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Special Section

Particle-based fluids for viscous jet buckling

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ABSTRACT

In this paper, we introduce a novel meshfree framework for animating free surface viscous liquids with jet buckling effects, such as coiling and folding. Our method is based on Smoothed Particle Hydrodynamics (SPH) fluids and allows more realistic and complex viscous behaviors than the previous SPH frameworks in computer animation literature. The viscous liquid is modeled by a non-Newtonian fluid flow and the variable viscosity under shear stress is achieved using a viscosity model known as Cross model. We demonstrate the efficiency and stability of our framework in a wide variety of animations, including scenarios with arbitrary geometries and high resolution of SPH particles. The interaction of the viscous liquid with complex solid obstacles is performed using boundary particles. Our framework is able to deal with different inlet velocity profiles and geometries of the injector, as well as moving inlet jet along trajectories given by cubic Hermite splines. Moreover, the simulation speed is significantly accelerated by using Computer Unified Device Architecture (CUDA) computing platform.

1. Introduction

A daily life example of viscous jet buckling is the coiling and folding of a thin thread of syrup or honey falling onto a spoon. The characteristic motion of a jet buckling is controlled by the balance among inertia, gravity and viscous forces that arise from the compressive stress caused by the impact of the fluid on a rigid surface. In the last years, Smoothed Particle Hydrodynamics (SPH) [1] has become a popular numerical meshfree tool for visually realistic animation of liquids [2]. However, simulating the complex free surface of a viscous jet buckling in an efficient and realistic way remains a big challenge for the previous SPH frameworks in computer animation. The difficulties are related to proposing a variable viscosity model which has a non-linear dependence of the fluid's shear rate, proposing an accurate and stable SPH approximation for viscous acceleration which involves second order derivatives of each component of the velocity field, and enforcing boundary conditions suited to SPH.

In this paper, we present a novel meshfree technique based on SPH fluids for simulating viscous jet buckling behaviors. Our technique allows a wide range of realistic viscous effects of the free surface of liquids, such as coiling and folding, as shown in Fig. 1. In order to capture the viscous behavior that is characteristic of jet buckling, the time interval between two consecutive frames needs to be very short, as discussed in Section 3.3, thus increasing the number of time-steps of the simulation total time. Since the computation in each time-step is highly intense, but can be performed in parallel and independently for each SPH particle, the problem can be suitably mapped to graphics processing units (GPUs). We use the Computer Unified Device Architecture (CUDA) by NVIDIA due to its efficiency, object-oriented programming capability, easy integration with the development environment we have used, and availability of a lot of libraries and demos which accompany the CUDA toolkit. The adequacy of using CUDA for standard SPH fluids can be demonstrated by other implementations reported in the literature [3,4]. In summary, the main contributions of this paper are:

Variable viscosity model: The viscous liquid is modeled as a non-Newtonian fluid flow and the variable viscosity is governed by a rheological model known as *Cross model* [5].

SPH viscous acceleration: We introduce a stable and robust SPH approximation of fluid's viscous acceleration using derivative operators of first order.

SPH boundary particles: Our framework allows us to impose boundary conditions on complex geometries to simulate rigid obstacles using boundary particles.

SPH jet buckling on CUDA: Using CUDA enables the animation of jet buckling scenes involving hundreds of thousands of SPH particles in affordable computational times, notably when compared to sequential processing, as showed by the experiments presented in Section 4, freeing the CPU for other tasks.

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Fig. 1. The liquid rope coiling effect: a real image of honey coiling (left), our technique with free surface (middle) and with SPH fluid particles (right).

1.1. Related work

In order to better contextualize our approach and highlight its properties, we organize the existing frameworks for animating viscous jet buckling into two main groups, Eulerian mesh-based and Lagrangian meshfree-based methods.

Eulerian mesh-based: A seminal work in computer animation was introduced by Goktekin et al. [6]. They simulate solids and viscoelastic fluids with a small effect of buckling using an explicit grid-based method with viscosity transition between solid and non-Newtonian fluid controlled by a quasi-linear plasticity model. Batty and Bridson [7] developed an implicit and unconditionally stable method using marker-and-cell (MAC) grid. Although this method provides high-accuracy free surface boundary conditions, it is limited to viscous Newtonian fluids. Bergou et al. [8] proposed a discrete model for viscous threads using elastic rods to represent thin Newtonian liquid jets. Despite this method's realistic results, spurious results may occur when the jet becomes thick. Recently, this model was extend to discrete viscous thin sheets [9]. Batty and Houston [10] presented an adaptive tetrahedral mesh solver to animate Newtonian liquids with high viscosity. However, the level set surface generated by this method does not preserve temporal coherence due to the slow motion of the liquid. In computational physics literature, there are several papers using variations of generalized simplified MAC (GENSMAC) method to simulate viscous jet buckling in arbitrary 2D/3D domains with explicit [11–13] and implicit [14] free surface boundary conditions.

Lagrangian meshfree-based: SPH fluids have been applied with success in simulations of highly viscous liquids with variable viscosity [15–19]. However, none of these methods in computer animation have captured viscous buckling behavior. In computational physics, Rafiee et al. [20] used an incompressible version of SPH to simulate 2D jet buckling of non-Newtonian fluids, while Xu et al. [21,22] extended the traditional weakly compressible SPH method to deal with 3D simulations. This paper is inspired in [21] and it improves that work in several ways: our stable SPH approximation of momentum equation does not require additional terms, artificial stress and artificial viscosity, to prevent particle clustering and unphysical behavior of free surface.

A previous version of this paper [23] focused on buckling effects in planar boundaries only. Here, we focus on buckling effects on arbitrary surfaces and injectors with complex geometry. In addition to the material on jet buckling presented in Section 4, we include a wide variety of examples using injectors with complex geometry and with different velocity profiles at the inlet. Moreover, we demonstrate the ability of our technique in applications with complex rigid surfaces using boundary particles.

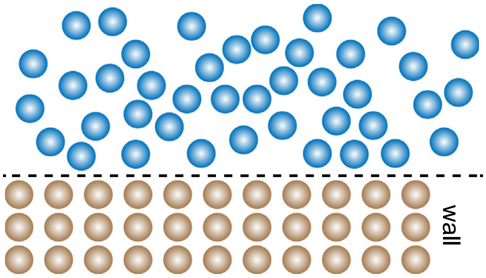

Fig. 2. SPH particles: fluid (blue) and boundary (brown) particles. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

2. Governing equations

The governing equations for simulating fluid flow are derived from mass and momentum conservation laws. Lagrangian framework describes these laws from the viewpoint of an infinitesimally small fluid element, i.e., a particle. In this framework the mass conservation is naturally satisfied, since the particle mass is constant, then the total mass of the system is preserved. For weakly compressible fluids, the momentum equation can be written as follows:

$$\frac{d\mathbf{v}}{dt} = -\frac{1}{\rho}\nabla p + \frac{1}{\rho}\nabla\cdot\tau + \mathbf{g} \qquad (1)$$

where t denotes the time, $\mathbf{v}$ the velocity field, ρ the density, p the pressure, $\mathbf{g}$ the gravity acceleration vector and τ the shear stress tensor.

Lagrangian formulation of Eq. (1) represents the acceleration of a particle moving with the fluid flow. The term $-\frac{1}{\rho}\nabla p$ is related to particle acceleration due to pressure changes in the fluid. While, the term $\frac{1}{\rho}\nabla\cdot\tau$ describes the viscous acceleration due to friction forces caused by particles with different velocities. This last term plays a key role in viscous jet buckling animation.

Cross model

In order to animate a wide variety of buckling effects, Newtonian and non-Newtonian fluid flows are used in this paper. In particular, non-Newtonian fluids have non-linear dependence of the shear stress τ with respect to the rate-of-deformation tensor $\mathbf{D} = \nabla\mathbf{v} + (\nabla\mathbf{v})^{\top}$ as follows:

$$\tau = \rho\nu(D)\mathbf{D} \quad \text{with} \quad D = \sqrt{\frac{1}{2}\cdot \mathrm{tr}(\mathbf{D})^2}. \qquad (2)$$