Wall-modeled LES of Turbulent Flows Past Airfoils and Periodic Hills

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August 11, 2020
AMS Seminar, NASA Ames Research Center
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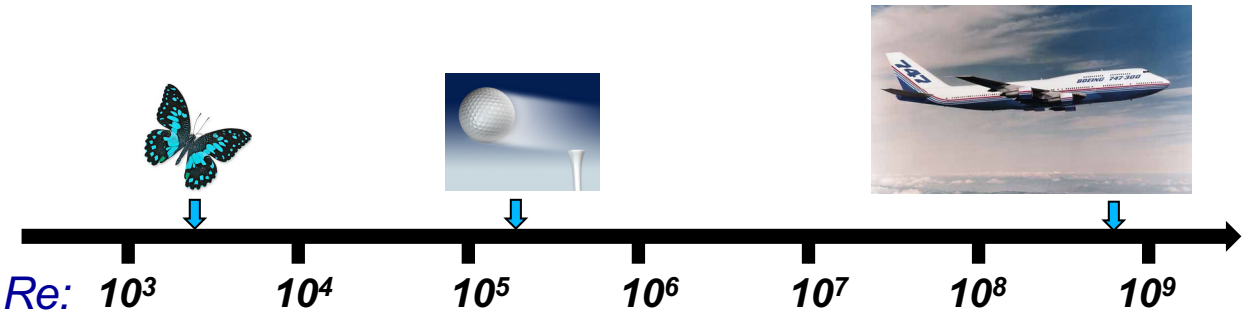
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Outline

- Introduction
- SGS and Wall Models
  - *Virtual wall boundary conditions*
- WMLES of flow past airfoils
- WMLES of flow past periodic hills
- Conclusion

Fluid Mechanics: Reynolds number (*Re*)



DNS (Direct Numerical Simulation)

No Modeling

LES (Large-eddy simulation)

Wall-resolved LES

Wall modeled LES

Modeling

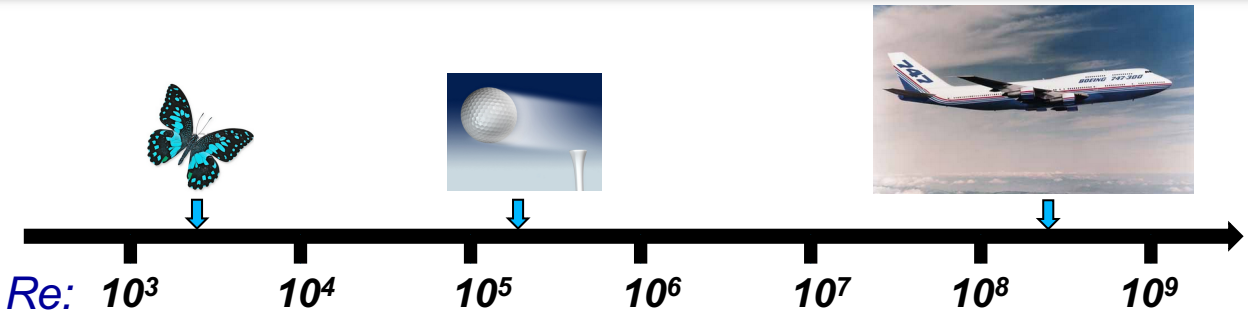
Hybrid RANS-LES

RANS (Reynolds-averaged Navier-Stokes)

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Fluid Mechanics: Reynolds number (*Re*)



DNS

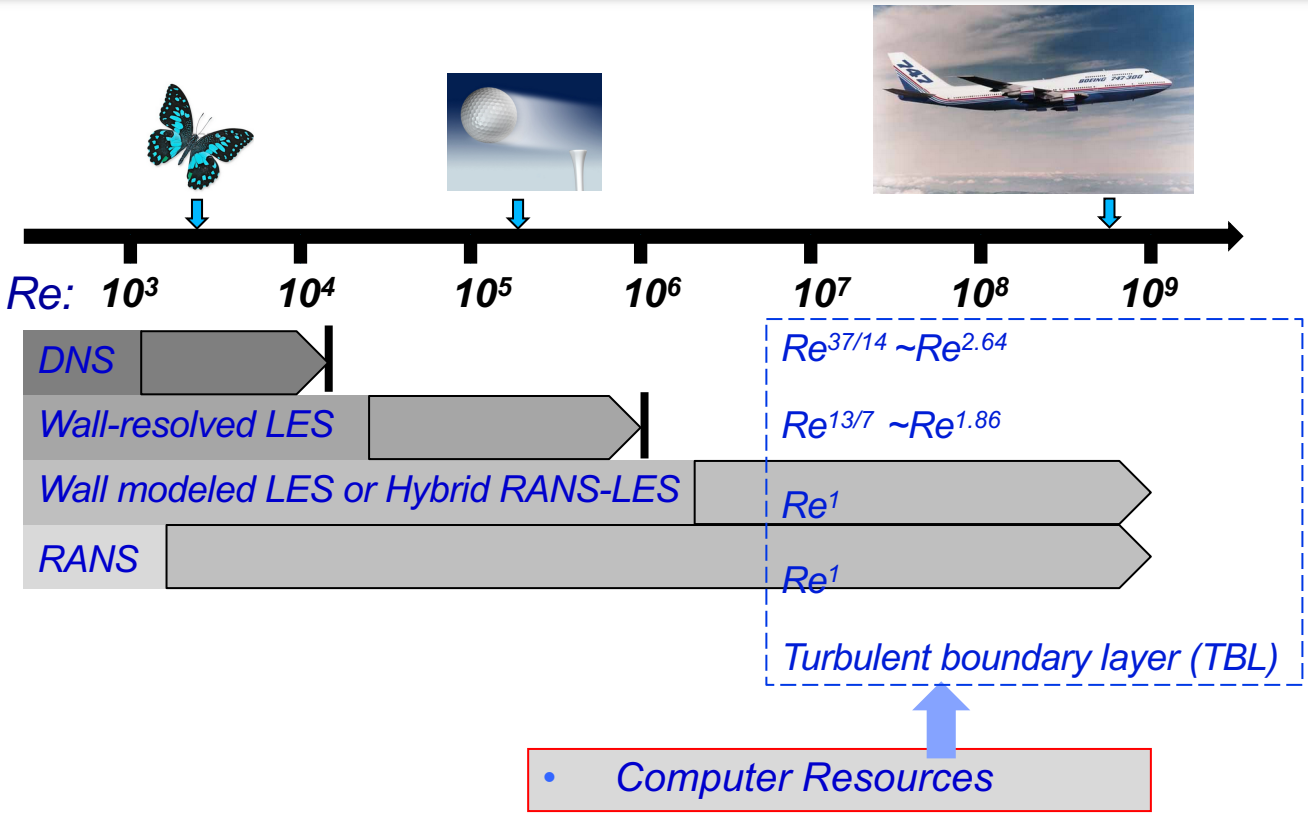
Wall-resolved LES

Wall modeled LES or Hybrid RANS-LES

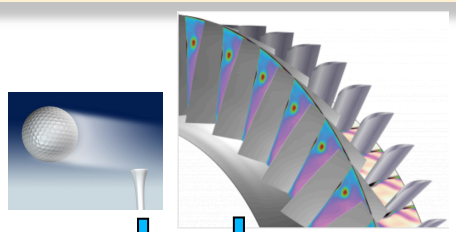
RANS

- *Computer Resources*

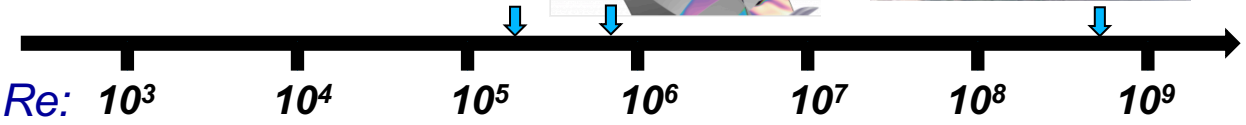
Fluid Mechanics: Reynolds number (*Re*)



Fluid Mechanics: Reynolds number (*Re*)







Wall-resolved LES — $Re^{13/7} \sim Re^{1.86}$

Wall modeled LES or Hybrid RANS-LES — Re^{1}

Turbulent boundary layer (TBL)

Key flow features:
- *Turbulence*
- *Transition*
- *Separation*

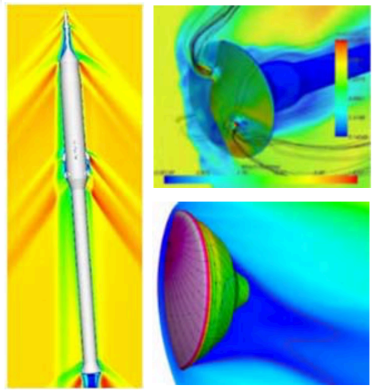
- *Computer Resources*
- *Accurate Modeling/Simulation*

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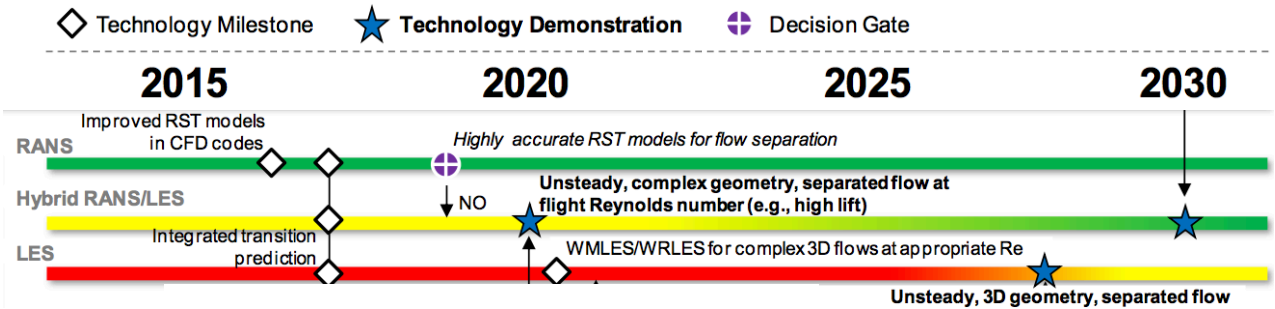
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NASA: Critical challenges in CFD ---- Separation

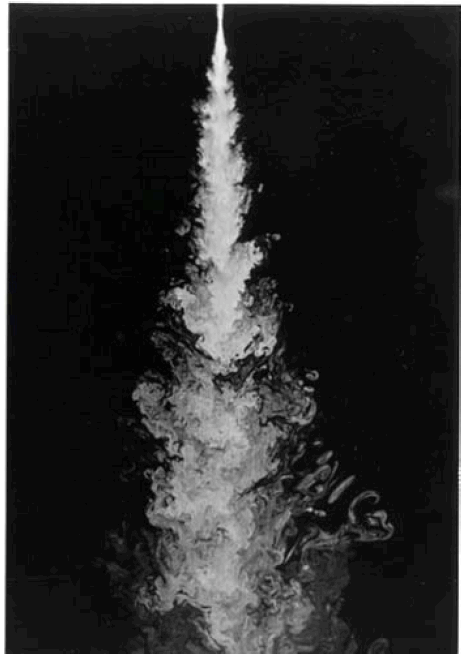
- NASA's 2014 Aerosciences: Top three challenges
  - Prediction of unsteady separated flows
  - Aero-plume interaction prediction
  - Aerothermal prediction



- NASA CFD 2030 VISION

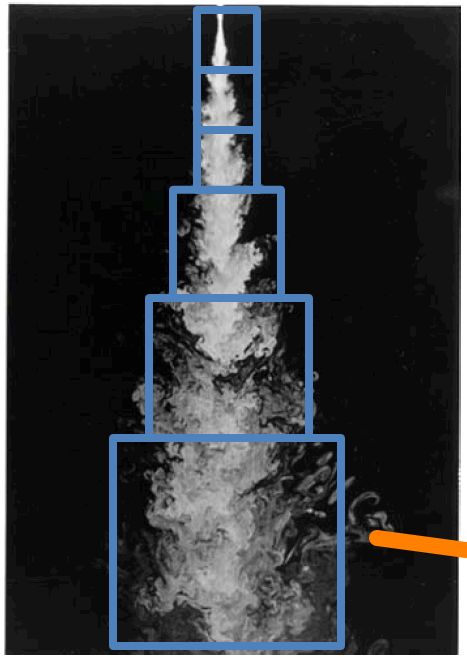


Direct Numerical Simulation (DNS) vs Large-Eddy Simulation (LES)

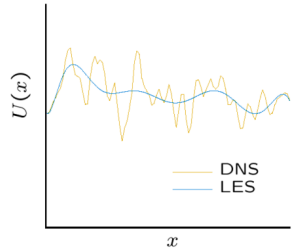


Re = 10k (Dimotakis et al. 1983)

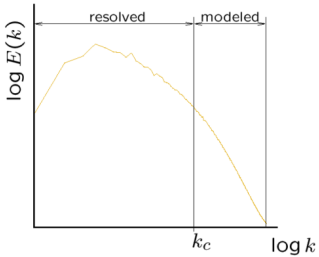
Direct Numerical Simulation (DNS) vs Large-Eddy Simulation (LES)



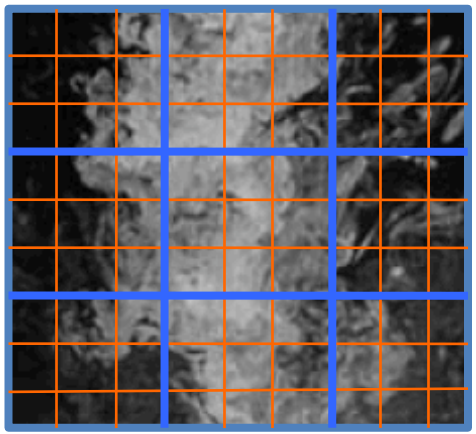
Re = 10k (Dimotakis et al. 1983)



physical space: fine-scale fluctuations not resolved, their influence is modeled.



spectral space: resolved range, $k < k_c$ (cutoff wavenumber k_c), subgrid range $k > k_c$.

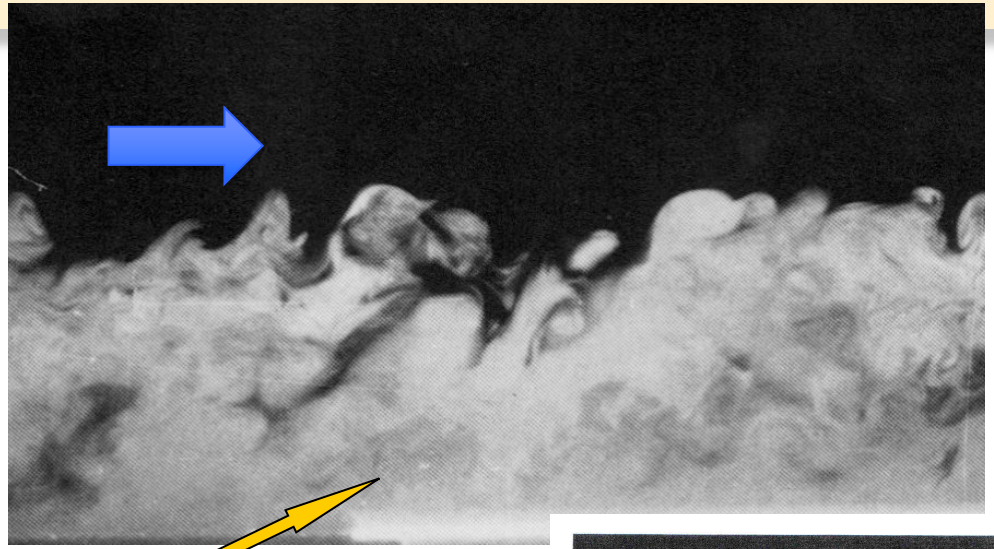


DNS

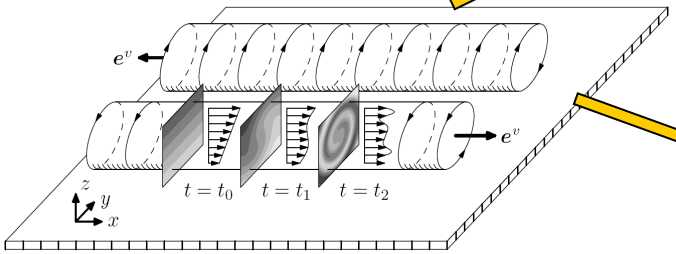
LES

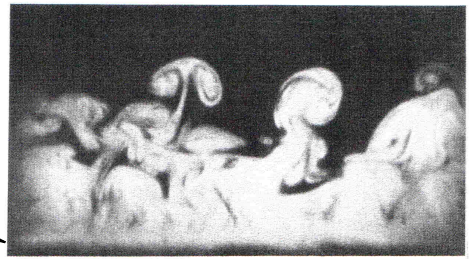
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LES for wall-bounded flows



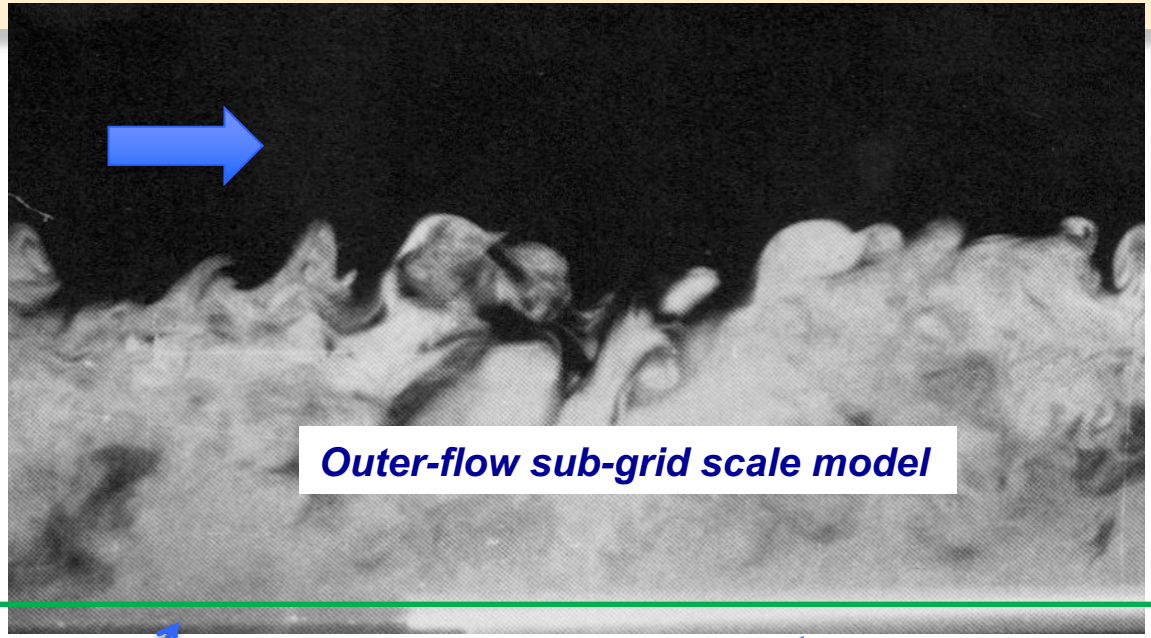
(Falco 1977)





Head & Bandyopandhyay (1981)

LES for wall-bounded flows



(Falco 1977)

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Filtered Navier-Stokes Equations

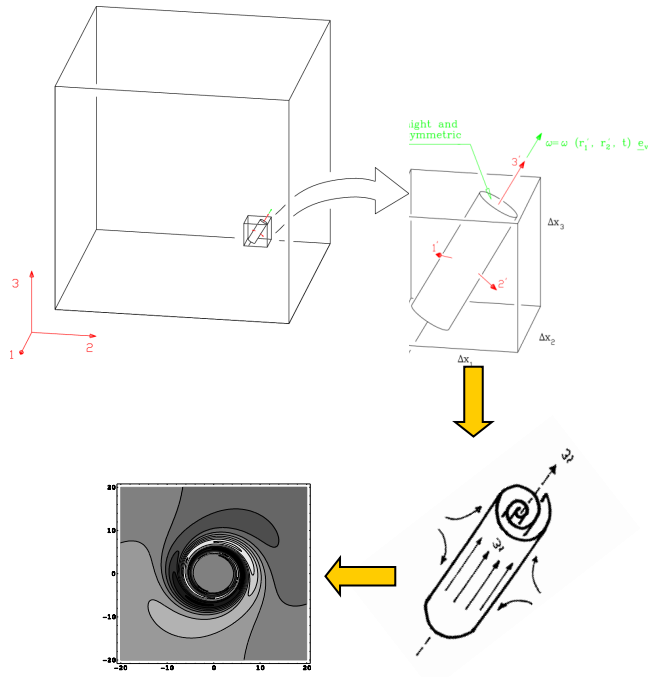
- Apply filtering operation to incompressible Navier-Stokes equations

$$
\begin{aligned}
\frac{\partial \widetilde{u}_i}{\partial x_i} &= 0 \\
\frac{\partial \widetilde{u}_i}{\partial t} + \frac{\partial}{\partial x_j}\left(\widetilde{u_i}\,\widetilde{u_j}\right) &= -\frac{\partial \widetilde{p}}{\partial x_i} + \nu \frac{\partial^2 \widetilde{u}_i}{\partial x_i^2} \\
\frac{\partial \widetilde{u}_i}{\partial t} + \frac{\partial}{\partial x_j}\left(\widetilde{u}_i \widetilde{u}_j\right) &= -\frac{\partial \widetilde{p}}{\partial x_i} - \frac{\partial}{\partial x_i}\underbrace{\left(\widetilde{u_i}\,\widetilde{u_j} - \widetilde{u}_i\,\widetilde{u}_j\right)}_{T_{ij}} + \nu \frac{\partial^2 \widetilde{u}_i}{\partial x_i^2} \\
\widetilde{u_i}\,\widetilde{u_j}(\boldsymbol{x},t) &\equiv \int_{-\infty}^{\infty} \mathcal{G}(\boldsymbol{x}'-\boldsymbol{x})\, u_i(\boldsymbol{x}')\, u_j(\boldsymbol{x}')\, d\boldsymbol{x}' \neq \widetilde{u}_i\,\widetilde{u}_j
\end{aligned}
$$

- T_{ij} ``unresolved stresses'' must be modeled: this is the ``closure problem''
- Filtering process on NS equations is strictly formal: no particular filter is actually needed

Explicit SGS model: stretched-vortex model

- Structure-based approach
- Subgrid motion represented by nearly axisymmetric vortex tube within each cell
- Local solution of NS equations for stretched-spiral vortex
  - *Lundgren (1982), Pullin & Lundgren (2001)*
- Subgrid stress:



$$T_{ij} = (\delta_{ij} - e_i^v e_j^v) K,$$

$$K = \int_{k_c}^{\infty} E(k)dk = \frac{1}{2}\mathcal{K}_0' \Gamma\left[-1/3, \kappa_c^2\right], \mathcal{K}_0' = \mathcal{K}_0 \epsilon^{2/3} \lambda_v^{2/3}$$

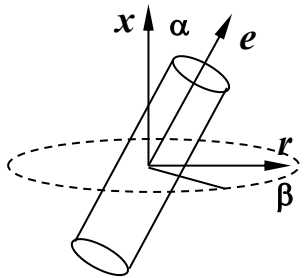
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Model parameters

- Subgrid energy spectrum (Lundgren, 1982)

$$E(k) = \mathcal{K}_0 \epsilon^{2/3} k^{-5/3} \exp[-2k^2\nu/(3|\tilde{a}|)]$$

$$\tilde{a} = \tilde{S}_{ij} e_i^v e_j^v, \qquad \tilde{S}_{ij} = \frac{1}{2}\left(\frac{\partial \tilde{u}_i}{\partial x_j} + \frac{\partial \tilde{u}_j}{\partial x_i}\right)$$



- Parameters obtained from resolved-scale, second order velocity structure-functions (Lesieur et al)

$$\mathcal{K}_0 \epsilon^{2/3} = \frac{\overline{\mathcal{F}_2}(\triangle)}{\triangle^{2/3} \mathrm{A}}, \qquad \mathrm{A} = 4\int_0^\pi s^{-5/3}(1 - s^{-1}\sin s)ds \approx 1.90695$$

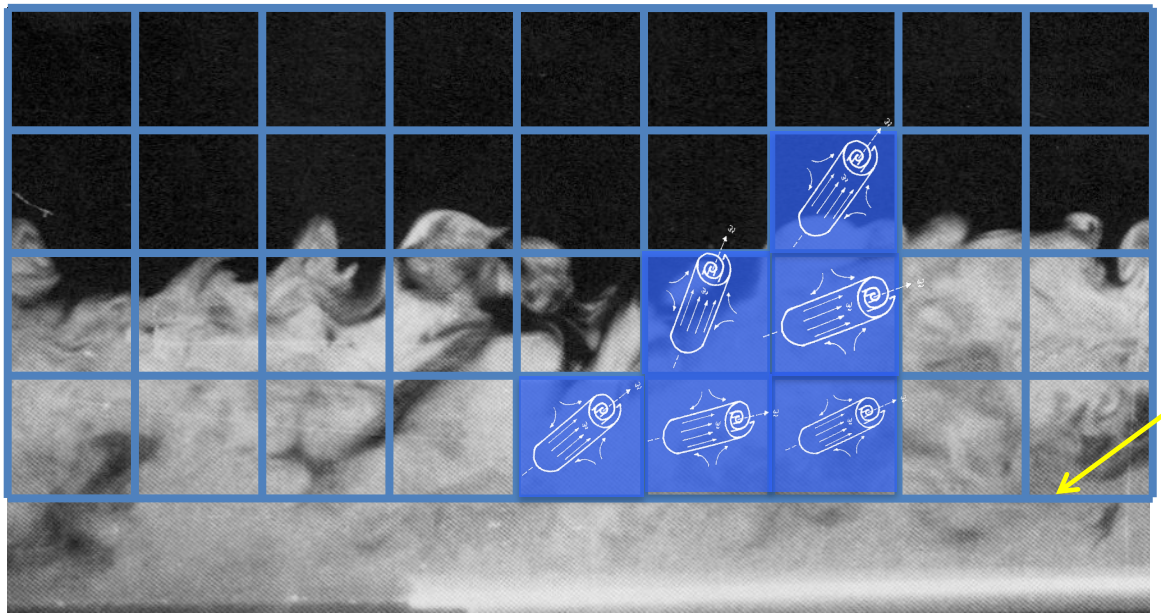
$$\overline{\mathcal{F}_2}(\triangle) = \frac{1}{6}\sum_{j=1}^{3}\left(\delta\tilde{u}_1^{+\,2} + \delta\tilde{u}_2^{+\,2} + \delta\tilde{u}_3^{+\,2} + \delta\tilde{u}_1^{-\,2} + \delta\tilde{u}_2^{-\,2} + \delta\tilde{u}_3^{-\,2}\right)_j,$$

- Align SGS vortex axis with principal extensional eigenvector of $\tilde{S}_{ij}$
- See Misra & Pullin (1997), Voelkl & Pullin (2000) for details

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LES + wall model for high Re flow

Outer flow: LES with stretched-vortex SGS model



LES + wall model for high Re flow

Wall-model based on idea of attached eddies (Townsend)

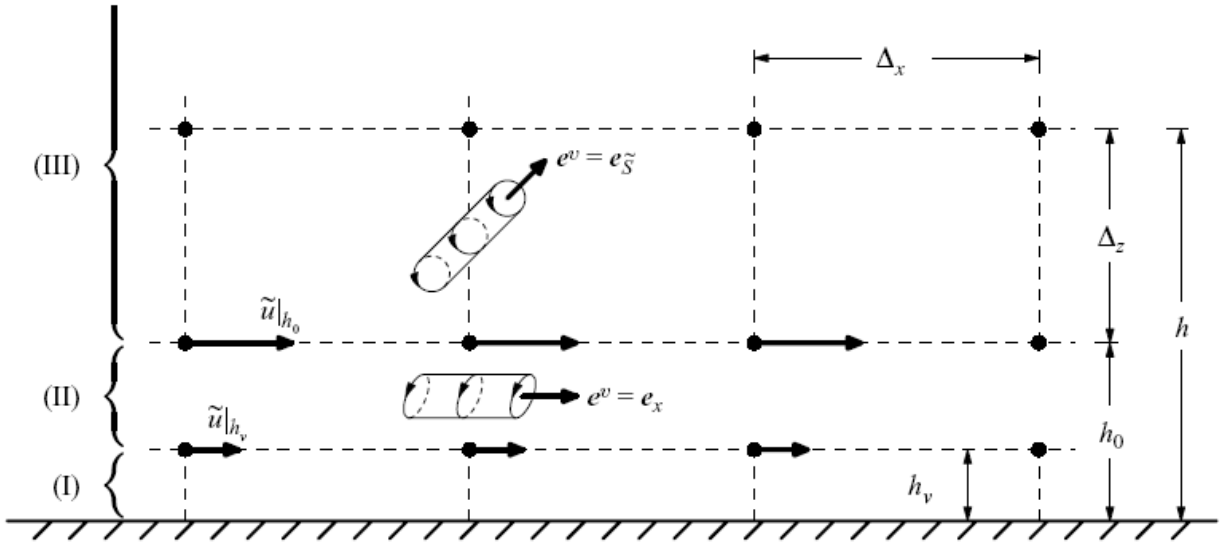
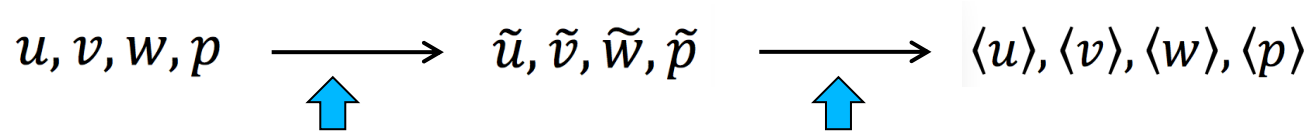


FIGURE 1. Schematic showing the near-wall set-up: h_0 locates the lifted virtual wall, where boundary conditions are applied; h locates the input plane to the wall shear stress equation, (3.10); h_v locates the outer edge of the viscous sublayer; $\boldsymbol{e}^v$ is the alignment of SGS vortices in their respective regions.

Wall Model

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Wall Model – Essential Idea



- Inner scaling combined with wall normal integration filter

$$\frac{\tilde{q}}{u_\tau} = F(z^+), \quad z^+ \equiv \frac{z}{l^+} = \frac{z u_\tau}{\nu}. \quad \Longrightarrow \quad \frac{\partial \langle q \rangle}{\partial t} = \frac{\tilde{q}|_h}{2\eta_0} \frac{\partial \eta_0}{\partial t}.$$

- Main points to note
  - *Mean flow aligned with streamwise direction*
  - *Classical inner scaling*
  - *Near wall integration approach*

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Wall Model

- ODE for wall shear stress (or u_τ) at every wall point $u_\tau^2 \equiv \nu\eta_0$ $\quad \eta_0 \equiv \left.\frac{\partial \widetilde{u}}{\partial z}\right|_0$
  - Wall-normal integration of streamwise momentum equation
  - Top-hat filter normal to the wall, $0 < z < h$: $h = \Delta z > h_0$
  - Local inner-scaling reduction for unsteady term

$$\frac{\partial \eta_0}{\partial t} = \frac{2\eta_0}{\widetilde{u}|_h}\left[-\frac{\partial \widetilde{uu}|_h}{\partial x} - \frac{\partial \widetilde{uv}|_h}{\partial y} - \frac{\partial \widetilde{uv}|_h}{\partial y} - \left.\frac{\partial \widetilde{p}}{\partial x}\right|_h + \frac{\nu}{h}\left(\left.\frac{\partial \widetilde{u}}{\partial z}\right|_h - \eta_0\right)\right]$$

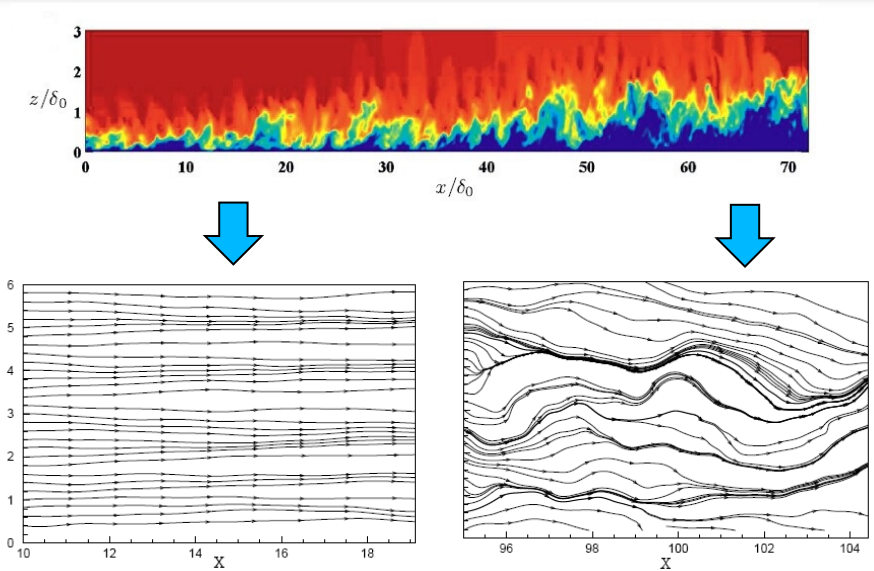
- Attached-eddy ansatz in overlap region (Townsend, 1976)
  - Hierarchy of streamwise ``attached'' SGS vortices whose size scales with distance from wall
  - Extended stretched-vortex SGS model with attached-eddy assumption
  - SGS model gives log relationship for slip-velocity at lifted wall position $z = h_0$
  - ``Karman constant'' calculated dynamically

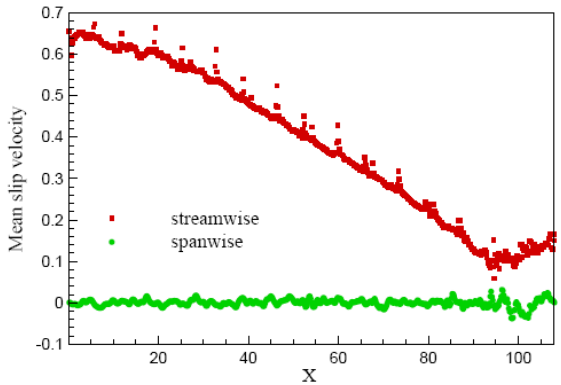
$$\widetilde{u}|_{h_0} = u_\tau\left(\frac{1}{\mathcal{K}_1}\log\left(\frac{h_0 u_\tau/\nu}{h_\nu^+}\right) + h_\nu^+\right) \qquad \mathcal{K}_1 = \frac{\gamma_{\mathrm{II}} K^{1/2}}{2\left(-T_{xz}|_{e_{\widetilde{S}}}\right)^{1/2}}$$

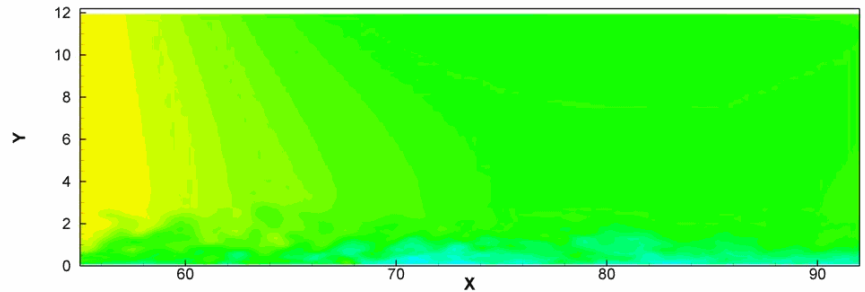
- ***Chung & Pullin , JFM (2009)***

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Wall model: 2D version







1D is not sufficient.
We need 2D wall model

W. Cheng, D. I. Pullin, R. Samtaney. Large-eddy simulation of separation and reattachment of a turbulent boundary layer, *Journal of Fluid Mechanics*, 2015.

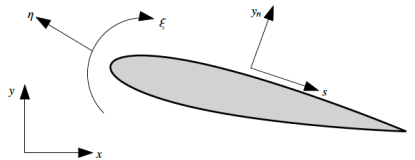
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Wall model: ODE for Wall Shear Stress and Dirichlet BC for Velocity

- Filtering (wall parallel and top hat in wall normal direction

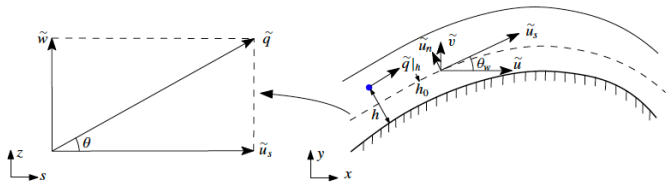
$$\tilde{\phi}(\xi,\eta,\zeta,t)=\iint \phi(\xi,\eta,\zeta,t)G(\xi-\xi',\Delta_f)G(\zeta-\zeta',\Delta_f)\,\mathrm{d}\xi'\,\mathrm{d}\zeta',$$

$$\langle\phi\rangle=\frac{1}{h}\int_0^h \tilde{\phi}(\xi,\eta,\zeta,t)\,\mathrm{d}\eta,$$



- Inner scaling combined with wall normal integration filter

$$\tilde{q}(\xi,\eta,\zeta,t)=u_\tau(\xi,\zeta,t)F(y_n^+),\qquad y_n^+=u_\tau y_n/\nu,$$



- ODE for wall shear stress
  - Terms C_1 and C_2 depend on resolved fields at first mesh point above virtual wall

$$\frac{\partial\eta_0}{\partial t}=C_1\eta_0-C_2\eta_0^2,\qquad \frac{\partial\langle q\rangle}{\partial t}=\frac{\tilde{q}|_h}{2\eta_0}\frac{\partial\eta_0}{\partial t},\qquad \eta_0\equiv\left.\frac{\partial\tilde{q}}{\partial y_n}\right|_w.$$

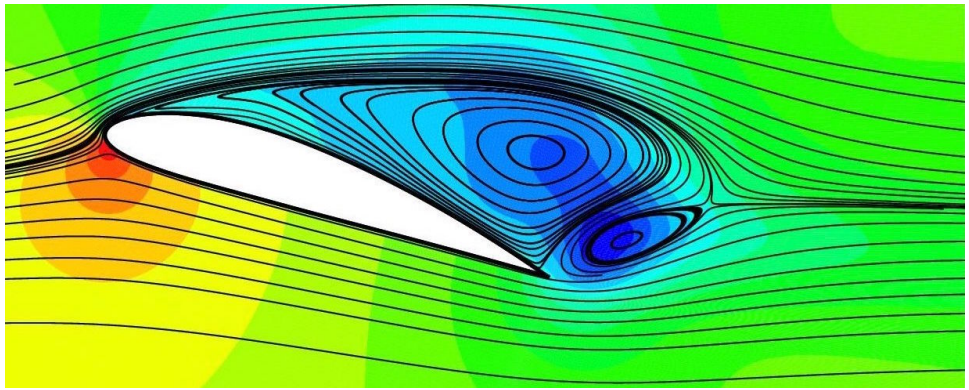
- Dirichlet Wall BC
  - *Similar to Cheng et al. (JFM 2015)*
- *θ dependence can be taken into account*
  - *θ does not vary from first mesh point to the wall (similar to Cheng et al.)*

$$\tilde{q}|_{h_0}=\begin{cases}u_\tau\left(\frac{1}{\mathscr{K}_1}\log\left(\frac{h_0^+}{h_v^+}\right)+h_v^+\right), & h_0^+>h_v^+, \quad \tau_{w,s}>0,\\ u_\tau h_0^+, & h_0^+<h_v^+,\\ u_\tau h_0^+, & \tau_{w,s}\leqslant 0,\end{cases}$$

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Application 1

Separated Flow Past Airfoils



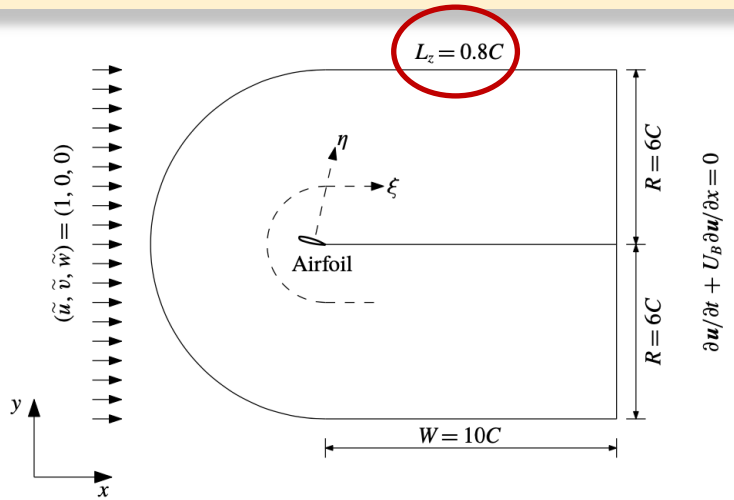
W. Gao, W. Zhang, W. Cheng, R. Samtaney. Wall-modelled large-eddy simulation of turbulent flow past airfoils, *Journal of Fluid Mechanics,* 2019, 873:174-210.

LES of Flow Past an Airfoil: Background

Author	Airfoil	Method	Re_c	AoA (deg.)	L_z/C	Results
Dahlstrom & Davidson (2001)	A-airfoil	WRLES	2.1 M	13.3	0.03	C_f, C_p, $\bar{u}$, $\overline{u'v'}$
Mary & Sagaut (2002)	A-airfoil	WRLES	2.1 M	13.3	0.012	C_f, C_p, $\bar{u}$, $\overline{u'v'}$
Morgan & Visbal (2003)	A-airfoil	WRLES	2.1 M	13.3	0.12	C_f, C_p, $\bar{u}$, $\overline{u'v'}$
Kawai & Asada (2013)	A-airfoil	WMLES	2.1 M	13.3	0.017	C_f, C_p, $\bar{u}$, $\overline{u'v'}$
Asada & Kawai (2018)	A-airfoil	WRLES	2.1 M	13.3	0.049	C_f, C_p, $\bar{u}$, $\overline{u'v'}$
George & Lele (2014)	NACA0012	WMLES	1.5 M	6	0.14	C_p, $\bar{u}$, $\overline{u'v'}$
Asada *et al.* (2014)	NACA0015	WRLES	1.6 M	20.11	0.05	C_p, $\bar{u}$
Sato *et al.* (2016)	NACA0015	WRLES	1.6 M	8.13	0.05	C_L, C_D, C_p, $\bar{u}$
Schmidt, Franke & Thiele (2001)	NACA4412	WRLES	1.64 M	12	0.05	C_p, $\bar{u}$, $\overline{u'v'}$
Bose & Moin (2014)	NACA4412	WMLES	1.6 M	13.8	0.1	C_p, $\bar{u}$
Park & Moin (2014)	NACA4412	WMLES	1.64 M	12	0.72	C_p, $\bar{u}$

TABLE 1. Summary of LES performed in flow past an airfoil at high Re_c. Here suffix 'M' refers to million; $\bar{u}$ denotes the velocity, $\overline{u'v'}$ refers to the Reynolds stress tensor components, C_p is the pressure coefficient, C_f is the skin-friction coefficient and L_z/C is the ratio of the spanwise domain size to chord length.

Numerical Setup



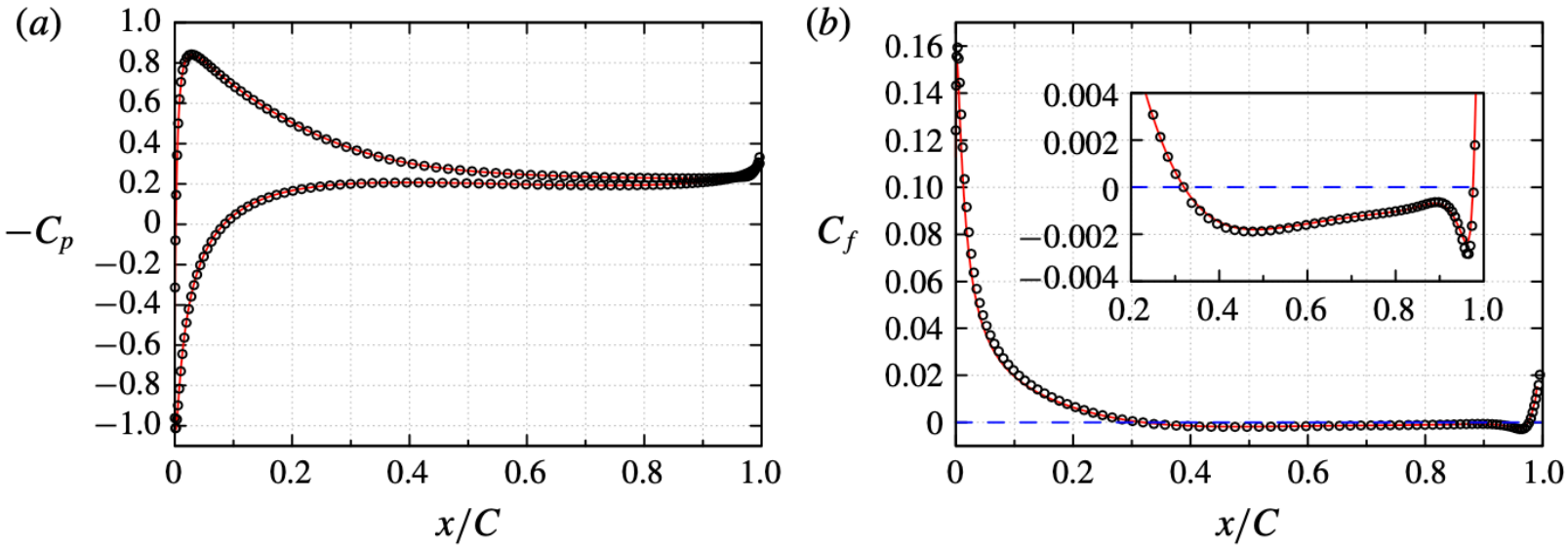
All model "parameters" held fixed for all cases.

No "tweaking"

Airfoil	Method	Re_c	AoA (deg.)	$N_\xi \times N_\eta \times N_z$	$\Delta\xi^+_{max}$	$\Delta\eta^+_{max}$	Δz^+_{max}
NACA0012	DNS	10^4	5	$2048 \times 256 \times 256$	7.4	0.8	8.8
NACA0012	WMLES	10^4	5	$768 \times 96 \times 64$	19.7	14.2	38.4
NACA0018	WMLES	10^5	5	$1600 \times 128 \times 128$	54.9	15.8	65.8
A-Airfoil	WMLES	2.1×10^6	13.3	$3200 \times 256 \times 256$	80.1	16.4	85.4

TABLE 2. Summary of the performed numerical cases.

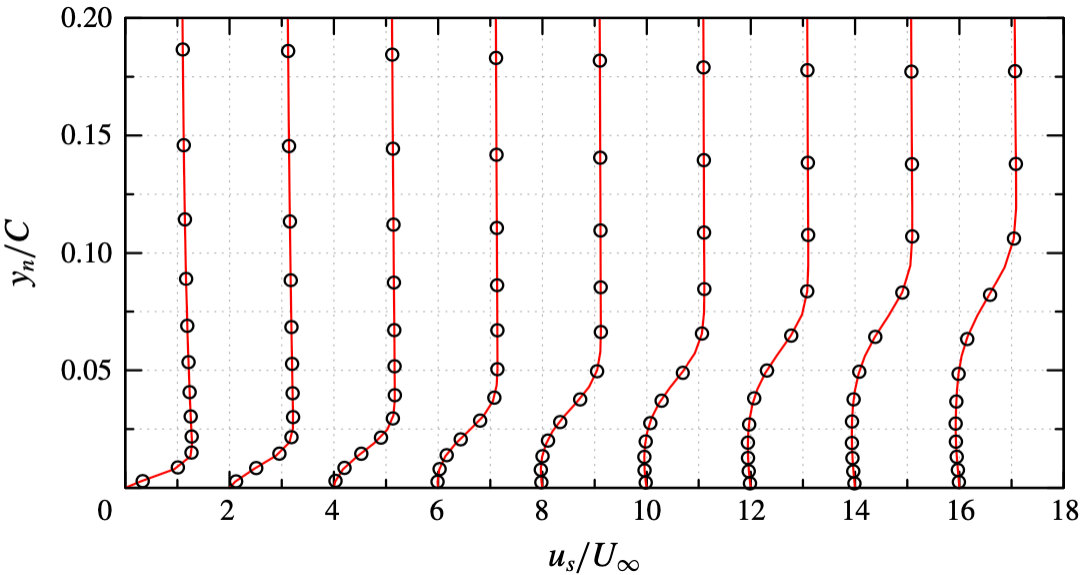
NACA0012, Re_c=10^4: C_p and C_f



Circles: WMLES; Lines: DNS

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NACA0012, Re_c=10^4: u_s

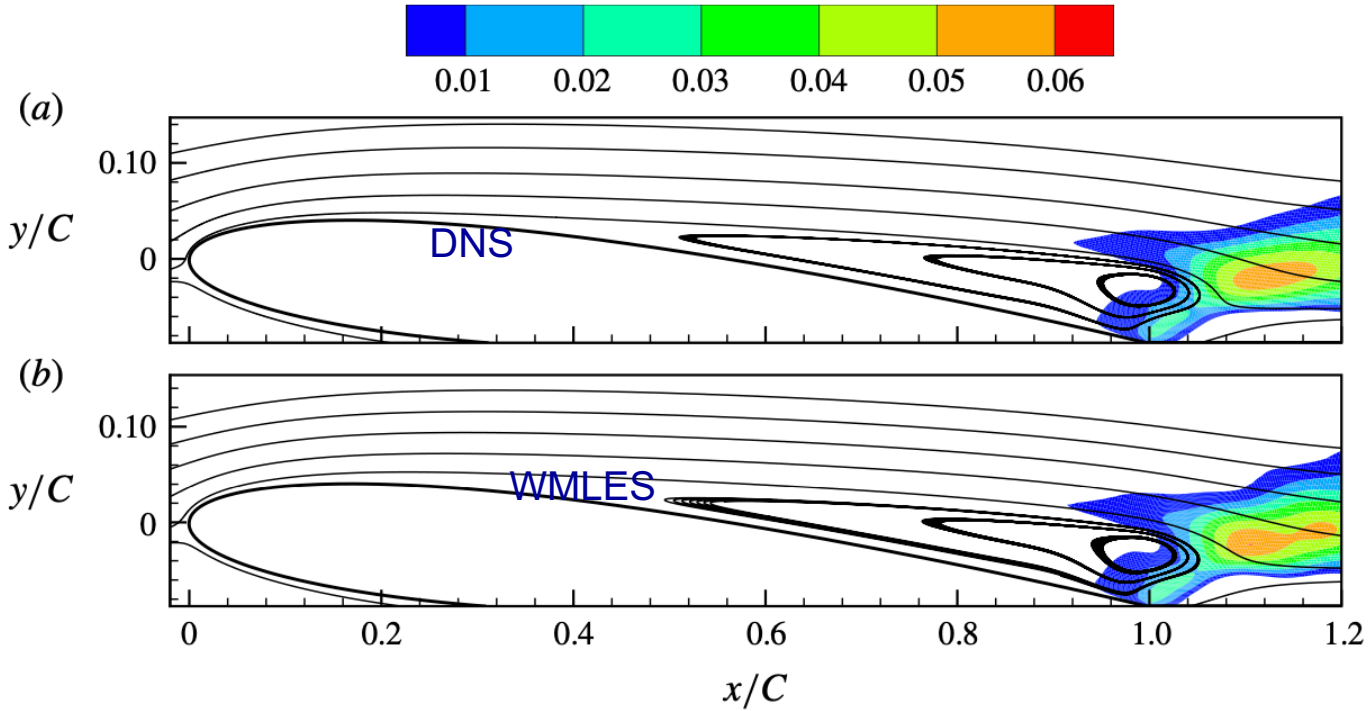


x/C=[0.1,0.9] with equal distance 0.1

Circles: DNS; Lines: WMLES

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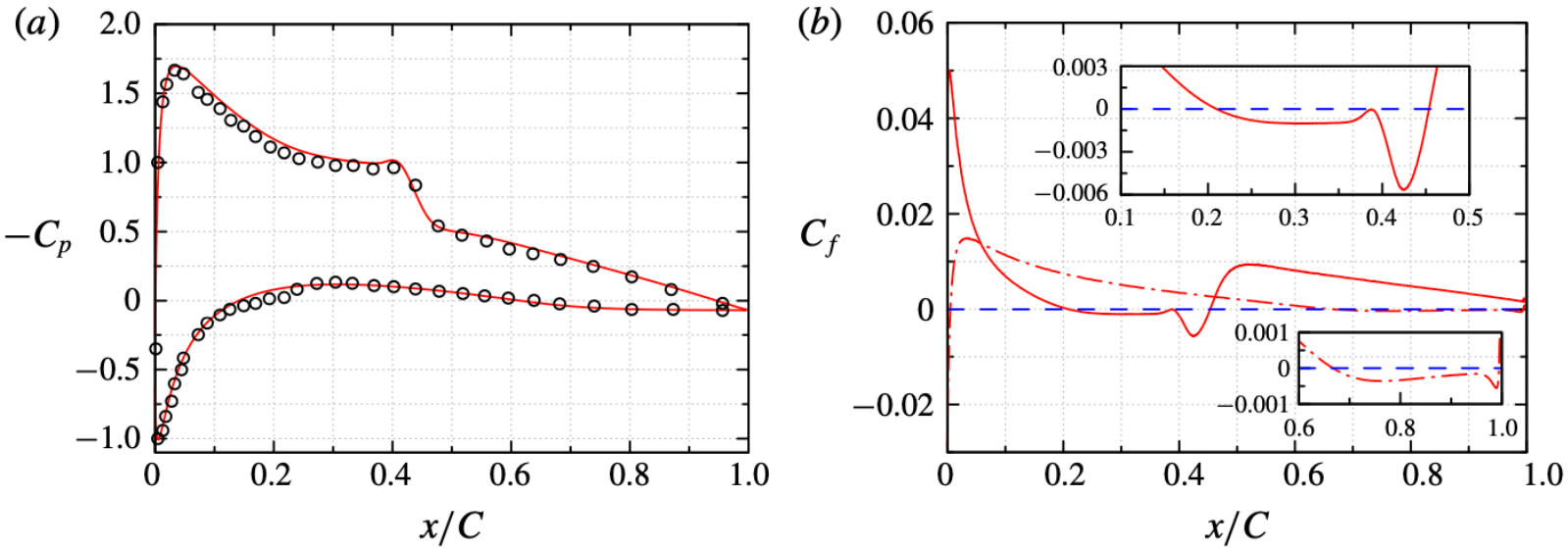
NACA0012, Re_c=10^4: $-\overline{u'v'}$



$$-\overline{u'v'}/U_\infty^2 = [-0.001, 0.06]$$

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NACA0018, Re_c=10^5: C_p and C_f



Circles: experimental data from Kirk & Yarusevych (2017)

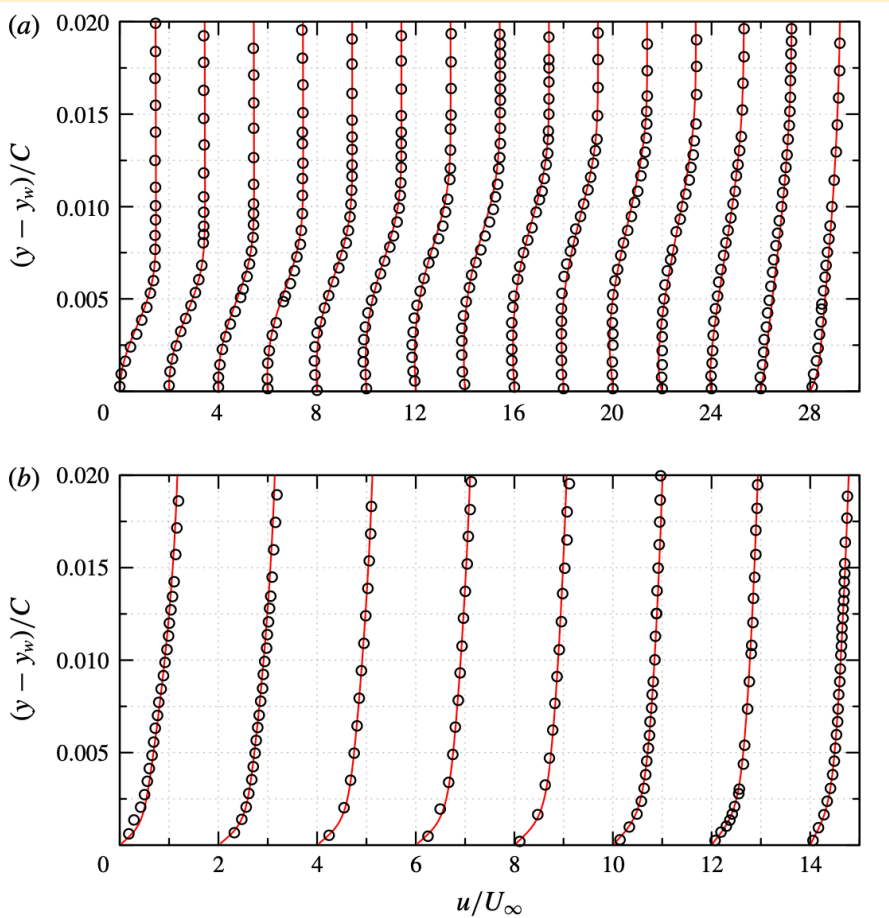
$$x_s/C = 0.24 \pm 0.02, x_r/C = 0.52 \pm 0.02$$

$$x_s/C = 0.21, x_r/C = 0.45$$

Red solid lines: WMLES

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NACA0018, $Re_c=10^5$: u



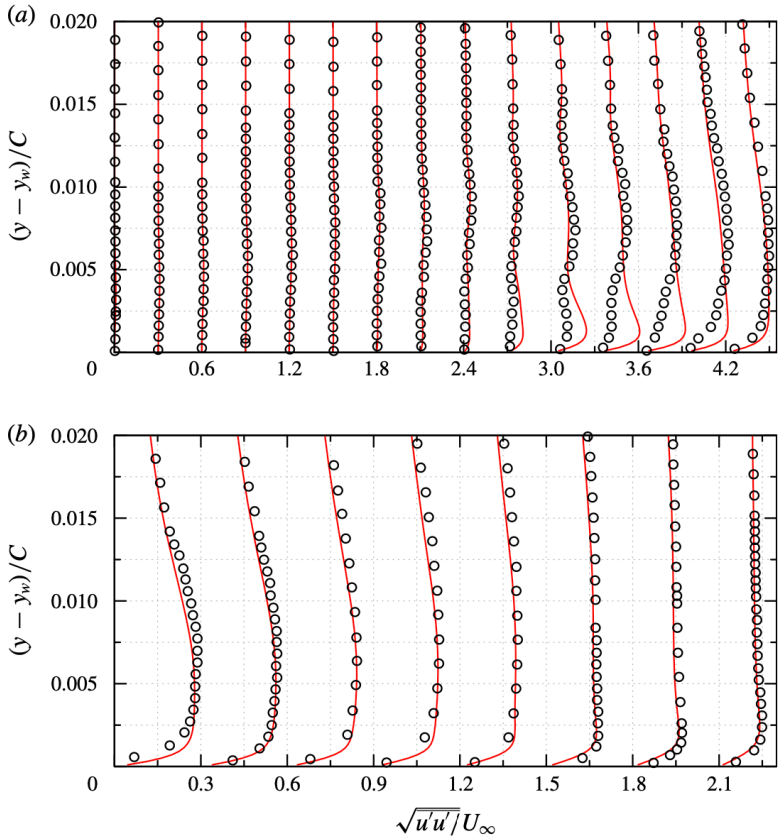
x/C=[0.2,0.48] with

equal distance 0.02

x/C=0.50, 0.52, 0.54,
0.56, 0.60, 0.66,
0.73, 0.87

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NACA0018, Re_c=10^5: $\sqrt{\overline{u'u'}}/U_\infty$

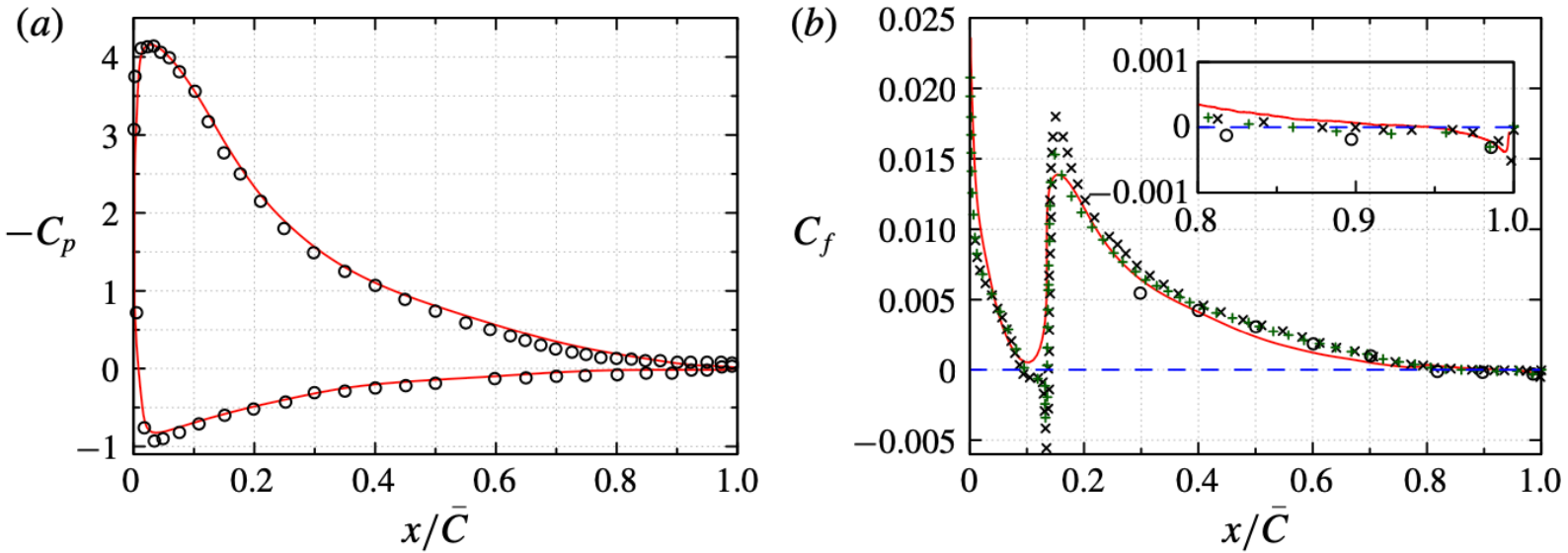


x/C=[0.2,0.48] with

equal distance 0.02

x/C=0.50, 0.52, 0.54, 0.56, 0.60, 0.66, 0.73, 0.87

Aérospatiale A-airfoil, Re_c=2.1x10^6: C_p and C_f



Circles: experimental data from Gleyzes (1988), $x_s/C \approx 0.82$

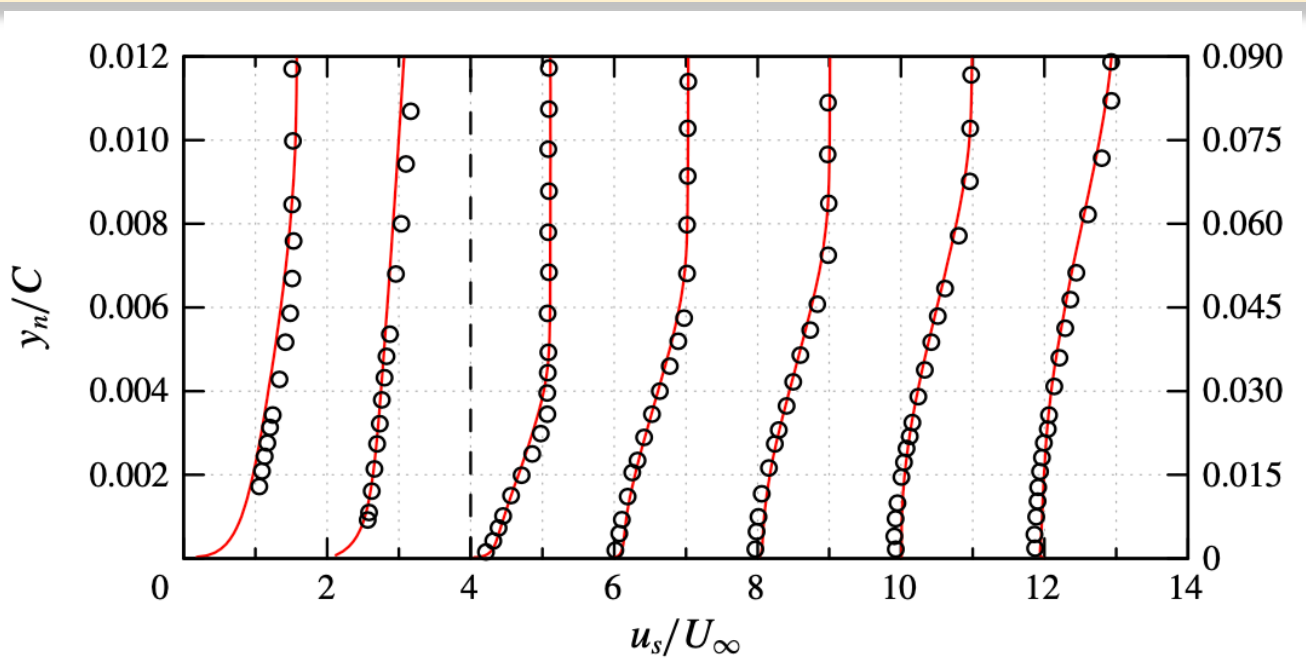
Cross: WRLES from Mary & Sagaut (2002)

Plus: WRLES from Asada & Kawai (2018)

Lines: WMLES, $x_s/C = 0.9$

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Aérospatiale A-airfoil, Re_c=2.1x10^6: u_s



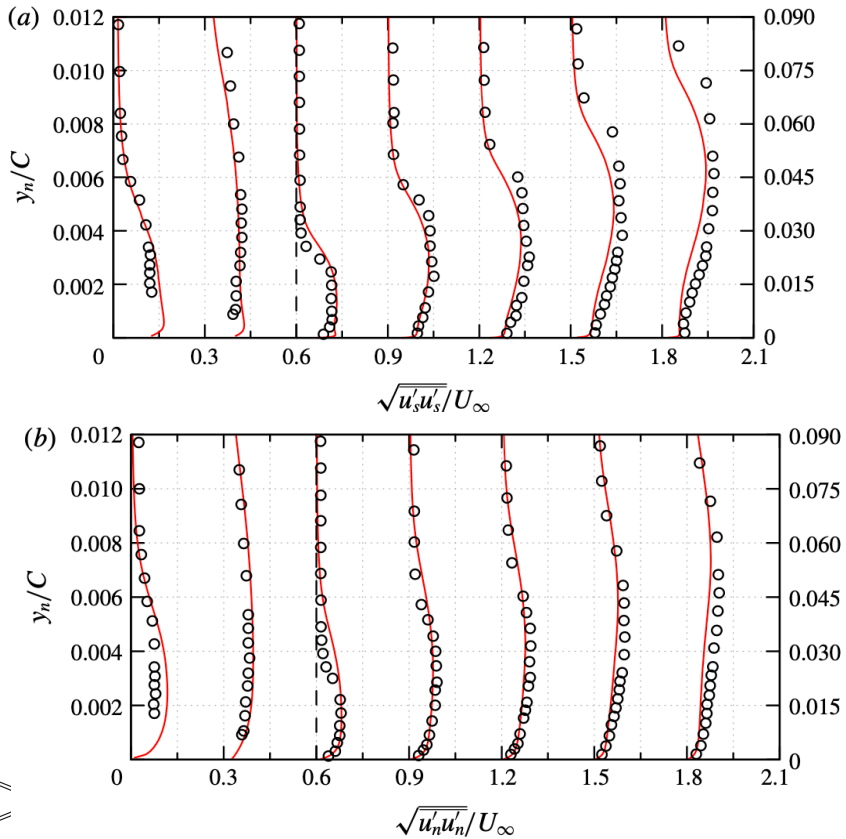
Circles: experimental data from Gleyzes (1988)

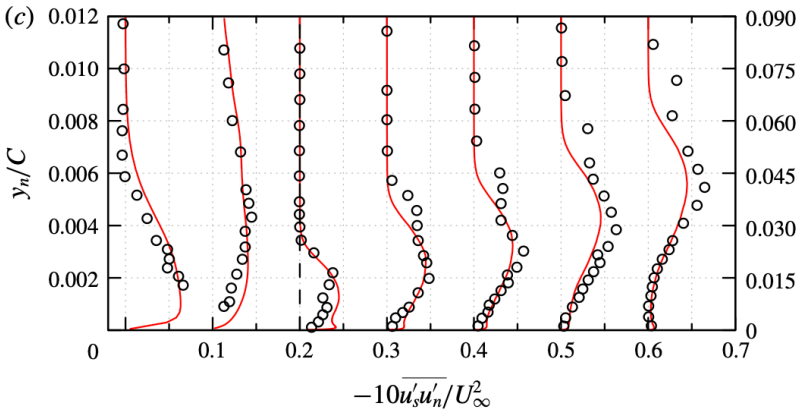
Lines: WMLES

x/C= *0.3, 0.5, 0.7, 0.825, 0.87, 0.93, 0.99.*

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Aérospatiale A-airfoil, Re_c=2.1x10^6: $\overline{u_i' u_j'}$





Anisotropy of the Flow: Lumley Triangle

Anisotropy tensor: $b_{ij} = \overline{u_i' u_j'} / \overline{u_k' u_k'} - \delta_{ij}/3$ characterized by two invariants (Lumley 1978, Choi & Lumley 2001):

$$II = -b_{ij} b_{ij}/2, \quad III = b_{ij} b_{jk} b_{ki}/3$$

Anisotropy invariant map (AIM): (ϕ, ψ)-Plane

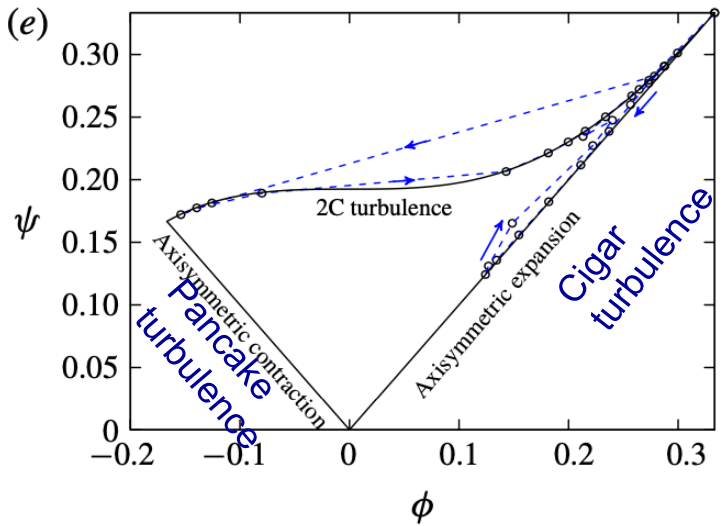
$$\phi = \left(\frac{III}{2}\right)^{1/3}, \quad \psi = \left(-\frac{II}{3}\right)^{1/2}$$

(0, 0): 3D isotropic turbulence

(-1/6,1/6): two-component (2C) isotropic turbulence

(1/3, 1/3): one-component turbulence

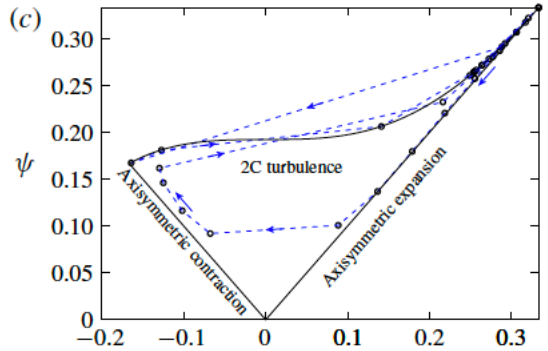
Realizability condition: all states must lie within Lumley Triangle

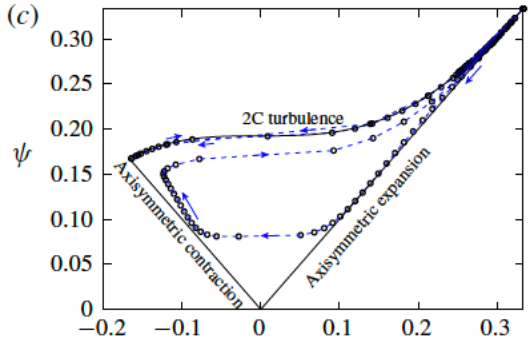


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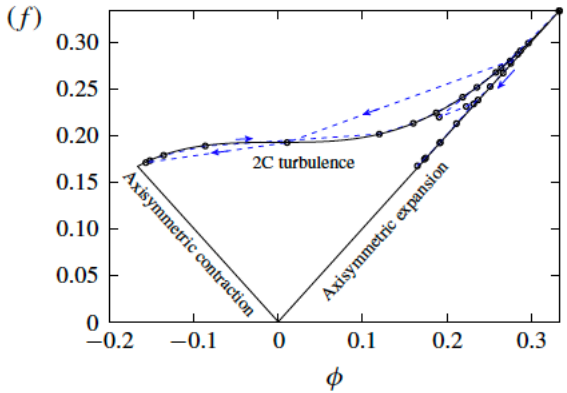
Anisotropy of the Flow: NACA0012, $Re_c=10^4$

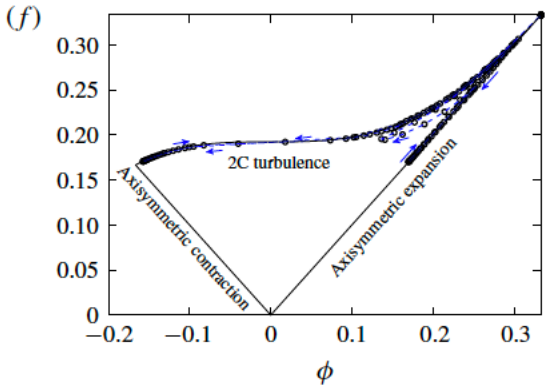
$x/C = 0.92$





$x/C = 0.98$



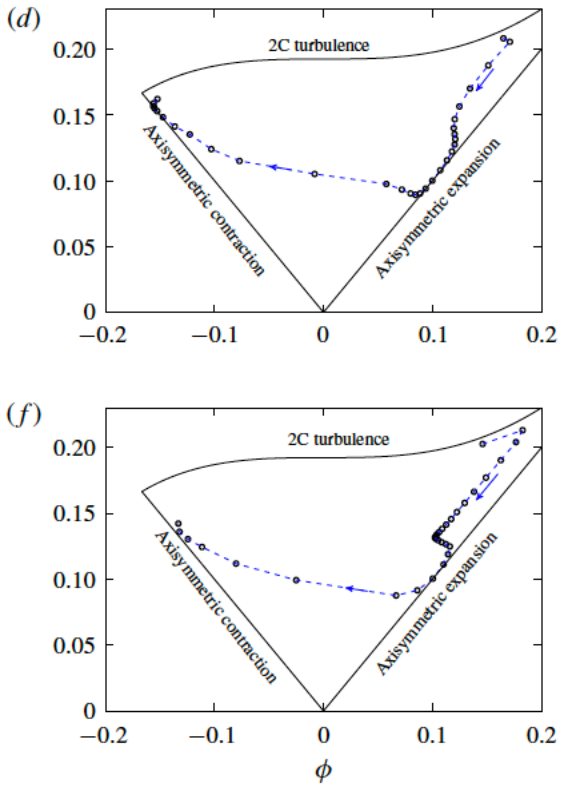


WMLES

DNS

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Anisotropy of the Flow: NACA0018, $Re_c=10^5$

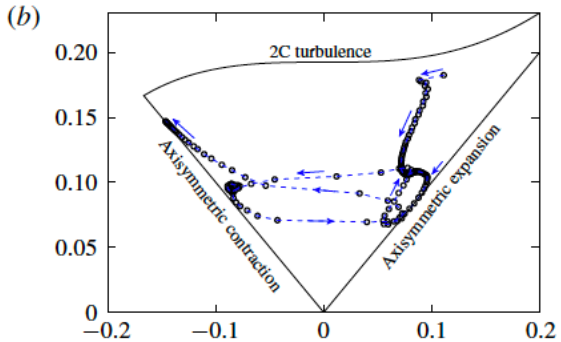


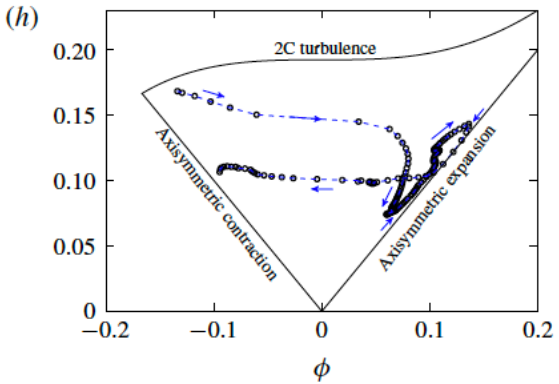
$x/C = 0.65$

$x/C = 0.95$

Anisotropy of the Flow: A-airfoil, Re_c=2.1x10^6

$r/C = 0.55$

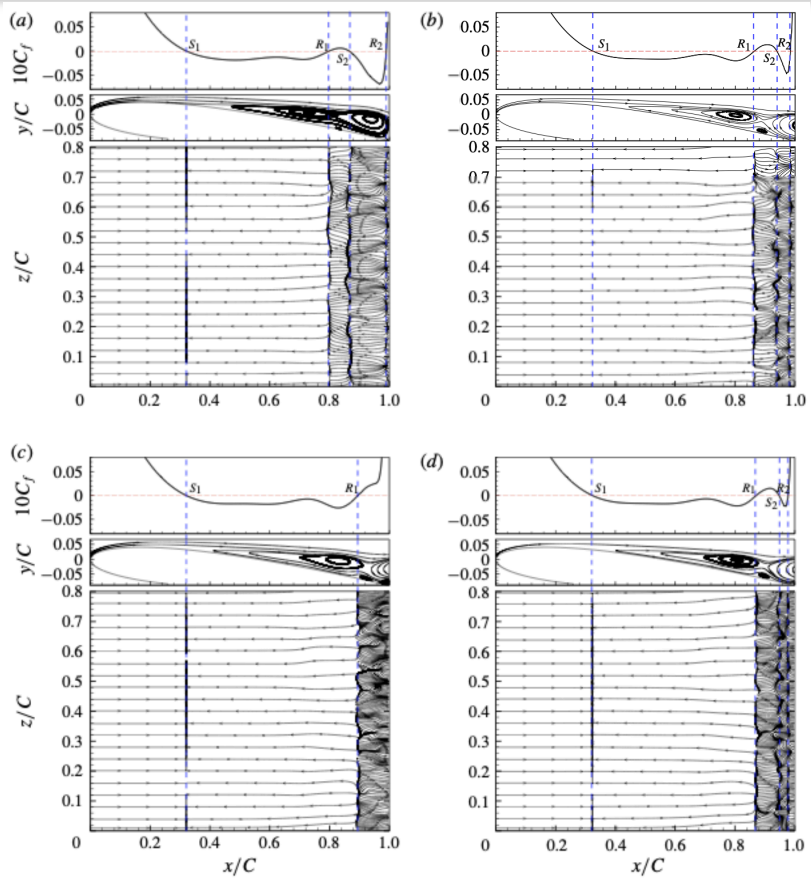




$x/C = 0.96$

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Unsteady Flow Separation and Reattachment



NACA0012

$Re_c=10^4$

$tU_\infty/C =$

(a) 80.21

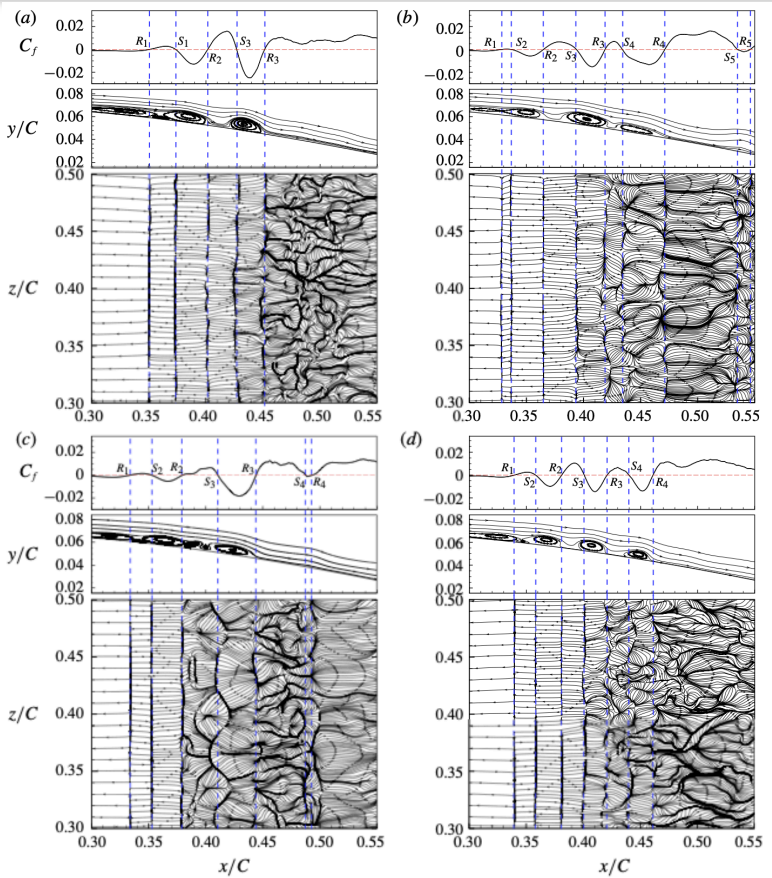
(b) 82.16

(c) 83.72

(d) 85.22

fps
Discovery through simulation
KAUST

Unsteady Flow Separation and Reattachment



NACA0018

$Re_c=10^5$

$tU_\infty/C =$

(a) 57.59

(b) 57.74

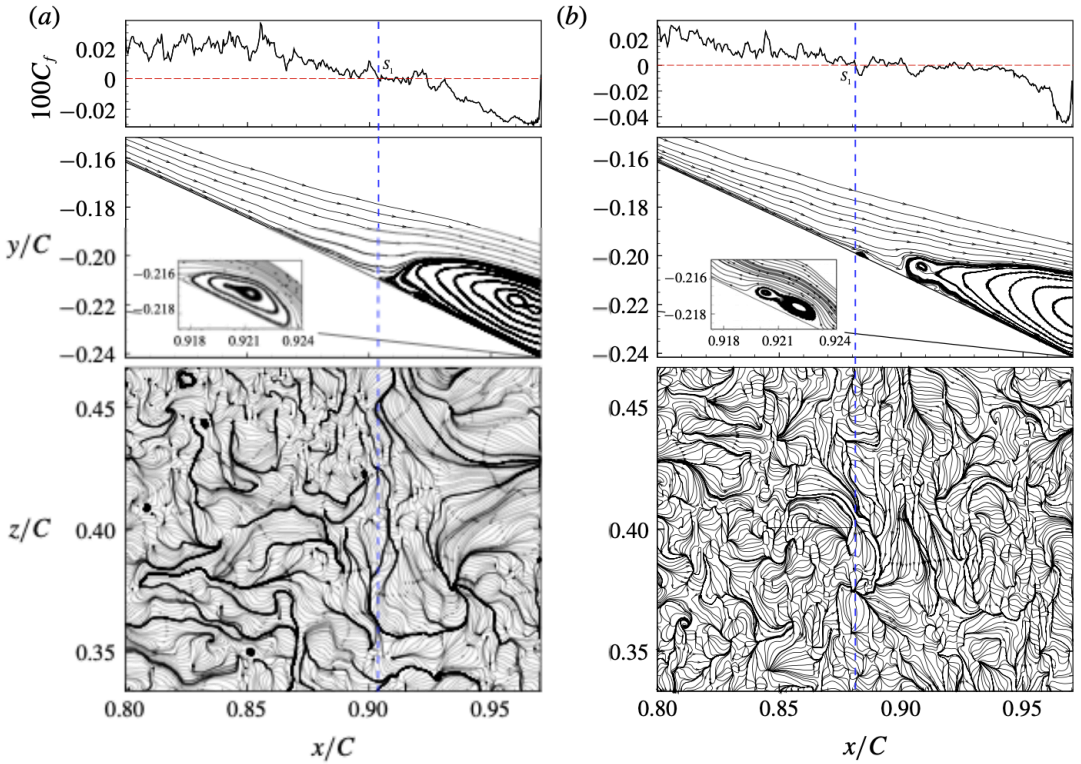
(c) 58.49

(d) 59.13

$x_s/C = 0.21, x_r/C = 0.45$

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Discovery through simulation
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Unsteady Flow Separation and Reattachment



A-airfoil

Re_c=2.1x10^6

$tU_\infty/C =$

(a) 15.92

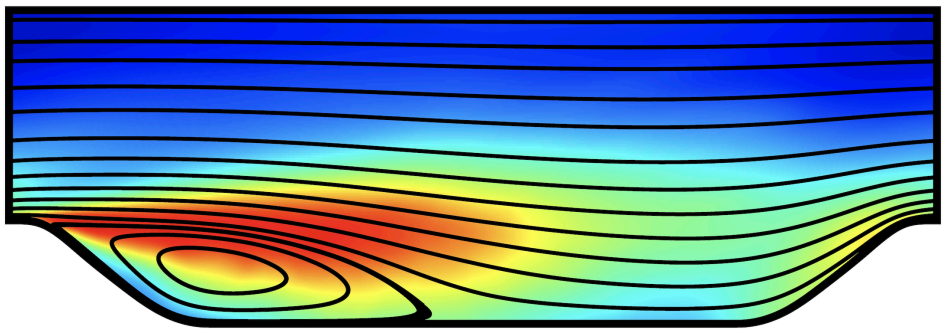
(b) 16.91

fps Discovery through simulation

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Application 2

Turbulent Flows in a Periodic Hill Channel

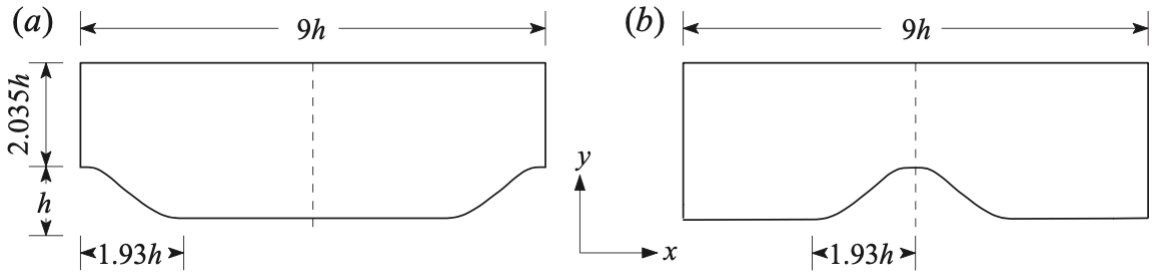


W. Gao, W. Cheng, R. Samtaney. Large-eddy simulations of turbulent flow in a channel with streamwise periodic constrictions, *Journal of Fluid Mechanics,* 2020, to appear.

Numerical Setup

All model "parameters" held fixed for all cases and same as the airfoil simulations

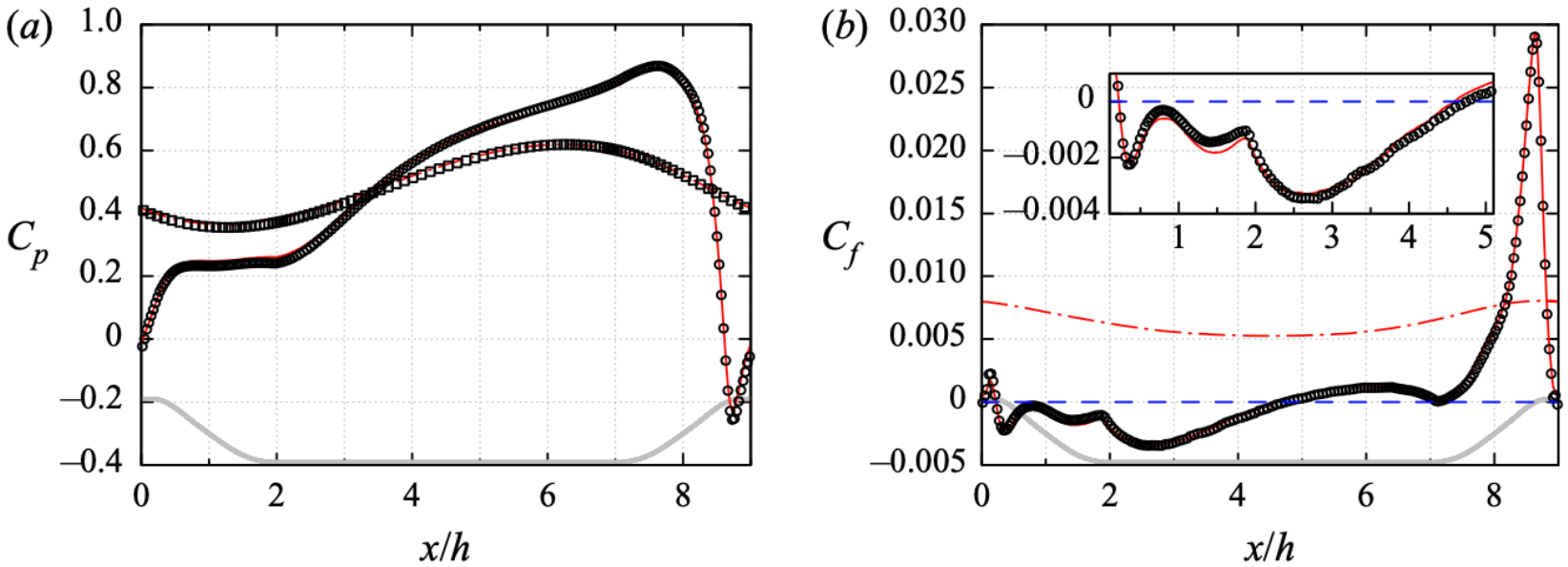
No "tweaking"



Case	Method	Re_h	$N_\xi \times N_\eta \times N_z$	$\Delta\eta^+_{(b,t)}$	$\Delta\xi^+/\Delta\eta^+_{(b,t)}$	$\Delta z^+/\Delta\eta^+_{(b,t)}$	t_a/t_r
M1	WMLES	10 595	$128 \times 64 \times 64$	(19.3, 13.4)	(5.1, 3.5)	(4.7, 3.5)	60
M2	WMLES	33 000	$384 \times 128 \times 128$	(16.1, 15.2)	(5.1, 2.6)	(7.0, 3.9)	46
R2	WRLES	33 000	$1280 \times 256 \times 256$	(0.97, 0.85)	(25.5, 14.1)	(58.6, 35.2)	30
M3	WMLES	10^5	$960 \times 256 \times 256$	(18.0, 15.9)	(4.1, 2.3)	(7.0, 4.4)	40

TABLE 1. Summary of the performed numerical cases. The '+' superscript indicates the expression of the mesh quantities using wall units and the subscripts 'b' and 't' denote the bottom and top walls, respectively. Time $t_r = 9h/U_b$ is the typical flow-through time and t_a is the total simulation time.

Re_h=10595: C_p and C_f



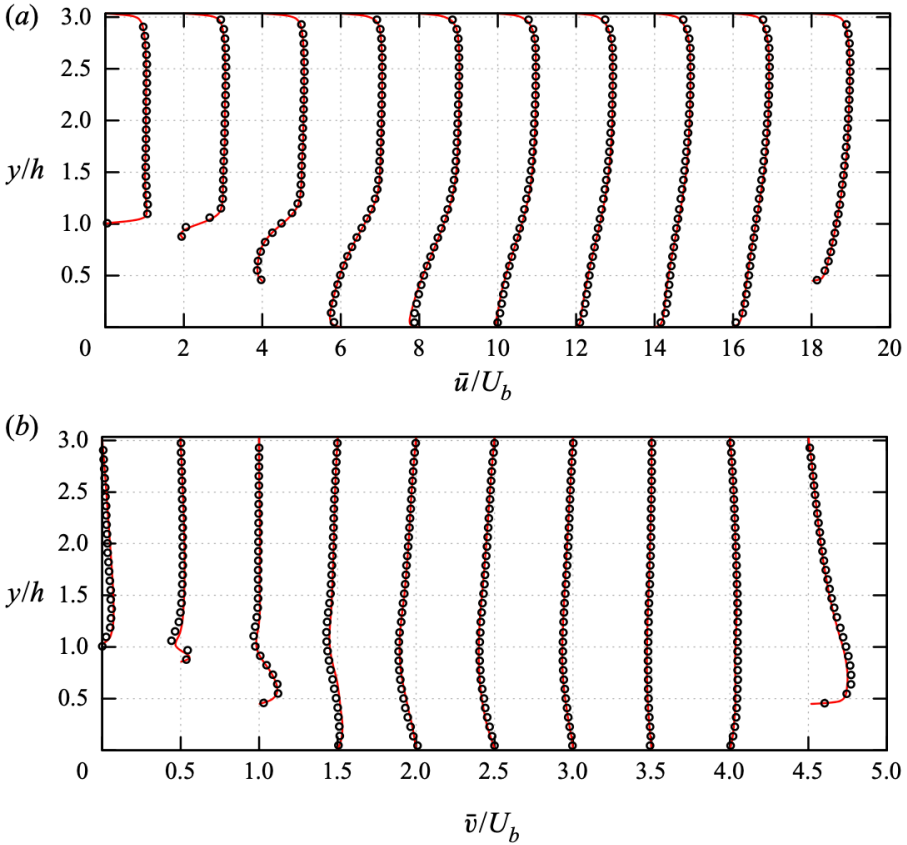
Circles: bottom wall; Square: top wall, WRLES by Fröhlich *et al*. (2005)

Lines: WMLES

x_s/h=0.22 x_r/h =4.6 (4.21 in expt by Rapp&Manhart, 2011)

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Re_h=10595: Mean Velocity Profiles



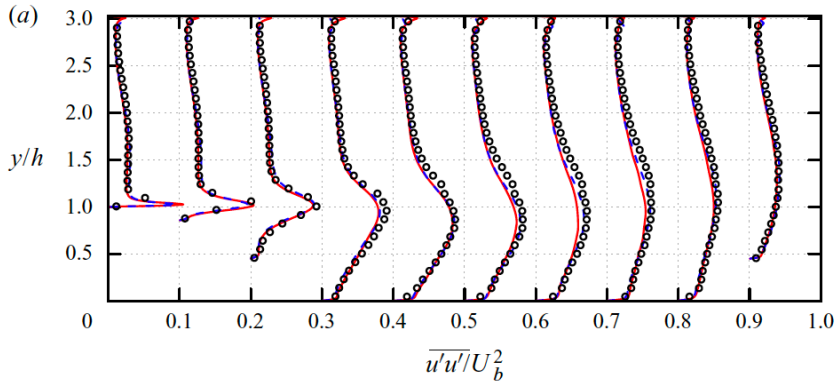
Circles: experiment by Rapp & Manhart (2011)

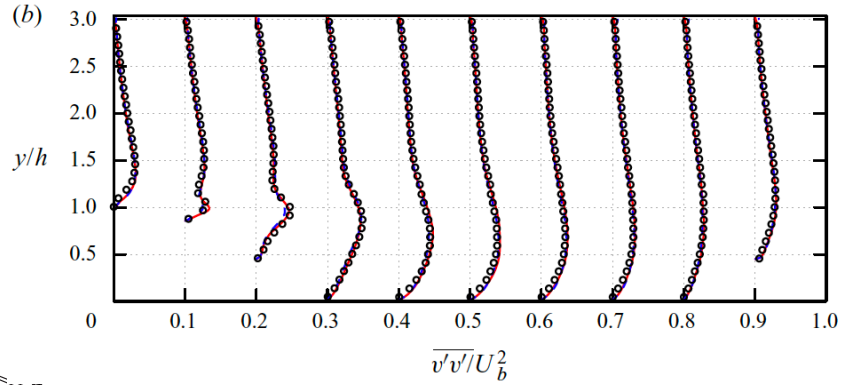
Lines: WMLES

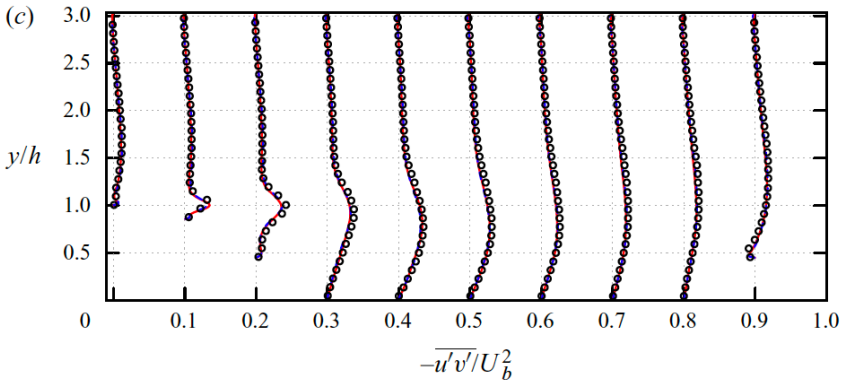
Monitor lines are at *x/h*= 0.05,0.5,1,2,3,4,5,6,7,8

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Re_h=10595: *Reynolds Stress*







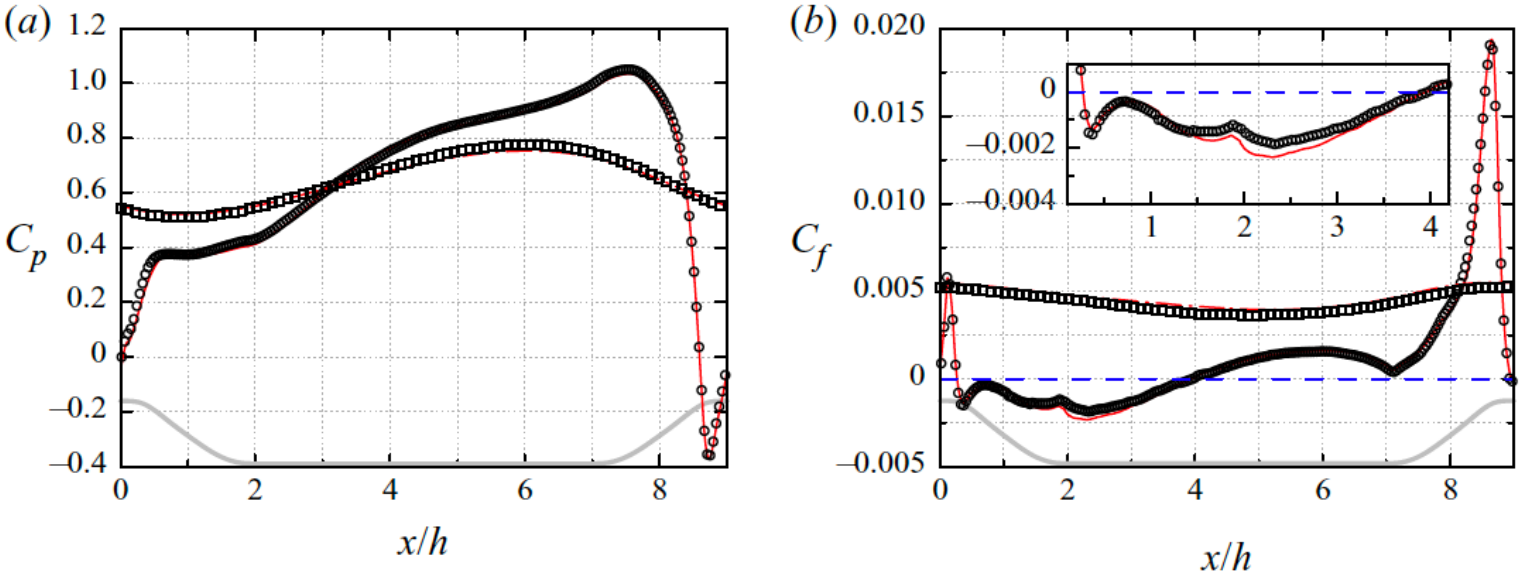
Circles: experiment by Rapp & Manhart (2011)

Dashed lines: WRLES by Fröhlich *et al*. (2005)

Solid red lines: WMLES

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Re_h=33000: C_p and C_f



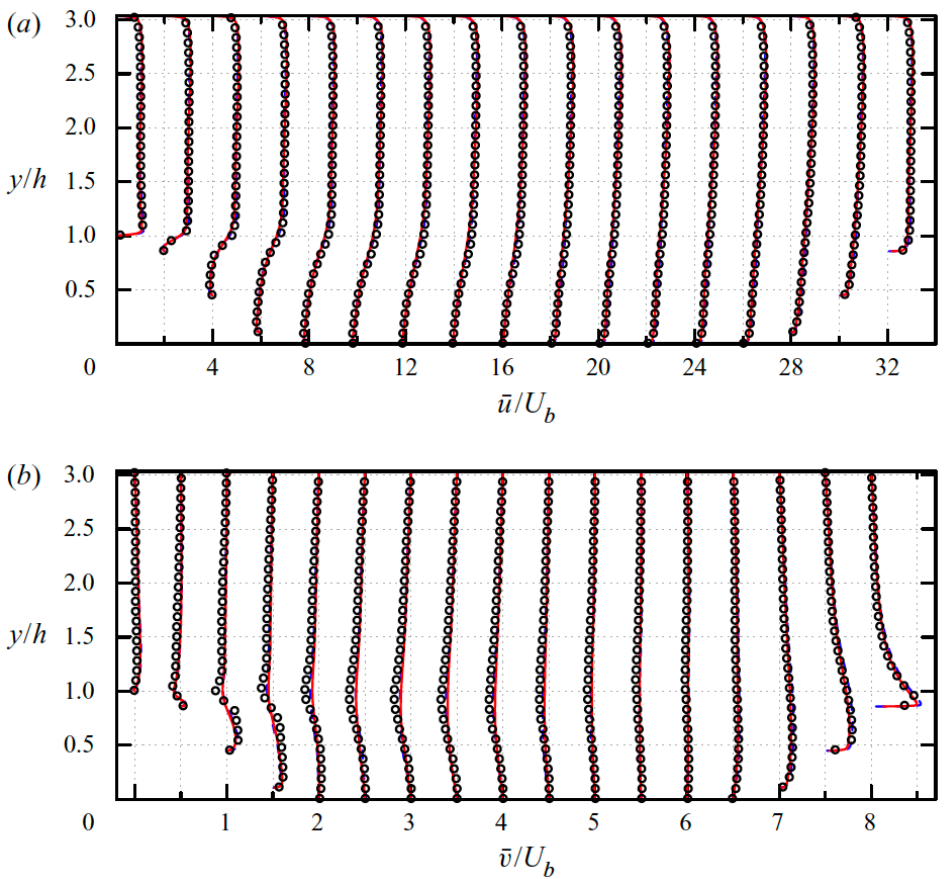
Circles: bottom wall; Square: top wall, WRLES

Lines: WMLES

x_s/h=0.27 x_r/h =3.94 (0.34±0.05, 3.80±0.05 expt by Kähler *et al*. 2016)

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Re_h=33000: *Mean Velocity Profiles*



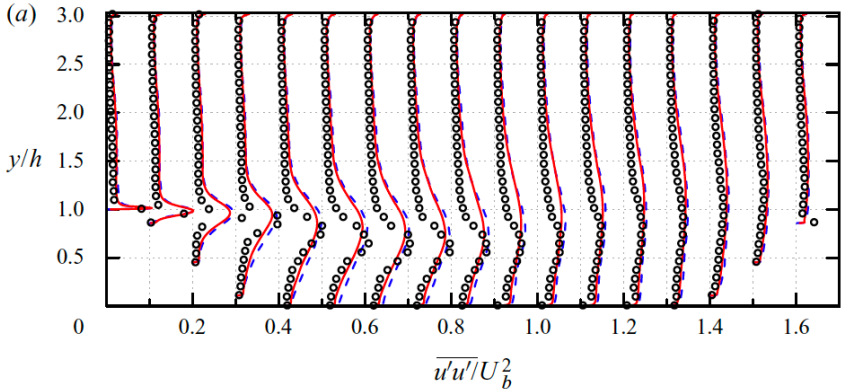
Circles: experiment by Kähler *et al*. (2016)

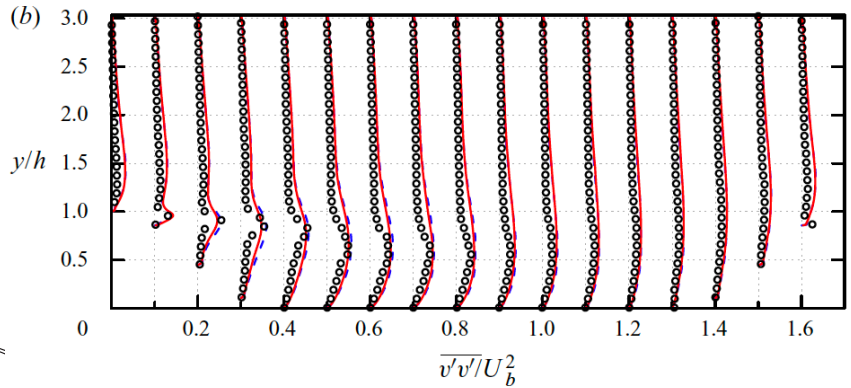
Lines: WMLES

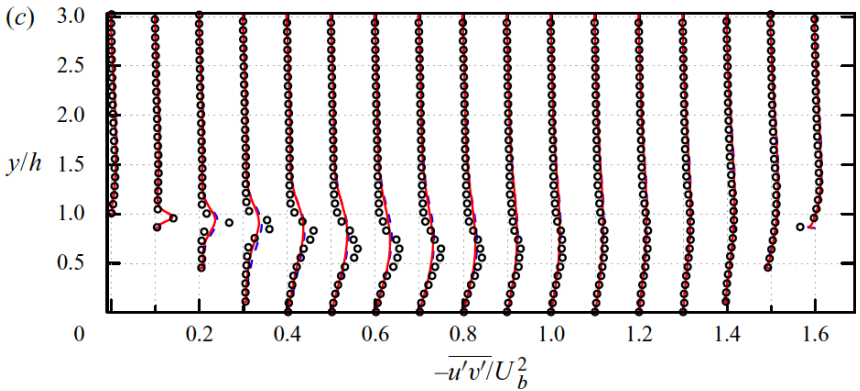
Monitor lines are at *x/h*= [0,9] with equal gap 0.5

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Re_h=33000: *Reynolds Stress*







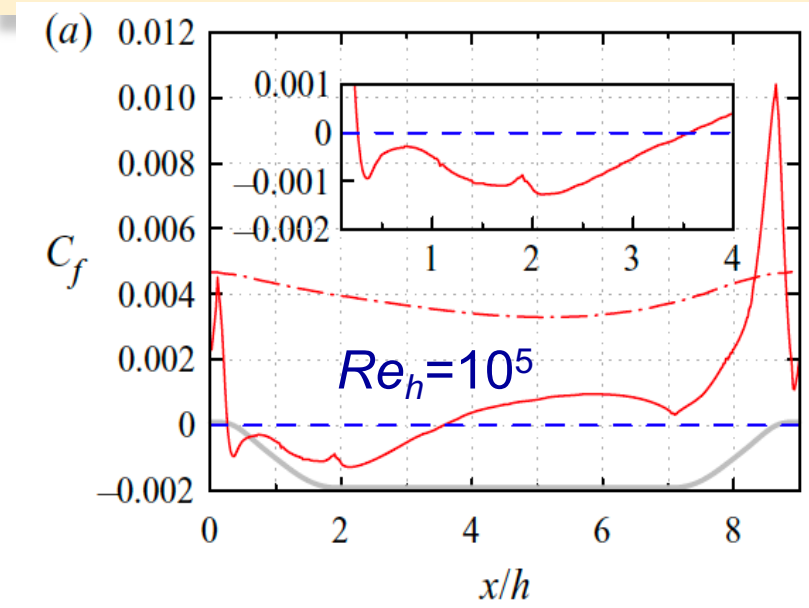
Circles: experiment by Kähler *et al*. (2016)

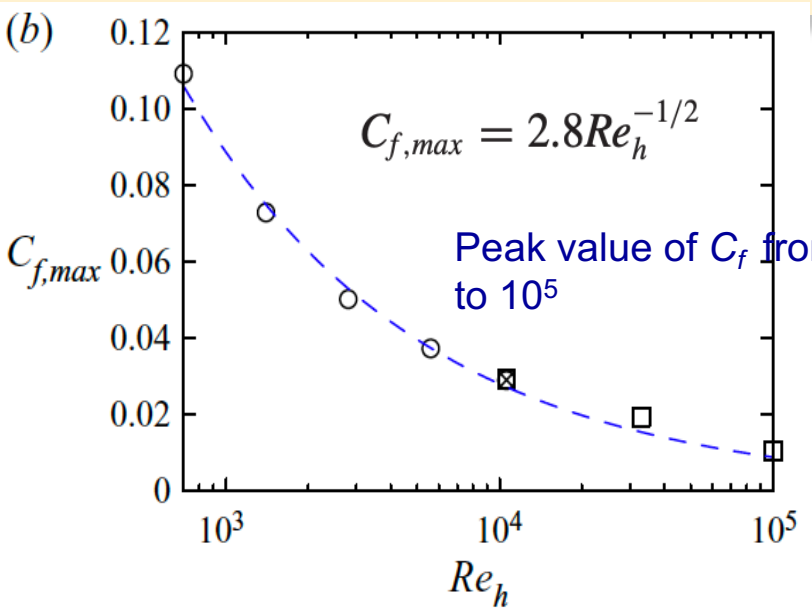
Dashed lines: WRLES

Solid red lines: WMLES

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Reynolds Number Effects and Peak Skin Friction





Peak value of C_f from 700 to 10^5

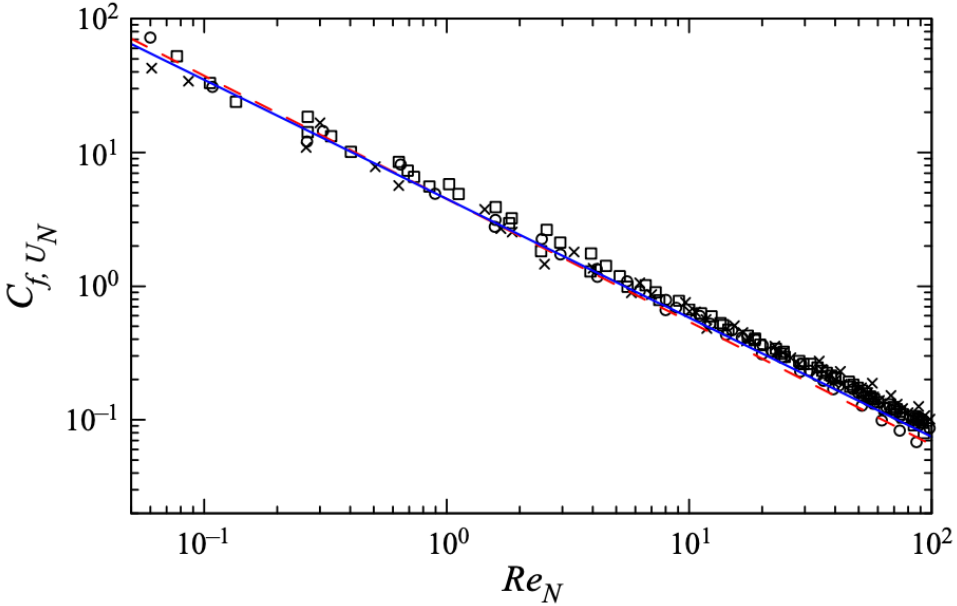
Circles: DNS/WRLES from Breuer *et al*. (2009)

Cross: WRLES from Fröhlich *et al*. (2005)

Squares: WMLES

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Skin Friction Inside the Separation Zone



$$C_{f,U_N} = 2\left|\tau_{w,s}\right| / \rho U_N^2$$

$$Re_N = U_N N / \nu$$

U_N: maximum back-flow velocity

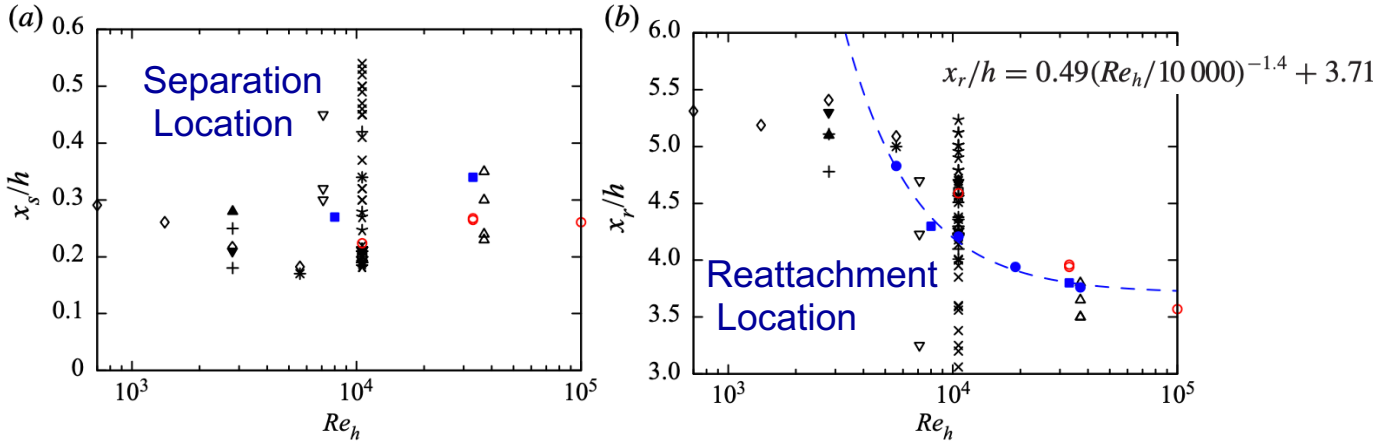
N: distance of U_N away from the wall

Circles: Re_h=10595; Squares: Re_h=33000; Cross: Re_h=10^5

Dashed line: $C_{f,U_N} \approx 4.5 Re_N^{-0.92}$ by Le, Moin & Kim (1997)

Solid line: $C_{f,U_N} \approx 4.5 Re_N^{-0.89}$

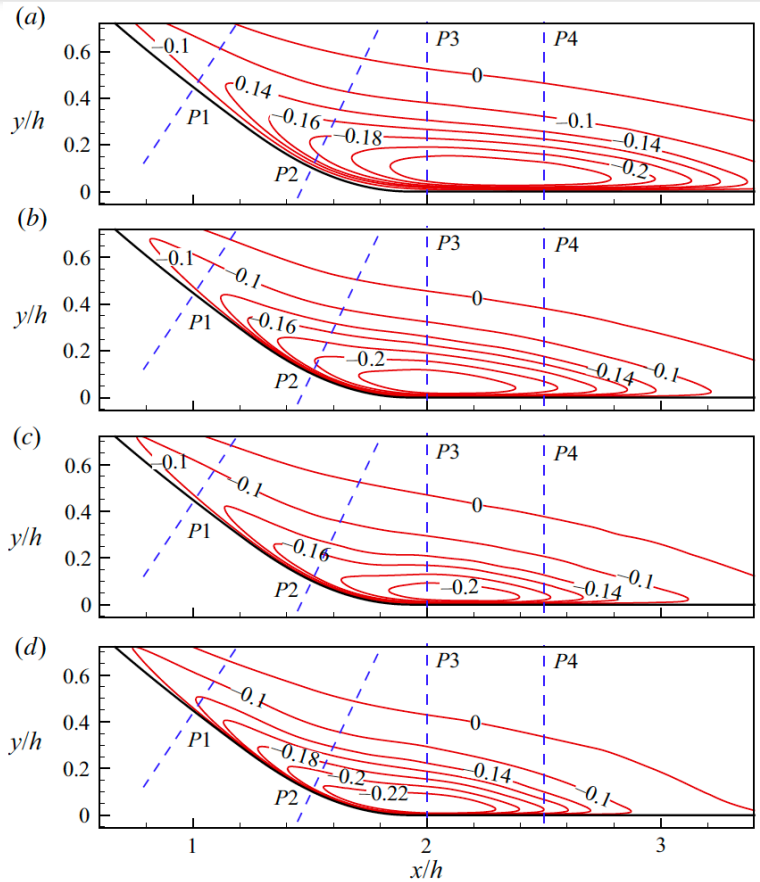
Reynolds Number Effects: Separation/Reattachment Locations and Bubble Centroid/Size



Case	Re_h	x_c/h	y_c/h	L_b/h	H_b/h
M1	10 595	2.01	0.53	4.37	0.91
Fröhlich *et al.* (2005)	10 595	2.07	0.53	4.40	0.93
M2	33 000	1.87	0.48	3.67	0.83
R2	33 000	1.88	0.49	3.69	0.82
Kähler *et al.* (2016)	33 000	2.05 ± 0.1	0.48 ± 0.02	3.46 ± 0.1	0.82
M3	10^5	1.82	0.46	3.31	0.80

TABLE 2. Comparison of bubble size with experimental and LES results: centre coordinate of the recirculation zone (x_c, y_c), length of the bubble (L_b) and height of the bubble (H_b).

Scaling of Streamwise Velocity Profiles in the Separation Zone



Re_h=10595

WMLES

Re_h=33000

WMLES

Re_h=33000

WRLES

Re_h=10^5

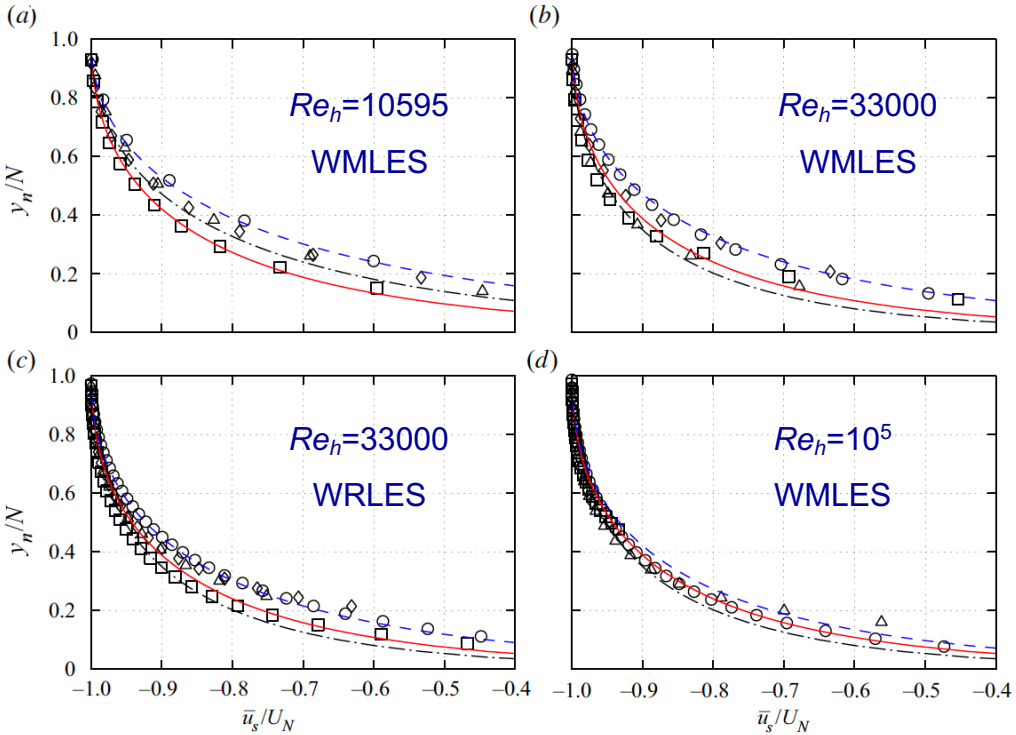
WMLES

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Scaling of Streamwise Velocity Profiles in the Separation Zone

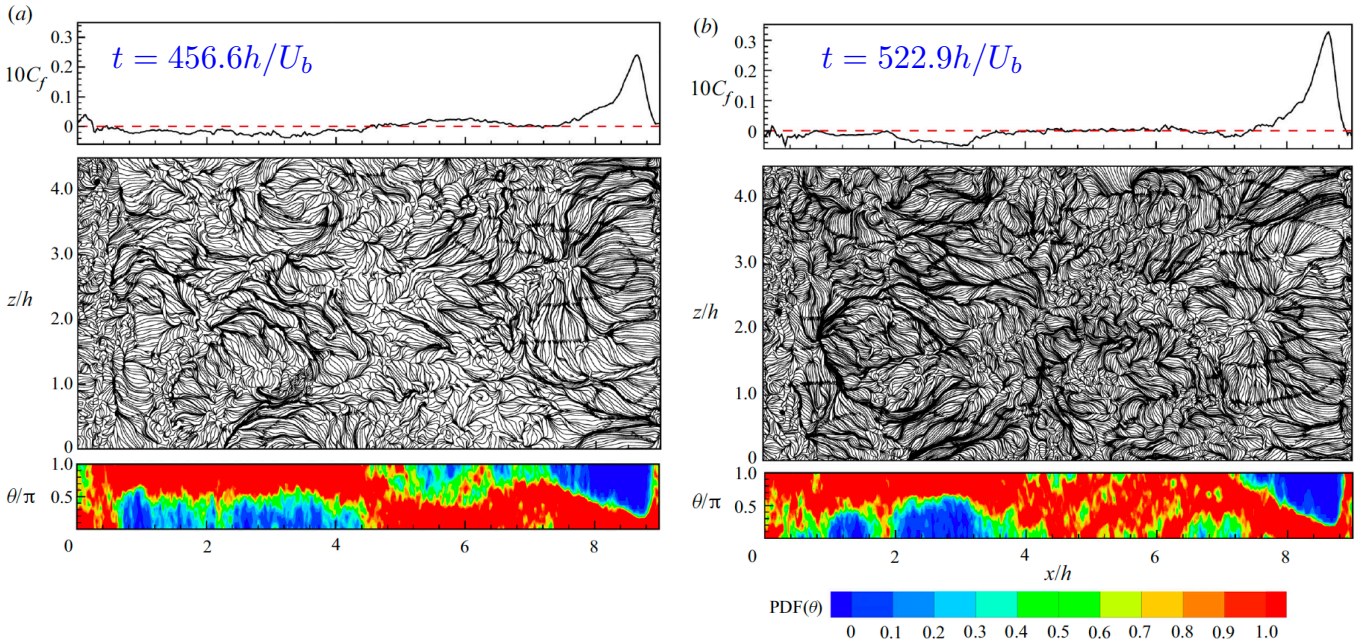
$$\frac{\bar{u}_s}{U_N} = A\left(\frac{y_n}{N} - \ln\left|\frac{y_n}{N}\right| - 1\right) - 1$$

A=0.3: solid lines, Simpson (1983)

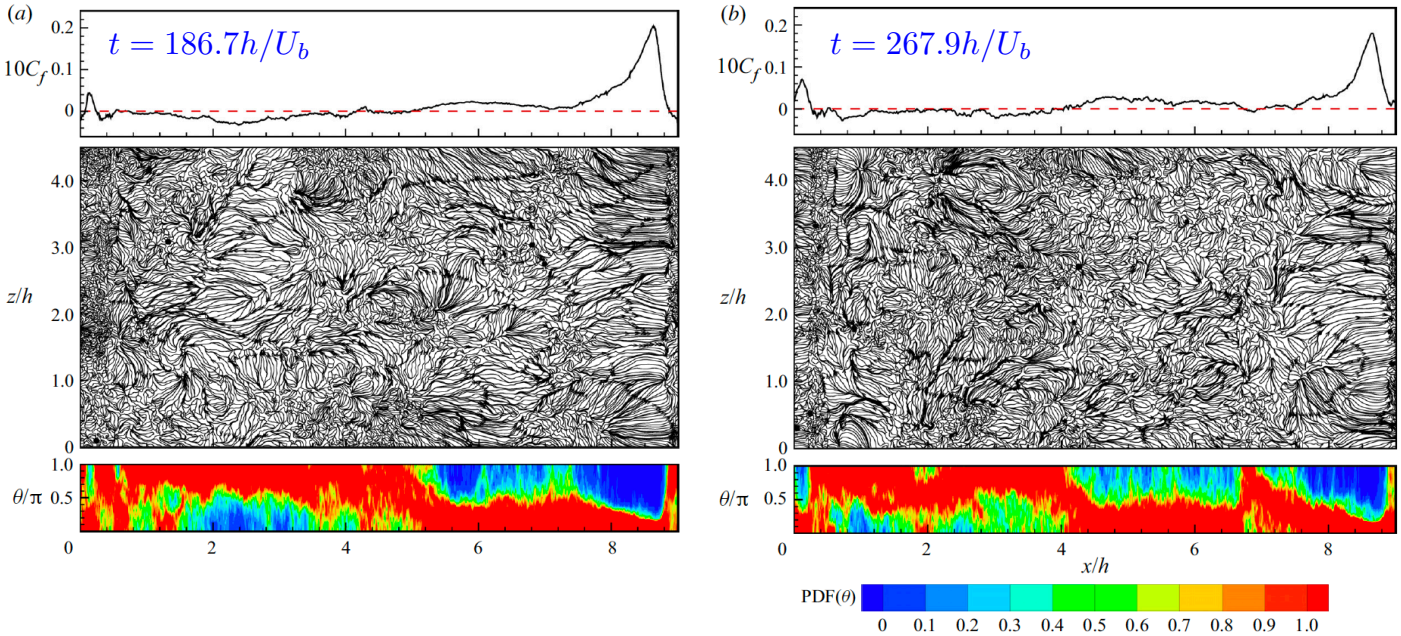


fps
Discovery through simulation
KAUST

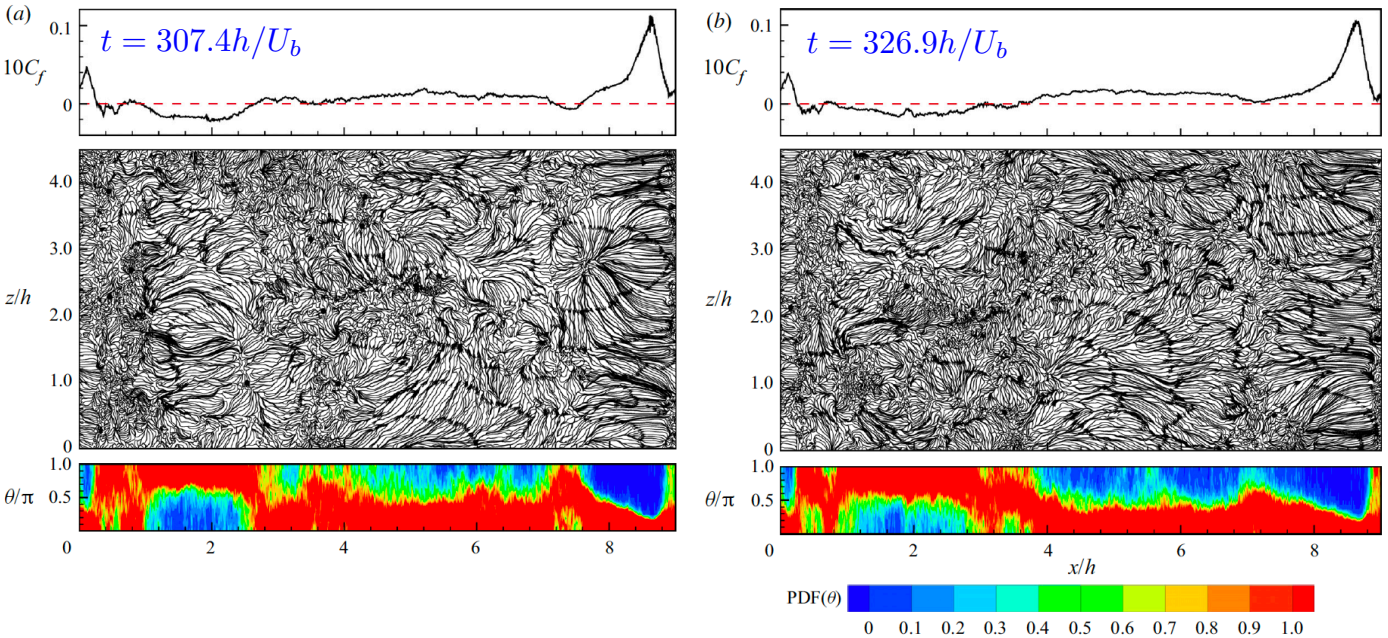
Instantaneous Skin Friction Field: Re_h=10595



Instantaneous Skin Friction Field: Re_h=33000



Instantaneous Skin Friction Field: Re_h=10^5



Conclusion and Future Work

- Wall-bounded turbulent flows may be computed with LES for the “outer” flow and a wall-model for the inner “universal” character
- For WMLES to be predictive STRONG VALIDATION is critical
- Stretched spiral SGS model employed for outer LES
- Wall model ➔ ODE for shear stress and Dirichlet BC for velocity at a virtual wall
- Two case studies presented: (a) Airfoils (external) and (b) Periodic hill (internal) with emphasis on validation of “sensitive” quantities such as skin friction and Reynolds stresses
- Future Directions: (a) extend compressible flows, (b) apply to more complex configurations (e.g. NASA CRM – collaboration with Prof. Parsani at KAUST)

Papers on DNS/LES

DNS

- W. Zhang, R. Samtaney, Assessment of spanwise domain size effects on the transitional flow past an airfoil, Computers and Fluids, 124:39-53, 2016
- W. Zhang, R. Samtaney, BiGlobal linear stability analysis of low-Re flow past an airfoil at high angle of attack, Physics of Fluids, 28(4): 044105, 2016.
- W. Zhang, R. Samtaney, A. Qamar, W. Cheng, W. Gao, Geometrical effects on the airfoil flow separation and transition. Computer and Fluids, 116, pp:60-73, 2015
- W. Zhang, R. Samtaney, A direct numerical simulation investigation of the synthetic jet frequency effects on separation control of low-Re flow past an airfoil. Physics of Fluids, 27(5): 055101, 2015

WMLES

- W. Cheng, D. I. Pullin, R. Samtaney, Large-eddy simulation of separation and reattachment of a flat plate turbulent boundary layer. Journal of Fluid Mechanics, 785, 78-108, 2015
- W. Cheng, R. Samtaney, Power-law versus log-law in wall-bounded turbulence: A large-eddy simulation perspective. Phys. Fluids, 26(1), art. no. 011703, 2014
- W. Cheng, R. Samtaney, A high-resolution code for large eddy simulation of incompressible turbulent boundary layer flows. Computers & Fluids, 92:82-92, 2013
- W. Gao, W. Zhang, W. Cheng and R. Samtaney, Wall-modeled large eddy simulation of turbulent flow past airfoils. Journal of Fluid Mechanics, vol. 873, pp: 174-210, 2019
- W. Gao, W. Cheng and R. Samtaney, Large-Eddy Simulations of Turbulent Flow in a Channel with Streamwise Periodic Constrictions. Journal of Fluid Mechanics, to appear, 2020

WRLES

- W.Cheng, D.I.Pullin, R.Samtaney, Large-eddy simulation of Taylor Couette flow at high Reynolds numbers. Journal of Fluid Mechanics, vol. 890, A17, 2020.
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- W.Cheng, D.I.Pullin, R.Samtaney, Large-eddy simulation of flow over a grooved cylinder up to transcritical Reynolds numbers. Journal of Fluid Mechanics, 835:327-362, 2017.

Thank you

- Acknowledgement
  - *KAUST Office of Competitive Research Funds under Award Number URF/1/1394-1*
  - *KAUST Supercomputing Laboratory for time on Shaheen II (Cray XC-40) (10s of millions of core hours)*
- Questions?