

# Review of Analysis and Modeling Techniques for Incompressible, Turbulent Bluff-Body Wakes

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**abstract here *LH&FZ***

## Nomenclature

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$\rho$  = density,  $kg/m^3$

Subscripts

( $\infty$ ) = freestream quantity

Acronyms

CFD = Computational Fluid Dynamics

## I. Introduction

INTRO sentence to paper should have this fancy capitalization.

### I. • Driving Physical Phenomena *FZ*

- differences from potential flow
- blunt/bluff body definition, differences from streamlined body flow
- massively separated flow
- base pressure
- wake

### I. • Real World Applications *LH*

- parachute
- reentry capsule
- vehicles
- buildings
- show similarity between cylinder/sphere wake and more complex bluff body

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*Big whorls have little whorls, which feed on their velocity, and little whorls have lesser whorls, and so on to viscosity (in the molecular sense).* Richardson (1922) [1]

## **II. Experimental Methods And Results**

*FZ*

- Historical Study
- Experimental techniques
  - ballistic range?
- Applications
  - Simple cases: cylinder/sphere
    - \* Drag vs Re?
    - \* Wake velocity profiles?
    - \* Wake structure?
  - Sharp vs bluff: sphere vs cube
  - Complex cases: capsule/building

## **III. Computational Methods and Results**

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- Historical Study
- Computational techniques
- Applications
  - Simple cases: cylinder/sphere
  - Sharp vs bluff: sphere vs cube
  - Complex cases: capsule/building

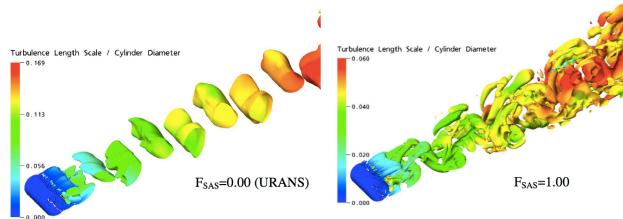
### **A. Turbulence Modeling Aspects**

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- Compare turbulence model performance for sphere/cylinder
  - SA
  - SST
  - SAS
  - URANS
  - LES

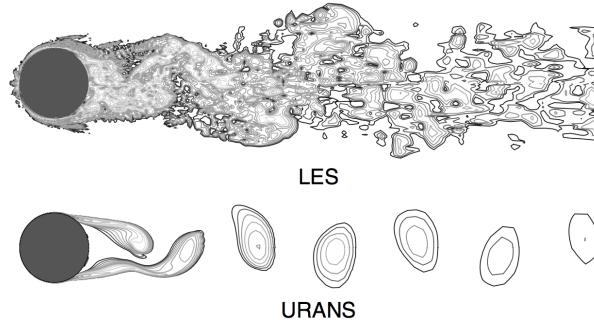
- DES
- DNS?

LIST ALL FIGURES HEAR, REORDER AND DESCRIBE LATER



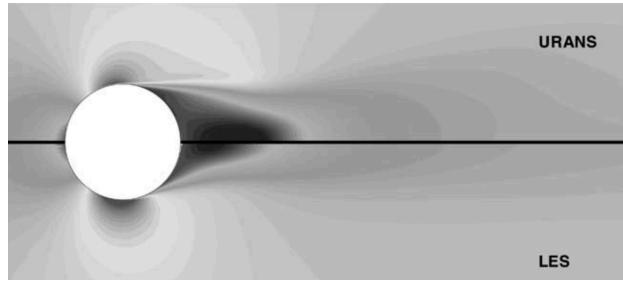
**Fig. 1 SAS vs URANS cylinder [2]**

Figure 5: Resolved structures for cylinder in crossflow using different constants FSAS



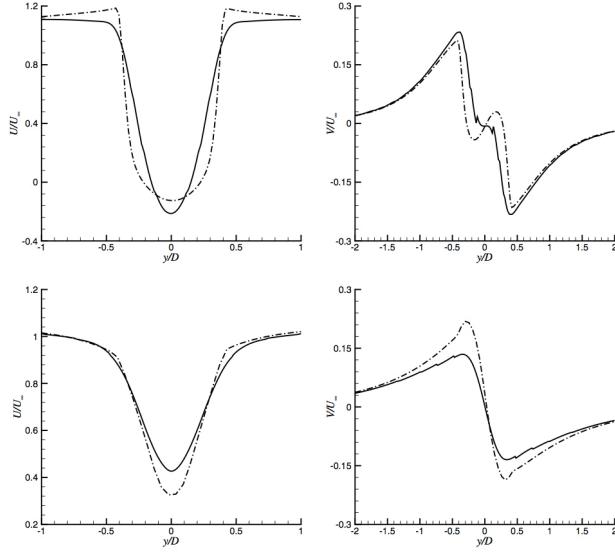
**Fig. 2 cylinder les vs urans instantaneous [3]**

Instantaneous vorticity magnitude at a given spanwise cut for flow over a circular cylinder at  $Re_D = 106.25$  contour levels from  $xD = U_1/4$  to  $xD = U_1/4 \cdot 575$  (exponential distribution) are plotted.



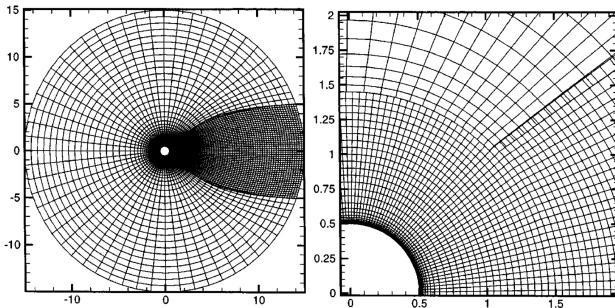
**Fig. 3 cylinder les vs urans averaged [3]**

Fig. 5. Mean streamwise velocity distribution predicted by LES and URANS. 45 contour levels from  $U = U_1/4 \cdot 0.2$  to  $U = U_1/4 \cdot 1.7$  are plotted.



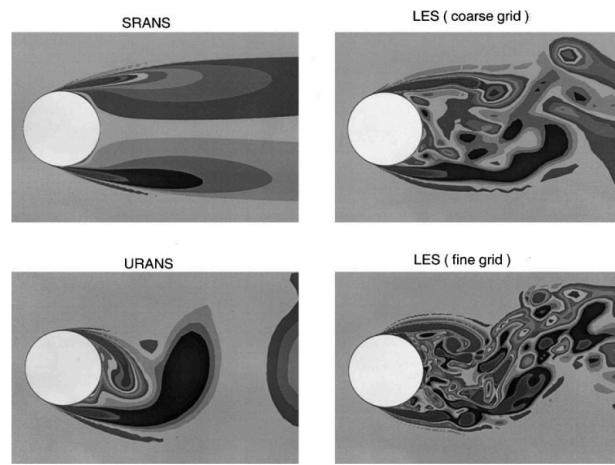
**Fig. 4 cylinder les vs urans velocity profiles [3]**

Fig. 6. Mean streamwise and vertical velocities at  $x=D 1/4 0.75$  (upper figures) and  $x=D 1/4 1.50$  (lower figures):  
 (—) LES; (--) URANS



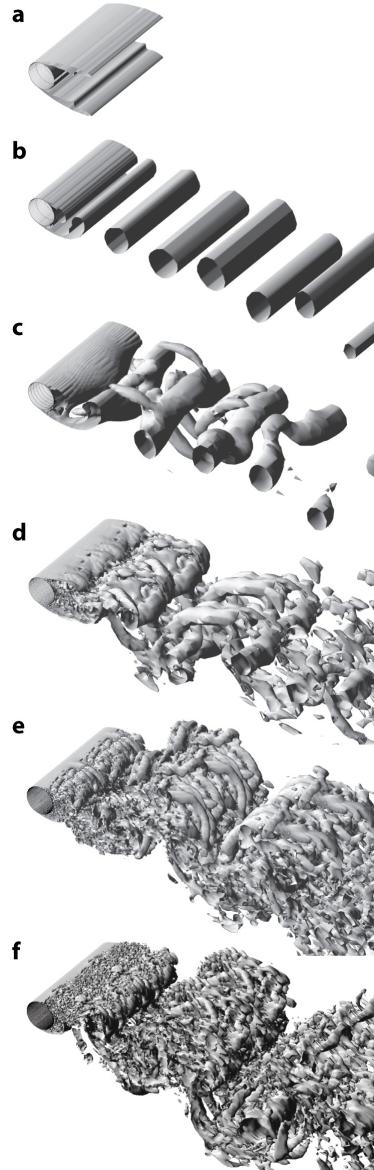
**Fig. 5 cylinder les vs rans grid [4]**

Figure1. Medium computational grid, CaseTS2. Innerblock  $150 \times 36$ , wakeblock  $74 \times 36$ , outer block  $59 \times 30$ . The three blocks meet near  $x = 1.06$ ,  $y = 1.03$ . Grid for spalart cylinders.



**Fig. 6 cylinder les vs rans [5]**

grid for LES shown above (actual simulations were DES)



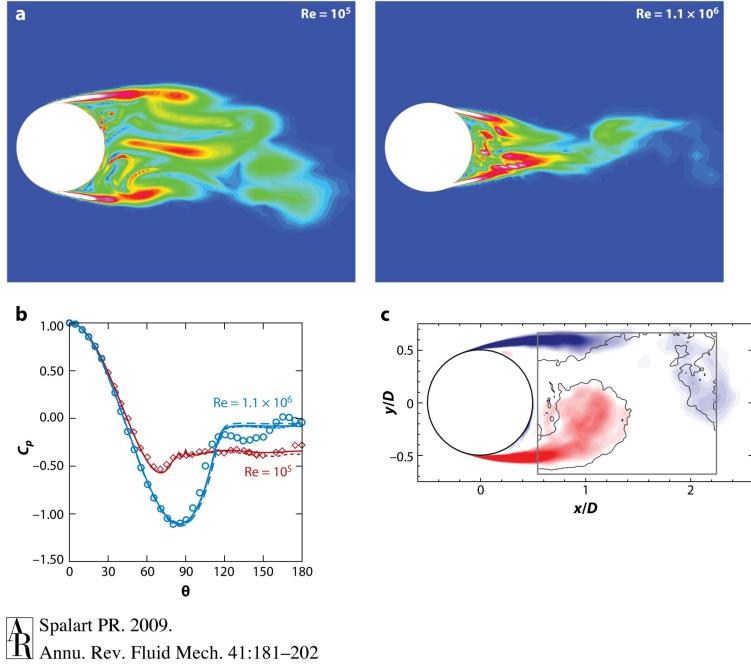
 Spalart PR. 2009.  
Annu. Rev. Fluid Mech. 41:181–202

**Fig. 7 cylinder simulation with RANS, 2DURANS, 3DURANS, SSTDES, SADES [6]**

Vorticity isosurfaces by a circular cylinder:  $ReD = 5 \times 10^4$ , laminar separation. Experimental drag coefficient  $C_d = 1.15\text{--}1.25$ . (a) Shear-stress transport (SST) turbulence model steady Reynolds-averaged Navier-Stokes (RANS),  $C_d = 0.78$ ; (b) SST 2D unsteady RANS,  $C_d = 1.73$ ; (c) SST 3D unsteady RANS,  $C_d = 1.24$ ; (d) Spalart-Allmaras (SA) detached-eddy simulation (DES), coarse grid,  $C_d = 1.16$ ; (e) SA DES, fine grid,  $C_d = 1.26$ ; (f) SST DES, fine grid,  $C_d = 1.28$ . Figure courtesy of A. Travin

illustrates the response of DES to grid refinement in its LES region.

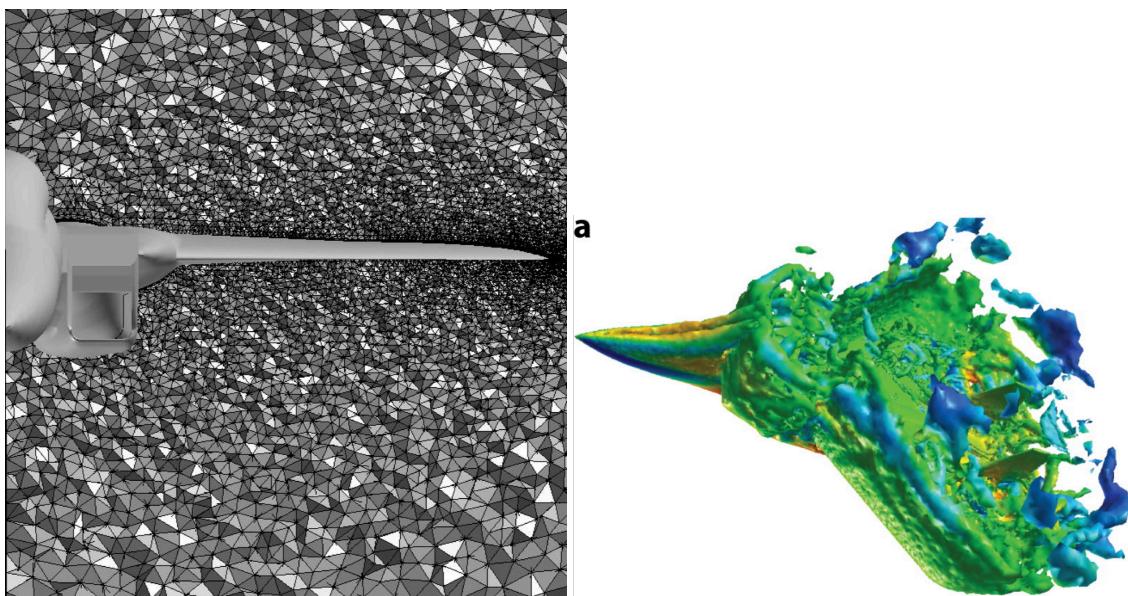
DES solutions with different base RANS models are not sensitive to model choice in the LES region (as opposed to the RANS region, particularly if separation occurs).



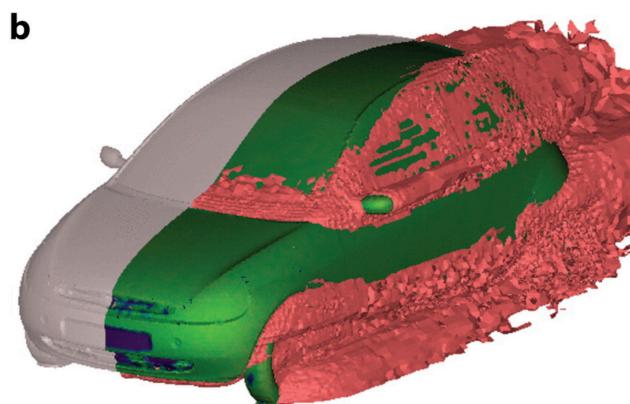
**Fig. 8 DES validation from [6]. Sphere transition and drag crisis from [7]. Vorticity validation from [8]**

Simple bluff bodies. (a) Flow visualizations and (b) pressure distributions for a sphere.  $Re = 10^5$  and  $1.1 \times 10^6$ . Open circles and diamonds denote experiments, whereas the dotted and dashed lines denote detached-eddy simulation (DES) on two grids. Panels a and b courtesy of K. Squires. (c) Phase-averaged vorticity contours for a cylinder. Color gradations denote DES conducted by Mockett et al. (2008), and the solid line denotes experiments by the same authors.

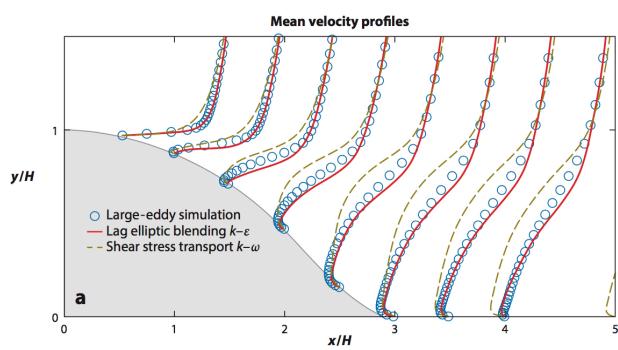
NOTE: DES could be used to emulate the dimples on a golf ball by setting the boundary layer separation point, but true simulation of flow in golf ball dimples requires DNS



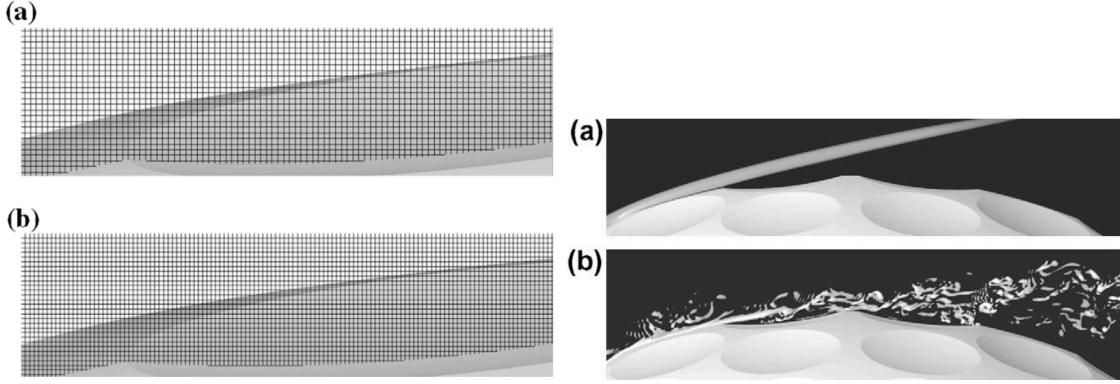
**Fig. 9** F-15 DES grid (left) [9] vorticity isocontours (right) [6]



**Fig. 10** car DES isocontours [10]



**Fig. 11** curve backstep velocity profile les vs rans [11]

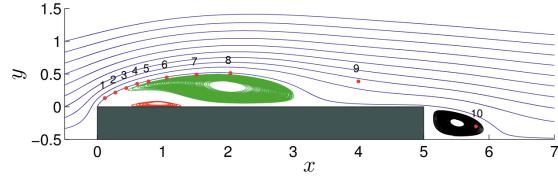


**Fig. 12 DNS non-rotating golf ball with dimples grid (left) vorticity (right) [12]**

Example grid resolution in a dimple near  $84^\circ$  (measured from the stagnation point at the front of the golf ball). (a)  $\text{Re} = 2.5 \cdot 10^4$ ; (b)  $\text{Re} = 1.1 \cdot 10^5$ .

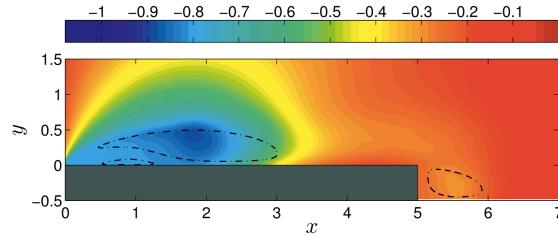
Contours of azimuthal vorticity. (a)  $\text{Re} = 2.5 \cdot 10^4$ ; (b)  $\text{Re} = 1.1 \cdot 10^5$

NOTE: Recall sphere example from Spalart review and say that this is the analogous DNS experiment to his DES



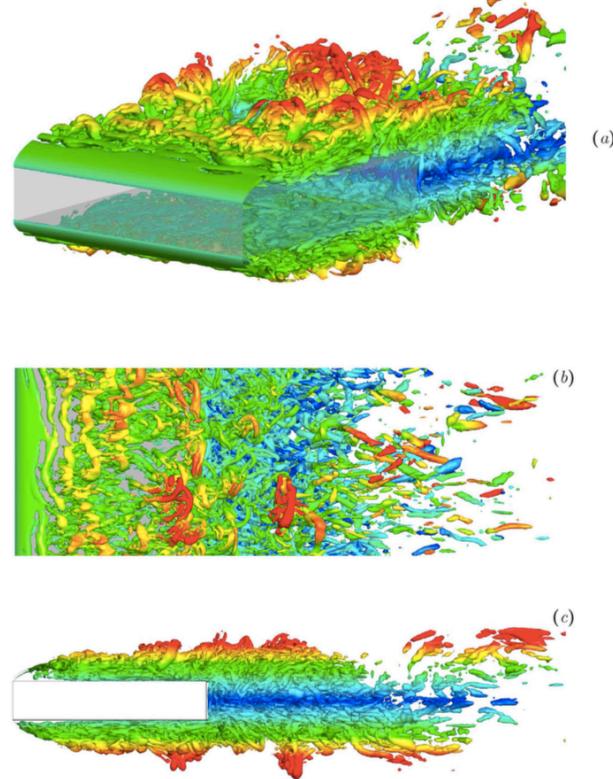
**Fig. 13 DNS square cylinder vortex locations  $\text{Re}=3000$  [13]**

Fig. 4. Streamlines of the mean velocity field ( $U, V$ ) ( $x, y$ ) The green lines show the primary vortex, the red lines mark the secondary vortex and the black lines denote the wake vortex. The red dots denote the locations of the probes used for the computation of time spectra in section x5. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)



**Fig. 14 DNS square cylinder mean pressure distribution  $\text{Re}=3000$  [13]**

Fig. 5. Isocontours of the mean pressure field  $P(x,y)$ . The dashed lines report the location of the primary vortex, secondary vortex and wake vortex.



**Fig. 15 DNS square cylinder vorticity contours  $Re=3000$  [13]**

Fig. 10. Instantaneous isosurfaces of  $\lambda_2 = -2$  colored with  $y$ . Perspective, top and lateral views in (a), (b) and (c) plots, respectively.

#### IV. Current State of Bluff-Body Turbulence Analysis

- Current State of Knowledge
- Remaining Challenges

##### A. Experimental Methods

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##### B. Computational Methods

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## V. Conclusions

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## Acknowledgments

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### Example citations

[14]

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