6th Joint MC/WG Meeting SIG43 Workshop, Oct. 23rd -25th, 2013

GRAVITY EFFECTS ON TURBULENT FIBER SUSPENSION FLOW IN A VERTICAL CHANNEL: FIRST RESULTS

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Outline

- ✓ Research Background
- ✓ Objective
- ✓ Methodology
- ✓ Results
- ✓ Summary

Fiber suspensions

- Occurs in variety of industries
  - Paper making, Polymer Processing, Oil and Gas etc.
- Final mechanical properties and quality of product depends on the distribution and orientation of fibers

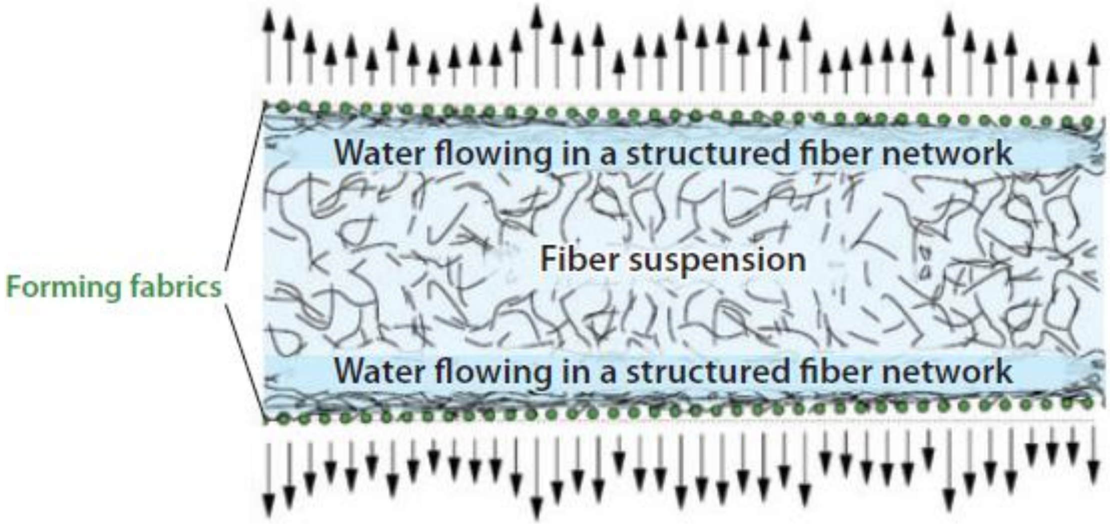

Fig. Fiber network between two wires Lundell (2011)

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Background

- Translational and rotational statistics for tiny fibers in turbulent channel flow were reported by Mortensen et al. (2008), Marchioli et al. (2010, 2013)
  - Accumulation in viscous sub layer and preferentially concentration in low-speed streaks
  - Aspect ratio (λ) affects
  - Preferential orientation behavior

- Gravity and lift affects on ellipsoidal particles transport and deposition in turbulent channel flow was studied by Zhang et al. (2001) later Marchioli et al. (2007) reported detailed particle statistics and deposition phenomena for wide range of spherical particles

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Objective

To study the dynamic behavior of tiny elongated fiber-like particles in turbulent vertical channel flow in presence of gravity. Statistics for translational motion and orientation behavior will be discussed.

Methodology

Eulerian-Lagrangian one way coupled approach**

- Fluid
  - Eulerian
  - DNS
- Particle
  - Lagrangian tracking
  - Forces considered on particle: Stokes drag and gravity

**Mortensen et al. 2007, Marchioli et al. 2008

Eulerian fluid representation

- Incompressible and isothermal Newtonian fluid.
- Frictional Reynolds number: $\mathrm{Re}_\tau = \frac{u_\tau h}{\nu}$
- Governing equations (non-dimensional):
  - Mass balance $\nabla \cdot \vec{u} = 0$
  - Momentum balance $\rho \left[\frac{\partial \vec{u}}{\partial t} + (\vec{u} \cdot \nabla)\vec{u} \right] = -\nabla p + \mu \nabla^2 \vec{u}$
- Direct numerical simulation (DNS)

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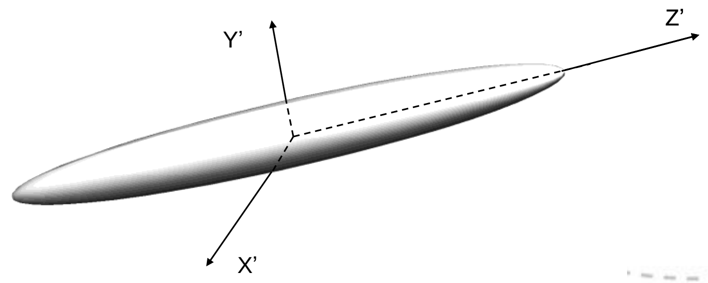
Lagrangian approach - Characteristic parameters



- Prolate ellipsoidal particle
  - a: radius in minor-axis
  - b: radius in major-axis

- Inertial
  - Fiber Stokes number:

$$St = \frac{2\lambda S a^{+2}}{9 Re_\tau} \frac{\ln(\lambda + \sqrt{\lambda^2 - 1})}{\sqrt{\lambda^2 - 1}} \quad \text{where} \quad \lambda = \frac{b}{a} \text{ and } S = \frac{\rho_p}{\rho_f}$$

- Smaller than Kolmogorov length
  - Point force assumption

Lagrangian approach: Translational motion

- The translational motion in the laboratory frame is governed by

$$\frac{dv_i}{dt} = f_i(x_p) + \left(1 - \frac{\rho_f}{\rho_p}\right) g$$

- The drag force in creeping flow conditions is given by:

$$f_i(x_p) = \mu A^T K_{ij}^{'} A(u_j - v_j) \qquad K_{ij}^{'} = \begin{pmatrix} K^{'}_{xx} & 0 & 0 \\ 0 & K^{'}_{yy} & 0 \\ 0 & 0 & K^{'}_{zz} \end{pmatrix}$$

  - Resistance tensor K' is an intrinsic property of the particle. Particle orientation is absorbed in the resistance tensor.
  - A is the orthogonal transformation matrix comprised the direction cosines

Lagrangian approach – Rotational Motion

- Rotational motion in particle frame is governed by Euler's equation,

$$I'_{ij}\frac{d\omega'_j}{dt} + \varepsilon_{ijk}\omega'_j I'_{kl}\omega'_l = N'_i$$

  – Where torque components N'_i were calculated using expressions derived by Jeffery (1922)

- Time evolution of Euler parameters,

$$\begin{pmatrix} \dot{e}_0 \\ \dot{e}_1 \\ \dot{e}_2 \\ \dot{e}_3 \end{pmatrix} = \frac{1}{2}\begin{pmatrix} e_0 & -e_1 & -e_2 & -e_3 \\ e_1 & e_0 & -e_3 & e_2 \\ e_2 & e_3 & e_0 & -e_1 \\ e_3 & -e_2 & e_1 & e_0 \end{pmatrix}\begin{pmatrix} 0 \\ \omega'_x \\ \omega'_y \\ \omega'_z \end{pmatrix}.$$

$$e_0^2 + e_1^2 + e_2^2 + e_3^2 = 1$$

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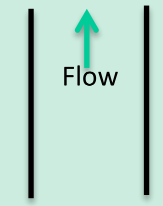
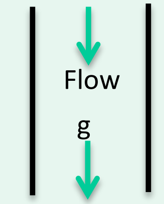
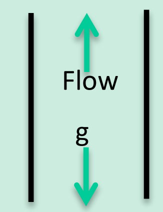
Parameters

- ✓ Channel Domain Size: $6h \times 3h \times 1h$
- ✓ *Mesh Size:* $192 \times 192 \times 192$
- ✓ $Re_\tau = 360$
- ✓ No. of particles: 200000
- ✓ Statistics: $\Delta t^+ = 5400$ to 10800

St	λ	Density Ratio (D)
1	1.001	34.72
	3	18.57
	10	11.54
5	1.001	173.6
	3	92.9
	10	57.7
30	1.001	1041.7
	3	557.1
	10	346.3
100	1.001	3472.33
	3	1857
	10	1154.33

Case	Flow Configuration
No Gravity (G0)	
Downward Flow (GD)	
Upward Flow (GU)	

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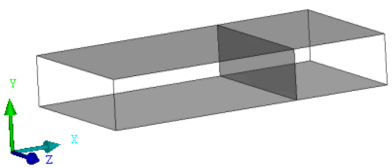
Instantaneous Results



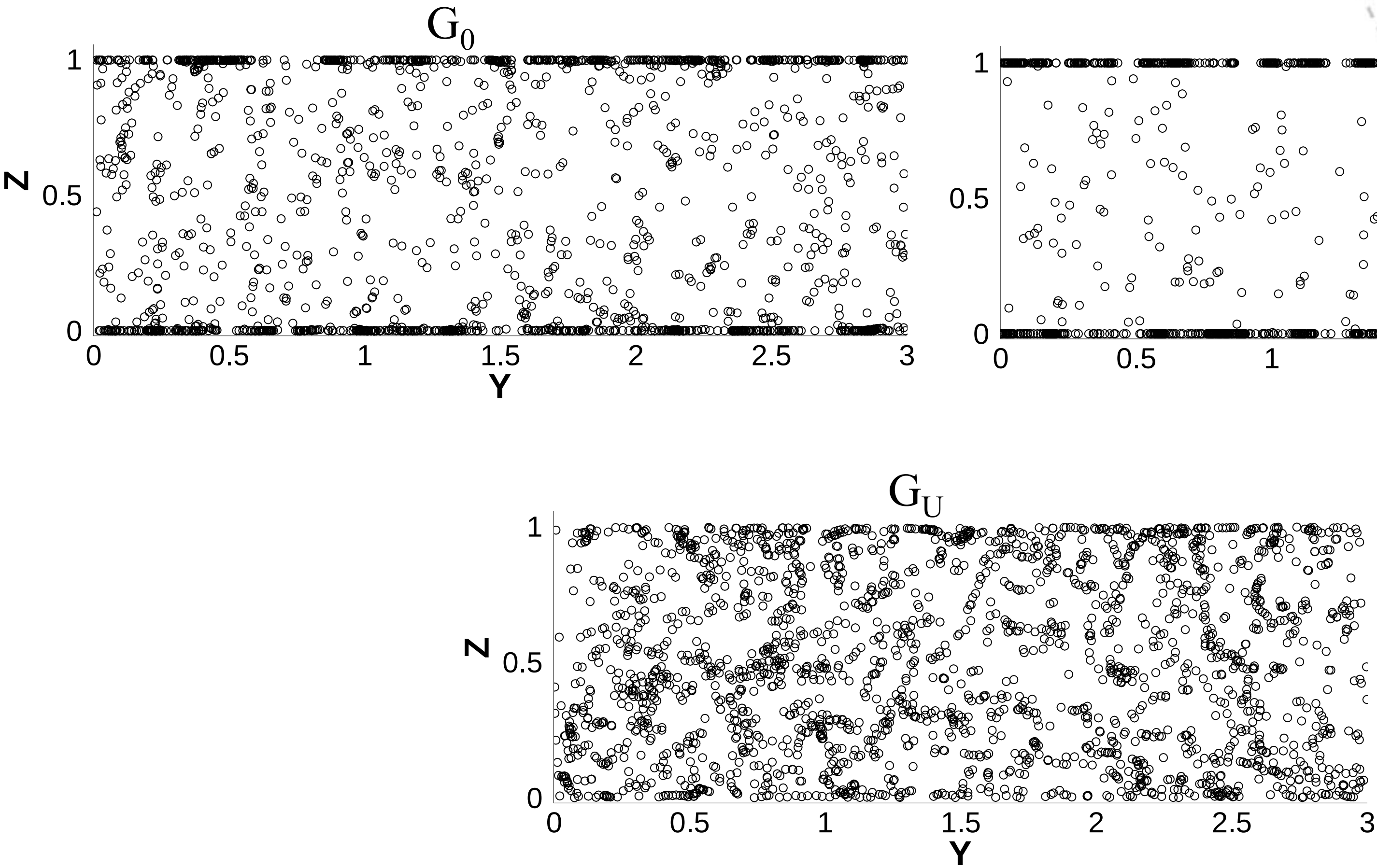


Fig. Fiber distribution for St = 5, λ= 10 in YZ plane at t^{+}=7200

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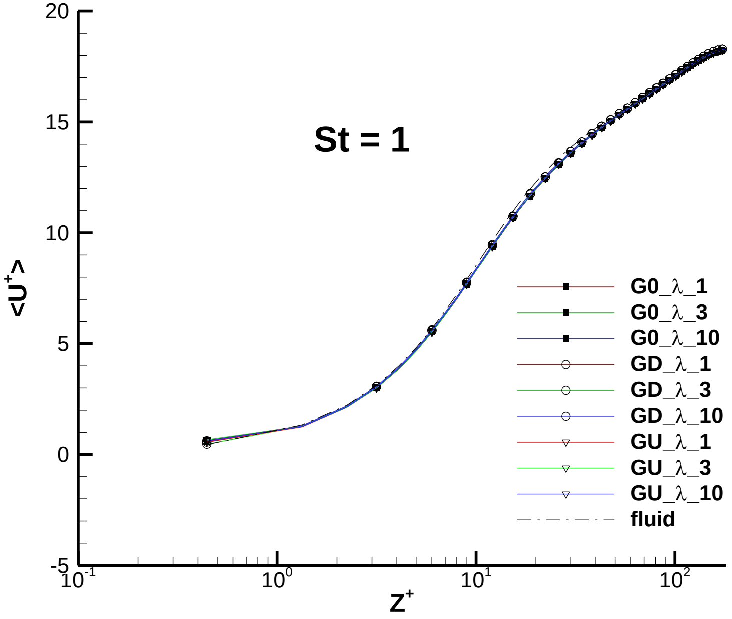
Statistics: Translational Motion



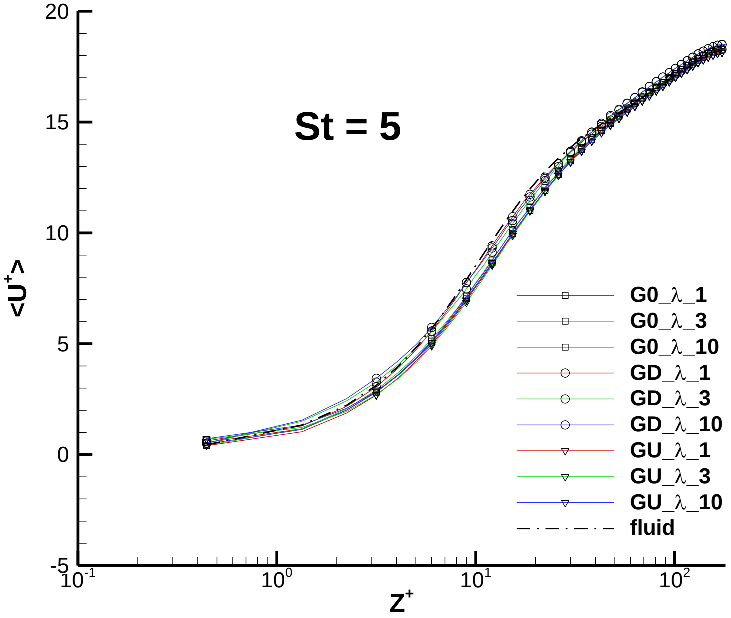


Fig. Mean stream wise velocity

Statistics: Translational Motion

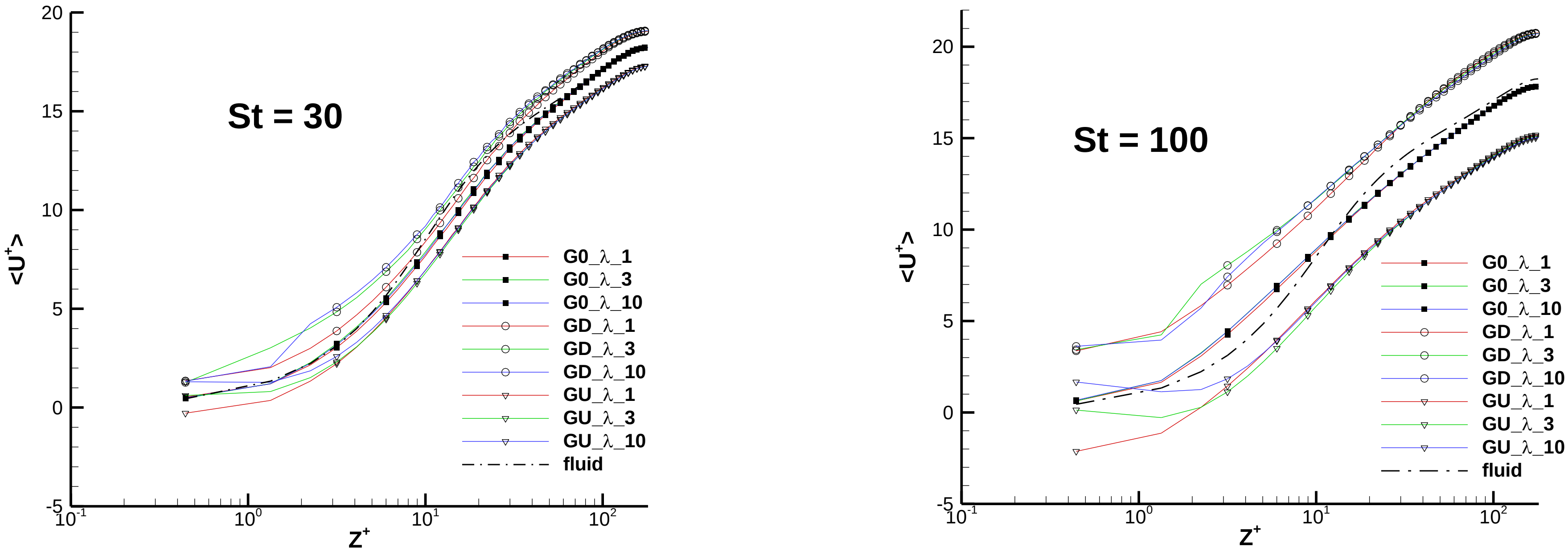


Fig. Mean stream wise velocity

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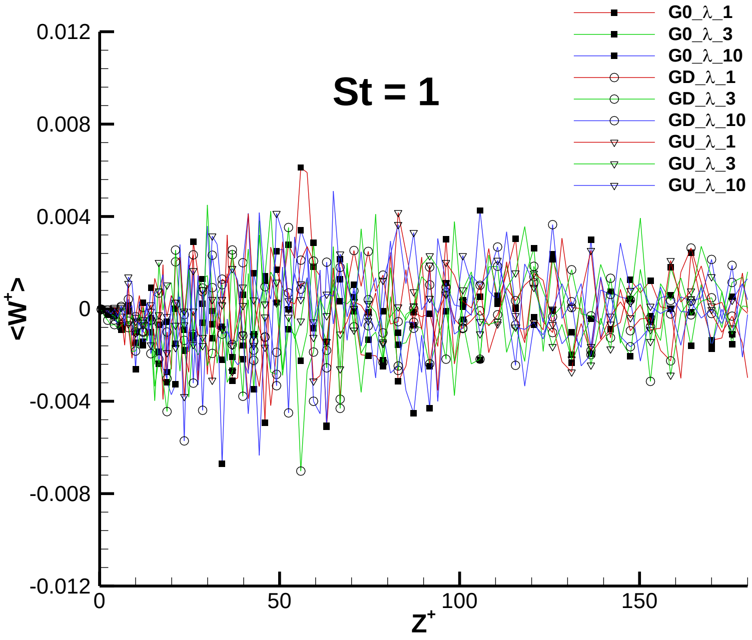
Statistics: Translational Motion



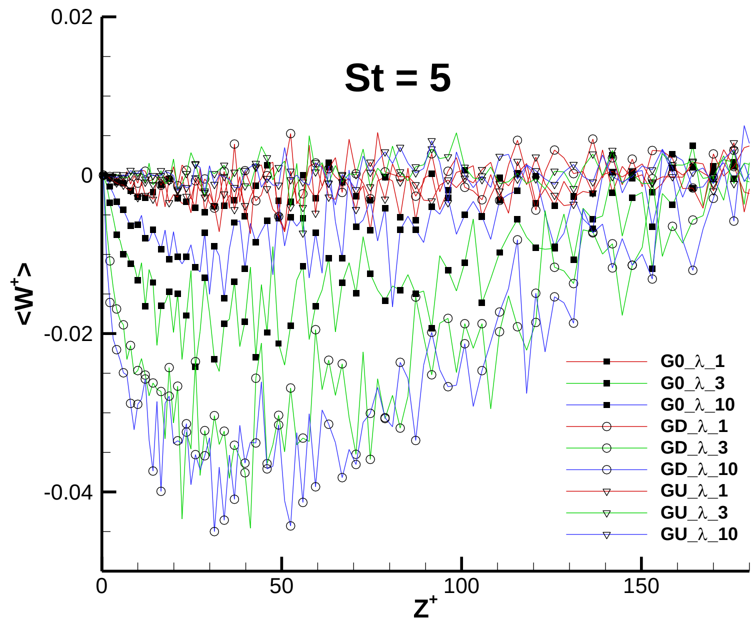


Fig. Mean wall normal velocity

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Statistics: Translational Motion

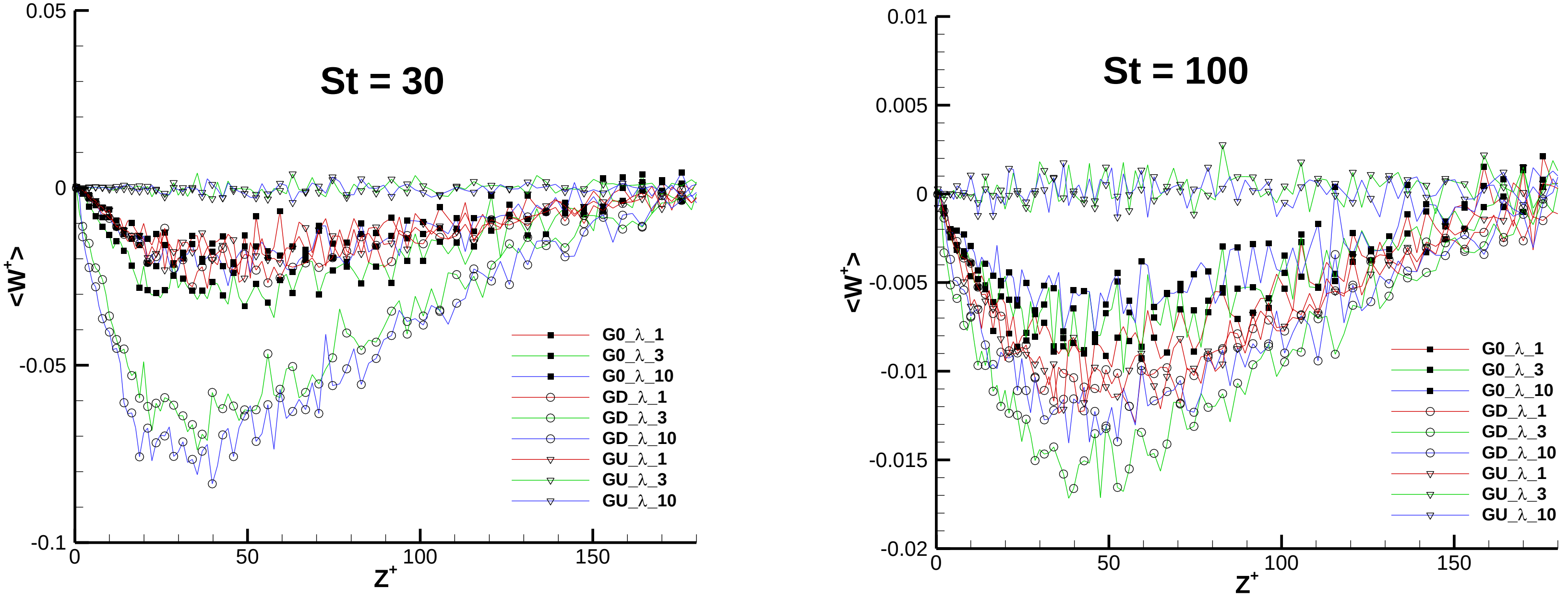

Fig. Mean wall normal velocity

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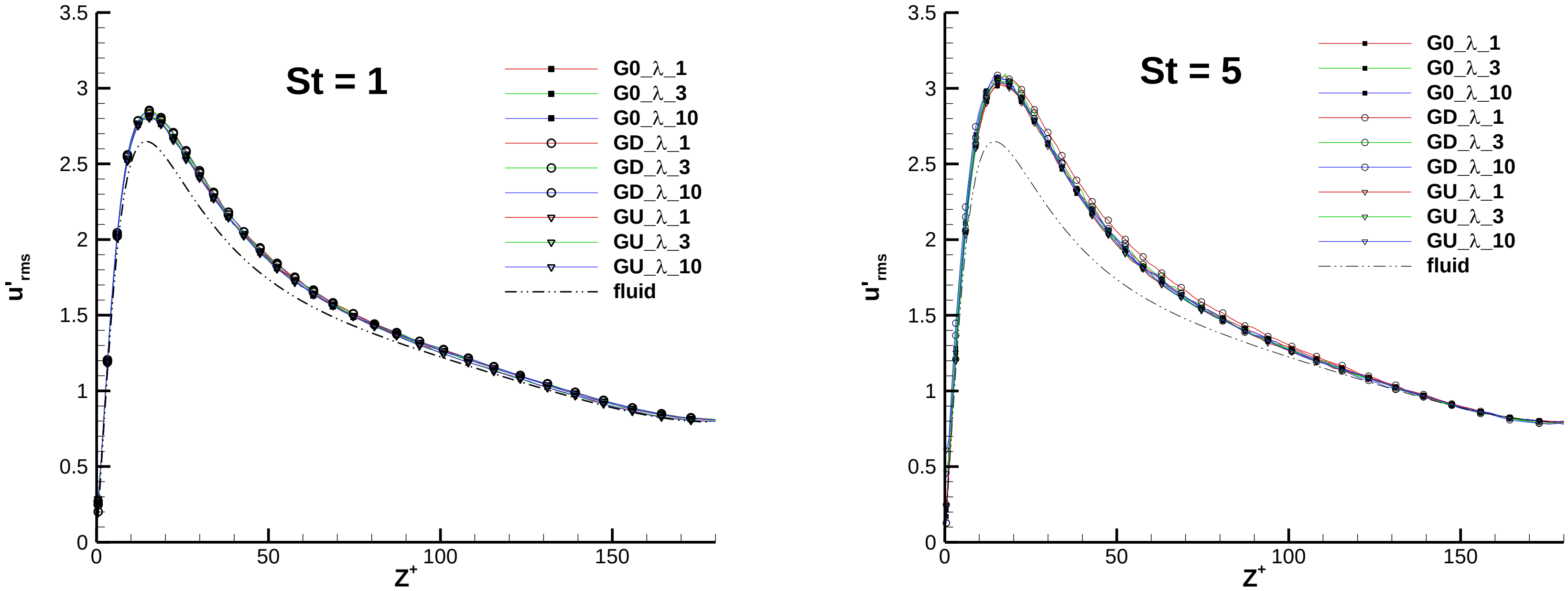

Fig. r.m.s. stream wise velocity fluctuation

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Statistics: Translational Motion

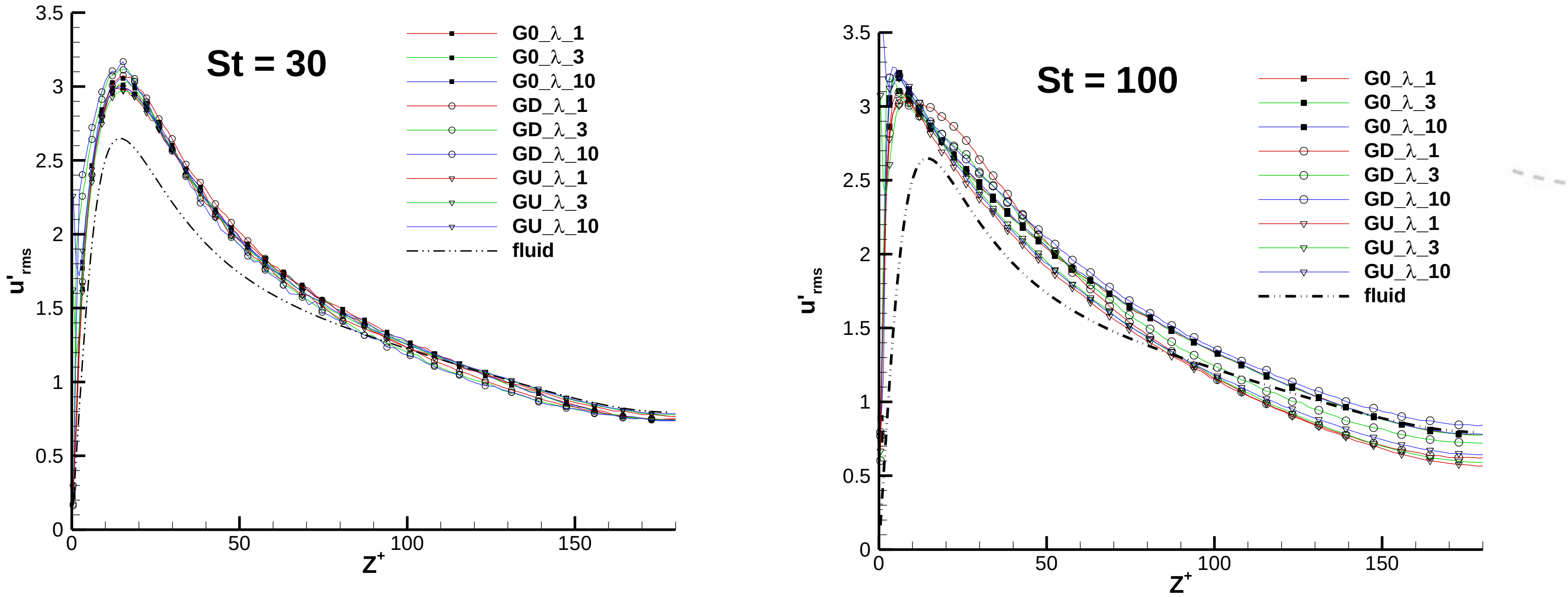

Fig. r.m.s. stream wise velocity fluctuation

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Statistics: Translational Motion

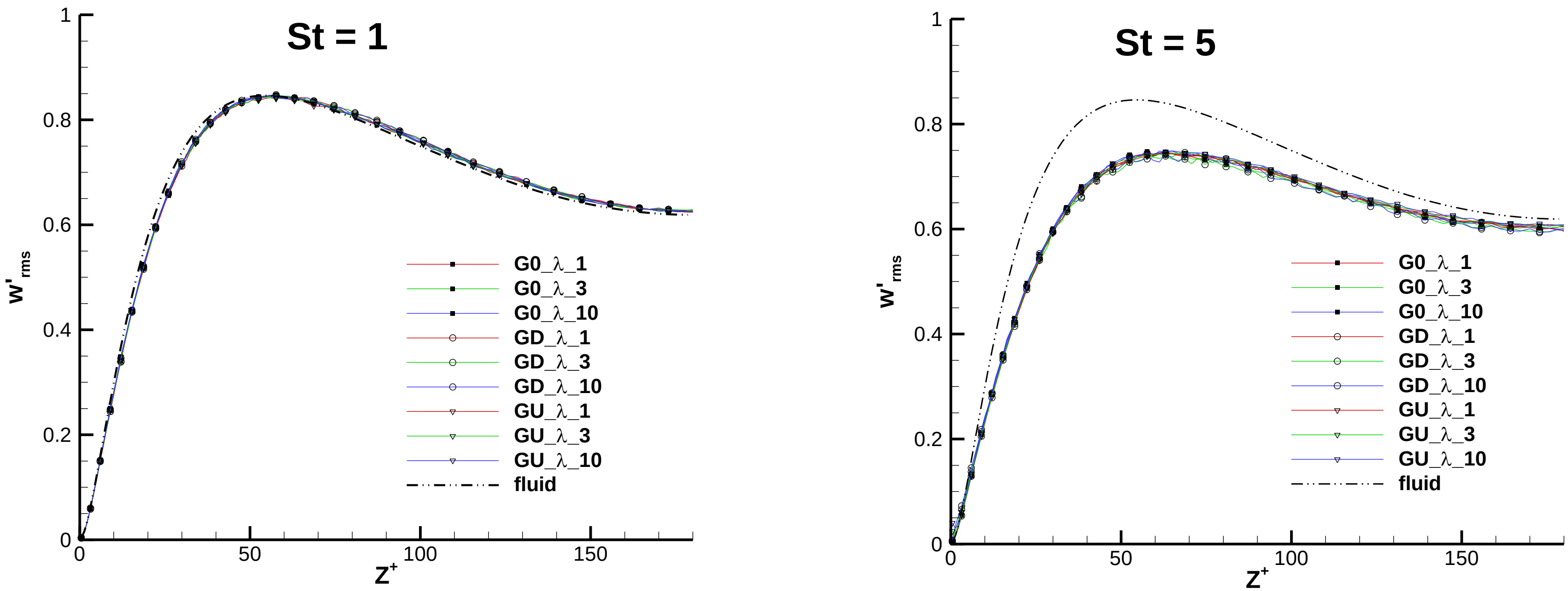

Fig. r.m.s. wall normal velocity fluctuation

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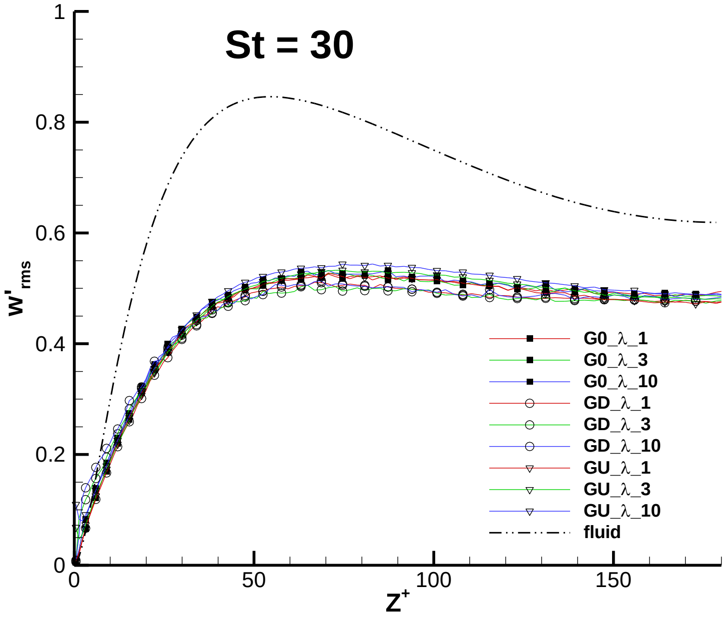
Statistics: Translational Motion



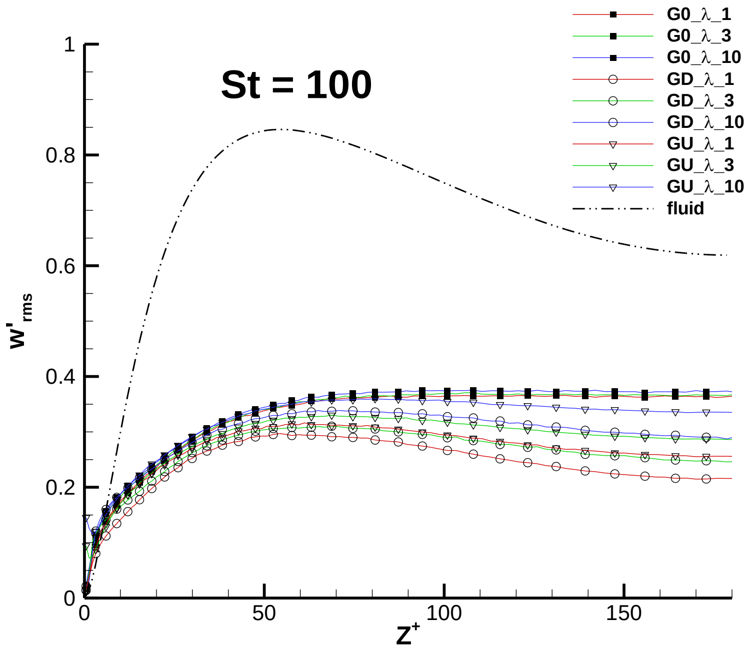


Fig. r.m.s. wall normal velocity fluctuation

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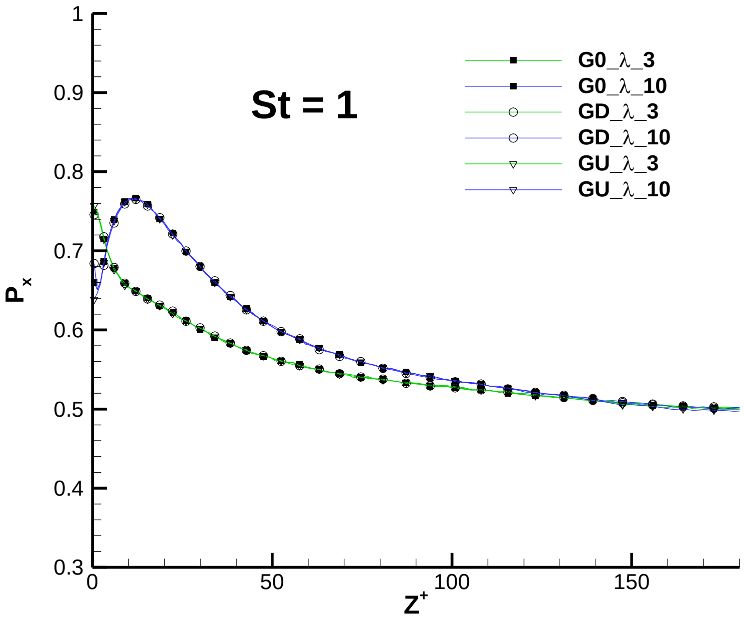
Statistics: Orientation



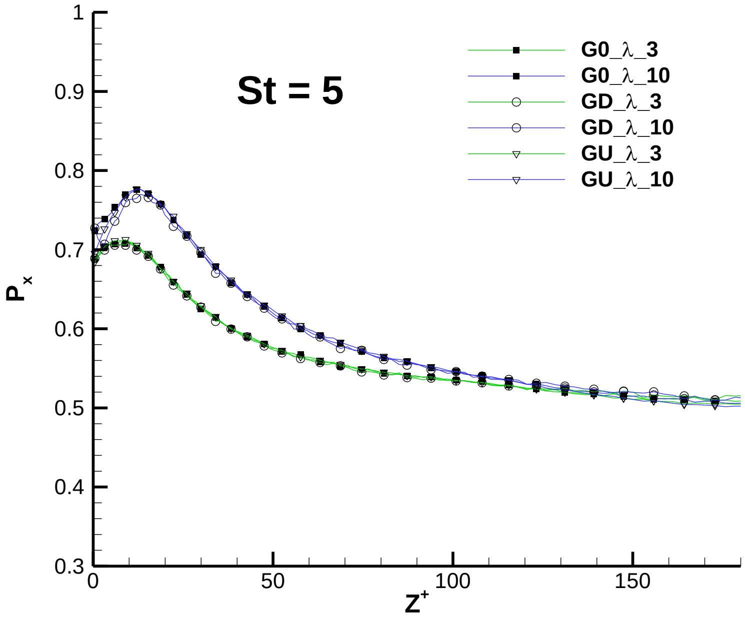


Fig. Mean stream wise orientation

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Statistics: Orientation

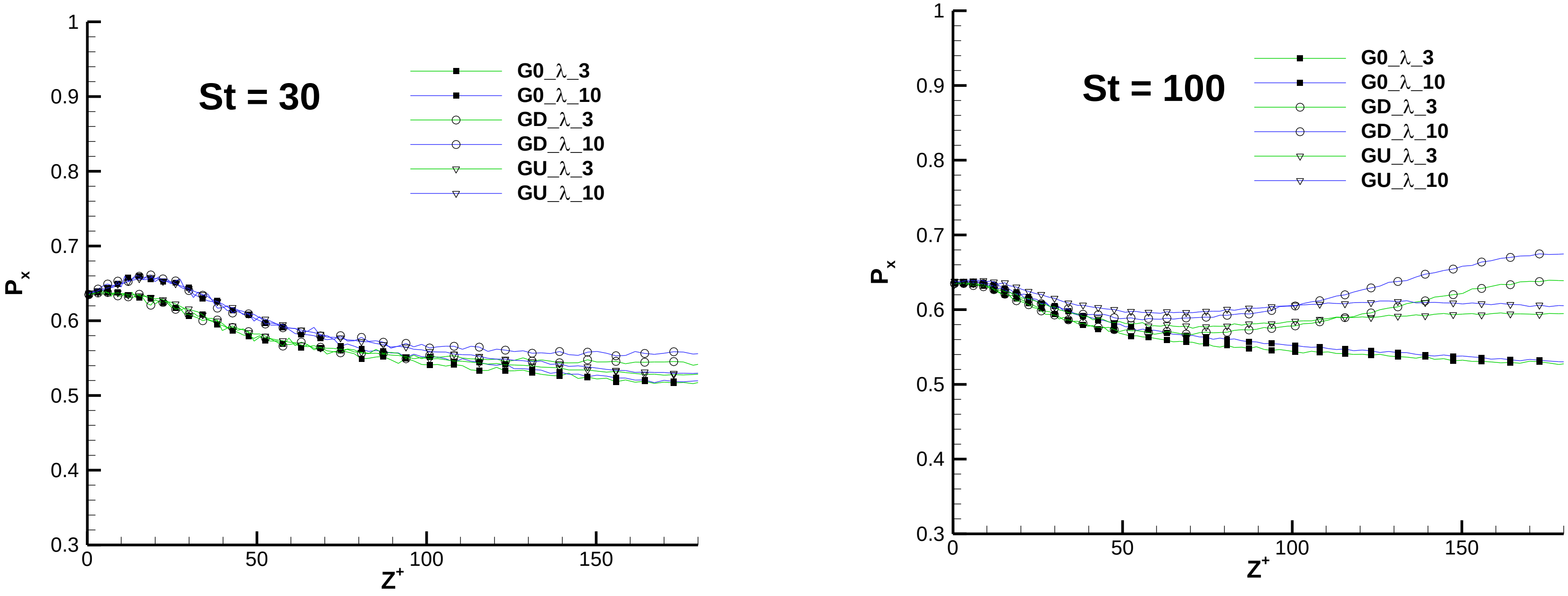

Fig. Mean stream wise orientation

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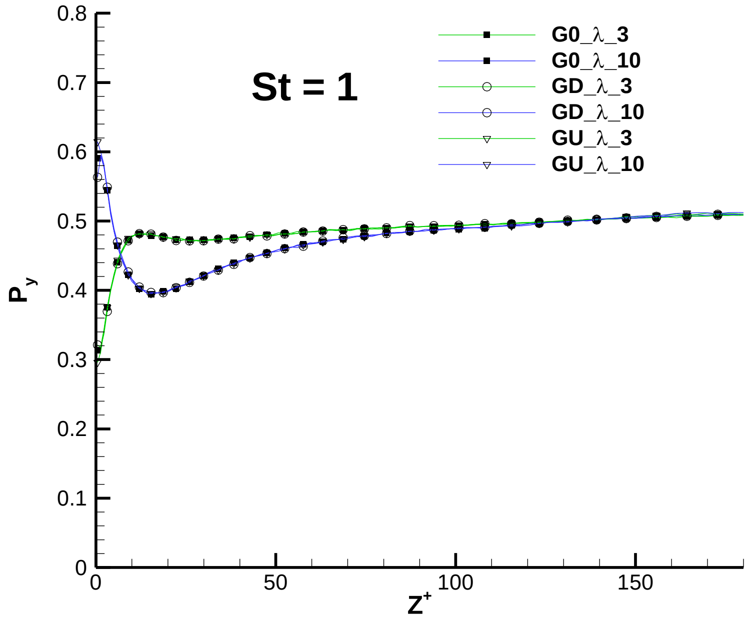
Statistics: Orientation



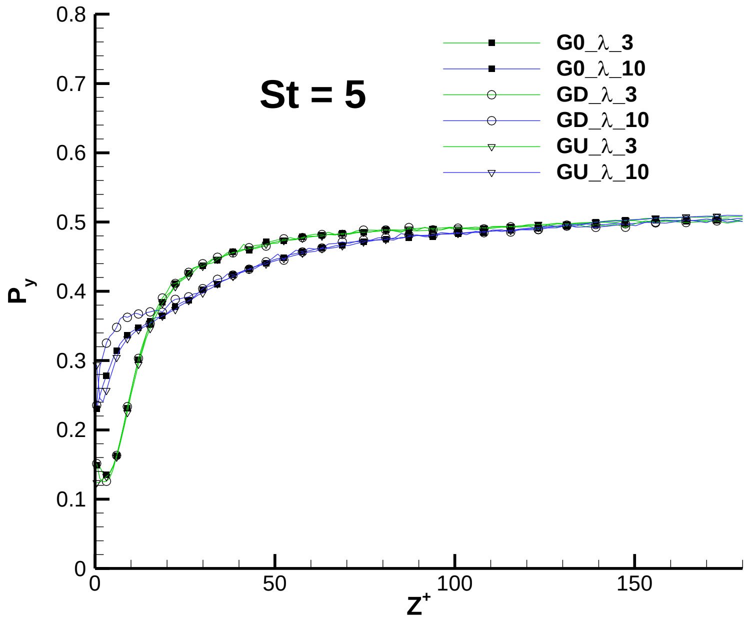


Fig. Mean span wise orientation

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Statistics: Orientation

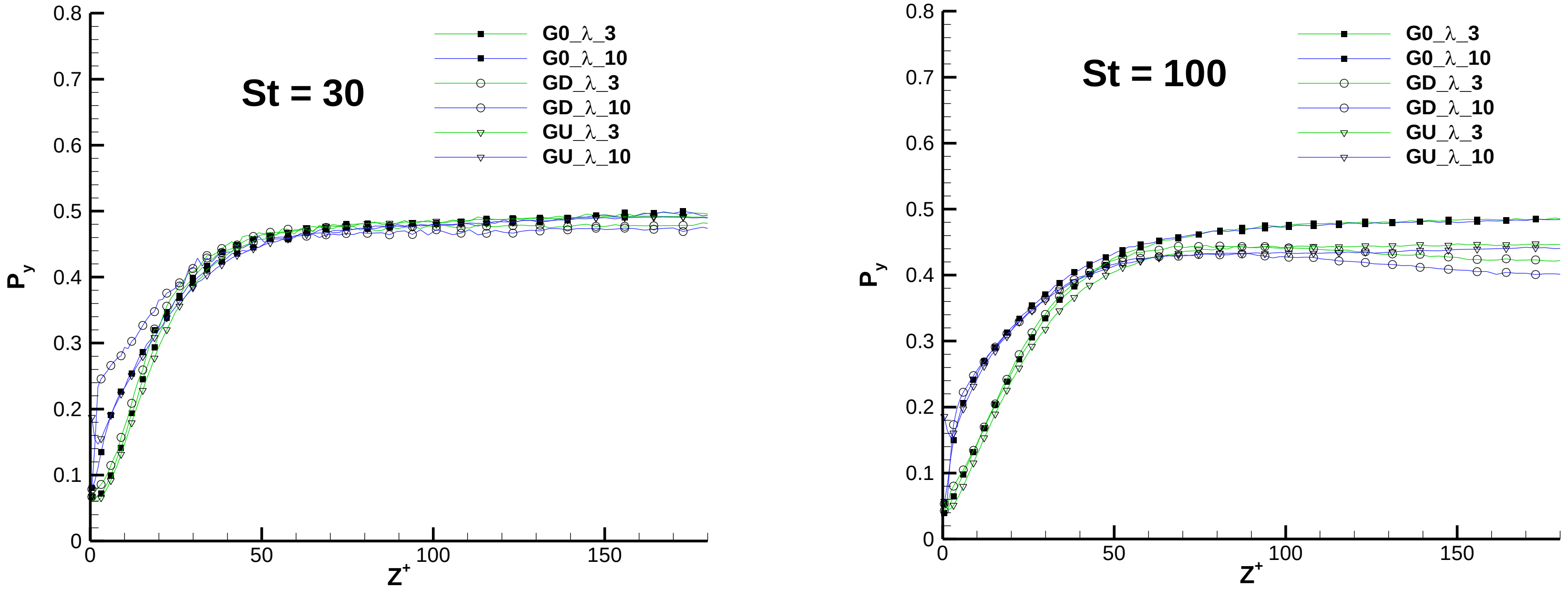

Fig. Mean span wise orientation

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Statistics: Orientation

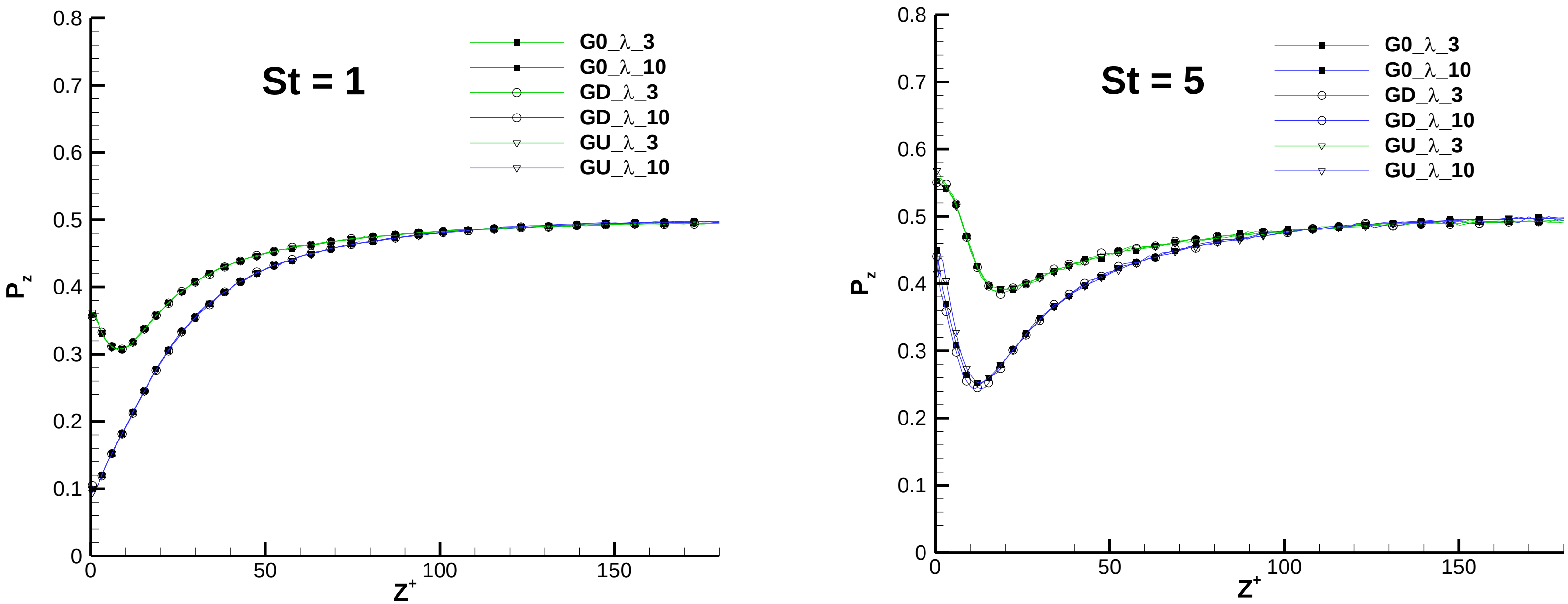

Fig. Mean wall normal orientation

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Statistics: Orientation

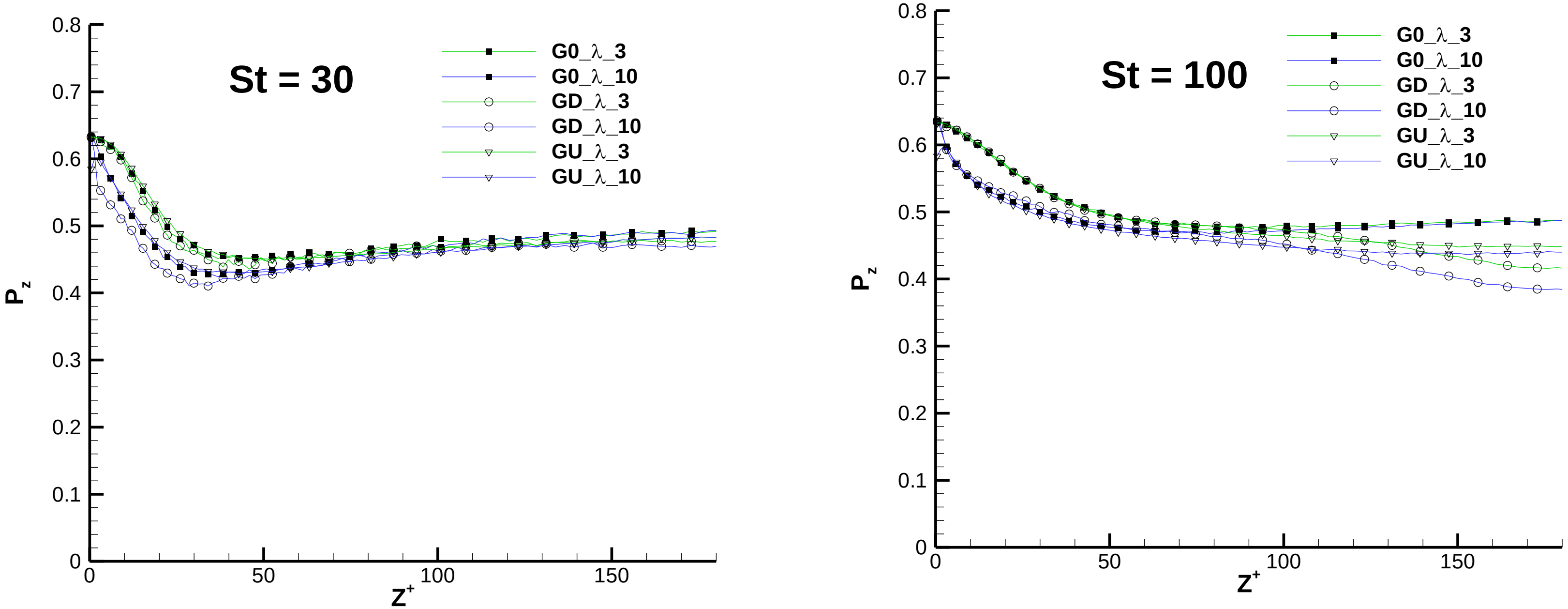

Fig. Mean wall normal orientation

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Summary

- Statistics for tiny elongated inertial fibers in turbulent vertical channel flow were reported for wide range of fibers
- Gravity has negligible effect on dynamics of lighter fibers
- The presence of gravity has significant effect on heavier fibers,
  - ✓ Mean stream wise velocity leads in downward flow and lags in upward flow compared to fluid
  - ✓ Wall ward drift velocity is suppressed in upward flow case compared to other cases
  - ✓ Increased stream wise fiber preferential orientation in center of the channel was observed in downward flow and it is more pronounced with aspect ratio

Thank You

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