Numerical Simulations of Unsteady Turbulent Flows: Temporal Acceleration

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Governing equations

The Navier-Stokes equations

$$\frac{\partial u_i}{\partial t} + \frac{\partial}{\partial x_j} u_i u_j = -\frac{\partial p}{\partial x_i} + \frac{1}{Re} \frac{\partial^2 u_i}{\partial x_j \partial x_j} + f \delta_{i1}, \quad (1)$$

$$\frac{\partial u_i}{\partial x_i} = 0. \quad (2)$$

where Re is the Reynolds number, $Re = \frac{U_{m0} h}{\nu}$.

Non-dimensionalisation

- h: the half channel height,
- U_{m0}: the initial bulk mean velocity.

Temporal acceleration

Non-dimensional acceleration parameter, f

- f is the non-dimensional acceleration parameter, $f = \dfrac{dU_m^*}{dt^*}$.

$$f = \frac{h}{U_{m0}^2}\frac{dU_m}{dt},$$

$$\gamma = \frac{D}{u_{\tau 0}U_{m0}}\frac{dU_m}{dt} = 2\frac{Re_{m0}}{Re_{\tau 0}}f.$$

The effect of f

f	0.2	0.35	0.5
	DNS/LES	LES	LES

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Numerical methods

Finite volume method

- Implicit, fractional step method (FSM) with Crank-Nicolson method,
  - Kim *et al*. (2001)
- Second-order accurate, finite volume scheme,
- Periodic boundary conditions in the streamwise and spanwise directions,
- Ensemble average with 15 realisations.

Validation: Steady DNS/LES comparison

Re	2800	3500	7000	11000	1200	15000	17000	20000	22600
Re_τ	180	210	395	590	640	780	860	1000	1110
	DNS	DNS	DNS	DNS	LES	DNS	LES	LES	LES

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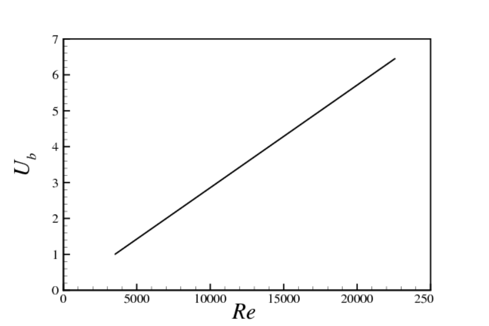
Temporal acceleration

Simulation parameters for LES

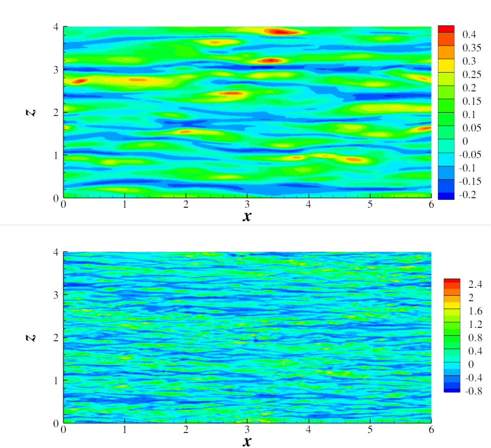
	initial	final (DNS/LES)	ratios
Re	3500	15000/22600	4.3/6.4
Re_τ	210	800/1110	3.8/5.2
τ_w			14.5/27.4



Low speed streaks

Challenges in grid resolution

- $Re = 3500$ and 15000



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Simulations parameters

DNS based on $Re_\tau = 800$

$L_x \times L_y \times L_z$	$N_x \times N_y \times N_z$	Δx^+	Δy^+_{min}	Δy^+_{max}	Δz^+
$6h \times 2h \times 4h$	$384 \times 384 \times 640$	12.5	0.4	9.7	5.0

- Acceleration time: $T = 16.4$

LES based on $Re_\tau = 1110$

$L_x^+ \times L_y^+ \times L_z^+$	$N_x \times N_y \times N_z$	Δx^+	Δy^+_{min}	Δy^+_{max}	Δz^+
$6780 \times 2260 \times 4520$	$256 \times 192 \times 384$	26.2	1.0	28.0	11.6

- Acceleration time: $T = 27.3$, 16.3 and 10.9.

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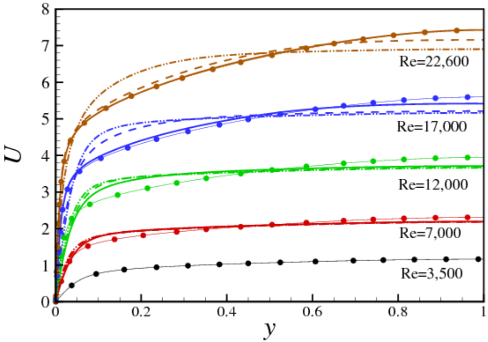
Temporal acceleration

Mean velocity profile variation

- Three f values ($f = 0.2$, 0.35 and 0.5) with steady results.



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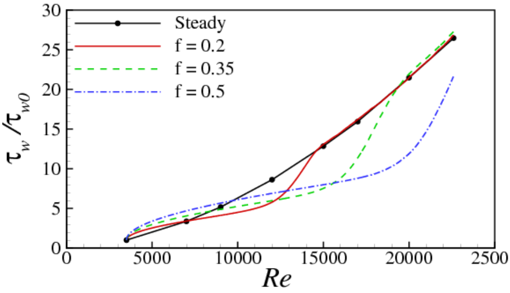
Wall shear stress

Four distinctive stages

- IT: initial transient ($3500 < Re < 4200$, or $0 < tU_{m0}/h < 1$)
- WT: weak transient ($4200 < Re < 12000$, or $1 < tU_{m0}/h < 12$)
- ST: strong transient ($12000 < Re < 16000$, or $12 < tU_{m0}/h < 17$)
- PS: pseudo-steady stage ($Re > 16000$, or $tU_{m0}/h > 17$)



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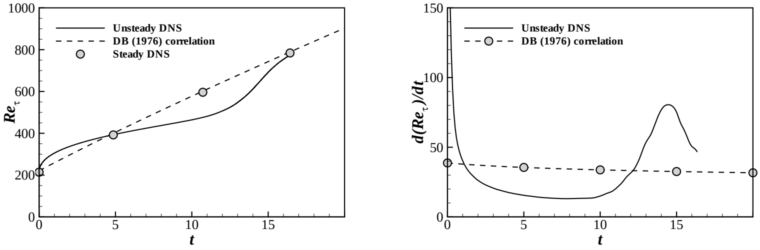
Wall shear stress

Wall shear stress variation

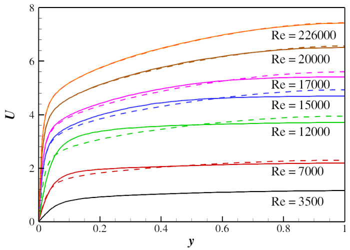
- Re_τ (left) and the rate of change of Re_τ (right)
- Good agreement with Dean and Bradshaw (1976)



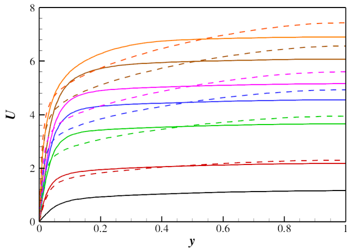
Mean velocity profile

Mean velocity profile variation with $f = 0.2$ and 0.5

- WT: Uniform increase in velocity in the early stage of transient.
- PS: It reaches the pseudo-steady velocity at the end of acceleration.



$f = 0.2$



$f = 0.5$

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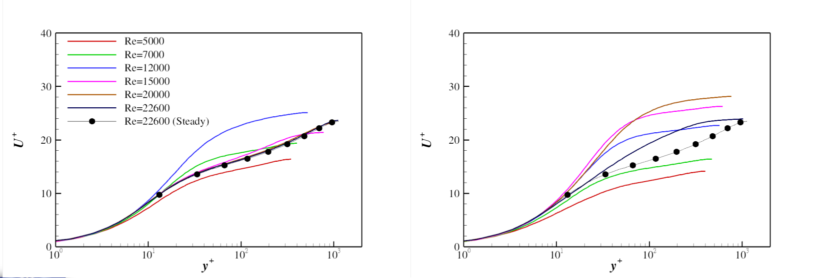
Log-law profile

Mean velocity profile variation

- A downward shift at the IT stage due to a higher u_τ value.
- An upward shift at the WT stage due to delay in new turbulence generation.



$f = 0.2$ $f = 0.5$

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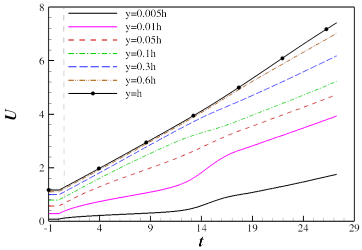
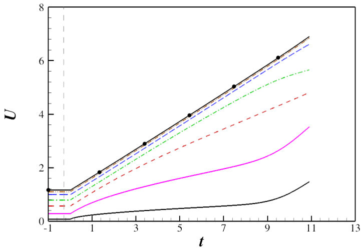
Mean velocity

Velocity change in time

- Near-wall region: smaller acceleration due to the no-slip condition
- Centre region: almost constant acceleration.



$f = 0.2$

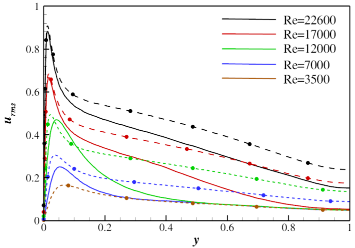


$f = 0.5$

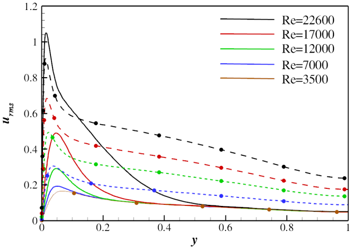
Velocity fluctuations

u_{rms}

- Near-wall turbulence ($y < 0.2$) responds first to acceleration.
- Turbulence intensities in the core region are smaller than steady values.



$f = 0.2$



$f = 0.5$

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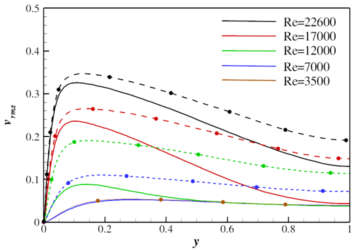
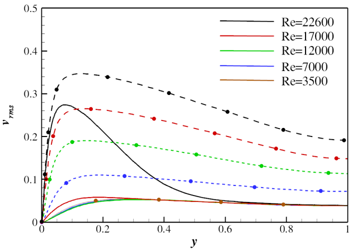
Velocity fluctuations

v_{rms}

- Slower response than u_{rms}
- v_{rms} in $y < 0.5$ region responded first to acceleration.



$f = 0.2$



$f = 0.5$

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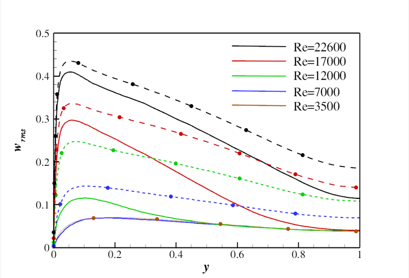
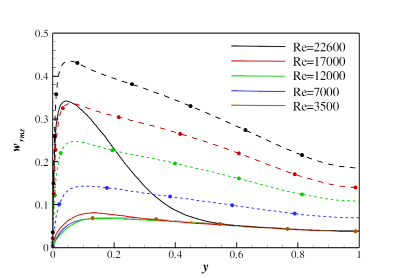
Velocity fluctuations

w_{rms}

- A similar trend to the response of v_{rms}.
- Slower response than u_{rms}



$f = 0.2$



$f = 0.5$

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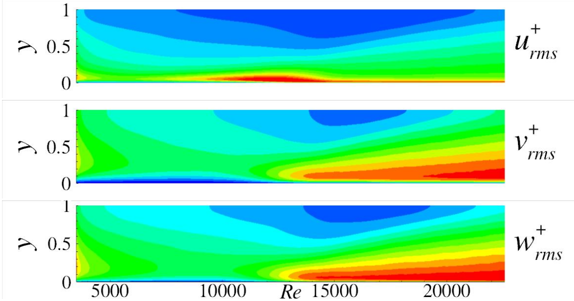
Velocity fluctuations

Velocity fluctuations in wall units

- Fluctuations are normalised by local u_τ.
- Near-wall turbulence responds to the acceleration first.
- Turbulence is transported to the core region.



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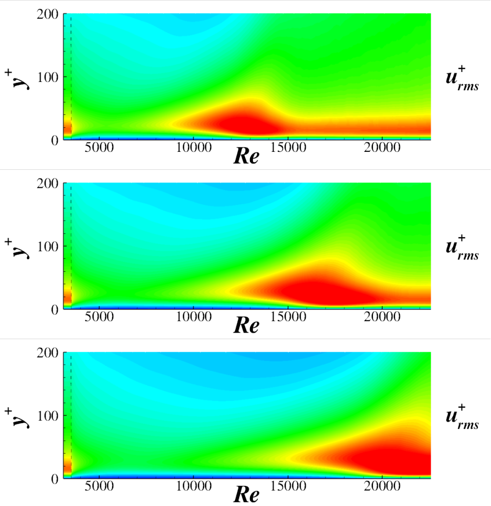
u_{rms} velocity fluctuations with three f values ($f = 0.2$, 0.35 and 0.5)



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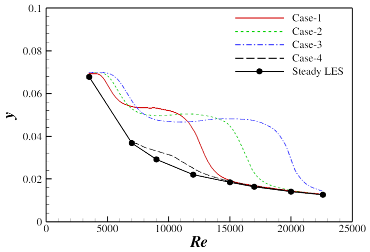
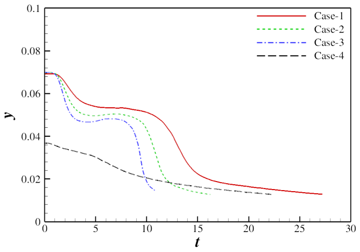
u_{rms} velocity fluctuations

Maximum u_{rms} location

- For steady, $y^+ = 15$.
- At $Re = 3500$, $y = 0.07$; and $Re = 22600$, $y = 0.015$.



Re



time

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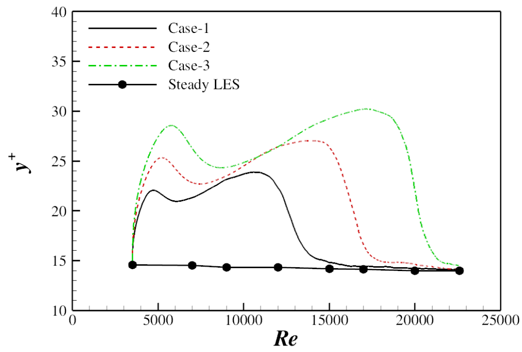
u_{rms} velocity fluctuations

Maximum u_{rms} location in wall units

- For steady, $y^+ = 15$.



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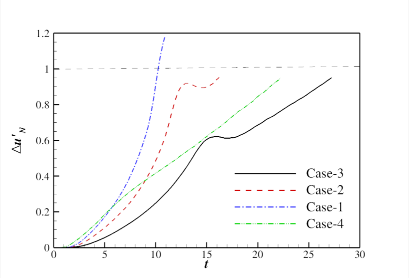
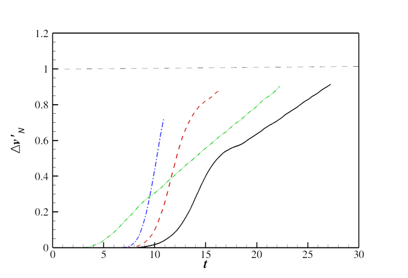
u_{rms} and v_{rms} velocity fluctuations

Maximum u_{rms} and v_{rms}

- $u_{rms}(t) - u_{rms}(0)$ normalised by the steady values.
- An overshoot for $f = 0.5$ case.



u_{rms}



v_{rms}

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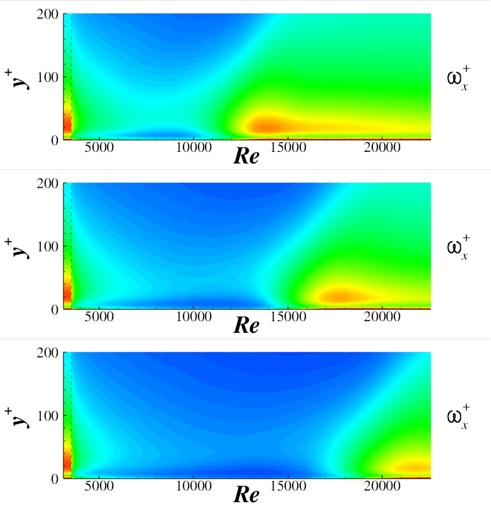
Vorticity fluctuations, ω_x' with three f values ($f = 0.2$, 0.35 and 0.5)



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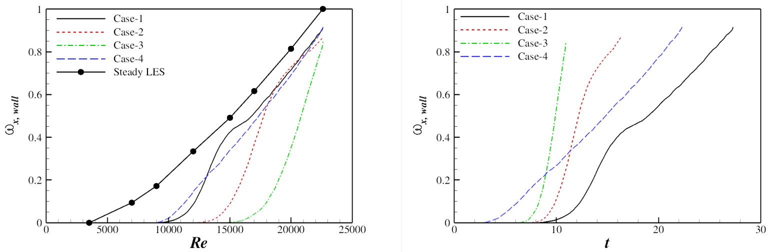
Streamwise vorticity fluctuations, ω'_x

Wall ω'_x value

- A delay followed by a sudden increase.
- A longer delay for a large f value.



Re time

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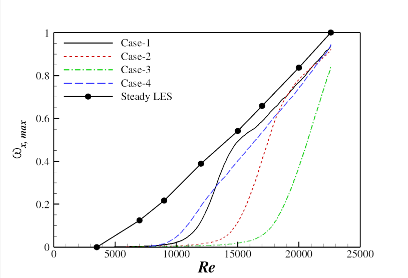
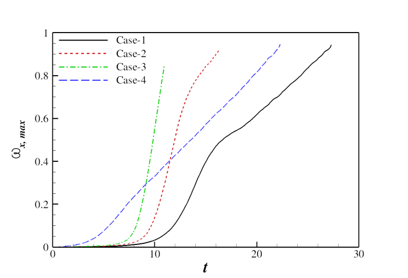
Streamwise vorticity fluctuations, ω_x'

Maximum ω_x' value

- A similar trend to the wall ω_x' value.
- Weaker than the steady state value.



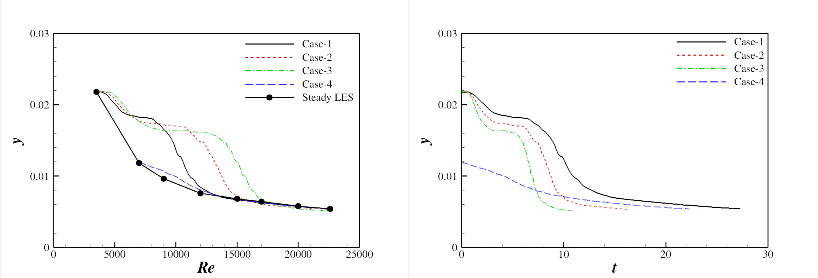


Re time

Streamwise vorticity fluctuations, ω_x'

Minimum ω_x' location

- Two sudden decreases.
- Located further away from the wall than the steady state case.



Re time

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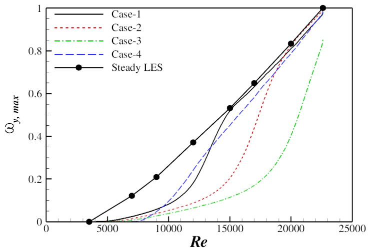
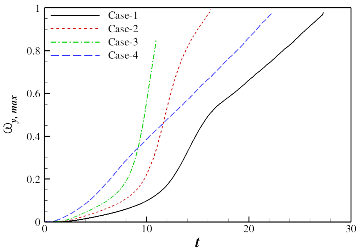
Wall-normal vorticity fluctuations, ω'_y

Maximum ω'_y value

- A similar trend to the wall ω'_x value.
- Weaker than the steady state value.



Re

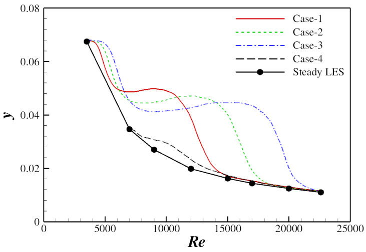


time

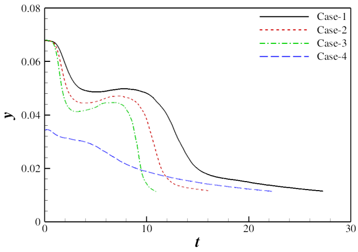
Wall-normal vorticity fluctuations, ω_y'

Maximum ω_y' location

- Similar to minimum ω_y' location: two sudden decreases.
- Located further away from the wall than the steady state case.



Re



time

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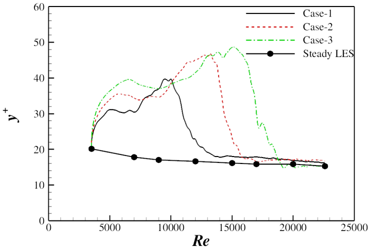
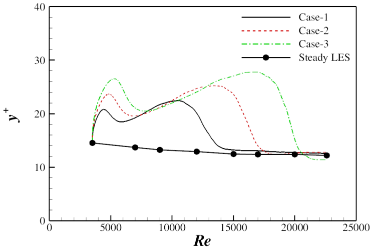
Wall-normal vorticity fluctuations, ω_y'

Maximum ω_x' and ω_y' location in wall units

- A similar trend to the wall ω_x' value.
- Weaker than the steady state value.



ω_x'



ω_y'

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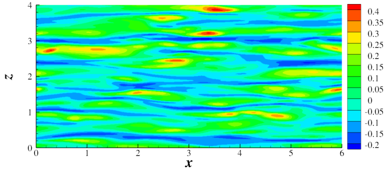
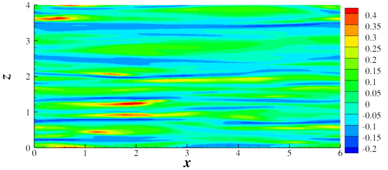
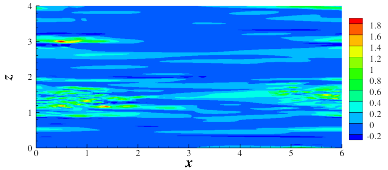
Low speed streaks



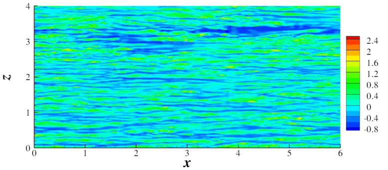
$Re = 3500$



$Re = 8000$



$Re = 12000$



$Re = 15000$

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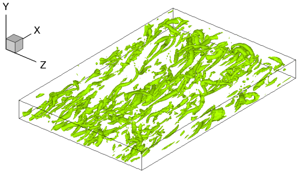
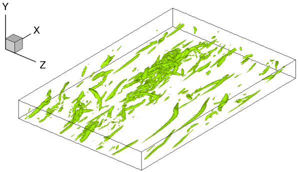
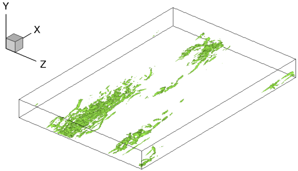
λ_2 iso-surface contours



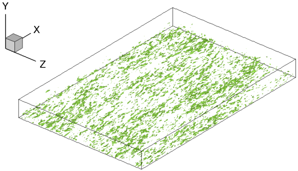
$Re = 3500$



$Re = 9000$



$Re = 12000$



$Re = 15000$

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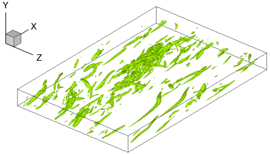
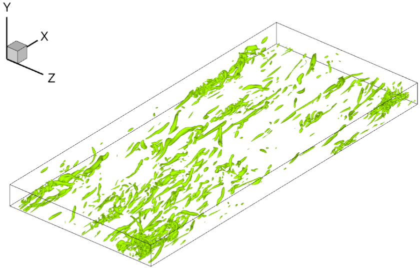
Domain size test

Destruction of turbulence at $Re = 9000$



$6 \times 2 \times 4$



$12 \times 2 \times 4$

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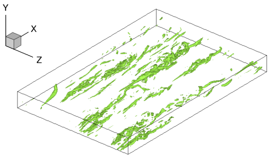
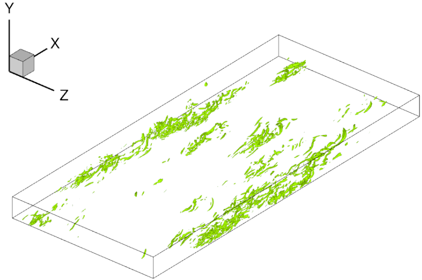
Domain size test

Turbulence structures at $Re = 11000$



$6 \times 2 \times 4$



$12 \times 2 \times 4$

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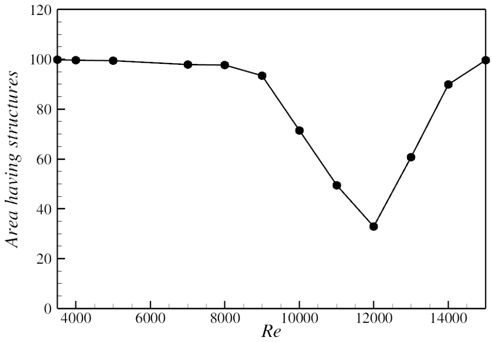
Active area

Percentage of active area during temporal acceleration

- Destruction of **old** turbulence.
- Generation of **new** turbulence.



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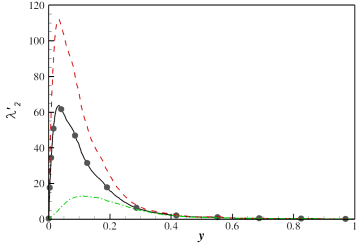
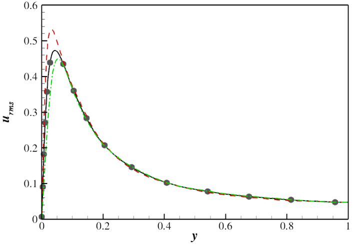
Conditional average at $Re = 12000$

Conditional avarage

- Area with/without active flow structures.
- Location for the maximum u_{rms}.



λ_2



u_{rms}

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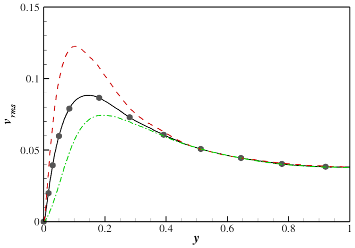
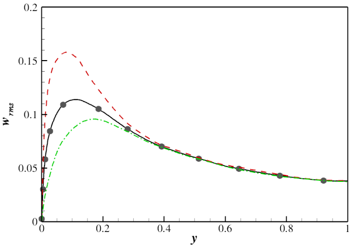
Conditional average at $Re = 12000$

Destruction of turbulence structure

- Large changes.
- New and old turbulence.



v_{rms}



w_{rms}

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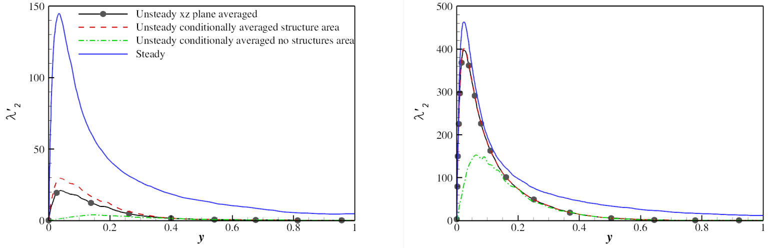
Conditional average (DNS)

Destruction of turbulence structure

- New turbulence is much weaker at $Re = 11000$ than the steady flow.
- Generation of new turbulence is almost completed at $Re = 15000$.



$Re = 11000$ $Re = 15000$

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Contents

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Conclusions

Turbulent channel flow with temporal acceleration

- Turbulence responds rapidly to the temporal acceleration after a certain delay until pseudo-steady equilibrium is achieved.
- u_{rms} velocity component responds to the acceleration first, followed by v_{rms} and w_{rms} velocity components.
- Three delays: production, redistribution, and transport.
- Destruction of the initial turbulence and generation of new turbulence.
- Effect of the acceleration parameter.
- Effect of the initial flow condition.

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The End

Thank You!

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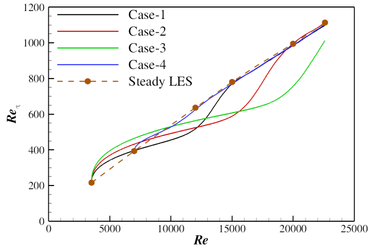
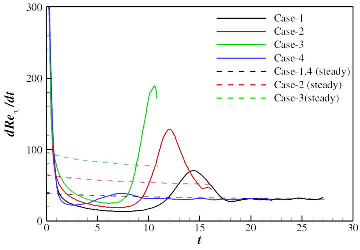
Wall shear stress

Wall shear stress variation

- Re_τ (left) and the rate of change of Re_τ (right)
- Good agreement with Dean and Bradshaw (1976)





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