Modelling of gas-solid turbulent flows with non-spherical particles

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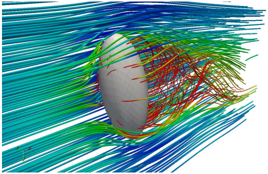
Berend van Wachem, George Mallouppas, Fan Zhao



EUROMECH COLLOQUIUM 513:
Dynamics of non-spherical particles in fluid turbulence

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Introduction

Numerical framework for analysis of turbulent flows with non-spherical particles:

- Aerodynamic forces determined by true DNS
- Eulerian - Lagrangian approach
  - Filtered fluid phase
  - Particle phase is tracked as individual particles
- Orientation dependent forces on point-particles

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Outline

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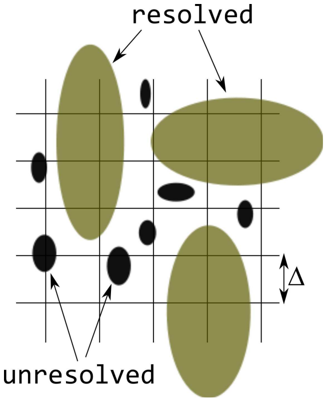
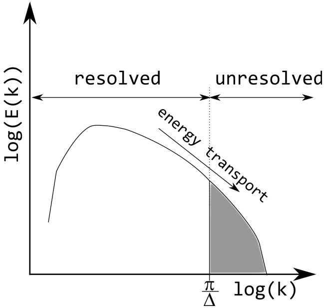
LES





In LES, we do not resolve all the eddies.

State vector

$$\begin{pmatrix} \frac{d}{dt}\boldsymbol{x}(t) \\ \frac{d}{dt}Q(t) \\ \frac{d}{dt}(m_p \boldsymbol{v}_p(t)) \\ \frac{d}{dt}(\boldsymbol{I}_p \omega_p(t)) \end{pmatrix} = \begin{pmatrix} \boldsymbol{v}_p(t) \\ \frac{1}{2}Q\omega_p(t) \\ \boldsymbol{F}_d + m_p\boldsymbol{g} - V_p \nabla P_f + \sum^N \boldsymbol{F}_{pp} + \boldsymbol{S}_p + \boldsymbol{F}_l + \dots \\ \boldsymbol{T}_{aero} - \boldsymbol{T}_{rot} \end{pmatrix}$$

Quaternions vs. Rotation matrix:

- No singularities - enhanced stability
- Higher computational efficiency
- Integration errors not propagated in time

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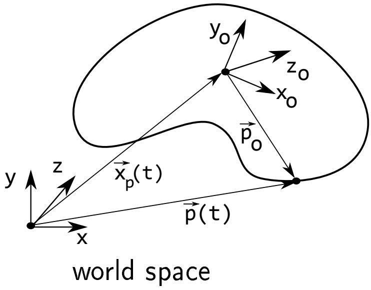
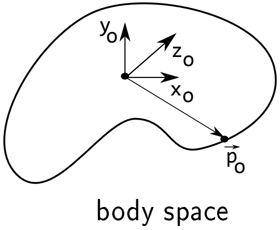
Body space vs World space





Relation between two systems can be expressed by:

- Rotation matrix
- Quaternions

Forces and Torques on a particle

Drag Force

$$F_d = C_D\left(Re,\varphi\right)\frac{1}{2}\rho_g\frac{\pi}{4}d_p^2\left(\tilde{\mathbf{v}}_f-\mathbf{v}_p\right)^2$$

Lift Force

$$F_l = C_L\left(Re,\varphi\right)\frac{1}{2}\rho_g\frac{\pi}{4}d_p^2\left(\tilde{\mathbf{v}}_f-\mathbf{v}_p\right)^2$$

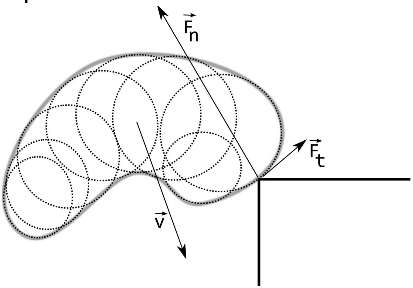
Aerodynamic Torque

$$T_{aero} = C_T\left(Re,\varphi\right)\frac{1}{2}\rho_g\frac{\pi}{8}d_p^3\left(\tilde{\mathbf{v}}_f-\mathbf{v}_p\right)^2$$

Rotational Torque

$$\mathbf{T}_{rot} = C_R\left(\omega_p,Re\right)\frac{\rho}{2}\left(\frac{d_p}{2}\right)^5|\omega_p|\omega_p$$

contacts are found through "spheres":



Hertzian contact model:

$$\boldsymbol{F}_n(t) = K_n(t)\delta_n^{\frac{3}{2}}(t)\boldsymbol{n}(t)$$
$$\boldsymbol{F}_t(t) = min(\mu \boldsymbol{F}_n(t), K_t(t)\delta_t(t))$$

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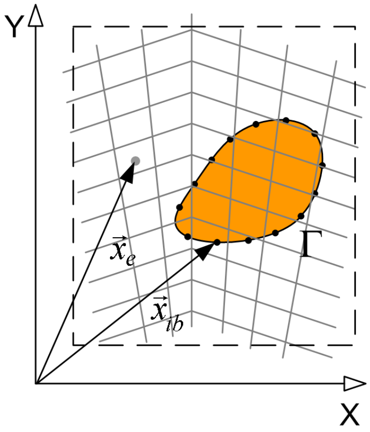
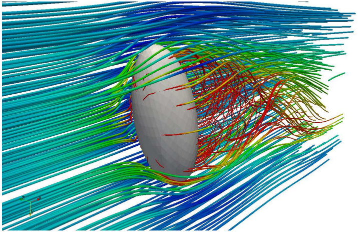


- Fluid domain is represented by an Eulerian grid.
- A Lagrangian grid represents the solid-fluid interface
- Non-distributed force method, Mark and van Wachem (2008); Zastawny, Van Wachem and Oliveira (2010).
- Implicit and 2nd order accurate.
- Geometric restriction: closed and solid bodies.

DNS Simulations



$$C_D(\varphi) = C_{D,\varphi=0^o} + (C_{D,\varphi=90^o} - C_{D,\varphi=0^o}) sin^{a_0}(\varphi)$$

$$C_{D,\varphi=0^o} = \frac{a_1}{Re^{a_2}} + \frac{a_3}{Re^{a_4}}$$

$$C_{D,\varphi=90^o} = \frac{a_5}{Re^{a_6}} + \frac{a_7}{Re^{a_8}}$$

$$C_L = \frac{b_1}{Re^{b_2}} + \frac{b_3}{Re^{b_4}} sin(\varphi)^{b_5 + b_6 Re^{b_7}} cos(\varphi)^{b_8 + b_9 Re^{b_{10}}}$$

$$C_T = \frac{c_1}{Re^{c_2}} + \frac{c_3}{Re^{c_4}} sin(\varphi)^{c_5 + c_6 Re^{c_7}} cos(\varphi)^{c_8 + c_9 Re^{c_{10}}}$$

Example

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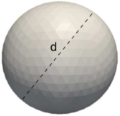
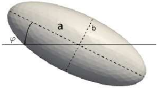
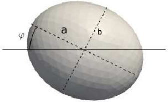
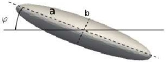
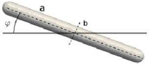
Particle shapes

Sphere $d = 200\,\mu m$



shape	parameters	shape	parameters
Ellipsoid 1 	$\phi = 0.88$ $\frac{a}{b} = \frac{5}{2}$ $a = 368\,\mu m$ $b = 147\,\mu m$	Ellipsoid 2 	$\phi = 0.99$ $\frac{a}{b} = \frac{5}{4}$ $a = 232\,\mu m$ $b = 186\,\mu m$
Disc 	$\phi = 0.63$ $\frac{a}{b} = \frac{5}{1}$ $a = 342\,\mu m$ $b = 68.4\,\mu m$	Fibre 	$\phi = 0.70$ $\frac{a}{b} = \frac{5}{1}$ $a = 510\,\mu m$ $b = 102\,\mu m$

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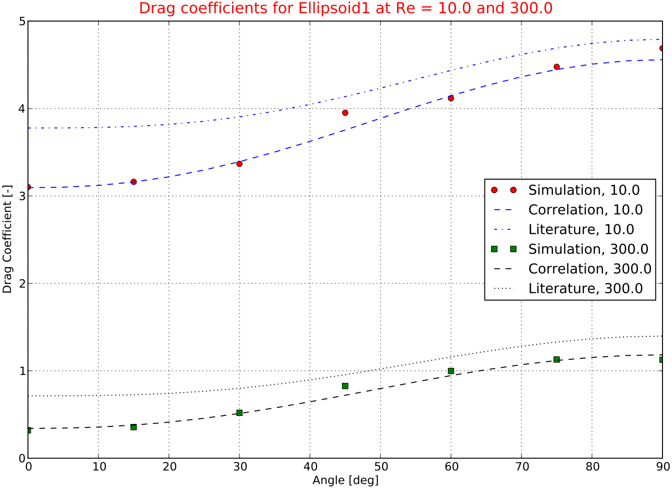
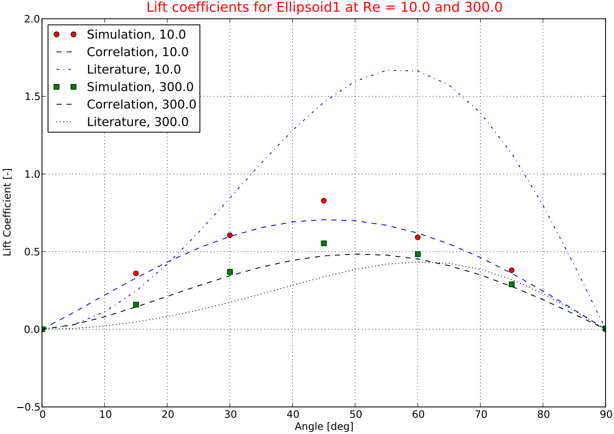
Results from DNS



Hölzer and Sommerfeld (2008)

Results from DNS



Similar for torque coefficient and for other particle types

Hoerner (1965), $C_L = C_D sin^2 \varphi cos \varphi$

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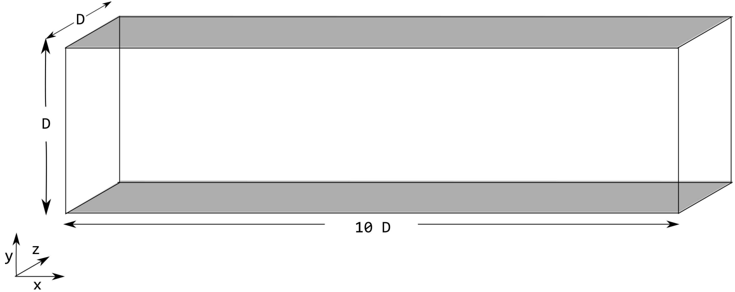
Simulation Domain



D	d_p	m	Re_D	$< U >$	St
$35\,mm$	$200\,\mu m$	1.0	$42,000$	$19.7\,m/s$	52

100 000 particles

Kussin and Sommerfeld (2002)

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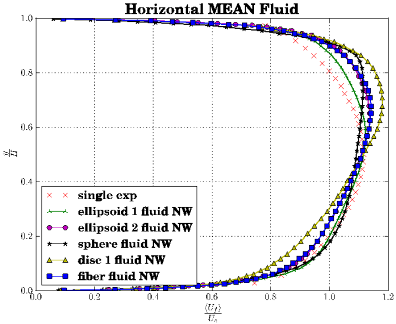

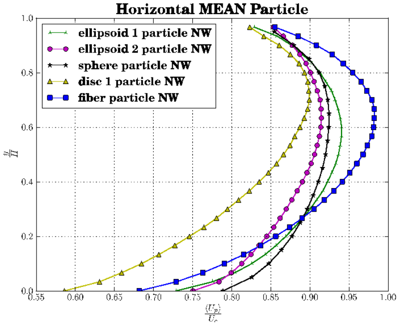

Snapshot

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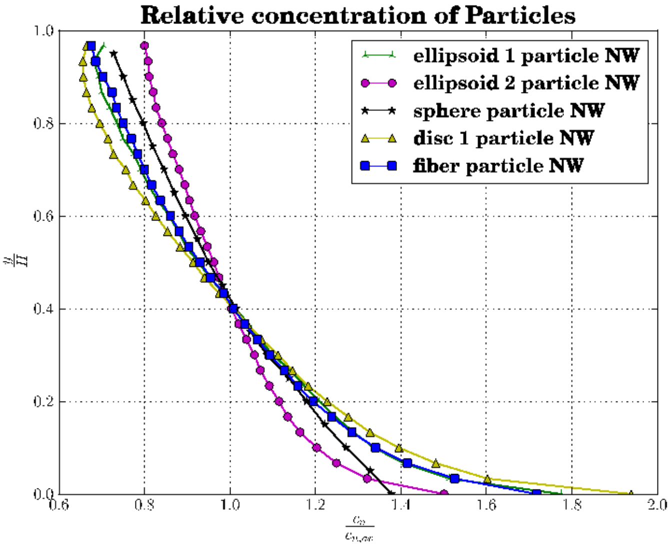
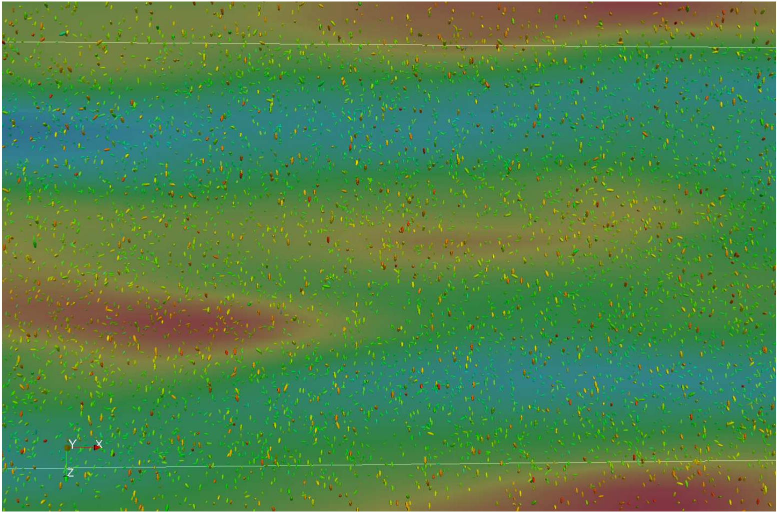
Particle concentration



Non-spherical particles: angles



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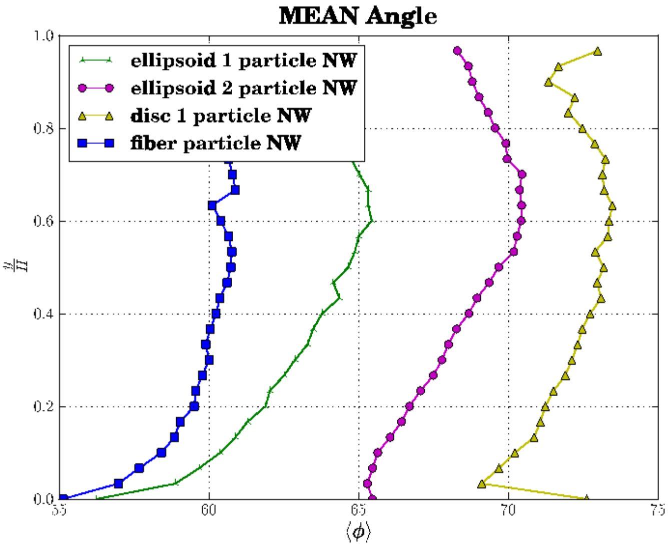
Non-spherical particles: angles



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Conclusions

- Framework to model flows with “heavy” non-spherical particles.
- Euler-Lagrange approach with quaternion integration for particle orientation.
- Accurate prediction of aerodynamic forces and torques.
- Preliminary results in line with experimental data.
- Improvements for forces prediction:
  - Volume fraction dependency in force correlations,
  - Shape-specific rotational torque coefficient.