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TITLE: **MEETING DAN JOSEPH'S CHALLENGE: SIMULATION OF A "DRAFTING–TUMBLING–KISSING" EXPERIMENT**

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Meeting Dan Joseph's Challenge:

Simulation of a "Drafting–Tumbling–Kissing" Experiment

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Abstract A general method for computation of fluid–structure–interaction problems is described briefly. This method is based upon solution of the multifield (multiphase) equations in a field–wise arbitrary frame of reference. That is, any field may be integrated in either an Eulerian or a Lagrangian frame of reference. The method is build upon the so–called Fluid Implicit Lagrangian Particle (FLIP) method of Brackbill and Ruppel (*J. Comput. Phys.***65**, p. 314, 1986). The acceleration due to a material stress is computed using the Material–Point method of Sulsky, *et al* (Comput. Methods Appl Mech. Engrg. **118** p. 179, 1994). The 2d fluidization of large objects is used to demonstrate and illustrate the utility of the FSI method. Hence Dan Joseph's "Drafting, Tumbling, Kissing" experiment is simulated. Implications for large eddy simulations for developments in multifield flow theory are discussed.

Outline

- Frames of reference.

- Sketch of the Immersed Boundary Method.

- Example: Drafting, Tumbling, Kissing.

- Example: Isolated mass points.

- Comment on large–eddy–simulations.

$$\boxed{\text{Frames of Reference}}$$

- Lagrangian or Arbitrary Eulerian Frames: Interactions must be computed in a common frame.

- Consider Leibnitz's Rule relative to material k:

$$\int_V \frac{\partial q_k}{\partial t} dV + \int_S \hat{\mathbf{n}} \cdot q_k \mathbf{u}_k dS = \frac{d_k}{dt} \int_V q_k dV$$

- And again relative to the mesh:

$$\int_V \frac{\partial q_k}{\partial t} dV + \int_S \hat{\mathbf{n}} \cdot q_k \mathbf{u}_m dS = \frac{d_m}{dt} \int_V q_k dV$$

- Now subtract:

$$\frac{d_m}{dt} q_k V + V \boldsymbol{\nabla} \cdot q_k (\mathbf{u}_k - \mathbf{u}_m) = \frac{d_k}{dt} q_k V$$

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- A "Lagrangian" scheme comes from letting

$$\mathbf{u}_m = \mathbf{u}_k$$

  and using the kinematic rule

$$\dot{\mathbf{x}}_k = \mathbf{u}_k$$

  to establish the location of material k.

- The right side of the conservation laws is the same in either frame. That is, no matter

  how one chooses to keep track of things, the physics remain the same.

> "Immersed Boundary Method"

- Introduced by Peskin for blood flow in the human heart, (J. Comput. Phys., **25**, 220–252, 1977).

- Extended to suspension flow by Sulsky and Brackbill, (J. Comput. Phys. **96**, 339–368, 1991).

- Currently being generalized for multiphase flow problems in CFDLIB.

- Uses many elements of the FLIP scheme made popular by Brackbill and Ruppel, (J. Comput. Phys. **65**, 314–343, 1986).

- The state vector is marched forward in time, in the Lagrangian frame relative to a finite mass of material.

- An underlying mesh of control volumes is used to assist in computing the changes along the Lagrangian trajectories.

- For example, consider the single–field incompressible case, for which the state vector is:

$$\{m_p, \ \mathbf{x}_p, \ \mathbf{u}_p, \ v_p\}^0$$

- The state vector advances according to:

$$m_p^{n+1} = m_p^n$$

$$\mathbf{x}_p^{n+1} = \mathbf{x}_p^n + \Delta t \sum_c \mathbf{u}_c^L S_{cp}^n$$

$$m_p^{n+1} \mathbf{u}_p^{n+1} = m_p^n \mathbf{u}_p^n - \sum_c V_c \rho_c^n (\mathbf{u}_c^L - \mathbf{u}_c^n) S_{cp}^n$$

$$v_p^{n+1} = v_p^n$$

$$0 = \boldsymbol{\nabla} \cdot \mathbf{u}_c^L$$

- Here $\sum_c (\ )_c S_{cp}^n$ represents a bilinear interpolation of data from mesh coordinates centered at $\mathbf{x}_c$, in volume V_c, to the point $\mathbf{x}_p^n$.

- The velocity in the mesh coordinate frame is defined:

$$\mathbf{u}_c^L = \mathbf{u}_c^n - \frac{\Delta t}{\rho_c^n} \left(\boldsymbol{\nabla} p \right)_c + \Delta t \mathbf{g}$$

- The "initial condition" is given by:

$$\mathbf{u}_c^n = \frac{\sum_p m_p^n \mathbf{u}_p^n S_{pc}^n}{\sum_p m_p^n S_{pc}^n} \equiv \frac{\text{expected momentum}}{\text{expected mass}}$$

and

$$\rho_c^n = \frac{\sum m_p^n S_{pc}^n}{\sum m_p^n v_p^n S_{pc}^n} \equiv \frac{\text{expected mass}}{\text{expected volume}}$$
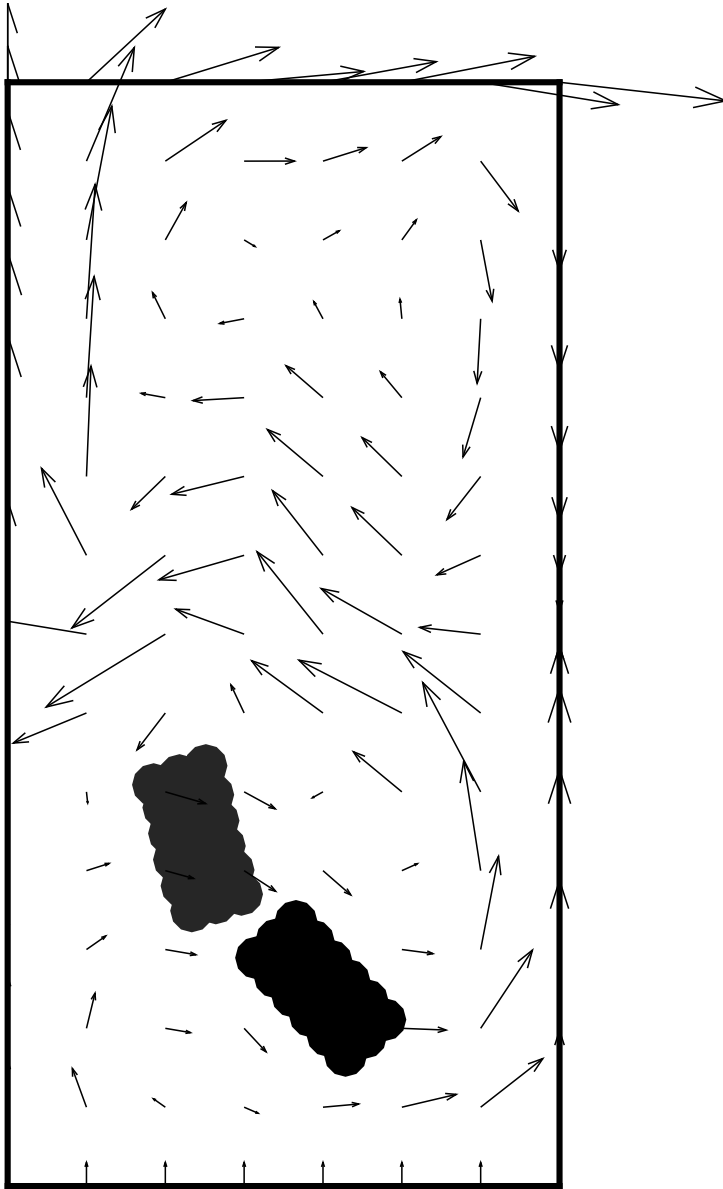
- In this, $\sum_p (\ )_p S_{pc}^n$ represents the transfer of data from points $\mathbf{x}_p$ to mesh coordinates

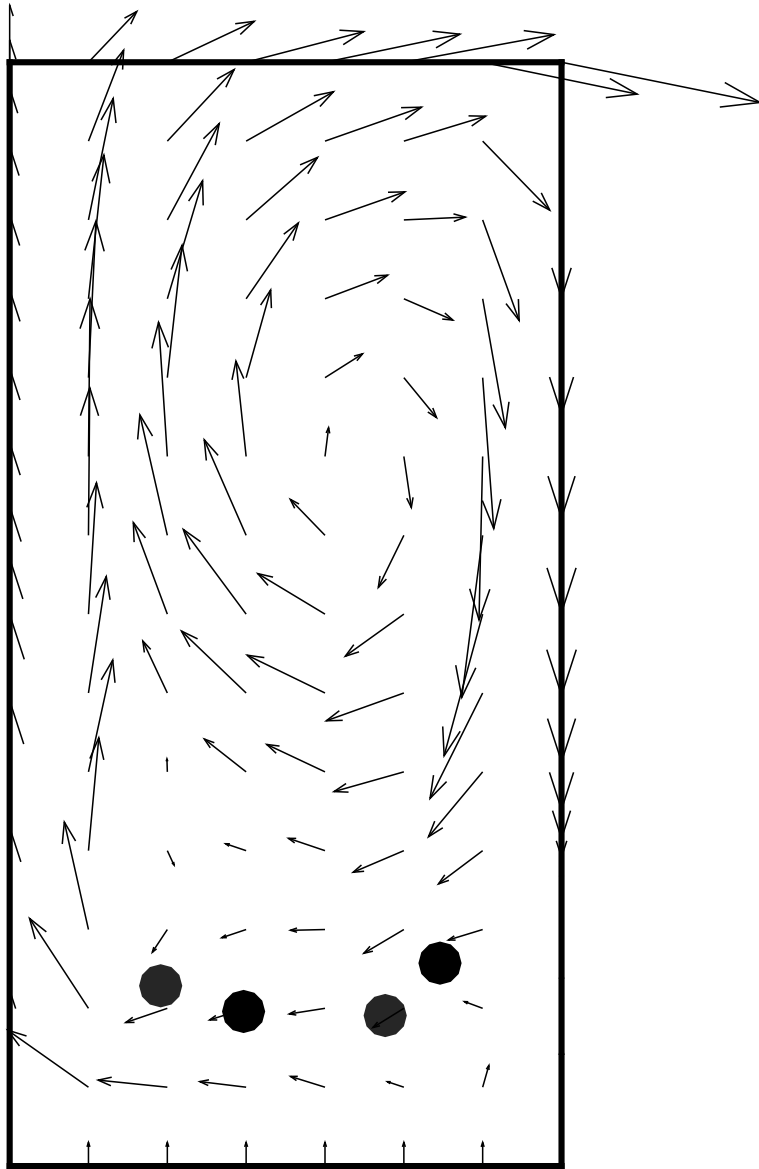 $\mathbf{x}_c$. As in the classical FLIP scheme, we use $S_{pc}^n = S_{cp}^n$.

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- Direct Numerical Simulation: Dan Joseph's Drafting, Tumbling, Kissing experiment.

- Single mass point representation of the same.

- Notice that the single mass point appears like the familiar Eulerian–Lagrangian scheme; but with an important difference. The volume of the mass point is present, leading to an approximation to the collective effect of wake interaction of dispersed bodies.

Acknowledgment

T =   .000E+00   CFDLIB 98.1

T = 1.026E+02   CFDLIB 98.1