HPC & CFD
a personal perspective from the origin up to nowdays

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thanks to Pirozzoli, Bernardini, Carnevale, Leonardi, Fabiani, Verzicco, Fatica and many others
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computer time CINECA

Motivations for CFD

- Lecture based on incompressible flows
  - Solve non-linear equations
  - Euler inviscid
  - Navier-Stokes viscous
- Atmosphere NCAR
- Nuclear Los Alamos
- Finite differences (easy)
- In the 70th psudospectral (complex)
- Finite elements complex geometries

- From continuous to discrete space
- Compact operators staggered variables
- High Reynolds conservation properties

CFD in Italy

- Absence of teaching in 60th and 70th
- Few groups
- Torino (compressible) linked to Moretti
- Roma (incompressible) isolated
- Bari (compressible and incompressible)
  - Laminar 2D flows no HPC
  - Attempts to turbulence RANS
  - No classes in turbulence
  - Absence of interaction among groups
  - Absence of contacts with foreign groups

CFD in the world

- HPC available at NCAR, NASA, Los Alamos ...
- England Germany RANS
- France spectral closures
  - CFD for LES and DNS
  - Large use of pseudospectral (Orszag)
  - Competition MIT (Orszag) Stanford,NASA (Reynolds)

- Luck to be in Stanford,NASA for one year
- Moin, Kim, Mansour ... Ph.D students
- Rogallo , Wray, researchers
- I learnt and enjoyed the physics of turbulence
- For lack of HPC in Italy I worked on RANS
- In 1981 I attended the OLYMPIC in turbulence

Turbulence

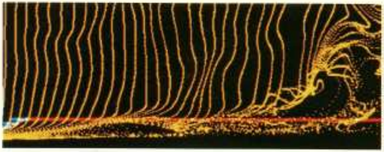
- RANS unable to be universal
- An efficient interpolation scheme (several constants)
- Unsatisfactory to homogeneous turbulence
- At the Stanford OLYMPICS Rogallo presented
- 128^3 DNS homogeneous turbulence
- Possible with ILLIAC IV
- Vectoral compiler (Rogallo Wray)
- Decrease interest in LES (constant adjustable)

Stanford cultural revolution

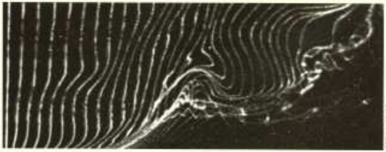
- Proof N-S solves turbulence

A Simulation Milestone

Until around 1980, few researchers attempted to simulate even very simple turbulent flows in their entirety. That year we and our co-workers at the NASA Ames Research Center used a pioneering parallel computer, the ILLIAC-IV, to perform the largest turbulence simulations achieved until then. The work was well received; soberingly enough, however, it was not the quality of the data that won over many of our colleagues but rather a five-minute motion picture of the simulated flow. The movie showed trajectories of marker particles in a turbulent flow between parallel plates (*left*); remarkably, it resembled similar visualizations made two decades earlier, by filming actual water flow in a laboratory at Stanford University (*right*). —*P.M. and J.K.*



PARVIZ MOIN AND JOHN KIM



From RANS to Spectral

- For lack of HPC in Italy I did not enter in LES or DNS
- Frustration to play with constants
- Impossibility to enter in RANS community (England Germany)
- Crocco offered me to enjoy spectral closures
- Crocco transformation for EDQNM
- Difficulty to apply spectral to homogeneous flows
- Crocco died 1985
- From this I learnt physics of turbulence

CFD of flows past complex geometries

- With Cunsolo N-S in general curvilinear coordinates (2D)
- Flow past airfoil (1977)
- Flow in a 2D elbow

$$\frac{\partial \omega}{\partial t} + \frac{1}{\sqrt{a}} \frac{\partial q^i \omega}{\partial x_i} = \frac{1}{Re} \frac{1}{\sqrt{a}} \left(\frac{\partial}{\partial x_k} \alpha^{kl} \frac{\partial \omega}{\partial x_l} \right)$$

$$q^1 = \partial \psi / \partial x_2 \quad , \quad q^2 = - \partial \psi / \partial x_1$$

$$\omega = - \frac{1}{\sqrt{a}} \left(\frac{\partial}{\partial x_k} \alpha^{kl} \frac{\partial \psi}{\partial x_l} \right)$$

Flow past airfoil

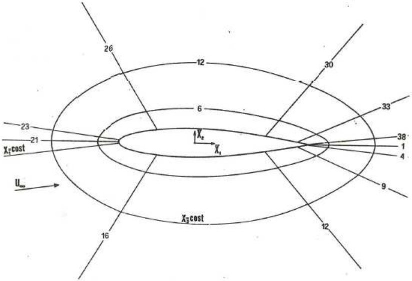
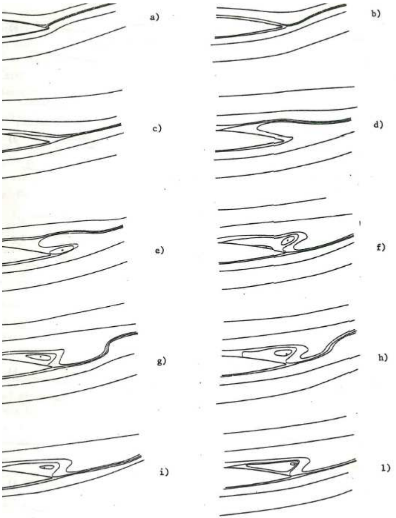


Fig. 1 - Coordinate system.



ig. 3 - Sequences in time of the streamlines around the trailing edge at 10°. a) t = .031, b) t = .25, c) t = 1.15, d) t = 2.19, e) t = 2.71, f) t = 3.23, g) t = 4.27, h) t = 5.31, i) t = 5.83, l) t = 6.87.

Flow in a 2D elbow

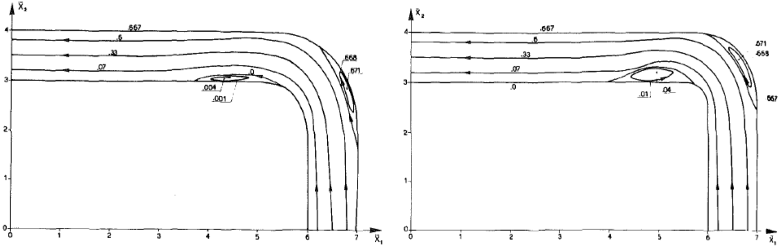


Fig. 2(a) Fig. 2(b)

Fig. 2 Steady state stream function at Re = 1,000; elbow having a nondimensional internal radius equal to 1 (*a*) and equal to 0.5 (*b*)

Complex boundaries

- NASA was interested in drag reduction by riblets
- Invited me to spend summers to develop
- 3D code for flows past complex 2D bodies
- Four years struggling with iterative methods
- General curvilinear coordinates
- The code was later on used by several scholars at the CTR
- I was again frustrated
- In Stanford by pseudospectral DNS of
- Channel KMM
- Minimal channel Jimenez
- Boundary layers Spalart
- Mixing layers Moser Rogers
- Wakes Rogers Moser
- Was the center of the world for turbulence
- Moin and Reynolds created the Center for Turbulence Research

Vortex dynamics

- In Roma interaction with Carnevale and van Heijst
- 2D dipole rebound *Orlandi rebound*
- Physics of Fluids A 1990 218 citations

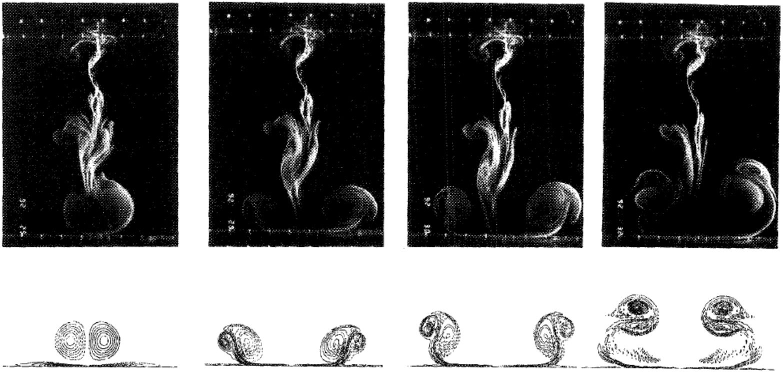
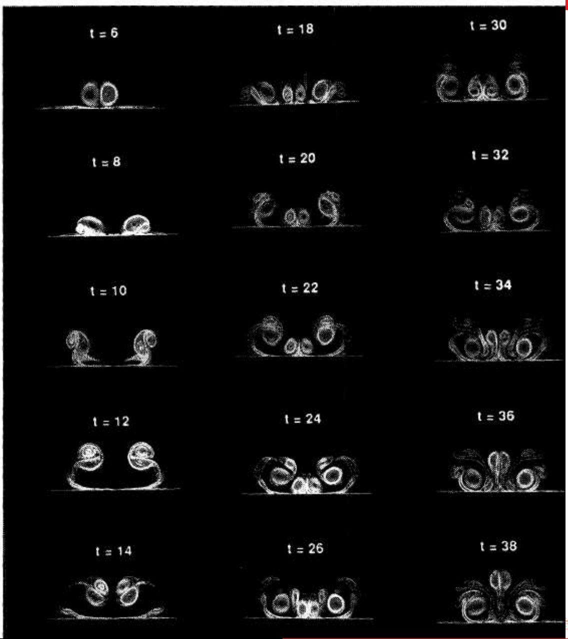


FIG. 5. Flow visualization of experiment in Ref. 4 compared with the contour plot of vorticity of numerical simulation.

Dipole and walls



Cylindrical coordinates

- The frustration with iterative schemes
- The use of FFT to solve elliptic equations
- The interest for vortex rings
- The use of staggered variables
- The trick to treat the geometrical singularity at $r = 0$
- Good students (Verzicco , Fatica)

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A Finite-Difference Scheme for Three-Dimensional Incompressible Flows in Cylindrical Coordinates

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Use of cylindrical coordinates

- Large number citations of JCP 496
- Today adapted to HPC
- Turbulent rotating pipe
- 3D tripole formation
- Stability vortex rings
- Vortex rings interacting walls
- DNS of transitional circular jets
- Thermal convection in cylindrical cells
- Drag reduction turbulent MHD pipes
- Code available in
- *Fluid Flow Phenomena: a numerical toolkit*

Comments of finite differences

- Widely accepted for cylindrical
- Criticised several paper rejected
- Large effort for validation
- Spectral and finite difference solutions of the Burgers equation
- Isotropic turbulence decay
- Statistics of KMM and Jimenez channel
- Time-reversibility of the Euler equations
- Turbulent channel flow simulations in convecting reference frames

- Appreciated
- More paper accepted

Burgers equation

- Computers & Fluids Vol. 14, No. I, pp. 23-41, 1986

Table 3. Maximum absolute value of the slope at the origin and time t_{max} at which this maximum value occurs for all the numerical algorithms and for the analytical solution.

Method	Interval	$\left\|\frac{\partial u}{\partial x}\right\|_{max}$	$\pi \cdot t_{max}$	N/M	$\Delta t \cdot \pi$
- Fourier Galerkin	[-1,1]	151.942	1.6035	682/1024	5.10^{-4}
		142.665	1.60	682/1024	10^{-2}
		148.975	1.603	170/256	5.10^{-4}
		142.313	1.60	170/256	10^{-2}
- Fourier Pseudospectral	[-1,1]	142.606	1.60	256/256	10^{-2}
		144.237	1.60	128/128	10^{-2}
- ABCN collocation	[-1,1]	145.877	1.60	512	5.10^{-3}
+coordinate transform.	[-1,1]	152.123	1.60	64	10^{-2}
- Spectral Element	[-1,1]	152.04	1.6033	16 x 4	$10^{-2}/6$
- FD	[-1,1]	150.1	1.63	81	10^{-2}
- Chebyshev					
ABCN spectral	[0,1]	152.05	1.60	64	1/300
Rosenbrock spectral	[0,1]	151.998	1.60	64	10^{-2}
	[0,1]	150.144	1.60	32	10^{-2}
ABCN collocation	[0,1]	152.126	1.60	64	10^{-2}
- Analytical		152.00516	1.6037		

Decay isotropic turbulence

- FFP (Pg.160)

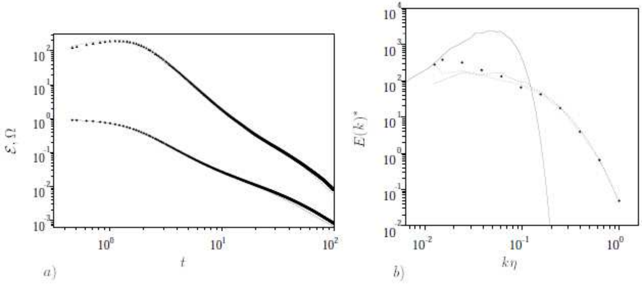
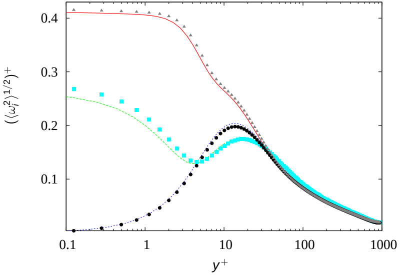


Fig. 8.5 Time history of $\mathcal{E}$ and Ω for finite difference symbols and pseudospectral (Wray) lines; b) Energy spectra (Kolmogorov units) at moderate Reynolds number, ——— initial spectrum, - - - - present simulation $R_\lambda = 54.3$, ······· Mansour & Wray $R_\lambda = 56.2$, □ Compte Bellot & Corrsin $R_\lambda = 60.7$

Validation turbulent channel vorticity rms

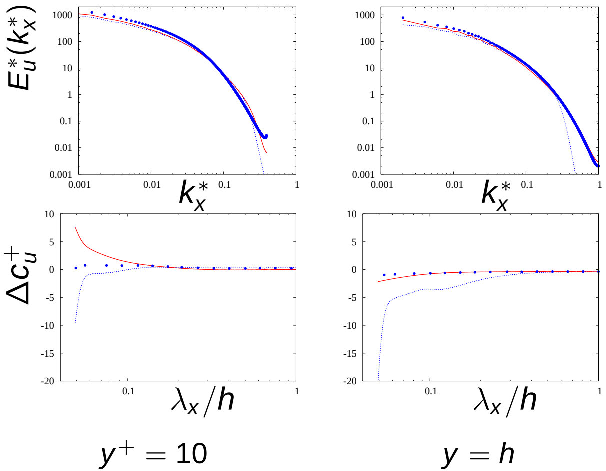
- Results for $R_\tau = 900$
- Comparison with pseudospectral DNS by Jimenez's group



- $x_1 = x, x_2 = y, x_3 = z$
- $u_1 = u, u_2 = v, u_3 = w$

Improvement turbulent channel

- Laboratory and convective frame Bernardini (JCP 2012)
- Phase velocity $c_u = -\dfrac{Im\langle \hat{u}^* \, \partial_t \hat{u} \rangle}{k_x \, \left\langle |\hat{u}|^2 \right\rangle}$

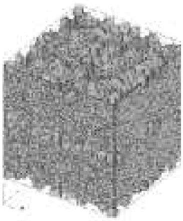


- Small effect on the statistics profiles

Inviscid Energy Conservation

- Resolution 96^3
- Time reversibility forward up to $t = 10$
- Then $V(10, X) = -V(10, X)$
- At $t = 20$ $V(20, X) = V(0, X)$

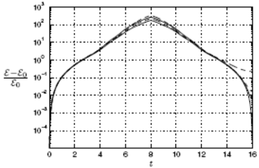
- Isosurface of $\lambda_2 = -0.025$



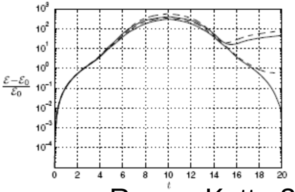
$t = 0$ $t = 10$ $t = 20$

Validation inviscid

- Comparison for unresolved Taylor Green Duponchel et al. (2008)
- Comparison FD2, FD4, Pseudospectral

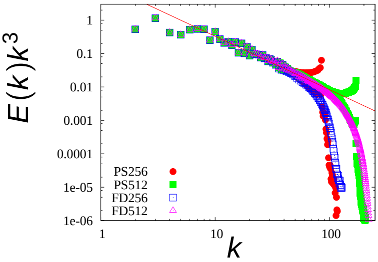


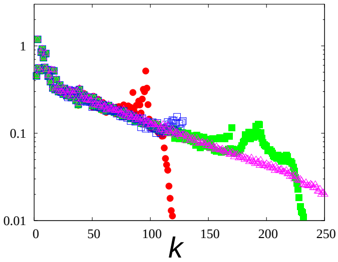
Adams Bashfort



Runge-Kutta 3rd order

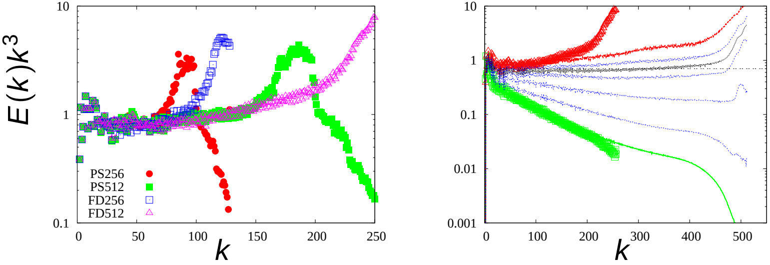
- Pseudospectral Cichowlas & Brachet (2006)
- Pile-up can be eliminated by exponential filters (Hou & Li)
- Second order finite difference FD2 Orlandi & Carnevale (2008)
- Simulations at 256^3 and 512^3





$t = 3.5$ $t = 4.0$

FTS Taylor-Green $E(k)$ $t = 4.5$



- FD2 symbols 512 lines 1024 $4.0 < t < 4.5$ black $t = 4.35$
- By FD2 YES but difficult to establish
- whether for $t \to t_s$, $\delta(t) \to 0$

Cartesian HPC FD for Clay prize

- Finite Time Singularity from smooth I.C.
  - Euler equations
  - Navier-Stokes equations
- Transition from Vortex Dynamics to Turbulence
- Link between Vortical Structures and
- Power Spectra
- Give insights to mathematician to prove
- Existence of FTS

- Insert passive scalar
- Look at the difference between
  - Energy and scalar spectra
  - Vortical and scalar structures

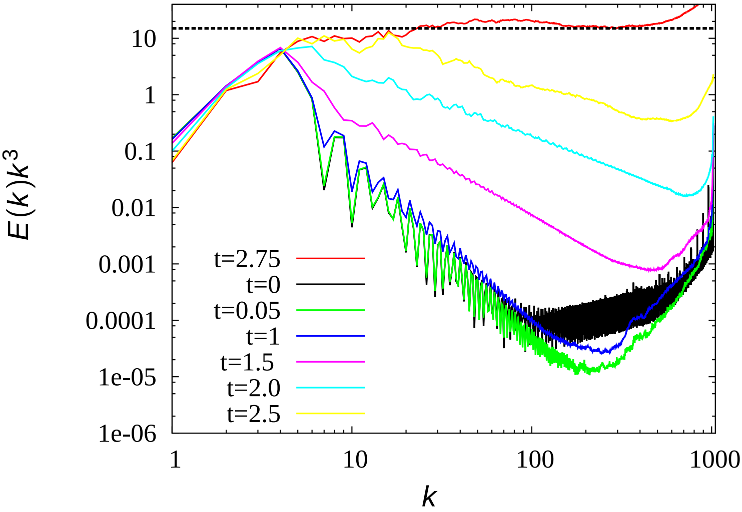
Euler

- FTS does exist if
- $|\omega|_{max} \propto (t_s - t)^{-1}$
- $E(k) \propto k^{-3}$ at t_s infinite enstrophy
- other requirements in Kerr (2006)
  - I.C. and numerics important
  - Lamb dipoles Orlandi & Carnevale (2008)
  - $t = 0\ E(k) = k^{-6}$
  - Lamb vortex solution Euler
  - for $t \to t_s$, $|\omega|_{max} \propto |\widetilde{\omega}_2|_{max}$, $\widetilde{\omega}_2 \propto \widetilde{S}_2$
  - $\frac{\partial \widetilde{\omega}_2}{\partial t} = \widetilde{S}_2 \widetilde{\omega}_2 = \widetilde{\omega}_2^2$
  - Having a FTS
- Close to FTS investigate
- Differences in the spectra between scalars and velocity
- Differences in the structures

Navier-Stokes

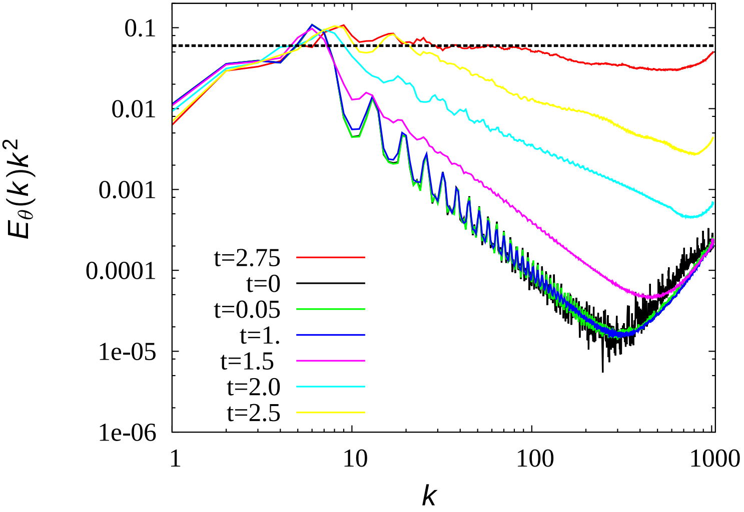
- FTS does not exist
- Interest to understand
- Turbulence from Vortex Dynamics
- Evolution of energy spectrum
- Different from forced DNS
- Evolution of spectra and tendency to equilibrium range

Inviscid energy spectra



- 2048^3
- Profs of FTS easier for persistence k^{-n} up to t_s

Inviscid Scalar spectra

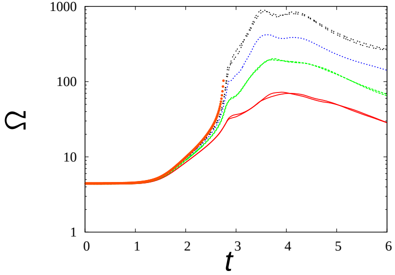


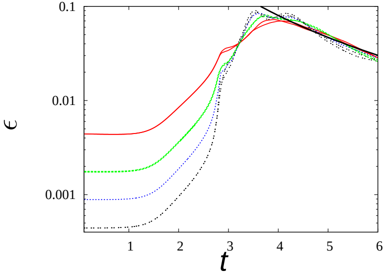
- 2048^3

Viscous Flows

- Energy $q = \langle u_i^2 \rangle$ equation
- $\frac{\partial q}{\partial t} = \frac{\Omega}{Re}$
  - Kolmogorov at large t $q \propto t^{-m}$
  - m does not depend on ν
  - If Re increases Ω increases
- Enstrophy equation
- $\frac{\partial \Omega}{\partial t} = P_\Omega - \frac{D_\Omega}{Re}$
- D_Ω / Re rate enstrophy dissipation
- $D_\Omega / Re = \langle (\frac{\partial \omega}{\partial x_i})^2 \rangle / Re; P_\Omega =< \omega_i \omega_j S_{ij} >$
  - Opposite effects of P_Ω and D_Ω / Re
  - However at high Re initially P_Ω strong
  - To create Ω at intermediate scales
  - Later on D_Ω / Re grows preventing FTS
- Scalar equation
- $\frac{\partial \theta_l}{\partial t} + \frac{\partial u_i \theta_l}{\partial x_i} = \frac{1}{RePr} \frac{\partial^2 \theta_l}{\partial x_i^2}$

Enstrophy evolution

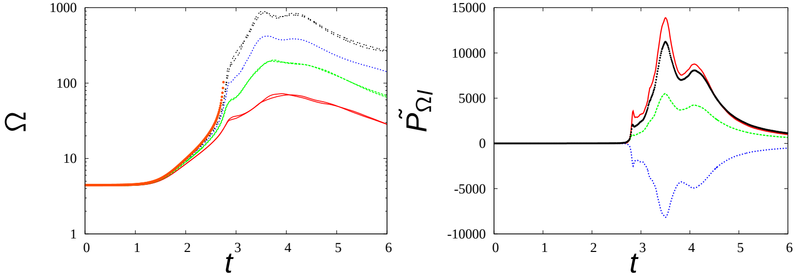




- For $t < 1$ $\Omega = const$
- For $1.8 < t < 2.4$ exp. growth
- For $2.6 < t < 2.7$ FTS for $\nu = 0$
- For $\nu \neq 0$ there is Ω_{max} tendency
- FTS Impossible to prove by DNS

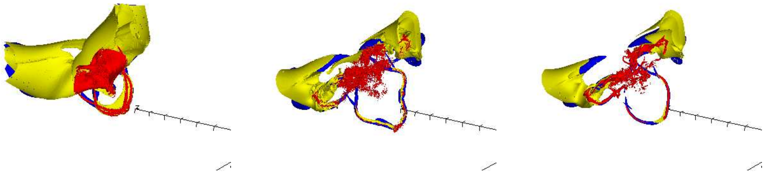
Enstrophy production

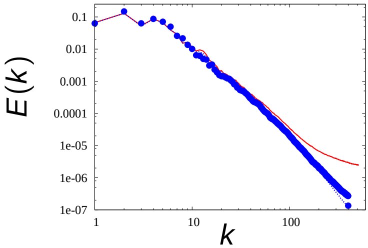
- $\frac{\partial \Omega}{\partial t} = < \omega_i \omega_j S_{ij} > + \frac{1}{Re} < \omega_i \nabla^2 \omega_i >, \quad P_\Omega = < \omega_i \omega_j S_{ij} >$
- $\tilde{P_{\Omega l}} = \tilde{\omega}_l^2 \tilde{S}_l$



Spectra and Structures

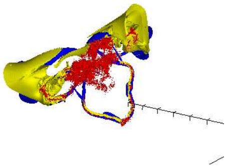
- Inviscid $t = 2.75$ filtered 1536^3
- Viscous $t = 3.0$ $Re = 10000$ 1024^3 , $Re = 2500$ 768^3

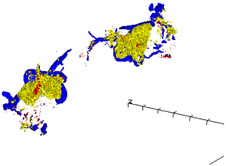


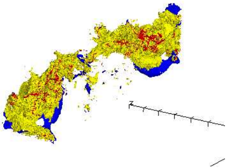


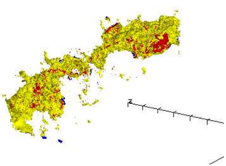
Spectra and Structures from Vortex to Turbulence

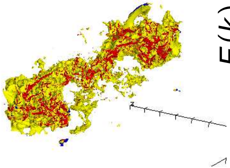
- $Re = 10000\ 1024^3$
- $t = 3.0$ $t = 3.5$ $t = 4.0$

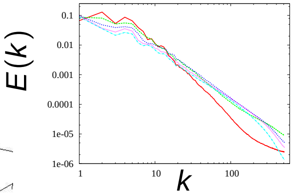








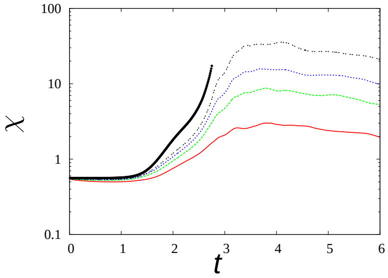


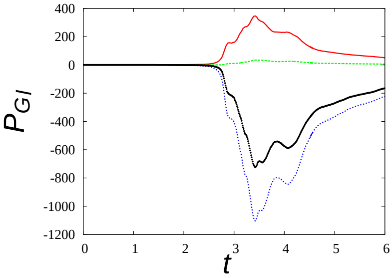


- $t = 4.5$ $t = 5.0$ local transfer

Scalar gradient variance and enstrophy evolution

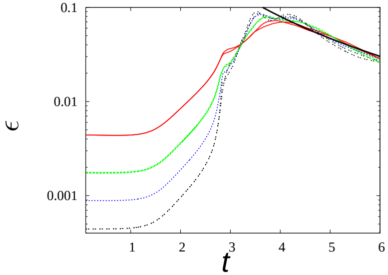
- Scalar dissipation $\chi =< (\frac{\partial \theta}{\partial x_i})^2 >=< G_i^2 >$
- $\frac{\partial \chi}{\partial t} = - < G_i G_j S_{ij} > + \frac{1}{RePr} < G_i \nabla^2 G_i >$ $\quad P_G =< G_i G_j S_{ij} >$
- $\tilde{P_{GI}} = \tilde{G_I}^2 \tilde{S_I}$

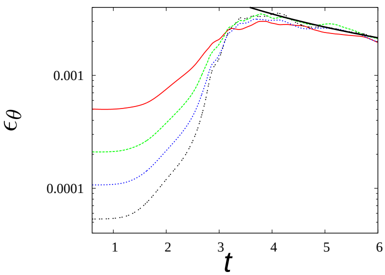




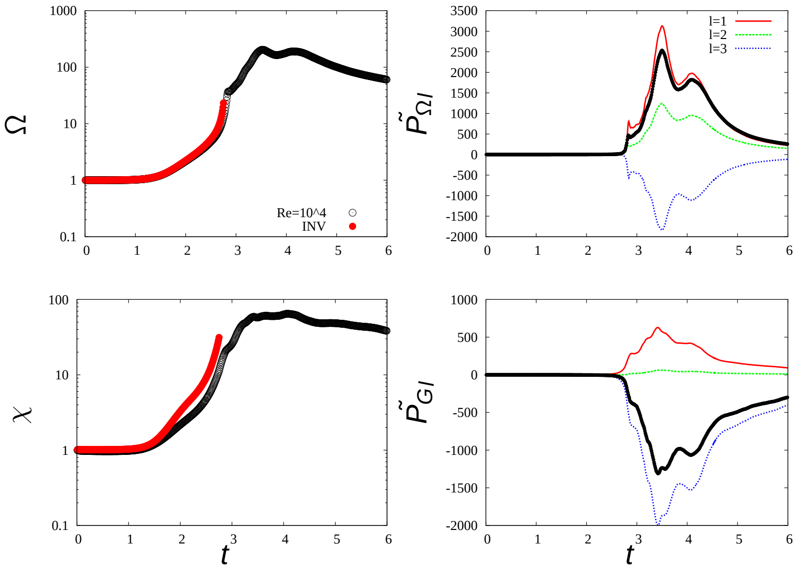
Rate of energy and scalar dissipation

- $\epsilon = \nu\Omega$
- $\epsilon_\theta = \alpha\chi$

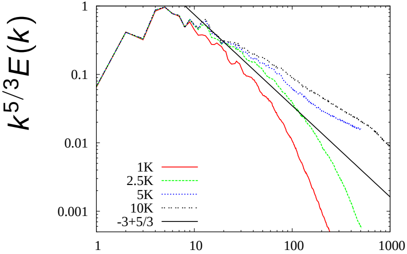


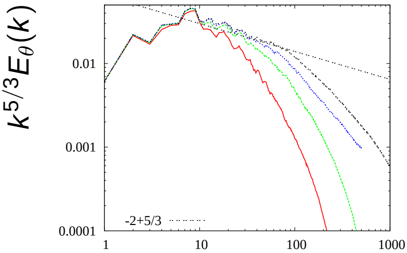


Difference between χ and Ω



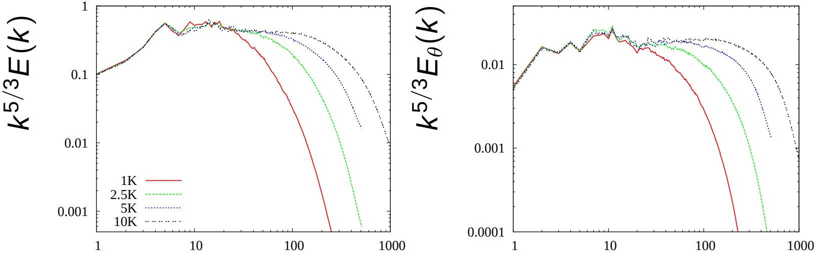
Energy and scalar spectra





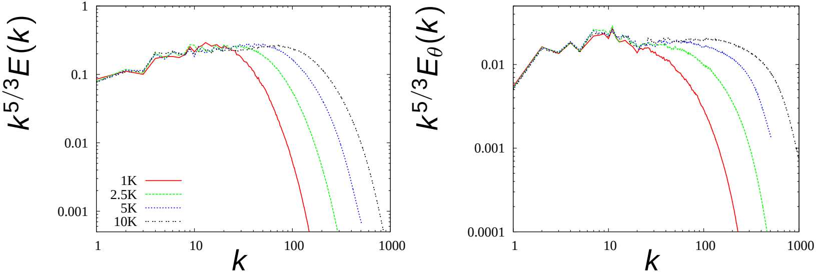
$t = 3.00$

Energy and scalar spectra



$t = 4.00$

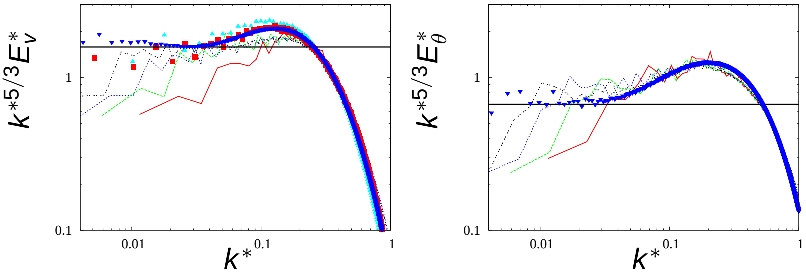
Energy and scalar spectra



$t = 6.00$

Energy and scalar spectra

- Comparison with forced isotropic turbulence
- Jimenez at $R_\lambda = 168$ Donzis & Sreenivasan $R_\lambda = 1100$



$t = 6.00$

Conclusions MFU Velocity

- DNS allow to establish
  - Euler has FTS
  - I.C. important for the best trend $(t_s - t)^{-1}$
  - Flows with power laws (Lamb) k^{-n} more efficient
  - Numerical methods affect the trend

- Navier-Stokes do not have FTS
- Depending on Re earlier deviation from $(t_s - t)^{-1}$
- Varying Re finite rate of energy dissipation ϵ
- In time Ω amplification $P\Omega > D_\Omega$
- Constant ϵ $P\Omega \approx D_\Omega$
- n varies from $n = -3$ (FTS) to $n = -5/3$ Kolmogorov
- Formation of exponential range

- More on JFM Vol.690 280-320.

Conclusions Scalar

- Inviscid
  - Passive scalar at $t = 0$ $E_\theta \approx k^-4$
  - at FTS $t = 0$ $E_\theta \approx k^-2$ sheets
  - Growth of χ similar to Ω
  - $- < G_i G_j S_{ij} >$ not too different from $< \omega_i \omega_j S_{ij} >$
- Viscous scalar
  - Maximum of χ and Ω at same t
  - Dependence on Re
  - Power law decay with t^{-n}
  - $E(k)$ and E_θ reach $k^-5/3$
  - Large differences in $- < G_i G_j S_{ij} >$ and $< \omega_i \omega_j S_{ij} >$
- More on JOT Vol.15 No. 11 731-751.

High Re_τ channels and Couette flows

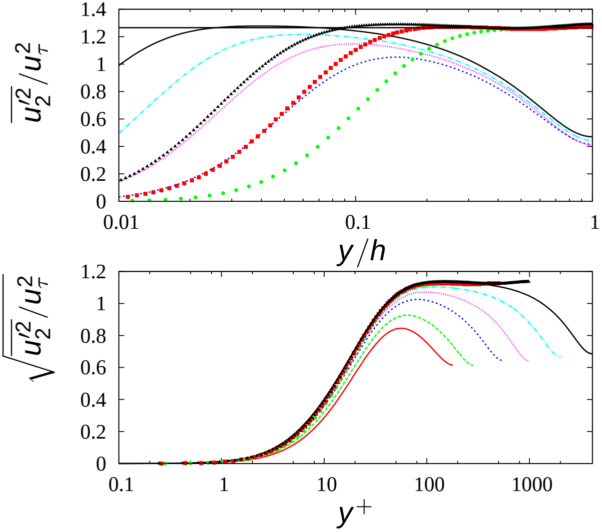
- Large interest in wall-bounded flows
- Boundary layers, circular pipes and plane channels
- Theoretical arguments
- Log-law for U^+ Prandtl
- Attached eddies (Townsend)
- Very high Re superstructures

DNS using HPC

- Channel Bernardini JFM 742, Orlandi JFM 770
- Superstructures at high *Re*
  - del Alamo *et al.* up to $Re_\tau = 2000$ not wide log-law
  - at $Re_\tau > 10^4$ very satisfactory for many question
  - at $Re_\tau \approx 4000$ crossover prod. at $y^+ \approx 100$
  - at $Re_\tau = 4000$ some answer
  - $Re_\tau = 4000$ Bernardini $8192 \times 1024 \times 4096$ in $12\pi \times 2\pi$
- Couette Pirozzoli JFM 758
- Production at centerline
- Superstructures at low *Re*
  - Re_τ up to 1000 $5120 \times 512 \times 1536$ in $12\pi \times 2\pi$

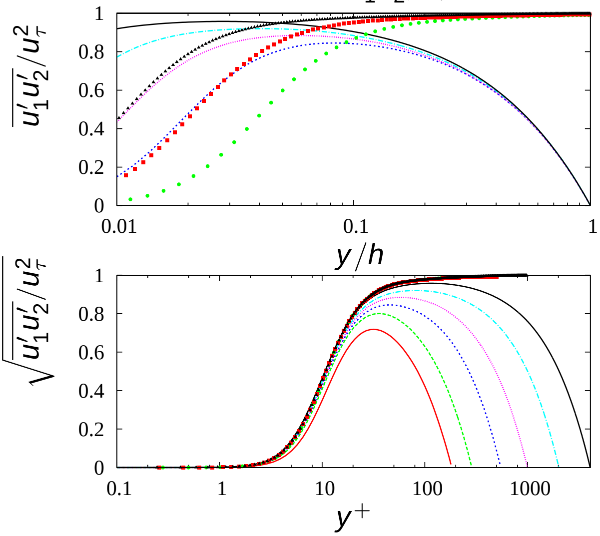
$\overline{u_2'^2}$ stress

- Townsend (attached eddies) $\overline{u_2'^2}/u_\tau^2 = C_2$



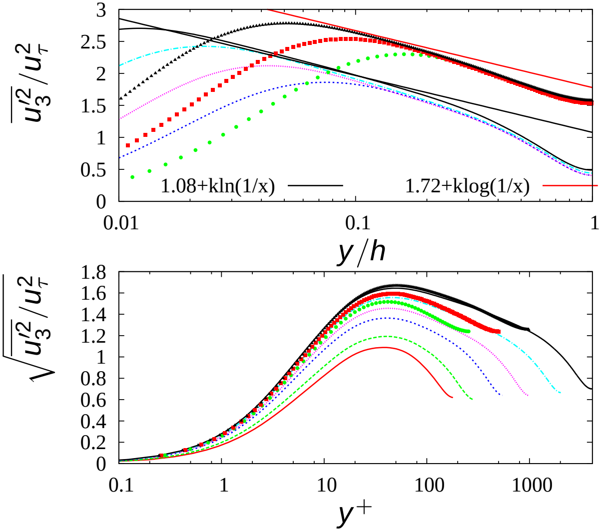
$\overline{u_1' u_2'}$ stress

- Townsend (attached eddies) $\overline{u_1' u_2'}/u_\tau^2 = 1$



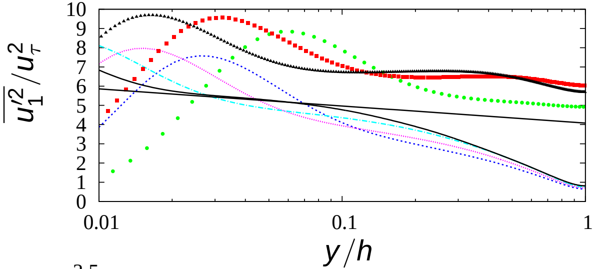
$\overline{u_3'^2}$ stress

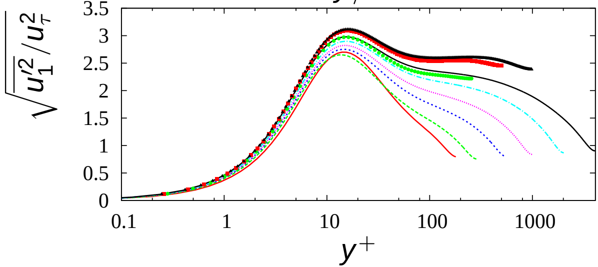
- Townsend (attached eddies) $\overline{u_3'^2}/u_\tau^2 = C_3 + k \log(h/y)$



$\overline{u_1'^2}$ stress

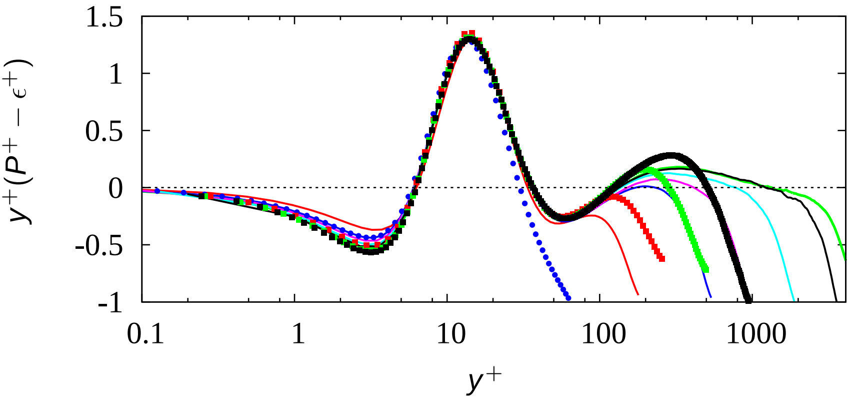
- Townsend (attached eddies) $\overline{u_1'^2}/u_\tau^2 = C_1 + k log(h/y)$





Transport of TKE

- Balance of production and ϵ
- In the outer region $y^+P^+ = y^+\epsilon^+$



$\langle u_2'^2 \rangle$ and N-S equations

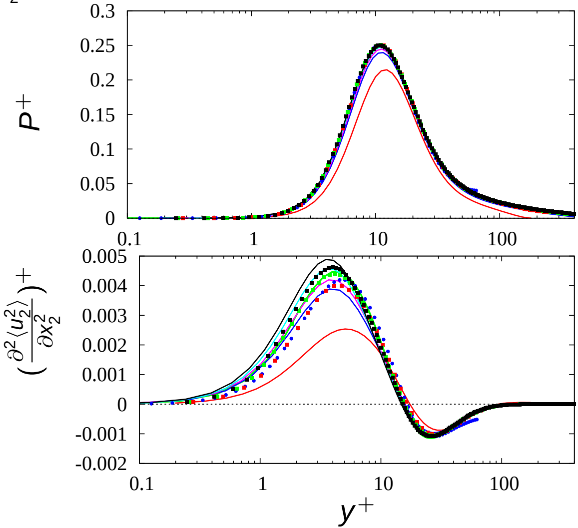
- $\langle u_2'^2 \rangle$ difficult to measure small dependence on Re
- $\tilde{u}_2|_{max} \approx u_\tau$ then $\tilde{u}_2^+ \approx 1$
- From u_2 equation $\langle p \rangle + \langle u_2'^2 \rangle = P_0$
- From pressure equation
- -$\nabla^2 p = s_{ij}s_{ji} - \omega_i\omega_i/2 = -Q$
- $Q > 0$ tube-like
- $Q < 0$ ribbon-like

$$-\frac{\partial^2 \langle p \rangle}{\partial x_2^2} = -\langle Q \rangle = \langle s_{ij}s_{ji} \rangle - \langle \omega_i\omega_i/2 \rangle = \frac{\partial^2 \langle u_2^2 \rangle}{\partial x_2^2} \tag{1}$$

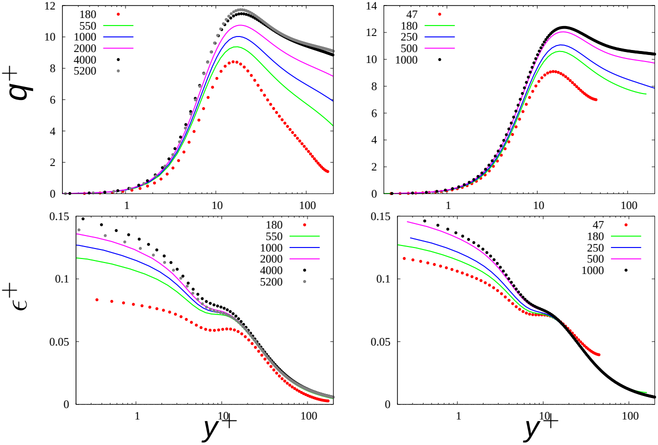
- $\frac{\partial^2 \langle u_2^2 \rangle}{\partial x_2^2}$ accounts for structures

Production and structures

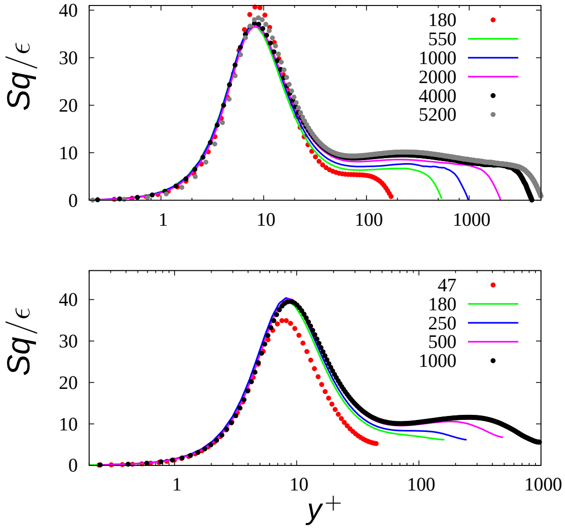
- $\frac{\partial^2 \langle u_2^2 \rangle}{\partial x_2^2}$ accounts for structures



q and ϵ



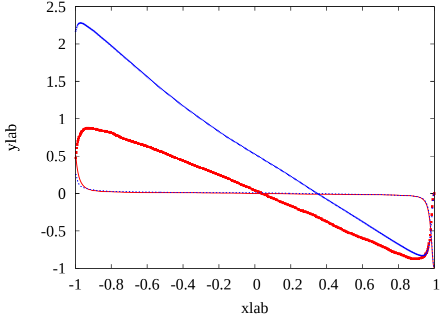
Sq/ϵ



- $Sq/\epsilon > 5$ formation longitudinal structures

Superstructures and drag Control

- Smits & Marusic Physics Today (2013)
- *connection between superstructures and wall structures could plausibly reveal new strategies to reduce drag by manipulating the super structures*
- Our view drag Control only by changing wall b.c.



- blue *3D* staggered cubes red longitudinal *2D* triangular

A numerical turbulent wind tunnel

- In Wind Tunnels a clean flow
- Requires an accurate design of
- inlet (contraction)
- test section
- exit (diffuser)
- return
- FOR A NUMERICAL WIND TUNNEL
  - Accurate basic numerical method

Complex bodies

- In wind tunnels flows past bodies
- Numerically
  - Body fitted coordinates non-orthogonal
    - Difficulties in numerics
    - Inefficient codes (elliptic equations)
- Orthogonal coordinates body surface discretized
  - Simple numerics
  - Efficient codes direct solver elliptic equations
  - Inaccuracy near walls
    - Small scales generated
    - Dissipated by viscosity

Early Immersed Boundary Methods

- Vieceli (1969) 2D steady
- Vieceli (1971) 2D unsteady
- Imposition impermeability

- Peskin body forces 1972 2D
- Basdevant , Briscolini & Santangelo Mask method
- Based on impositions of body forces
- Inaccurate near surface
- Small Δt
- Impossibility to deal with turbulence

Rediscover Immersed Boundary Methods

- Fadlun (JCP 2000 1430 citations) revisited Vieceli approach
  - Zero velocity inside body
  - Interpolation first point external body
  - Large Δt
  - Turbulent flows accessible
- Huge number of versions available

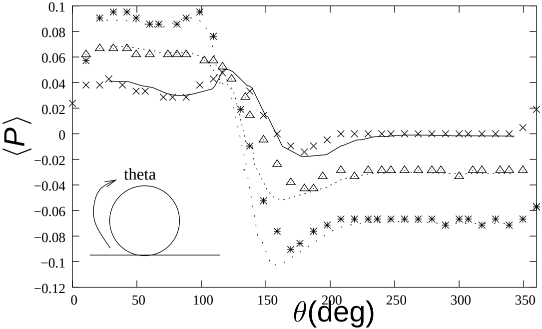
Our immersed boundary methods

- Rough channels
- No constant mass with interpolation
- Interpolation does not give true friction
- No Balance between pressure gradient and wall friction

- Present
- Inside body as Fadlun
- Metric at the first external point
- For viscous terms
- No correction for non-linear
- No correction for pressure
- Impermeability more than sufficient

Validation IBM roughness

- Turbulent flows past circular rods
- Comparison between boundary layers (exp)
- and channels (DNS)



Validation IBM through experiments

- Turbulent flows past square bars
- Experiment ad hoc designed
- Burattini JFM 600

Case	$Re_b = \frac{U_b H}{\nu}$	$Re_{\tau_r} = \frac{u_{\tau_r} H}{\nu}$	$Re_{\tau_s} = \frac{u_{\tau_s} H}{\nu}$	$k^+ = \frac{k u_{\tau_r}}{\nu}$	y_U/H	u_{τ_r}/U_M	u_{τ_r}/u_{τ_s}
E1	3600	300	230	30	1.24	0.073	1.31
E2	7100	620	430	62	1.32	0.074	1.44
E3	13000	1120	760	112	1.33	0.072	1.48
D1	2800	260	190	26	1.22	0.078	1.38
D2	6900	634	430	63	1.27	0.076	1.46
D3	12000	1094	730	109	1.27	0.076	1.50

TABLE 3. Main results for measurements (E1, E2, E3) and simulations (D1, D2, D3).

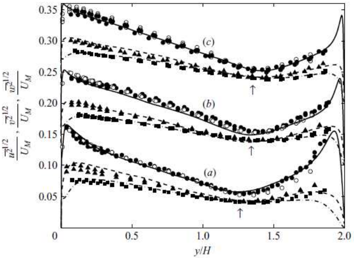
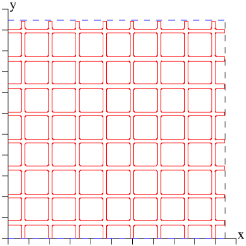
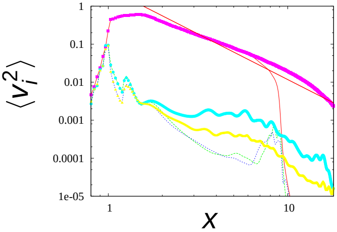
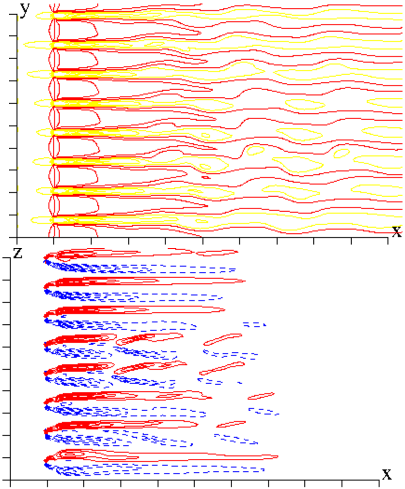


FIGURE 6. RMS turbulence intensities. (*a*) E1 and D1; (*b*) E2 and D2; (*c*) E3 and D3. (*b*) and (*c*) are shifted upwards by 0.1 and 0.2. Symbols: experiments; lines simulations. Filled symbols: X-wire; empty symbols: single wire. ●, ○,—, u; ■, -·-, v; ▲, – –, w. Arrows indicate y_U/H from experiments. Repeated symbols are for different streamwise positions (MW and

- Grid turbulence in wind tunnels
- Intermediate solidity

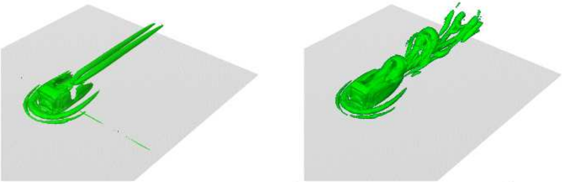






Laminar-turbulent b.l. transition

- Orlandi (arXiv.1503.08614.pdf 2015)
- Paper rejected twice for numerics
- Solid element



a) b)

Figure 6: Surface contours of surface contour of $\lambda_2 = 1$ a) cube $Re = 5500$, a) SU at $Re = 5500$.

2D trip

- Transverse square bar

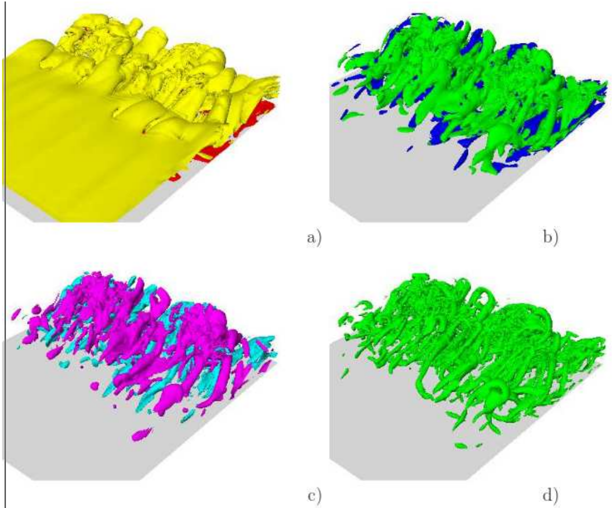
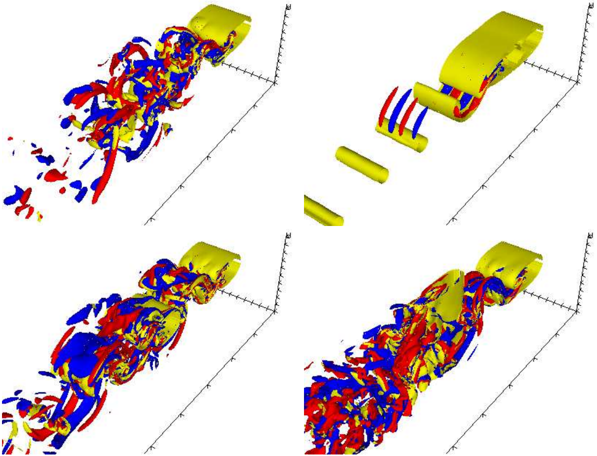


Figure 7: Surface contours for the case SQ at $Re = 5500$: a) $\omega_3 = -2.5$ yellow and

Bluff bodies

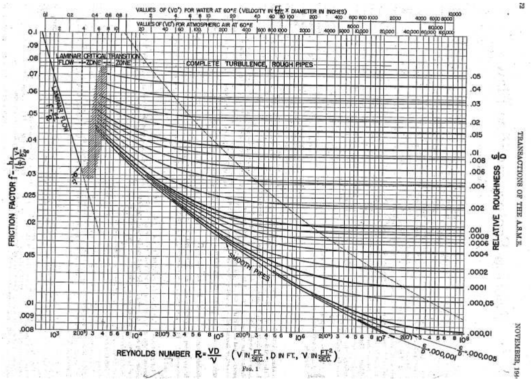
- Two cylinders
- Vorticity at $Re = 600$



Rough walls

- Darcy (1857) resistance function of friction factor $C_f(V, D, \epsilon, \nu)$
- Several exp. performed to find C_f
  - Pigott (1933) real pipes fully rough
  - Nikuradse (1933) fully rough sand-grain
  - Schlichting (1936) roughness elements spheres cones etc.
  - Colebrook (1938) sand-grain + large elements
  - Moody (1944) produced a diagram of practical interest

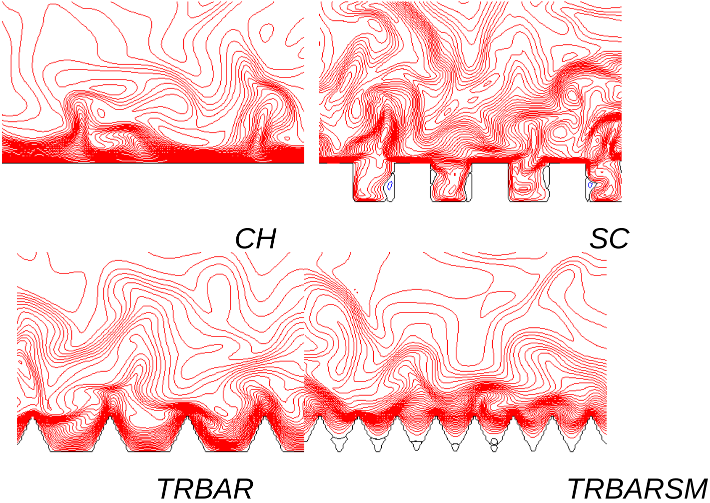
Moody diagram



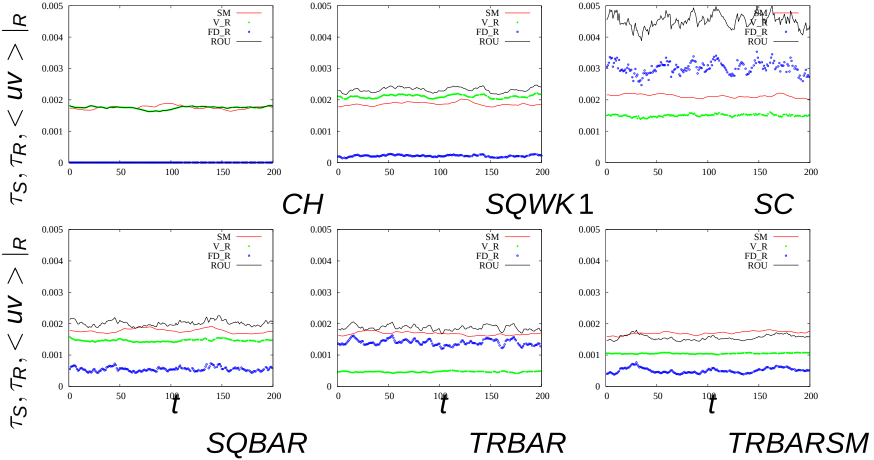
- Three regimes
  - Laminar independent from surface depends on Re
  - Fully turb. depends on surface indep. from Re
  - Transitional depends on surface and Re

Roughness description

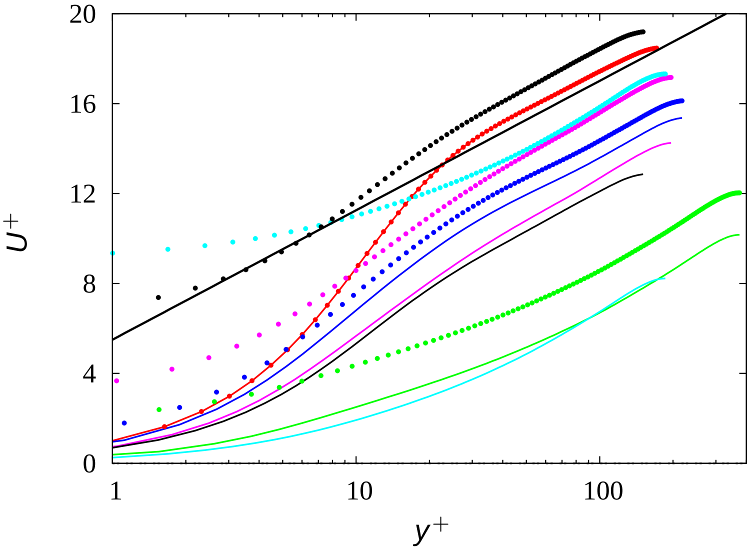
- U contours in a $z - y$ plane



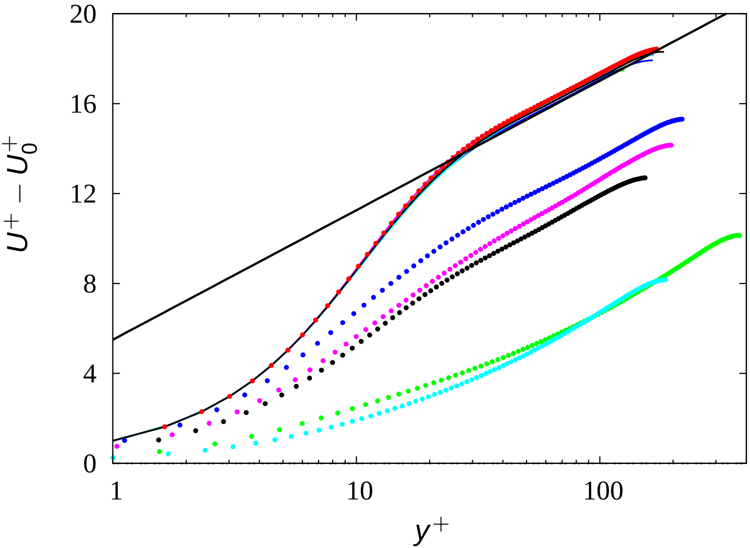
Time evolution of components flow resistance



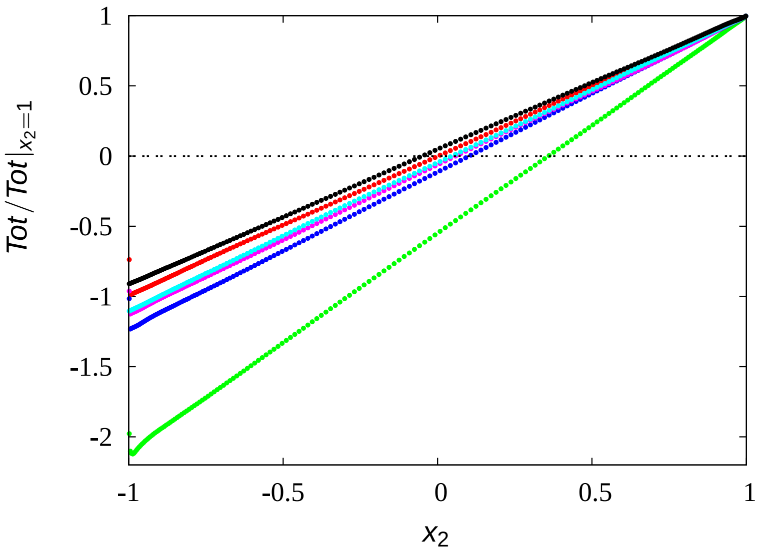
U^+ profiles definition



U^+ profiles

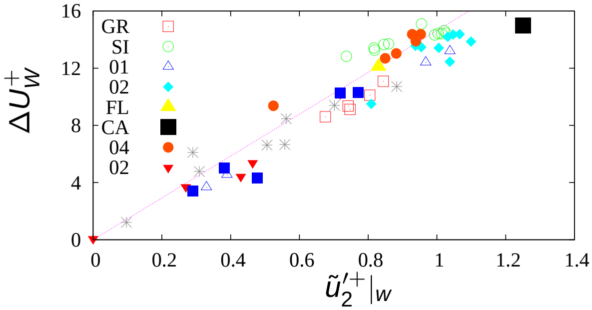


Total stress



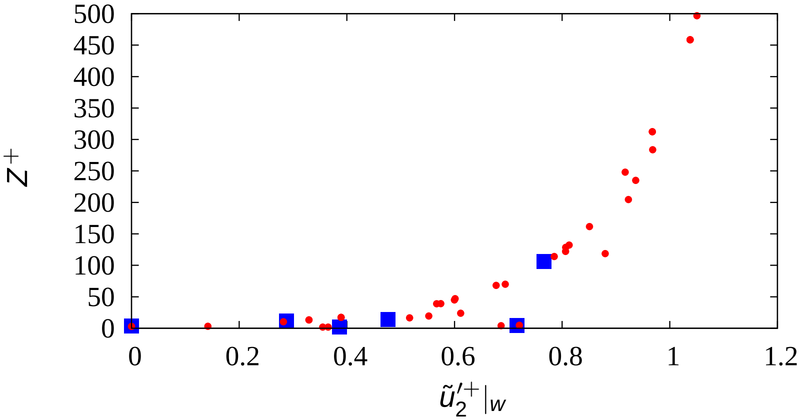
Roughness parametrization for channel

- Roughness function ΔU_W^+ vs $\tilde{u}_2'^+|_w$
- $\tilde{U}^+ - \tilde{U}_W^+ = \kappa^{-1}\ln(\tilde{y}^+) + B(1 - \frac{\tilde{u}_2'^+|_w}{\kappa})$
- Roughness classified by $\tilde{u}_2'|_w$
- Holds for any kind of rough surface



Eguivalent roughness height and $\tilde{u}_2'^+|_w$

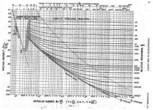
- $8.48 + \frac{1}{\kappa}\ln(y^+/Z^+) = \kappa^{-1}\ln(\tilde{y}^+) + B(1 - \frac{\tilde{u}_2'^+|_w}{\kappa})$

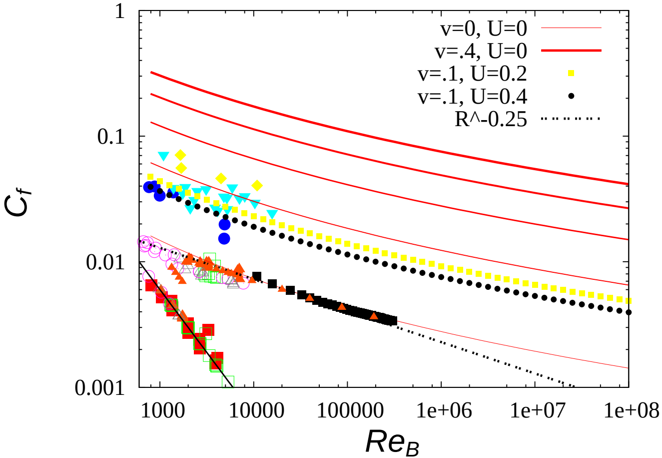


A new Moody diagram

- Based on $\tilde{u}'_2$ and U_W
- $\tilde{U} - \tilde{U_W}^+ = \kappa^{-1} \ln(\tilde{y}^+) + B(1 - \frac{\tilde{u}'^+_2|_W}{\kappa})\,, \quad B = 5.0$
  - $\tilde{U_H}^+ = \kappa^{-1} \ln(H^+) + B(1 - \frac{\tilde{u}'^+_2|_W}{\kappa})$
  - Since $U^+_H = C + U^+_{bulk}$
- If $\lambda = u_\tau / U_{bulk}$, $C_f = 2\lambda^2$
- $\lambda = \frac{(1. + B/\kappa \tilde{u}'_2|_W / U_{bulk} - U_W / U_{bulk})}{[C + ln(Re_b \lambda)]}$
- To fit with $C_f = 0.0725 Re_b^{-.25}$ $\quad C = 4.5$

The new diagram





Conclusions

- CFD is a useful toll to explore
  - Vortex dynamics
  - Turbulence
- Lucky to have theoretical models
- Euler and Navier-Stokes equations

- Hard life in the 60th and 70th
- Easy life today HPC and software

- I WAS UNLUCKY
- HOPING MY EFFORT WILL MAKE YOU
- HAPPY