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Control of water flow to avoid twining of artificial seaweed

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Abstract: This study presents a control method for a water flow to avoid seaweed twining in a cultivation pool. The water flow in the pool is modeled by the lattice Boltzmann method (LBM). Morphology of the seaweed is determined by L-system. Physics Modeling (PM) represents its physical model. Three physical properties, gradual collision, adhesiveness, and tear phenomenon for the seaweed are artificially introduced into simulation. Motion of the seaweed is examined in the virtual underwater pool by PM simulation. A water flow pattern is realized by controlling particles distributed in lattices. We ascertained that some water flow pattern can avoid the seaweed twining phenomenon by changing the water flow pattern in the simulation.

Keywords: Physics modeling, Seaweed, L-system, Computational Fluid Dynamics, Lattice Boltzmann Method

1 INTRODUCTION

The technology of renewable energy is required for solving the global warming problem. In recent years, seaweed has been attracted for this purpose [1]. It absorbs CO_2 and emits O_2 in growing. The growth rate of the marine plant is 10 times faster than the terrestrial plant. Because the marine plant grows in a rich nutrition sea and the terrestrial one grows in soil. The grown seaweed is available as a material of bio-ethanol. Growing seaweed in seawater dissolving high concentration CO_2 can accelerate the growth rate of seaweed.

There arise some difficulties to introduce seaweed cultivation in large-scale bio factory. One of problems is to control a water flow for avoiding seaweed twining. Factors of the environment for effectively growing the seaweed are CO_2 assimilation of seawater and water temperature. Physical motion of seaweed with the growth process is also an important factor. Twining of seaweed causes depression of assimilation efficiency of CO_2 and death. It makes an adverse effect to effective growing. Therefore, the control of water flow is required for solving these problems.

Understanding physical motion of seaweed in fluid is important. Seaweed motion in fluid is flexible. This is one of biological properties and cause seaweed twining. Finding out conditions to generate twining has significant meaning.

This study aims at making a simulation model that examines water flow conditions causing seaweed twining. We make a physical model of seaweed and develop a virtual underwater pool where some water flow occurs. The motion of the seaweed is physically realized in the virtual underwater pool and verifies that our model can simulate suitable seaweed motion and fluid flow.

2 ARTIFICIAL SEAWEED

The physical model of seaweed is represented by connecting some small rigid spheres. It has three degrees of freedom and approximates soft motion of plants.

2.1 Physical model

The algorithm called L-system can represent the growth process in plants [2]. It was proposed by Hungarian theoretical biologist and botanist, Aristid Lindenmayer. We adopt L-system for modeling seaweed morphology and the grow process. L-system is shown in (1)-(4). Notations to make a growth model in fig.(1) are introduced as follow; V is the replaceable set of rigid bodies shown in fig.1, S is the invariable set of rigid bodies, ω is the initial state and P is the replacement rule.

$$\begin{aligned} V &= \{A, B, C\} && (1)\\ S &= \{E, D\} && (2)\\ \omega &= A && (3)\\ P &: (A \rightarrow EBA), (B \rightarrow C), (C \rightarrow D) && (4) \end{aligned}$$

The seaweed grows by iteratively dividing branches. By applying L-system, the growth process of the artificial seaweed is represented in a natural form of plants.

A physical model is designed as shown in fig.3. It consists of 340 rigid bodies. Each rigid body has the same volume as the sphere one with 0.25 meters in radius.

2.2 Physical property

In order to mimic real seaweed as much as possible, we give physical properties to the artificial seaweed model. Such properties are gradual collision, adhesiveness and tear.

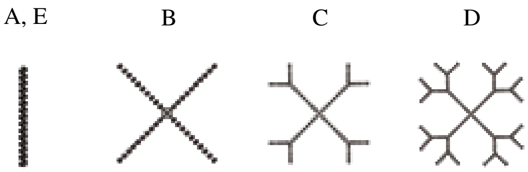


Fig. 1. The component of the physical model

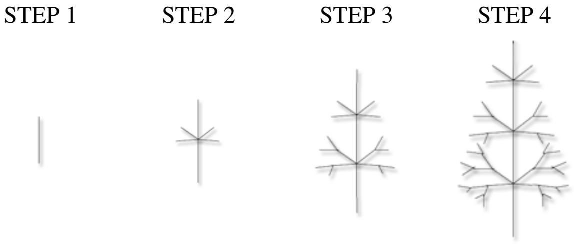


Fig. 2. The growth process of the physical model

2.2.1 Gradual collision

Gradual collision is observed among actual plants. An automatic calculation of collision by physical engine depends on a value of reflection coefficient. We set 0.05 to the value of reflection coefficient e. The gradual collision is realized by relatively reducing force in collision.

2.2.2 Adhesiveness

When some seaweeds colide each other, attractive forces among them appear. We model this phenomenon as adhesiveness. We add a small force similar to Coulomb one between two rigid bodies as the adhesiveness when a distance between two rigid bodies is less than the threshold r_t. This force is given by eq.(5),

$$F_A = k_a \frac{1}{r^2} \quad \text{for} \quad r < r_t \tag{5}$$

where k_a is an adhesive coefficient, r is a distance between two rigid bodies.

2.2.3 Tear

Seaweed is teared when a strong force works to it. In our model connection of rigid bodies is teared into two parts when receiving the external force larger than 10,000[N]. Teared parts cannot be reconnected any more.

3 VIRTUAL UNDERWATER ENVIRONMENT

A physical model for a virtual underwater pool is constructed by using PhysX that is the physical engine provided by NVIDIA cooperation. PhysX can do fast physical calculation and physical simulation on rigid bodies easily. However, functions for the buoyancy and drag forces in a fluid are not supported in the PhysX. We implement three forces as referred in [3].

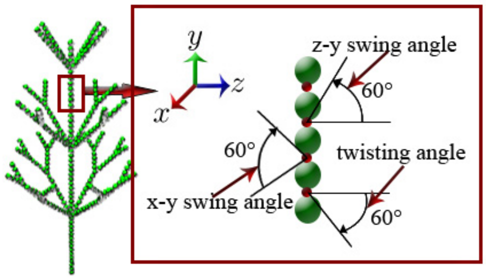


Fig. 3. The artificial seaweed model

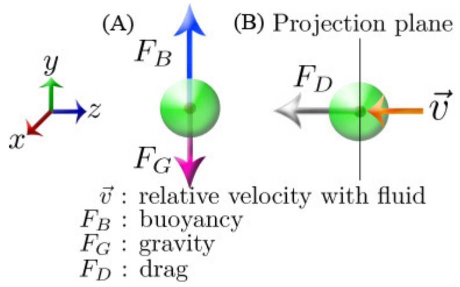


Fig. 4. Buoyancy and drag calculation

3.1 Buoyancy

In a fluid environment, the upward force called the buoyancy F_B works to the center of objects as shown in fig.4(A). A calculation of this force is given in eq.(6),

$$F_B = \rho V g \tag{6}$$

where ρ is a density of the water, V is a rigid volume, g is acceleration of gravity.

3.2 Drag force

Drag force F_D shown in fig.4(B) works to the rigid body in a fluid. This force that directs to opposite movement is proportional to a square of a relative velocity with a fluid. A calculation of this force based on fluid dynamics is given in eq.(7),

$$F_D = \frac{1}{2} \rho A C_D v^2 \tag{7}$$

where ρ is a density of the water, A is an area to which the drag works, C_D is a drag coefficient of inherent nature of rigid body, v is relative velocity of rigid with fluid.

4 WATER FLOW

In order to examine a pattern of water flow that makes avoiding seaweed twining, we require a realistic water flow model. Water is a fluid and its density is not changed by pressure. Therefore, the water flow can be treated as an incompressible fluid. In this study, it is modeled by the lattice Boltzmann method (LBM) [4].

4.1 Lattice Boltzmann Method

LBM is one of analytical techniques in computational fluid dynamics [5]. The method uniformly discretizes a simulating space into lattices and make it possible to simulate fluid movement as a continuum by use of particles distributed in the lattices. A particle distribution function is obtained by calculating ensemble average of a number of particles in each lattice. A fluid density and velocity is easily computed in this way. The number of particles is provided by real number. It can represent a high-precision flow without noise.

Particles have some velocities in LBM. In a discretizing time, they leave lattice or move to other lattice once at each time step $\quad t$. Some particles change the direction of velocity by collision. All particles are located in lattices at each time step. Particle collision appears in all lattices at the same moment.

4.2 Fluid model

We employ D3Q15 model as a particle distribution model in LBM [6]. The particles have velocities as shown in fig.5. The model only considers the mass conservation and momentum one.

4.2.1 Time evolution of particle distribution

To calculate a time evolution of particle distribution, we use the lattice Boltzmann equation defined by eq.(8).

$$f_i\left(x + e_i \quad t, t + \quad t\right) = \left(\frac{\lambda \quad 1}{\lambda}\right) f_i\left(x, t\right) + \frac{1}{\lambda} {f_i}^{eq}\left(x, t\right) \quad (8)$$

This equation is an evolution equation for the virtual particles. λ is a relaxation frequency. Particles move by iterating collision and they transit from a movement state to a equilibrium state at a constant rate. ${f_i}^{eq}$ is a local equilibrium distribution. This particle equilibrium distribution function is given by eq.(9),

$${f_i}^{eq}\left(x, t\right) = \omega_i \rho \left(1 \quad \frac{3}{2}\vec{u}^2 + 3\left(\vec{e_i} \quad \vec{u}\right) + \frac{9}{2}\left(\vec{e_i} \quad \vec{u}\right)^2\right) \quad (9)$$

$$\text{where, } \omega_i = \begin{cases} \dfrac{2}{9} & : \quad i = 0, \\ \dfrac{1}{9} & : \quad i = 1..6, \\ \dfrac{1}{72} & : \quad i = 7..14. \end{cases}$$

and ρ is a density of fluid, $\vec{u}$ is a velocity of fluid, $\vec{e_i}$ is a velocity of particle. By adding ${f_i}^{eq}$ to the particle distribution function, eq.(8) guarantee a situation that fluid transit to the equilibrium state [6].

4.2.2 Boundary condition

In a lattice making a border as obstacles, the particle distribution function cannot give particles' direction to the fluid as obstacles. Therefore, we apply *bounce-back* to such lattices as a boundary condition. This condition rebounds particles into 180 degrees of direction from an obstacle shown in fig.6.

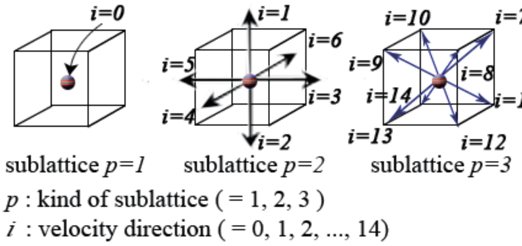


Fig. 5. D3Q15 Model

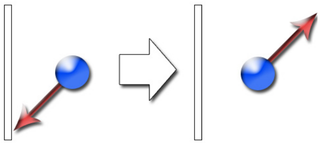


Fig. 6. This figure gives an overview of the translate and collide processes for a fluid lattice next to an obstacle.

5 NUMERICAL SIMULATION

In order to study the growth environment for avoiding seaweed twining, we examine two water flow patterns. We simulate physical motion of the artificial seaweeds in the virtual underwater pool considering in the water flow.

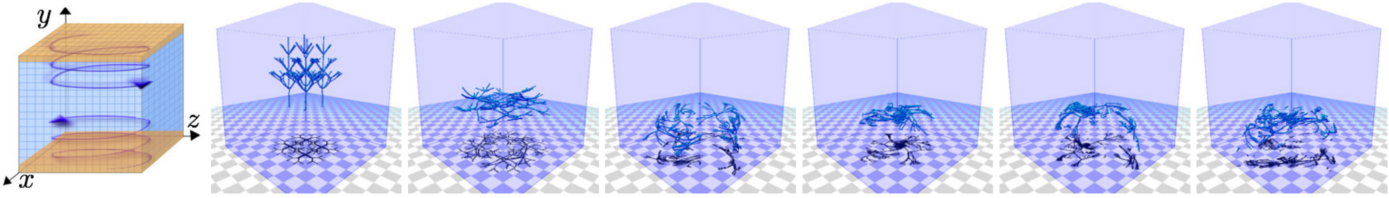
5.1 Conditions

Two patterns of water flow are experimented. The virtual underwater pool consists of 100 meters square cube and it is split up into 10^6 lattices. A central coordinate in the square cube is (0[m], 50[m], 0[m]).

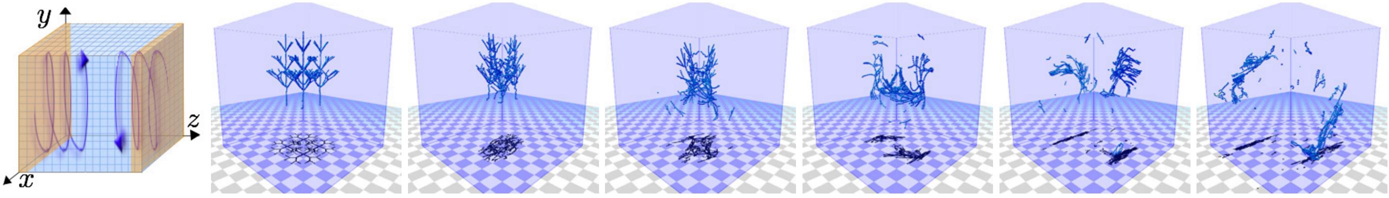
We prepare two patterns of water flow as the forced convection. One of water flows is set by two spiral flows which are generated along y axis from 0[m] to 100[m] toward each other. The other is set by two spiral flows along z axis from -50[m] to 50[m] toward each other. The number of artificial seaweeds is four and initial positions of them are located at (10[m], 50[m], 10[m]), (-10[m], 50[m], 10[m]), (10[m], 50[m], -10[m]) and (-10[m], 50[m], -10[m]). A density of the model ρ_r equals to 1000.0[kg/m^3], a density of the water ρ 998.2[kg/m^3], drag coefficient C_D 1.0 and the project area A 0.25^2 . The initial state in the underwater is perfectly motionless. The simulation time is 20[sec]

5.2 Results of experiment

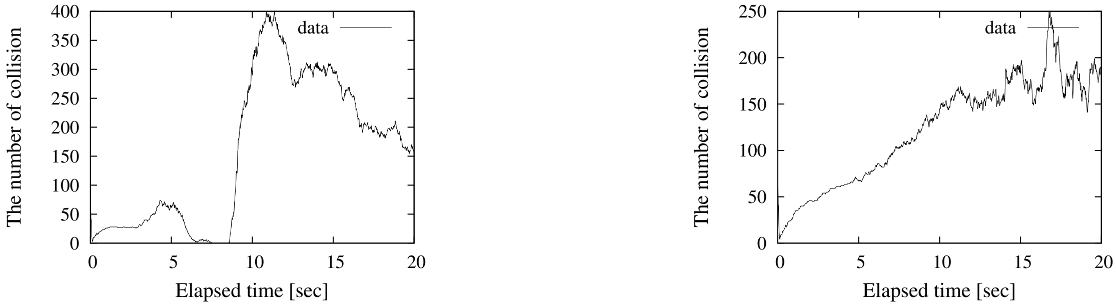
The results obtained from the computer simulation are shown in fig7. As for the pattern of water flow 1, the artificial seaweeds move outside in a spiral water flow from the upper surface. They move toward the position y=0 and are



(a) Pattern of water flow 1



(b) Pattern of water flow 2



(c) Pattern of water flow 1

(d) Pattern of water flow 2

Fig. 7. Results of physical motion of artificial seaweed in underwater. (a) and (b) shows two patterns of water flow 1 and 2 respectively. Two graphs show the number of collision between rigid bodies at each time.

involved in a vortex generated by convection. Then the artificial seaweeds repeat to move upward and are involved in a vortex. Fig.7(c) shows the number of collision among rigids calculated by physical modelling rapidly increases up to 12 [sec] and them it decreases gradually. This shows that twining is generated and a part of the artificial seaweed teared is lost.

As for the pattern of water flow 2, the seaweed moves to right and left surfaces in the generated water flow when two artificial seaweeds keep in contact each other. Fig.7(d), the number of collision increases with the elapsed time and the moving range of artificial seaweeds is gradually partitioned into two ranges. Note that the number of collision does not decrease. In two separated regions twined artificial seaweeds cannot be observed but tear phenomenon.

6 CONCLUSION

We present a seaweed model having physical properties and realized seaweed twining phenomenon by physical simulations. High density of seaweed in the virtual underwater pool is one of conditions to generate twining. A tear occurs by adding forces in multiple directions into rigids. Water flows and circulating realize seaweed twining including tear. However, a water flow along a specific orbit cannot be introduced. We would like to find some patterns for avoiding the tear and seaweed twining.

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