CFD with OpenFOAM software

Lagrangian Particle Tracking

Jelena Andric

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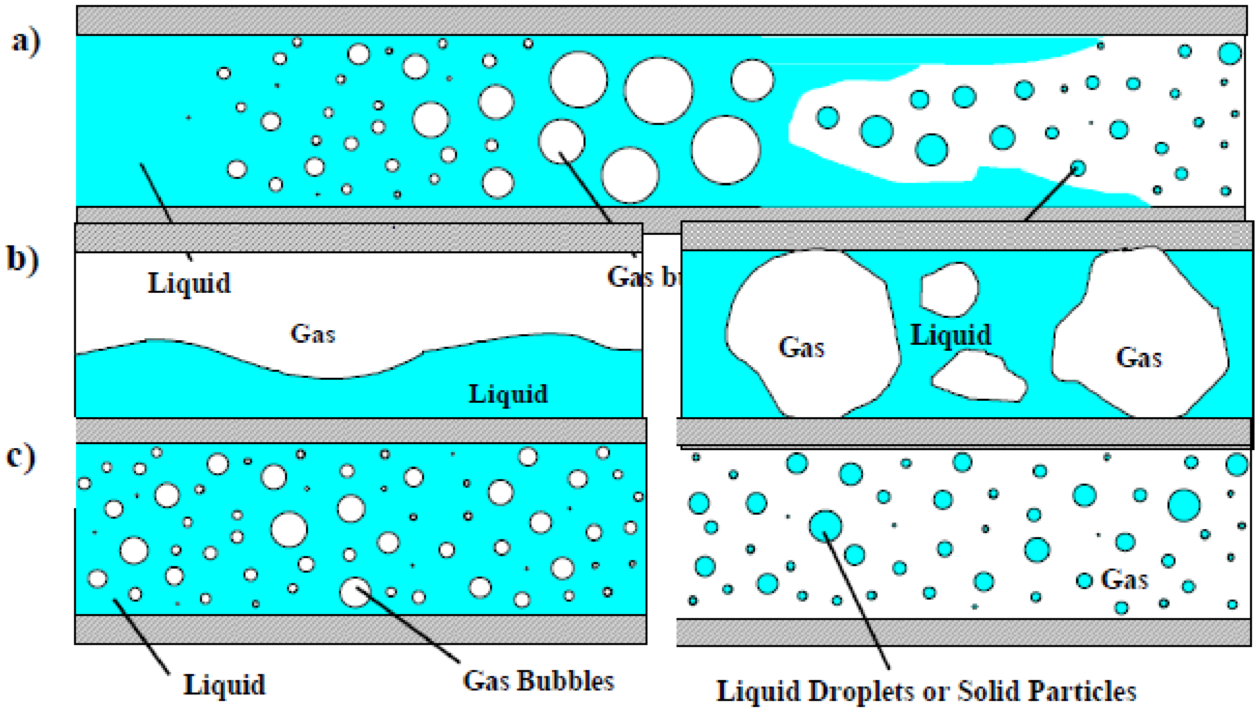
About multiphase flows

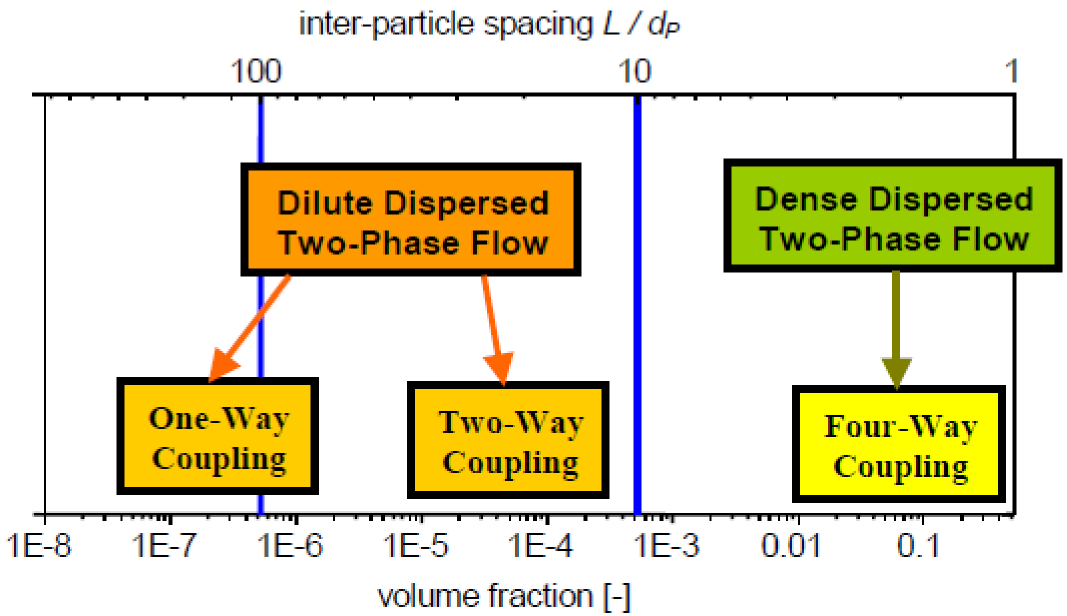
- great importance
- can occur even more frequently than single phase flows
- correct formulation of the governing equations for multiphase flows- still subject to debate
- Interaction between different phases- flows are complicated and very difficult to describe theoretically
- present in various forms in industrial practice (transient flows , separated flows, dispersed two-phase flows)
- dispersed two-phase flows - one phase is present in the form of particles, droplets, or bubbles in a continuous carrier phase (gas or liquid)

Different regimes of two-phase flows



a)transient two-phase flow, b)separated two-phase flow, c)dispersed two-phase flow

Different regimes of dispersed two-phase flows



- One-Way coupling - influence of the particle on the fluid flow may be neglected

Forces acting on particles

- The motion of particles in fluids is described in a Lagrangian way
- Set of ordinary differential equations along the trajectory is solved in order to calculate the change of particle location and the linear and angular components of particle velocity.
- The relevant forces acting on the particle need to be taken into account.
- For spherical particles the differential equations for calculating the particle location and velocity are given by Newtonian second law:

$$\frac{dx_P}{dt} = u_P$$

$$m_P \frac{d\,u_P}{dt} = \sum F_i$$

$$I_P \frac{d\,\omega_P}{dt} = T$$

- Analytical solutions - available for small Reynolds numbers
- An extension to higher Reynolds-including a coefficient in front of the force(based on empirical correlations derived from experiments DNS)
- In most fluid-particle systems - the drag force is dominating the particle motion.
- Its extension to higher particle Reynolds number -introduction of a drag coefficient :

drag coefficient

$$C_D = \frac{F_D}{\frac{\rho_F}{2}\left(u_F - u_P\right)^2 A_P}$$

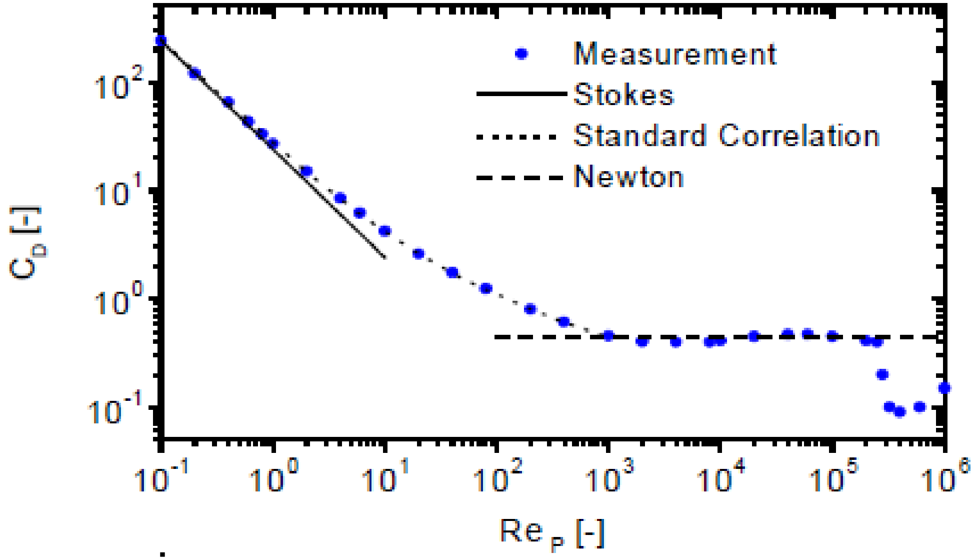
drag force

$$\mathrm{Re}_P = \frac{\rho_F\, d_P \left| u_F - u_P \right|}{\mu_F}$$

particle Re number

$$F_D = \frac{3}{4}\frac{\rho_F\, m_P}{\rho_P\, d_P} C_D \left(u_F - u_P\right)\left| u_F - u_P \right|$$

drag coefficient= function (particle Re number)



Different flow regimes:

- Stokes flow $\mathrm{Re}_P < 0.5$ $$C_D = \frac{24}{\mathrm{Re}_P}$$
- Transient region $0.5 < \mathrm{Re}_P < 1000$ $$C_D = \frac{24}{\mathrm{Re}_P}\left(1 + 0.15\ \mathrm{Re}_P^{0.687}\right) = \frac{24}{\mathrm{Re}_P} f_D$$
- Newtonian region $$C_D \approx 0.44$$

Drag of non-spherical particles

- Cylinders-regularly shaped particles
- Aspect ratio $E_{cyl} = L_{cyl} / D_{cyl}$
- non-spheroidal particles –no analytical solution for the drag even in the creeping flow limit
- introducing the shape factor $f_{shape} \equiv \dfrac{C_{D,shape}}{C_{D,sphere}}$ $f_{shape} \equiv \left.\dfrac{C_{D,shape}}{C_{D,sphere}}\right|_{\mathrm{Re}_P \ll 1 \ \& \ const.vol.}$

- the surface and the projected area ratios –shape factor

$$A^*_{surf} \equiv \frac{A_{surf}}{\pi d^2}, \quad A^*_{proj} \equiv \frac{A_{proj}}{1/4\,\pi d^2}$$

$$E_{cyl} \equiv \frac{L_{cyl}}{d_{cyl}}, \quad A^*_{surf} = \frac{2E_{cyl}+1}{\left(18E_{cyl}^2\right)^{1/3}}, \quad d = d_{cyl}\left(\frac{3E_{cyl}}{2}\right)^{1/3}.$$

- For cylinders

$$f_{shape} = \frac{1}{3}\sqrt{A^*_{proj}} + \frac{2}{3}\sqrt{A^*_{surf}} \qquad \mathrm{Re}_P \ll 1$$

creeping flow

Newtonian regime: $10^4 < \mathrm{Re}_P < 10^5$

$$C_{shape} = \left. \frac{C_{D,shape,crit}}{C_{D,sphere,crit}} \right|_{cont.vol.} \qquad C_{D,sphere,crit} = 0.42$$

$$\left\langle C_{shape} \right\rangle \approx 1 + 0.7\sqrt{A^*_{surf} - 1} + 2.4\left(A^*_{surf} - 1\right), \quad E > 1$$

Intermediate Reynolds number flow:

- combination of the Stokes drag correction and the Newton-drag correction
- dependence similar for all particle shapes, difference correction at two extremes
- dependency –result of dimensional analysis

$$C^*_D = f\left(\mathrm{Re}^*_P\right), \qquad C^*_D = \frac{C_D}{C_{shape}}, \qquad \mathrm{Re}^*_P = \frac{C_{shape}\,\mathrm{Re}_P}{f_{shape}}$$

$$C^*_D = \frac{24}{\mathrm{Re}^*_P}\left[1 + 0.15\left(\mathrm{Re}^*_P\right)^{0.687}\right] + \frac{0.42}{1 + \dfrac{42{,}500}{\left(\mathrm{Re}^*_P\right)^{1.16}}} \qquad for \approx circular\, C/S$$

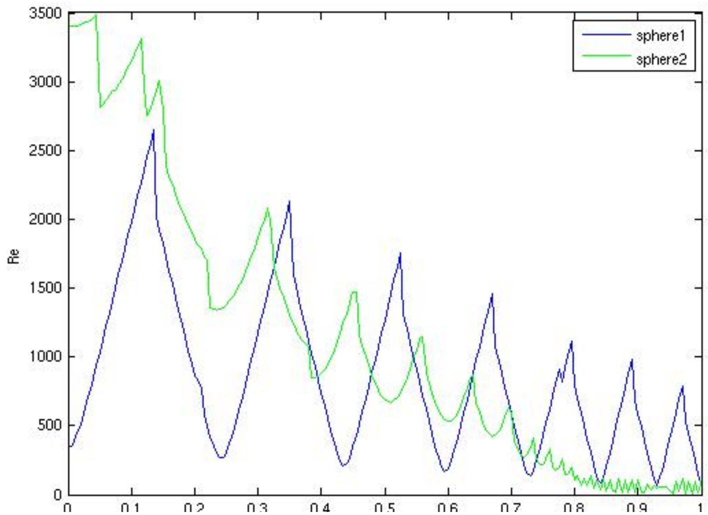
Implementation in OpenFOAM

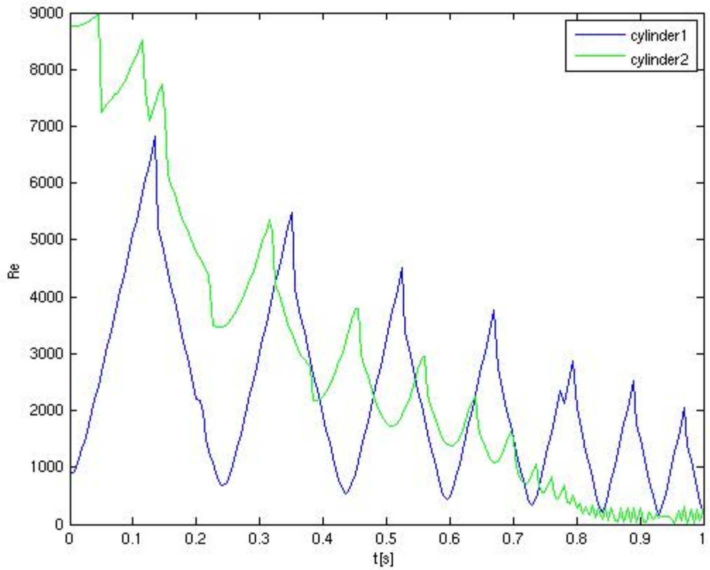
- Class solidParticle - *simple solid spherical particle class with one-way coupling with the continuous phase*
- Class solidParticleCloud
- Coding-advanced C++style plus complex inheritance
- Spherical particles-rigid bodies
- Particle properties – diameter, coefficient of restitution, friction coefficient, density
- Box –test case - two spherical particles are inserted at different initial velocities into the fluid at test
- Solver solidParticleFoam –solves for the particel position and velocity
- Forces –drag and gravity

Implementation of new classes

- solidCylinder
- solidCylinderCloud
- Created in order to track the motion of cylindrical particles
- Correction in geometrical properties – cylinder length needs to be specified
- Correction in drag force – in order to take into account for the change in particle shape
- Solving for cylindrical particles

Reynolds numbers



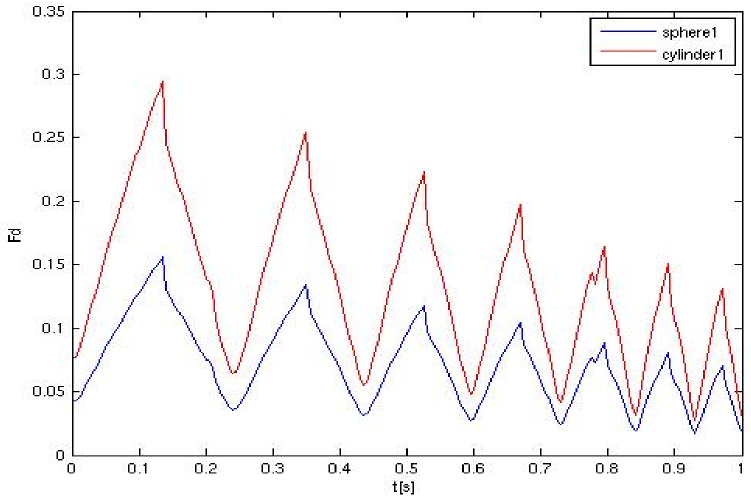


•cylinders - higher Re-numbers

•sphere and cylinder with higher initial velocity firstly have rather high Re- numbers, but for a quite short time are approaching very low values

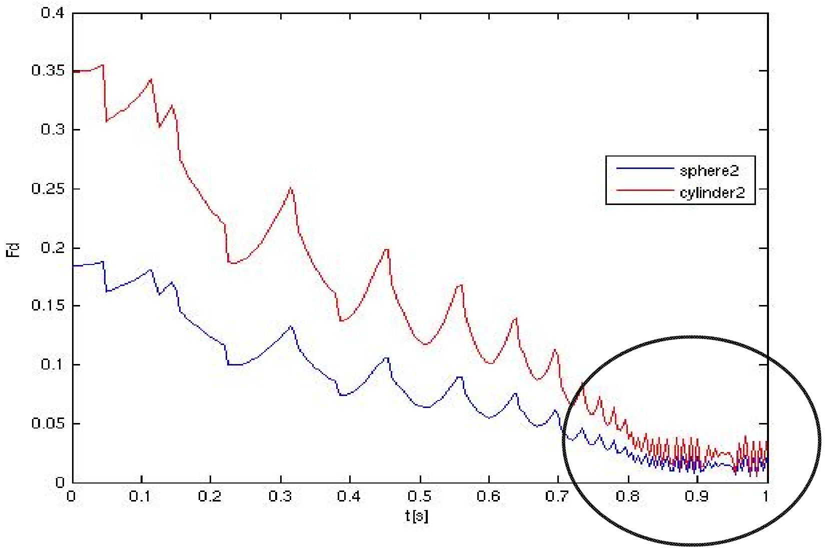
•sphere and cylinder with lower initial velocity - decreasing trend for Re-numbers ;except for the beginning of the simulation the values remain higher

Drag forces



approaching steady-state

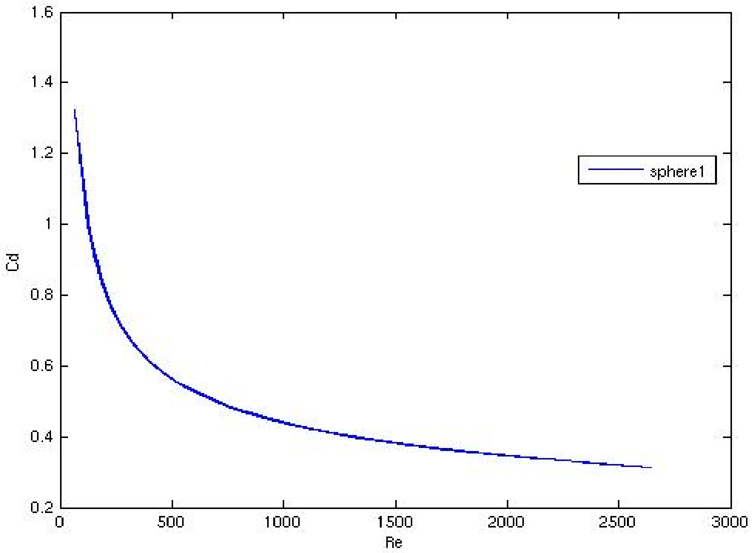
- Drag force higher for cylinders
- Achieving steady-state condition

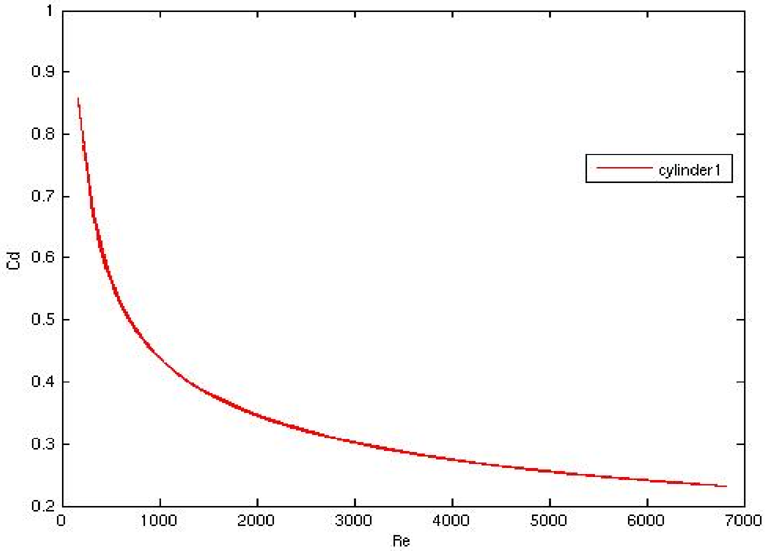


steady state after 0.8s

Drag coefficients

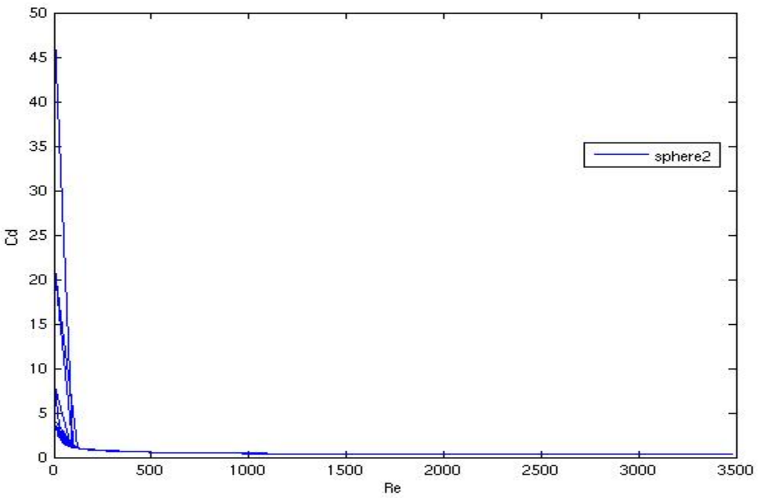
sphere ad cylinder with lower initial velocity

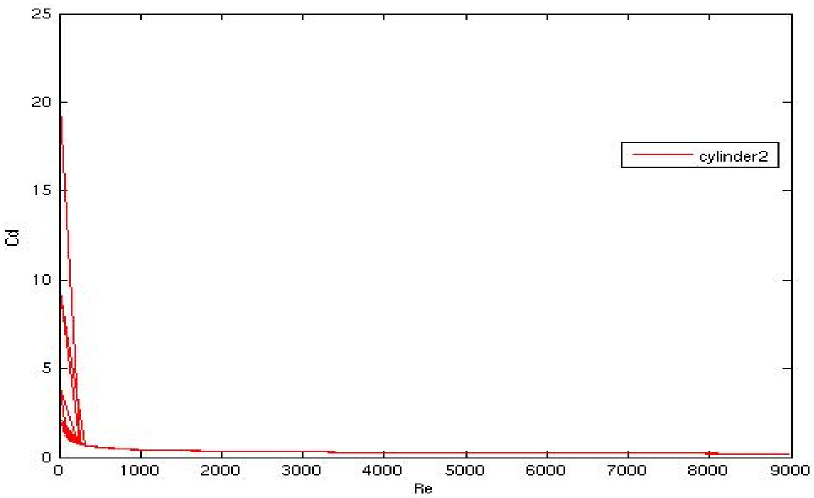




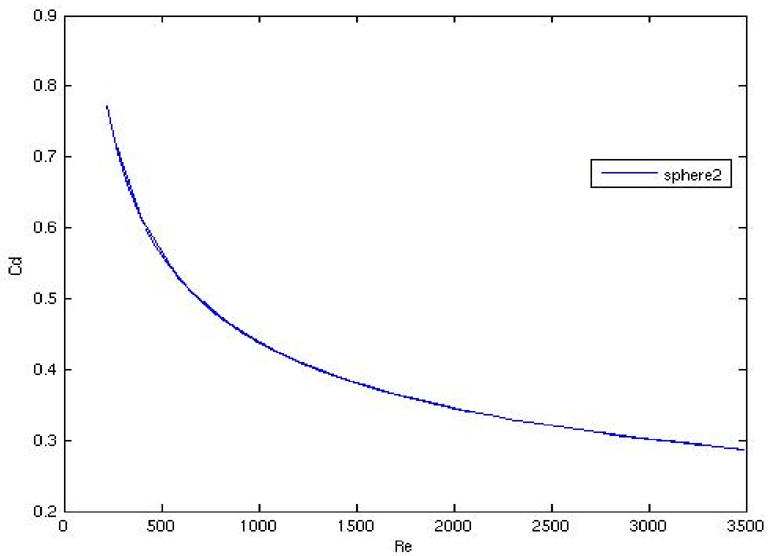
- physical agreement
- different flow regions can be identified

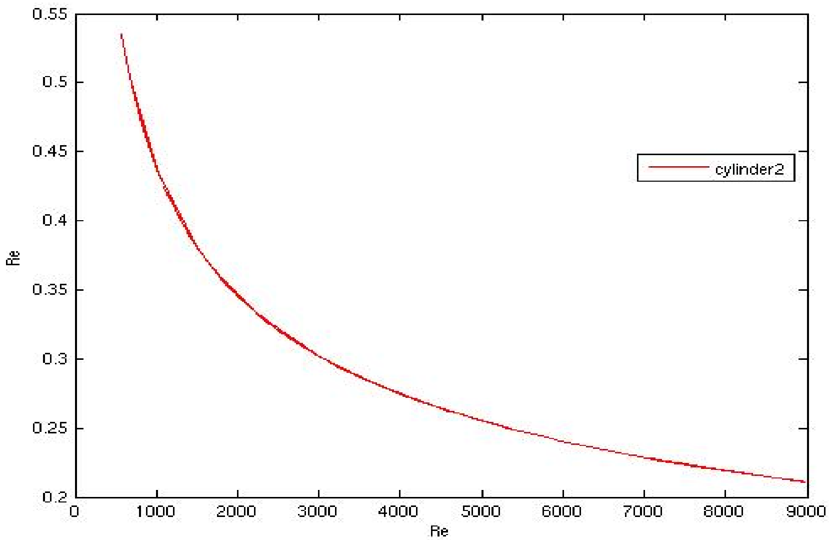
sphere and cylinder with higher initial velocity (t=1s)



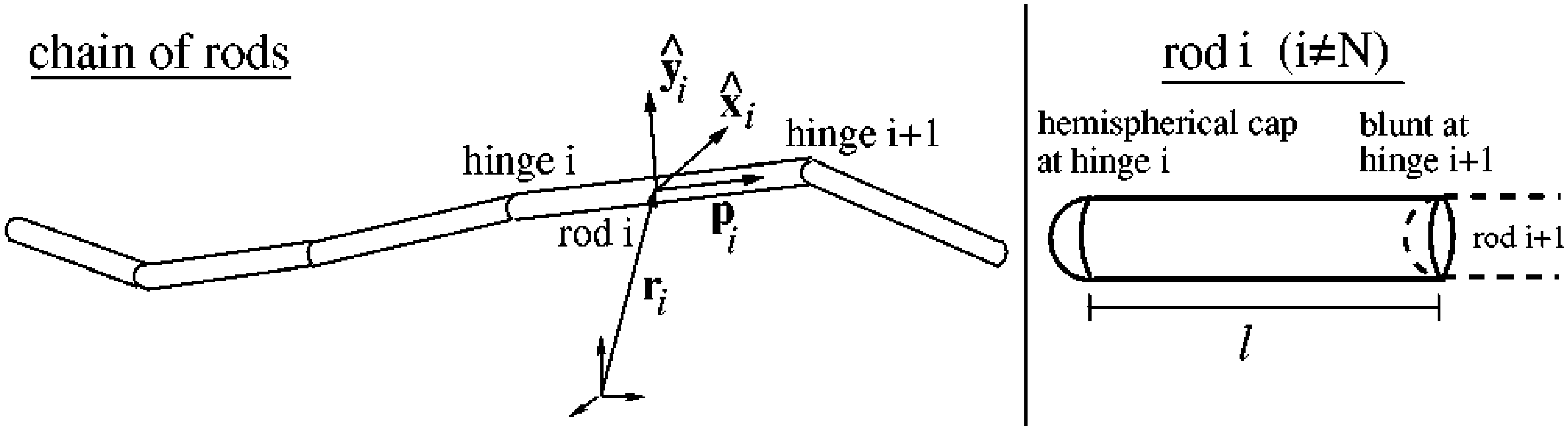


sphere and cylinder with higher initial velocity (t=0.8s)





Purpose and project idea



Mechanical model of a fiber

How to take into account for contact forces?!