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Robust turbulence simulation for particle-based fluids using the Rankine vortex model

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ABSTRACT

We propose a novel turbulence refinement method based on the Rankine vortex model for SPH (smoothed particle hydrodynamics) simulations. Surface details are enhanced by recovering the energy lost in the rotational degrees of freedom of SPH particles. The Rankine vortex model is used to convert the diffused and stretched angular kinetic energy of particles to the linear kinetic energy of their neighbours. Our model naturally prevents the positive feedback effect between the velocity and vorticity fields since the vortex model is designed to alter the velocity without introducing external sources. Experimental results show that our method can recover missing high-frequency details realistically and maintain convergence in both static and highly dynamic scenarios.

Index Terms: Computing methodologies—Computer graphics—Animation—Physical simulation

1 INTRODUCTION

As one of the most popular approaches to simulating fluids in computer graphics and virtual reality, smoothed particle hydrodynamics (SPH) has been widely used to generate fluid animations with lively details and vivid motions. Although many novel models for animating various materials and enforcing incompressibility have been proposed, much work remains to be done to achieve and enhance realistic visual effects of complex phenomena. For example, simulating turbulent details is still elusive due to numerical dissipation [4] or coarse sampling of grids [5].

The up-res and vortex-based methods have been used to increase the resolution of turbulent fluids. The up-res method is commonly used in Eulerian simulations, using coarse grids for the simulation and increasing resolution via fine turbulence models [6,7]. Vortex-based methods aim to create and preserve turbulence through the vorticity field, which includes the vorticity confinement and Lagrangian vortex methods. The vorticity confinement (VC) method recovers existing vortices and enhances them by adding an extra force [3]. The Lagrangian vortex (LV) method builds on the vorticity representation of the Navier-Stokes equations [1,8]. However, the VC method tends to add more energy than the fluid dissipates, and only existing vortices can be amplified. The LV method does not work well in scenarios involving liquids. Finally, the up-res method usually acts as a post processing step and thus does not address the dissipation issue directly.

To solve the problems mentioned above, we utilise the vorticity field to approximate angular velocity of particles and feed it back to the velocity field using the Rankine vortex model. When the particle size is large enough, the inertia tensor absent from the equation will result in severe numerical dissipation.

2 THEORY

To prevent the loss of rotational kinetic energy when pursuing efficiency, we add angular velocity as a three-dimensional attribute to each fluid particle, through which the missing rotational kinetic energy can be restored. Tangential viscosity from angular velocity is incorporated, and thus vortex models are ideal to capture the required rotational influence.

We derive the angular velocity $\boldsymbol{\Omega}$ through the vorticity field $\boldsymbol{\omega}$ as $\boldsymbol{\Omega} = \boldsymbol{\omega}/2$. We compute the vorticity field using the differential form as:

$$\boldsymbol{\omega}_i = \nabla \times \boldsymbol{u}_i = \frac{1}{\rho_i} \sum_j m_j (\boldsymbol{u}_i - \boldsymbol{u}_j) \times \nabla_i W_{ij}. \tag{1}$$

Compared with Wang et al [9], a more accurate form of vorticity dissipation for each particle can be derived as:

$$\frac{d\boldsymbol{\omega}_i}{dt} = (\boldsymbol{\omega}_i \cdot \nabla)\boldsymbol{u}_i + \nu \nabla^2 \boldsymbol{\omega}_i, \tag{2}$$

where ν is the kinematic viscosity.

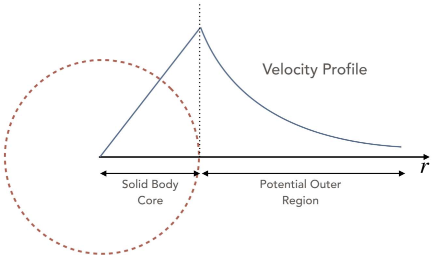

Figure 1: Diagram of a solid core in the two-dimensional Rankine vortex.

A two-dimensional Rankine vortex model can be expressed as:

$$V(r) = \begin{cases} \left(\frac{\Gamma}{2\pi r_c}\right) \bar{r} & 0 \le \bar{r} \le 1, \\ \left(\frac{\Gamma}{2\pi r_c}\right) \frac{1}{\bar{r}} & \bar{r} > 1, \end{cases} \tag{3}$$

where Γ is a fixed circulation, and $\bar{r} = r/r_c$ with r the radical location and r_c the radius of the viscous core. We apply the viscous core according to the vortex model given by Lamb and Ossen, which is derived as a solution to the one-dimensional Navier-Stokes equations:

$$r_c = \sqrt{4\alpha\nu t}, \tag{4}$$

where α is the Oseen parameter with a value of 1.25643. Considering the time-step Δt and the kinematic viscosity ν of the fluid, the largest possible viscous core used in each simulation step is $r_{c_{\max}} = \sqrt{4\alpha\nu\Delta t}$, and the smallest is $r_{c_{\min}} = 0$. In order to enable our users to alter the performance directly, we introduce an adjustable viscous coefficient β to make our method controllable

$$r_c = \beta r_{c_{max}} = \beta\sqrt{4\alpha\nu\Delta t} \tag{5}$$

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with $0 \leq \beta \leq 1$. The default value of $\beta = 0.6$ is used throughout the paper, unless stated otherwise.

In order to recover the missing details in a simulation, we transform the angular velocity to let it reasonably affect the linear velocity. To extend the two-dimensional vortex model to a fully three-dimensional simulation, we apply the model in a point-symmetrical way. So the refinement from particle with index j to that of index i can be expressed as:

$$\delta \boldsymbol{u}_{i\to j} = \frac{r_c}{\|\boldsymbol{r}_{ij}\|}\,\frac{-\delta\boldsymbol{\omega}_j}{2} \times \frac{r_c\boldsymbol{r}_{ij}}{\|\boldsymbol{r}_{ij}\|}, \tag{6}$$

where $\boldsymbol{r}_{ij} = \boldsymbol{x}_i - \boldsymbol{x}_j$, i.e., the distance between the involved particles. Consequently, we obtain the velocity refinement for all particles in a linear fashion and thus with little computation overhead.

3 Experiments and Discussion

In this section, we compare the simulation results of our method to several fluid and turbulence simulation methods. We integrated MPSPH [2] and our method with the DFSPH and IISPH.

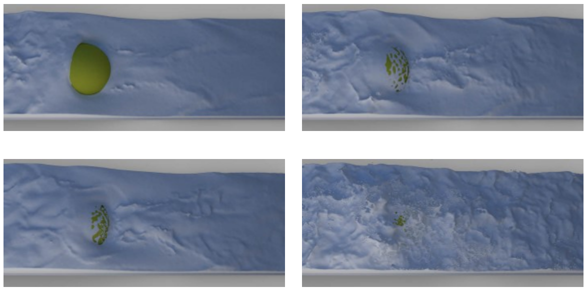
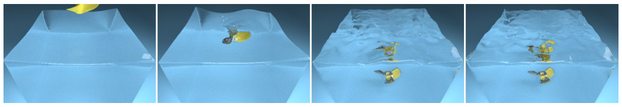
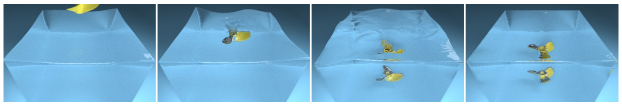


Figure 2: A simulation using 94K/s turbulent fluid particles with an inserted hemisphere modelled with our method and MPSPH. Top row: Our method with $\beta = 0.2$ and 0.4. Bottom row: MPSPH with $v_t = 0.2$ and 0.4.

In a classical scenario in Fig. 2, 94K fluid particles run over a hemisphere in a tunnel. As β increases, the flow gets more violent at the injection port and the traces become more irregular and apparent.Compared with our method, MPSPH increases the turbulence in a fiercer way. The fluid behaviour with $\beta = 0.4$ looks as furious as that of $v_t = 0.2$.



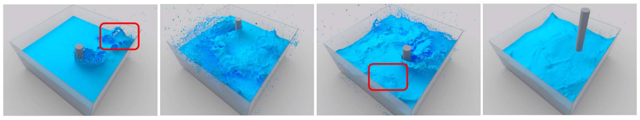
MPSPH [2]



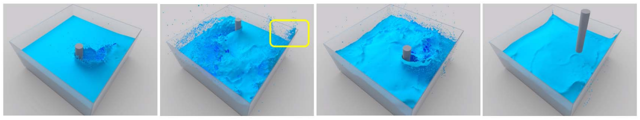
Our method

Figure 3: A propeller interacts with water using 1.13M fluid particles.

In Fig. 3, a propeller was slowly submerged into water and rotated clockwise, at a speed of 5 radians per second.The turbulence recovered by our method shows a trend of clockwise movement on a macroscopic level, which is more in line with reality. By contrast, the turbulence effect produced by MPSPH is very fragmented, lacking macroscopic motion. Although the details in MPSPH are more abundant, this is at a cost of energy surge.



MPSPH [2]



Our method

Figure 4: A stirring water experiment with 1.48M fluid particles.

In Fig 4, a cylindrical stick was inserted into a tank of water, and stirred at a uniform speed for eight seconds. The water splashed around due to the quick movement of the stick. Observe that the simulation result under our method and MPSPH is more delicate than DFSPH. This is due to the recovery of the dissipated velocity by vorticity, while maintaining a certain amount of energy.

4 Conclusion

We have presented an SPH-based method for recovering turbulence details for low-viscosity incompressible fluids. Built on the Lagrangian modeling approach, our method can be easily integrated into any SPH method with negligible computational overhead. According to the unconditional stability of potential flow in the SPH simulation process, we showed that the Rankine vortex model is preferable to adjust the linear velocity and to generates small vortices in the vicinity of each particle.

Acknowledgments

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