$ was calculated with CSF (Continuum Surface Force) model as follows, and free surface particles were connected each other with springs [Nishikawa et al. 2016].

$$\boldsymbol{f} = \kappa\beta\delta\boldsymbol{n} \tag{11}$$

where, κ is curvature, β is surface tension coefficient, δ is delta function, and $\boldsymbol{n}$ is normal vector of surface. In this paper, we employ potential based surface tension [Koshizuka 2014]. The following potential force $P(r_{ij})$ works between particles i and j, and the surface tension $\boldsymbol{f}$ is calculated with the potential coefficient C_p as follows.

$$P(r_{ij}) = \begin{cases} \frac{1}{3}C_p(r_{ij} - \frac{3}{2}l_0 + \frac{1}{2}r_e)(r_{ij} - r_e)^2 & (r_{ij} \le r_e) \\ 0 & otherwise \end{cases} \tag{12}$$

$$\boldsymbol{f} = \Sigma_{j \ne i} C_p(r_{ij} - l_0)(r_{ij} - r_e) \tag{13}$$

where, r_{ij} is distance between particles i and j, l_0 is initial distance between particles, and r_e is radius of influence.

3 SIMULATION RESULTS

We have performed three kinds of following simulations.

Method 1 calculates deviation stress and surface tension with **linear combination** and **potential based surface tension** (Eq.(13)).

Method 2 calculates deviation stress and surface tension with **Giesekus model** and **potential based surface tension**.

Previous Method [Nishikawa et al. 2016] calculates deviation stress and surface tension with **linear combination** and **CSF model**, where free surface particles are connected with springs (Eq.(11)).

Simulations of stretching viscoelastic fluid were performed with a PC having Intel Core i5-2500 3.30 GHz CPU, 4GB memories, and GeForce GTX 570 GPU. The numbers of particle were 29,791 and 16,950 for viscoelastic fluid and solid body attached to the fluid for stretching, respectively. Figs. 1 and 2 show three kind of stretching behavior and the comparison of stretched thread lengths among three methods and one real material, respectively.

4 CONCLUSION

In this paper, we have evaluated stretched thread lengths for three kinds of stretching simulations. As a result, both of Methods 1 and 2, which employed potential based surface tension, elongated the string more than Previous Method that calculated surface tension with CSF model. There was not much difference in the stretched thread length between Method 1 (linear combination) and Method 2 (Giesekus model) compared with the Previous Method. Both results were very similar to a real material (Acetyl Cellulose) except for high stretching velocity, greater than 0.14 [m/s].

In the future, we have to investigate which model is better for spinnability simulation: linear combination of viscous and elastic stresses or Giesekus model. We also have to consider how to modify our model for better results even in high stretching velocity.

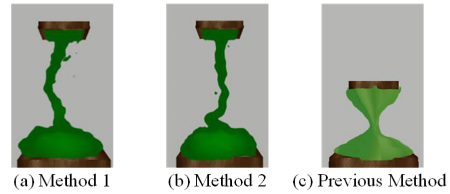

Figure 1: Results of stretching simulations. (a) calculates DS (deviation stress) and ST (surface tension) with LC (linear combination) and PBST (potential based surface tension). (b) calculates DS and ST with Giesekus model and PBST. (c) calculates DS and ST with LC and CSF model.

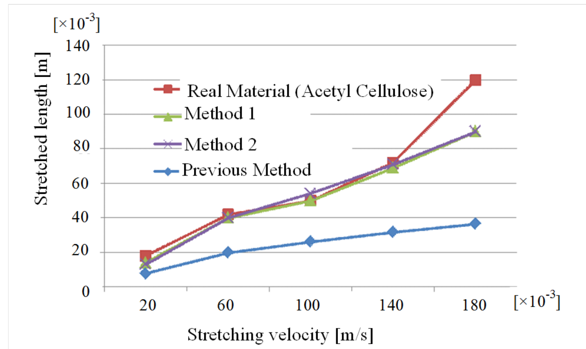

Figure 2: Comparison of stretched thread lengths among three methods and one real material.

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