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Boundary handling and porous flow for fluid–hair interactions

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ABSTRACT

We present a two-way coupling technique for simulating the complex interaction between hair and fluids. In our approach, the motion of hair and fluids is simulated by evaluating the hydrodynamic forces based on boundary handling techniques used in SPH (Smoothed Particle Hydrodynamics) fluids. Water absorption inside the hair volume is simulated with a diffusion process by treating the hair volume as porous media with anisotropic permeability. The saturation of each hair strand is then used in boundary density estimation as well as fluid–boundary force computation to greatly stabilize the simulation. We also utilize the saturation of hair to derive the adhesive force between wet hair strands. This enables us to simulate the formation of hair clumps dynamically without the need to employ post clumping processes. As a result, the proposed method realistically reproduces subtle fluid–hair interactions and can be easily applied to any SPH fluid as well as hair solvers.

1. Introduction

While hair–fluid interaction has become more and more common in the movie industry, it requires artists' time and effort to iterate over a two-pass methodology: first the fluids are simulated in a fluid solver then the results are used as obstacles for the simulation of the motion of hair (and vice versa). Although this method produces plausible fluid–hair interactions, some important details, including the modification of hair properties from dry to wet, underwater hair dragging and dynamic hair clump formation, are difficult to reproduce. To simulate these complex interactions between fluids and deformable solids, a two-way hair–fluid coupling technique with proper hydrodynamic force models is required. Moreover, since there may be no fluid particles in the vicinity of wet hair strands, a self-adhesion model is necessary for dynamic hair clump formation.

In recent years, two-way coupling techniques have been developed for simulating the interaction between Lagrangian fluids and deformable solids. These techniques successfully capture the small scale phenomena between fluids and solids. For instance, Akinci et al. [1] sampled rigid or deformable solids [2] with boundary particles, then computed the representative volume of boundary particles for fluid density correction and pressure computation. This results in impressive interactions between rigid bodies, cloth and fluids.

Although these techniques seem to be applied to hair–fluid coupling directly, one will encounter numerical instabilities which are caused by erroneous pressure forces when fluid particles are at the interface of constantly moving hair boundary particles. To address the stability issue, Lin [3] proposed to manipulate the hydrodynamic forces between hair and fluids by taking into consideration the wetness of hair strands which is calculated by tracing the fluid flow inside of the hair volume. In this paper, modifications on the evaluation of various fluid forces are made to increase the stability while retaining fluid forces when hair is completely wet.

Rungjiratananon et al. [4] introduced a Cartesian grid to represent the dynamic capillary system for water absorption inside the hair volume. However, the force transfer between fluids and hair strands is not clearly described in their paper. Moreover, their method seems to be limited to some specific hairstyles. Lenaerts et al. [5] exploited porous particles and model the evolution of absorbed fluid mass using SPH to simulate porous flow at a macroscopic scale. Inspired by Lenaerts et al. [5,3] proposed a similar method to account for the fluid absorption inside the hair volume. Instead of using an isotropic permeability in the fluid absorption process, an anisotropic one is used to better approximate the structure of the void space inside the volume of hair. Based on Lin [3], we make further improvement on the equations of integrating the mass of the absorbed water on boundary particles.

Lin [3] proposed an algorithm to manipulate the forces between fluids and hair and introduced new forces between wet hair strands. The method extended the boundary handling technique that previously was used for solid–fluid coupling [1] by incorporating a diffusion process before the density evaluation and the fluid force computation. The wetness of hair strands is used in the fluid density evaluation on the boundary as well as to

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attenuate fluid pressure force, this results in a stable hair–fluid interaction. For the dynamic formation of hair clumps, a hair self-adhesive force was proposed, allowing the simulation of the sticking effects which can be observed on wet hair with various hairstyles. Moreover, the self-adhesive force can be added to existing post clumping procedure to enhance the realism. Combining these, it is possible to simulate a variety of challenging scenarios such as the transition from dry to wet hair, gradual hair submerging and clump formation when hair is leaving water surface (Fig. 7). Furthermore, the method is generic and therefore can be easily added to existing fluid and hair solvers. In this paper, we make further improvement on equations of porous flow and fluid forces, therefore gaining a more stable simulation. Moreover, the experimental results presented in this paper demonstrate the possibility of the coupling of different substances (hair/fluids/rigid bodies).

The rest of the paper is composed as follows: Section 2 briefly discusses previous works related to hair–fluid coupling. Section 3 explains how the water absorption inside of the hair volume is considered for evaluating the density on the boundary and exchanging the hydrodynamic forces between hair and fluids. Section 4 introduces a self-adhesive force for the dynamic hair clumping process. Section 5 describes some implementation details of the proposed algorithm. Section 6 shows the experimental results, including the coupling between fluids, hair and rigid bodies. Section 7 discusses the limitations of our method before the conclusion in Section 8.

2. Related work

In this section, we briefly discuss some of the techniques that have been proposed for the interaction between deformable solids and Lagrangian fluids. Note that in the following context, we call a sampled particle used for hair–fluid coupling on each hair segment *hair boundary particle*, as illustrated in Fig. 1(c).

2.1. Two-way rigid-fluid coupling in SPH fluids

Typically, for the handling of solid boundary in Lagrangian fluids, deformable solids are sampled with boundary particles and a boundary handling method is used for two-way solid–fluid coupling. A commonly used technique is the distance-based penalty method [6–9]. However, these approaches suffer from sticking artifacts. Although Harada et al. [8] proposed a wall weight function to alleviate the sticking artifacts in these approaches, a small time step is required to achieve a stable simulation because large penalty forces are used. The sticking particle issues can be alleviated either by frozen and ghost particles as proposed by [10–13]. In their approaches, the relevant field variables are well approximated by sampling the boundary with fluid particles, resulting in continuous pressure gradients that prevents fluid particles from sticking to the boundaries. However, for fluid interacting with thin-shells or rods, fluid particles on both sides of the boundary affect each other in their approaches.

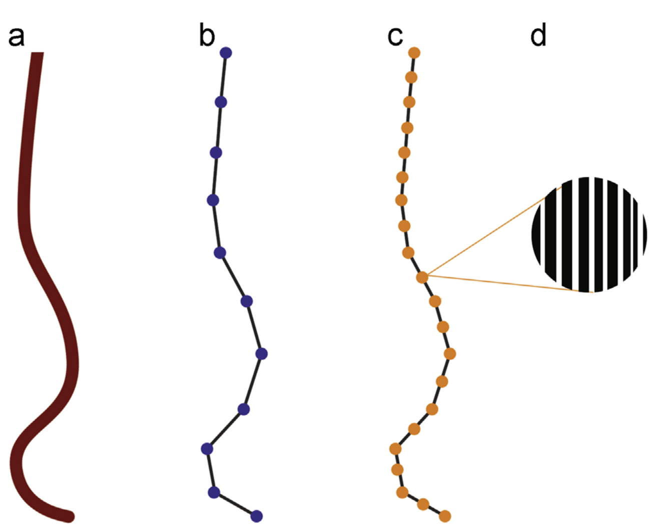

Fig. 1. The discretization (b) of a hair strand (a) and the sampled hair boundary particles (c) used in fluid force evaluation and fluid absorption. Each hair boundary particle is also treated as porous particle for the fluid absorption process (d).

Akinci et al. [1] proposed a boundary handling method that successfully alleviates particle sticking artifacts by including boundary particles in fluid density estimation. In their approach, however, the diameter of rods as well as the thickness of shells cannot be smaller than the diameter of a fluid particle. In [3], the fluid pressure force on each colliding hair boundary particle is attenuated by considering its wetness. As a result, two neighboring hair strands can move as closely as possible without inducing instabilities if a fluid particle is sandwiched between them. In other words, fluid particles are allowed to move through the volume of hair.

For the two-way rigid-fluid coupling, Clavet et al. [14] considered the fluid particles as rigid spheres that exchange impulses with surrounding rigid bodies. In [15,16], the pressure at the boundary is taken into account for two-way coupled fluid–rigid interactions. In those models, however, viscosity is neglected. Oh et al. [17] proposed an impulse-based approach to solve rigid body interaction in SPH. However, this approach relies on normal information of rigid bodies and does not guarantee non-penetration for thin boundaries.

Hadap and Magnenat-Thalmann [18] proposed to treat hair as fluids (*hair fluid*) and used SPH to simulate hair dynamics. In their work, the air drag is simulated using two fluids, air and hair, and controlled by the drag coefficient. However, no actual fluid particles exist to exert hydrodynamic forces to neighboring hair strands.

In [19], a surface tension model and a fluid–solid adhesion model are proposed to improve the treatment of fluid–air and fluid–solid interfaces. Their approach can handle large surface tensions by minimizing surface area in all scales while conserving momentum. In [3], a similar adhesion model was used for handling the fluid–hair interfaces. In addition, a self-adhesive force between neighboring hair strands, which is computed by modifying the cohesion force described in [19], was introduced to simulate dynamic hair clump formation.

2.2. Porous flow in SPH fluids

Researchers outside the field of computer graphics have studied fluid flow through porous media. Sawley et al. [20] presented an SPH framework in which porous media are modeled by fixed particles in the fluid domain. Morris et al. [21,22] extended SPH to allow incompressible porous flow. Although these methods produce accurate results, modeling porous flow at a pore scale using SPH is too expensive for hair–fluid coupling. Lenaerts et al. [5] treated the pores at a macroscopic scale and reused the particle representation of the deformable objects to model the diffusion process within porous materials. Similar to [5], Lin [3] sampled each rod segment with several hair boundary particles both for the boundary handling and the diffusion process. Moreover, an extension to [5] was made by adopting anisotropic permeability in the diffusion process to model the directional fluid flow along void space within the hair volume.