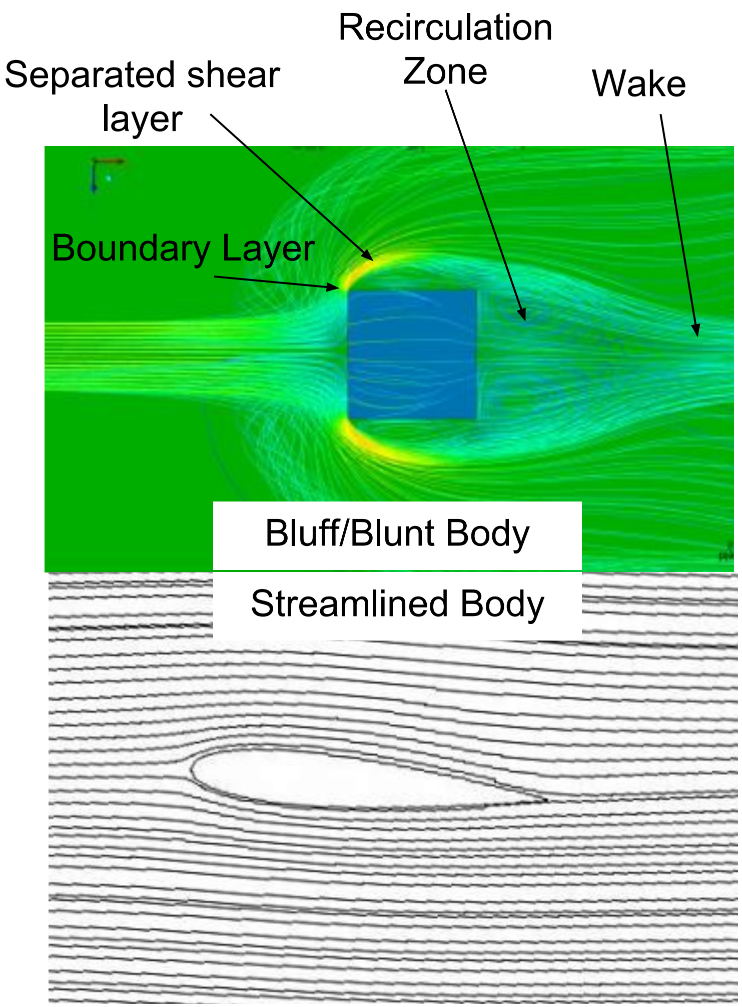
MAE 210B – Bluff Body Turbulence

Federico Zabaleta and Logan Halstrom

March 14, 2018

Bluff vs. Streamlined Bodies

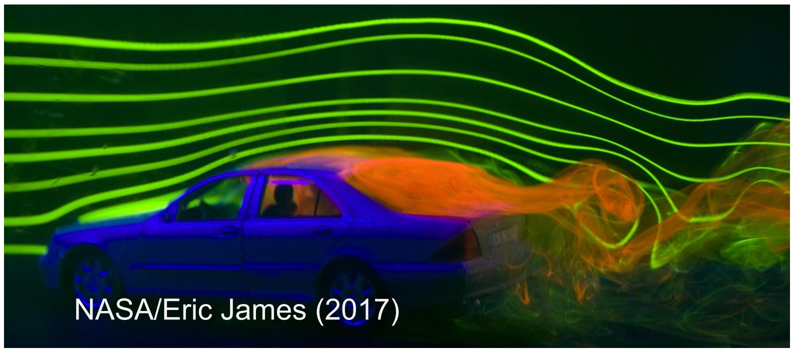


- Drag = Friction drag + Pressure drag
- Friction drag dominates streamlined body (attached BL)
- Pressure drag dominates bluff body
  - Separated flow/no pressure recovery
  - Constant pressure in recirculation zone called “base pressure”

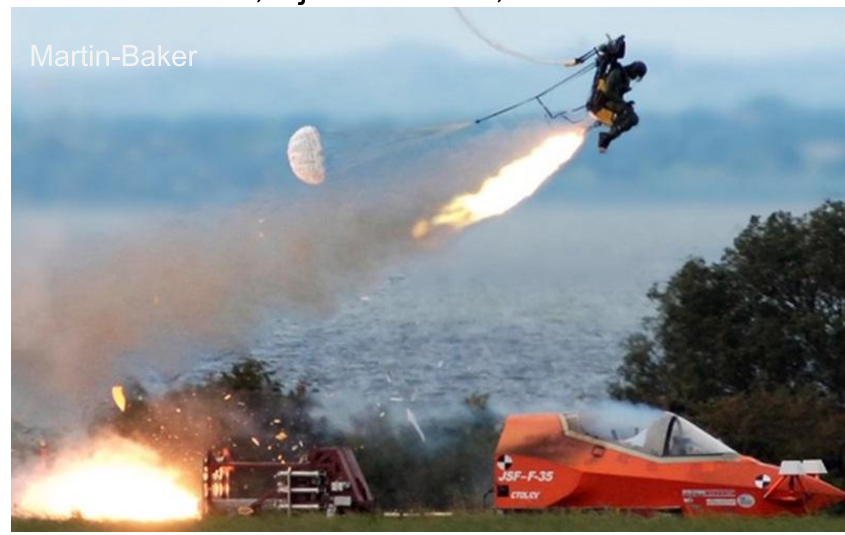
Real-World Applications

Concerns: acoustics, vehicle stability, buffeting/unsteady loads, mixing, etc.

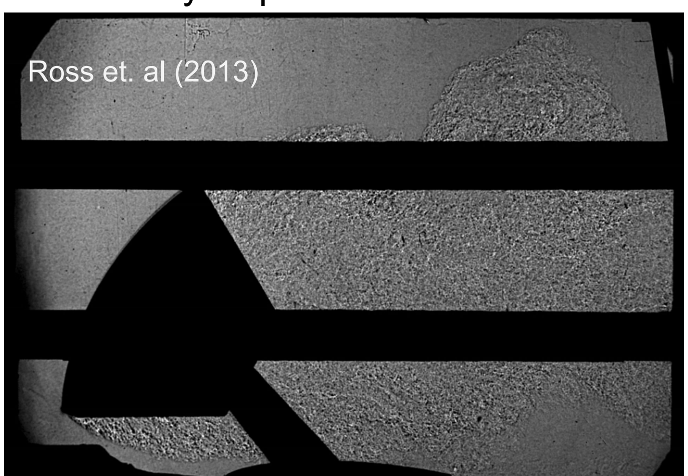
Passenger Vehicle Wake



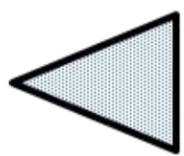
Human, Ejection Seat, and Parachute



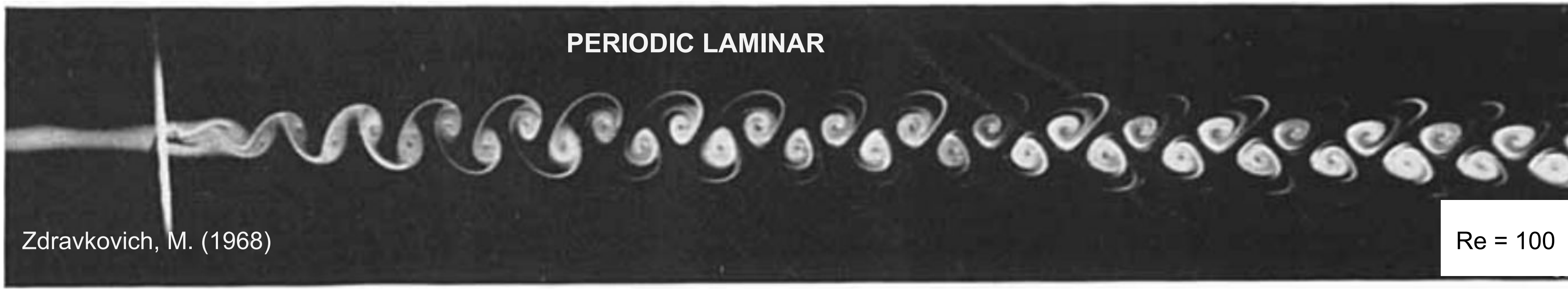
Reentry Capsule Subsonic Wake

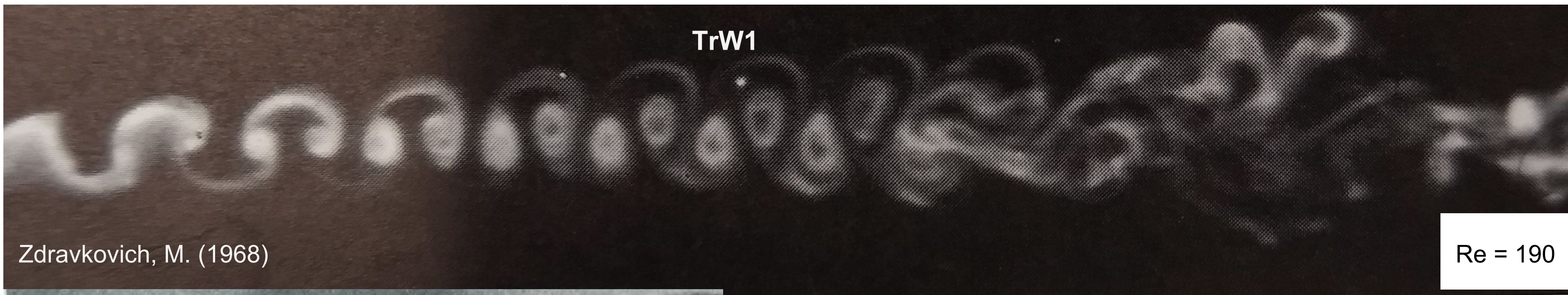


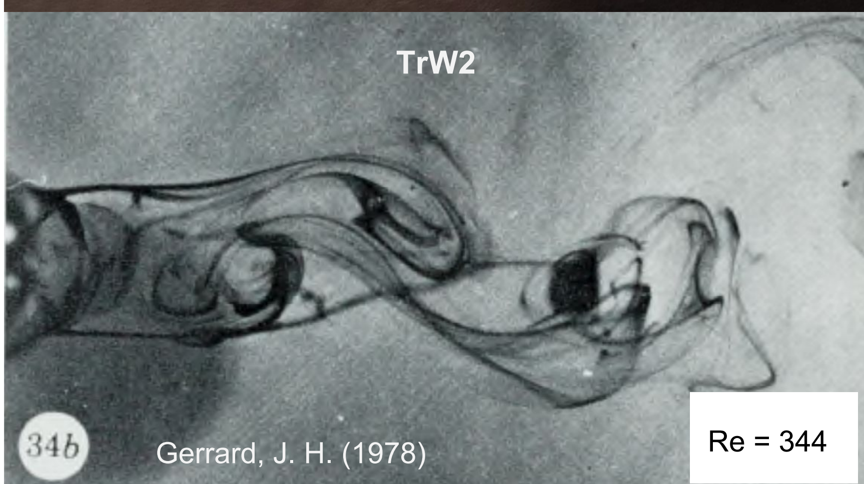
Bluff Body Flame Holder



Flow around a cylinder







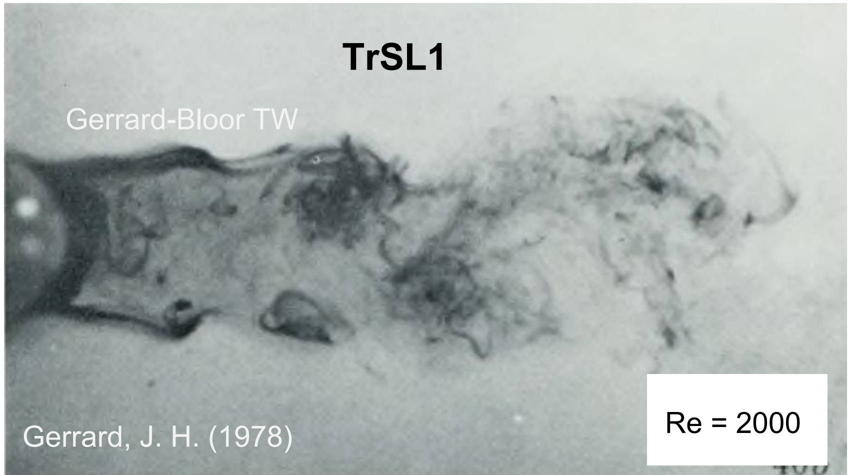
LAMINAR STATE REGIMES

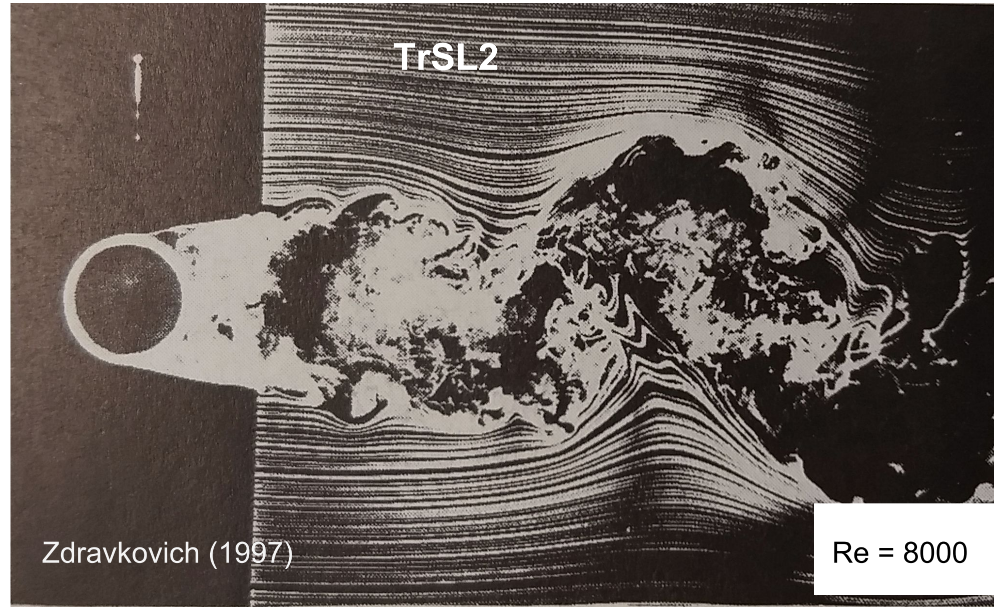
- Creeping Flow; 0 < Re < 4-5
- Steady separation; 4-5 < Re < 30-48
- Periodic laminar; 30-48 < Re < 180-200

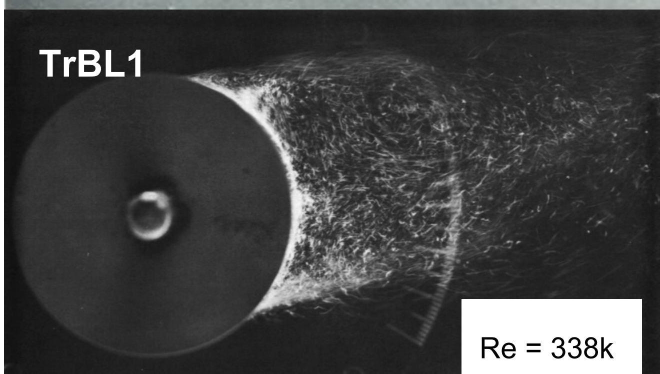
TRANSITION IN WAKE

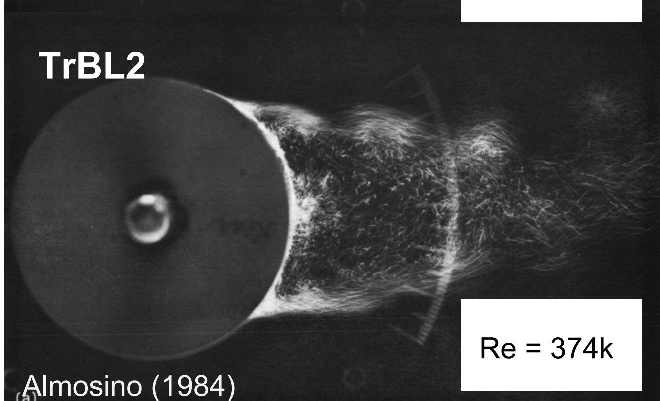
- TrW1; 180-200 < Re < 220-250
- TrW2; 220-250 < Re < 350-400

Flow around a cylinder









TRANSITION IN SHEAR LAYER

- TrSL1: Transition waves; 350-400 < Re < 1k-2k
- TrSL2: Transition Eddies; 1k-2k < Re < 20k-40k
- TrSL3: Burst to turbulence; 20k-40k < Re < 100k-200k

TRANSITION IN BOUNDARY LAYER

- TrBL0; precritical regime; 100k-200k < Re < 300k-400k
- TrBL1: one-bubble regime; 300k-400k < Re < 380k-400k
- TrBL2; two-bubble regime; 380k-400k < Re < 0.5M-1M
- TrBL3; supercritical regime; 0.5M-1M < Re < 3.4M-6M
- TrBL4; postcritical regime; 3.4M-6M < Re < unknown

FULLY TURBULENT FLOW

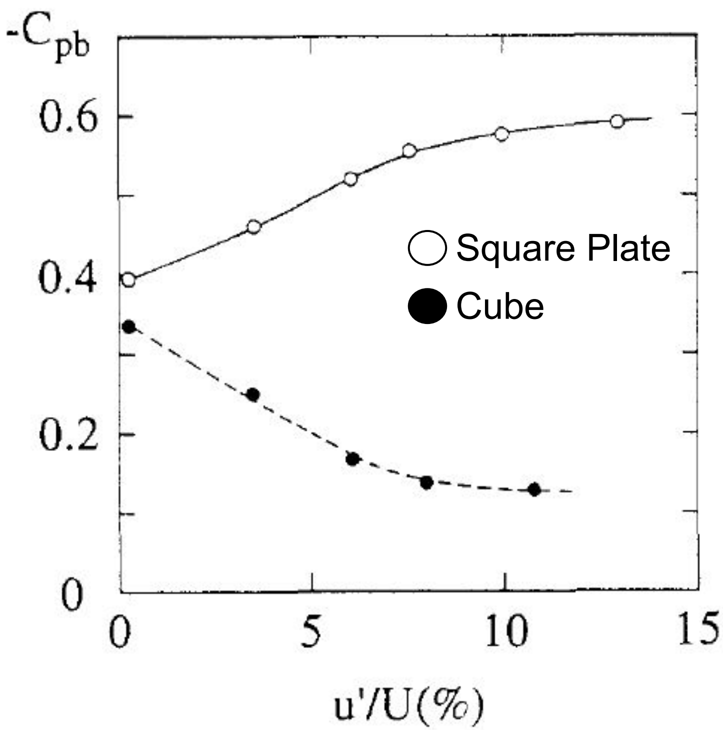
Influence of FS turbulence

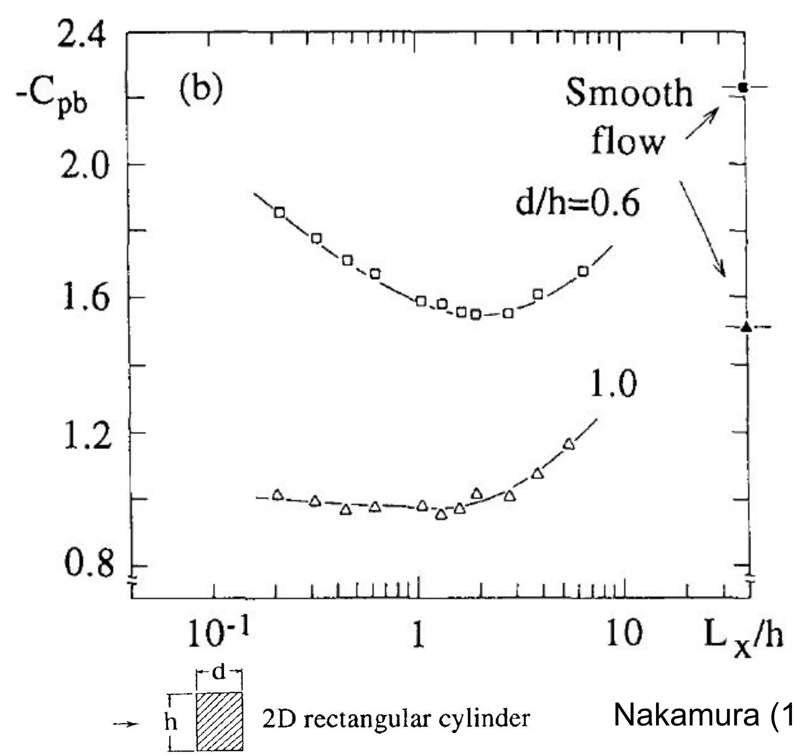
Free stream turbulence affects flow around bluff bodies

$$C_D, C_L, C_P = f(u'/U, Lx/h)$$

Turbulence Intensity

Turbulence lengthscale
(Integral lengthscale)

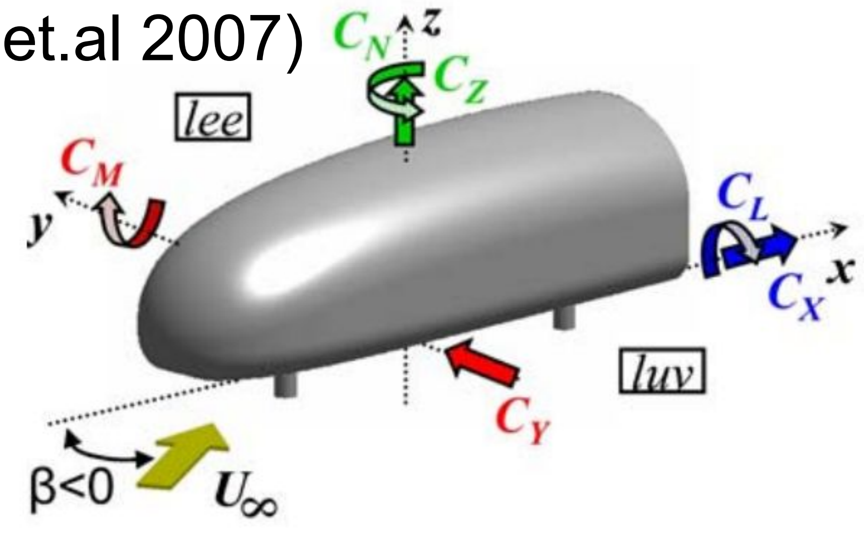




Nakamura (1993)

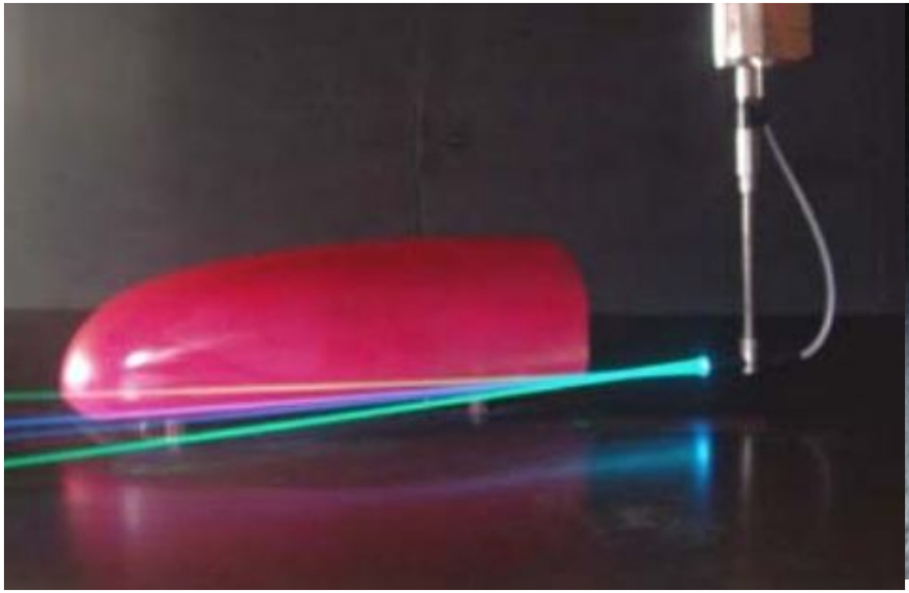
Exp methods: Example 1

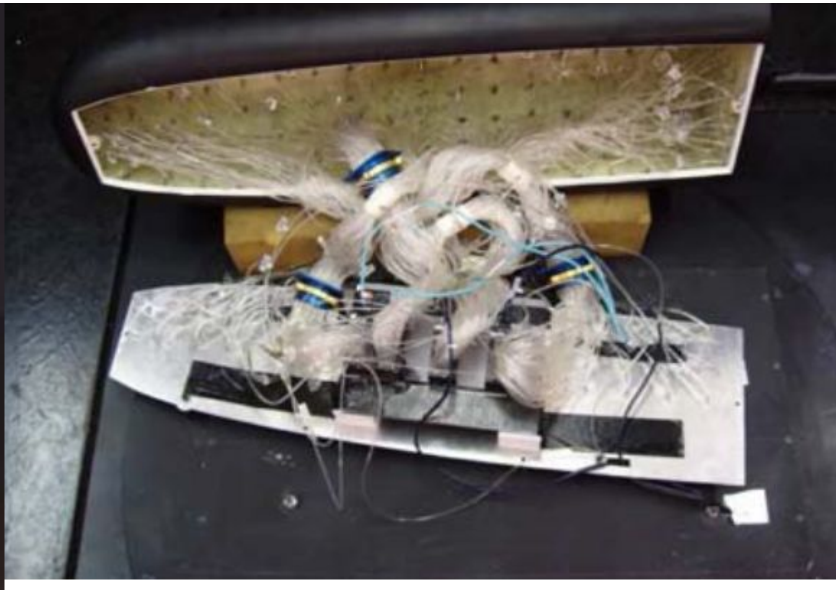
3D-Bluff-Body crossflow (Gohlke et.al 2007)



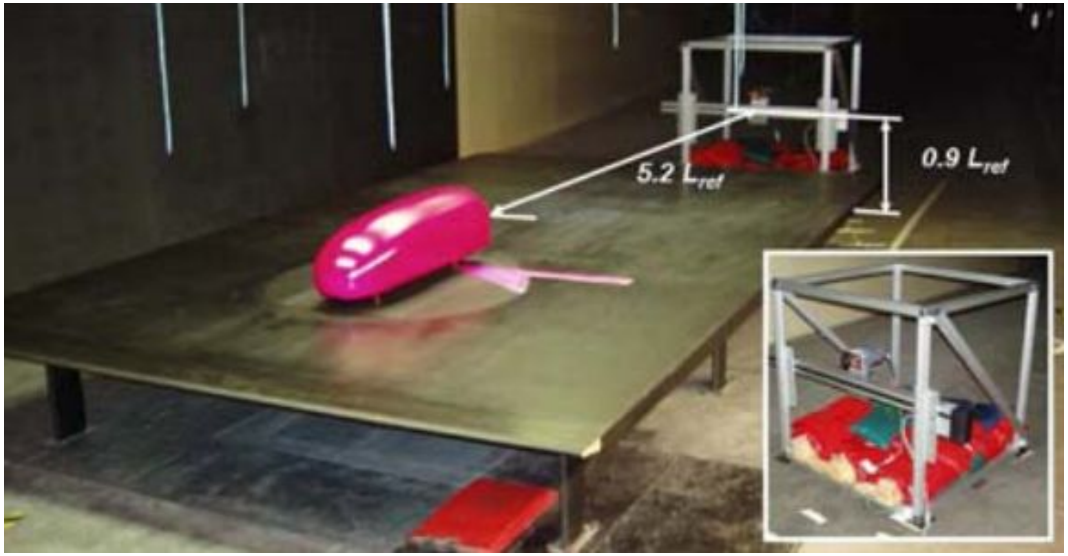
Trains - Trucks

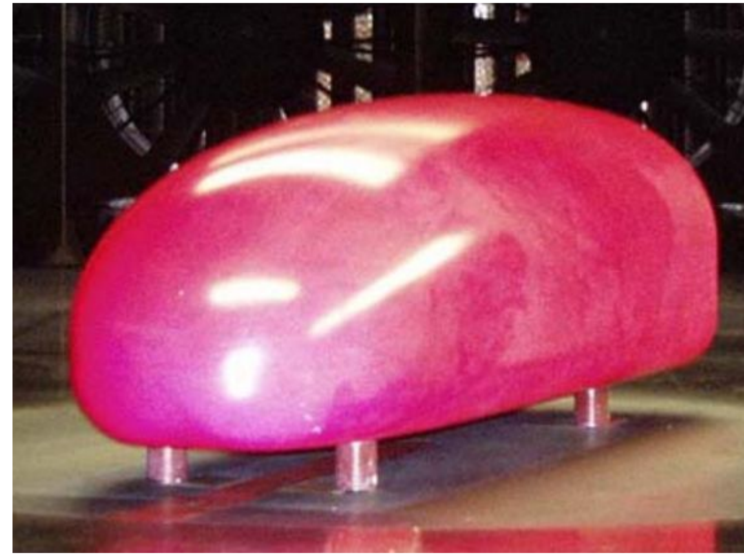
- PIV
- Force measurements - Gauges
- 249 Pressure sensors
- Oil flow - Time averaged flow patterns
  - Separation and reattachment.
- Laser Doppler velocimetry

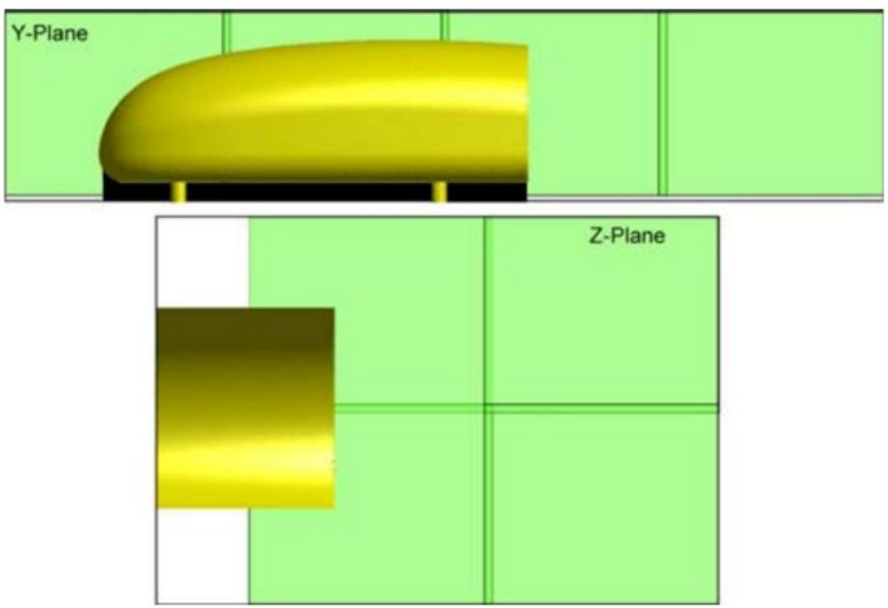


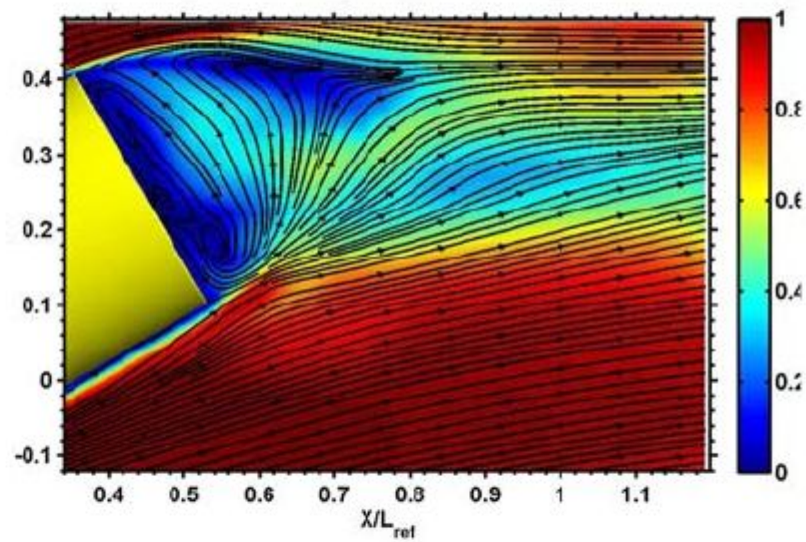


Exp methods: Example 1





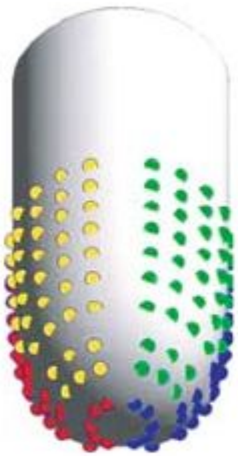


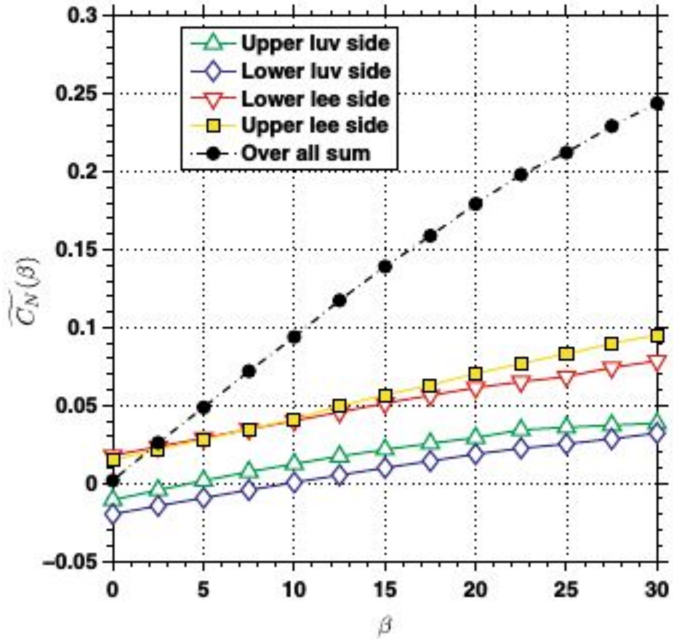


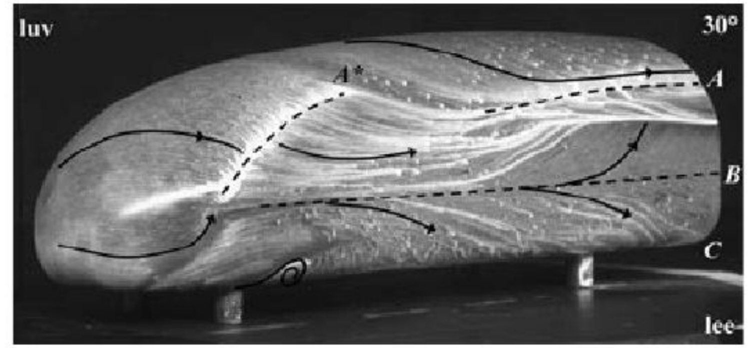
(d) $\beta = 30°$

Golhke et.al (2007)

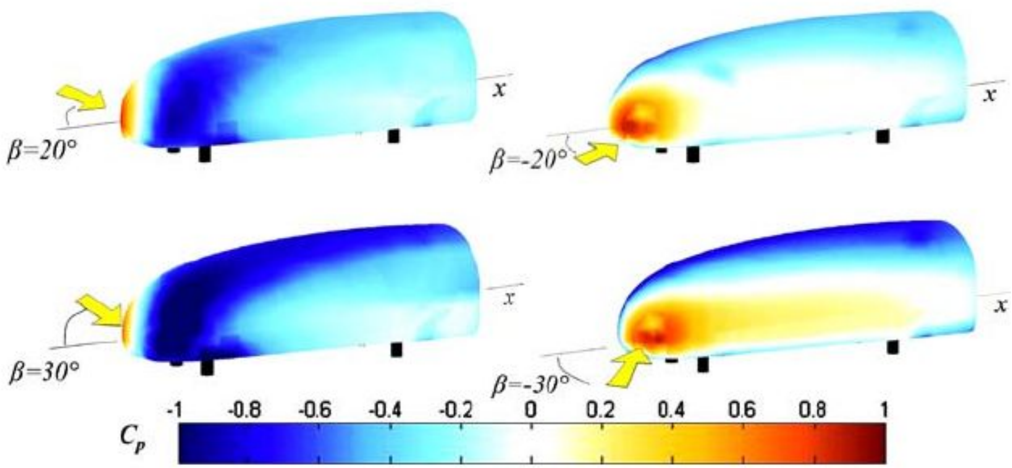
Exp methods: Example 1

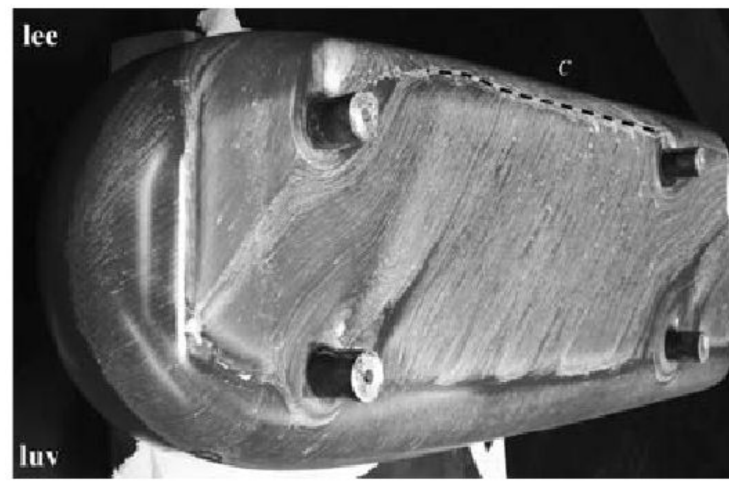






23 Oil-flow visualisation of the lee-ward side at $\beta = 30°$





24 View of the underbody flow at $\beta = 30°$

Golhke et.al (2007)

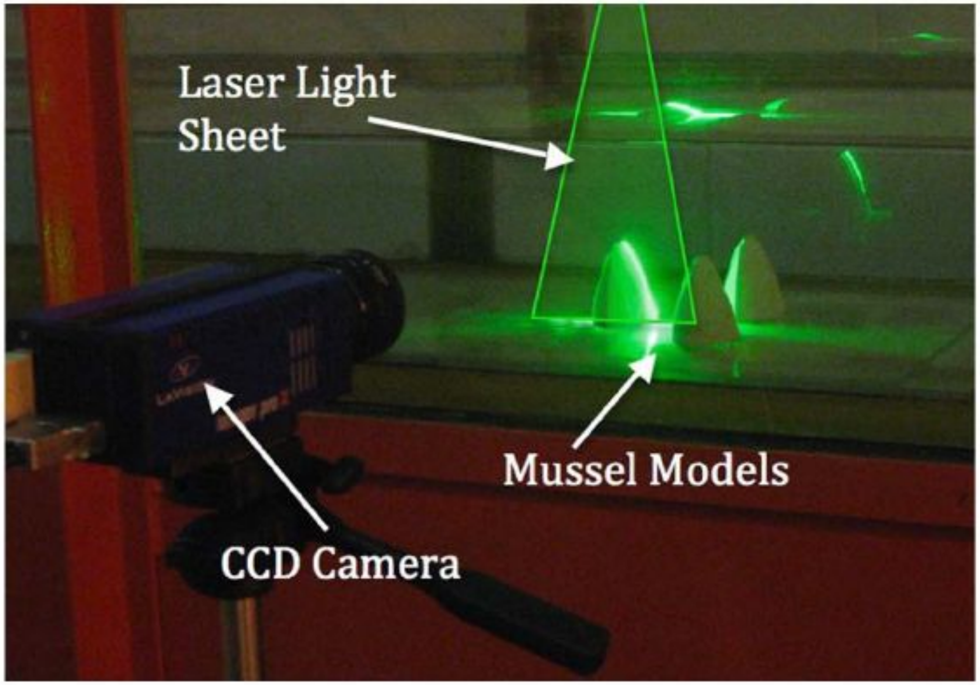
Exp methods: Example 2

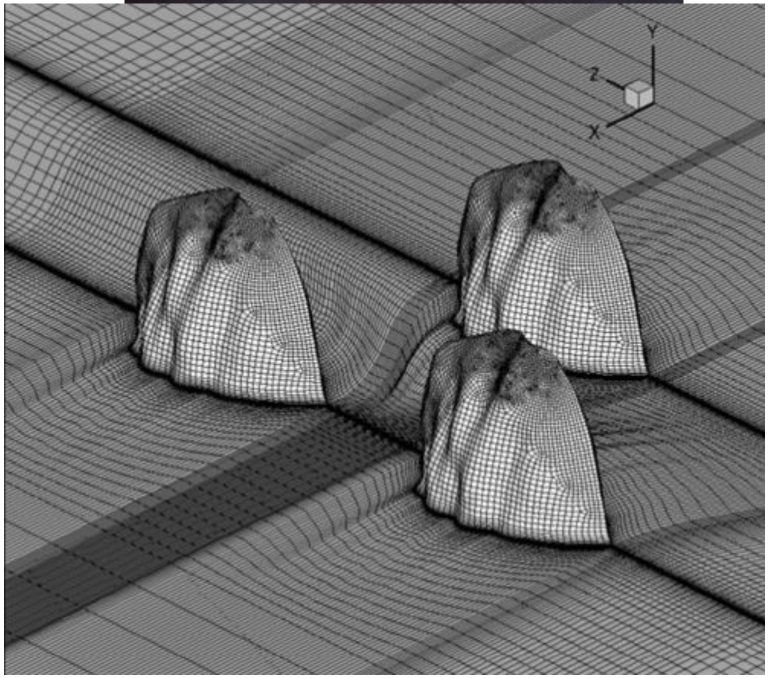
Flow and Turbulence structures around Mussels. Constantinescu et al (2013)

Megalonaias nervosa

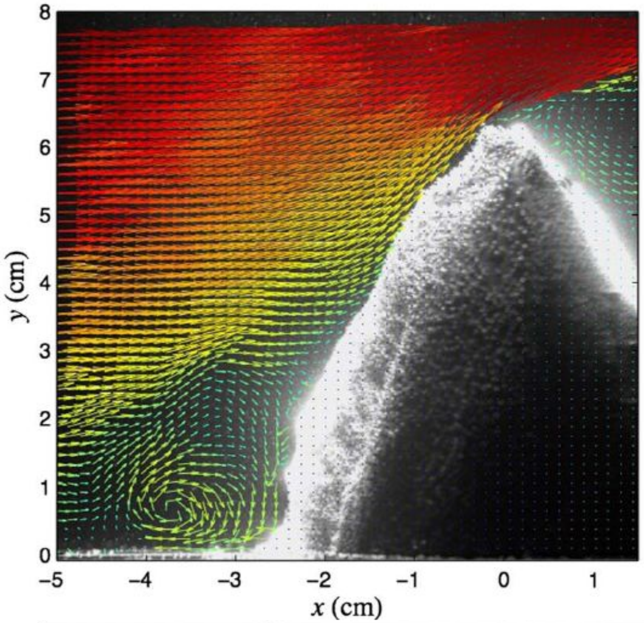
Computerized axial tomography (CAT)

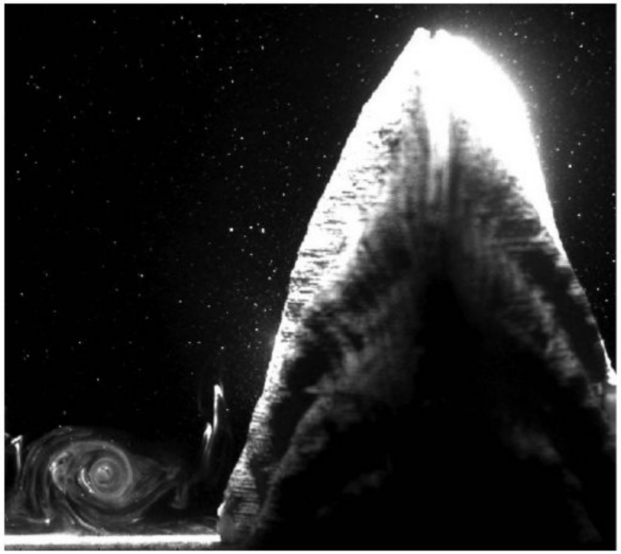
Physical model. Injection technique from CAT

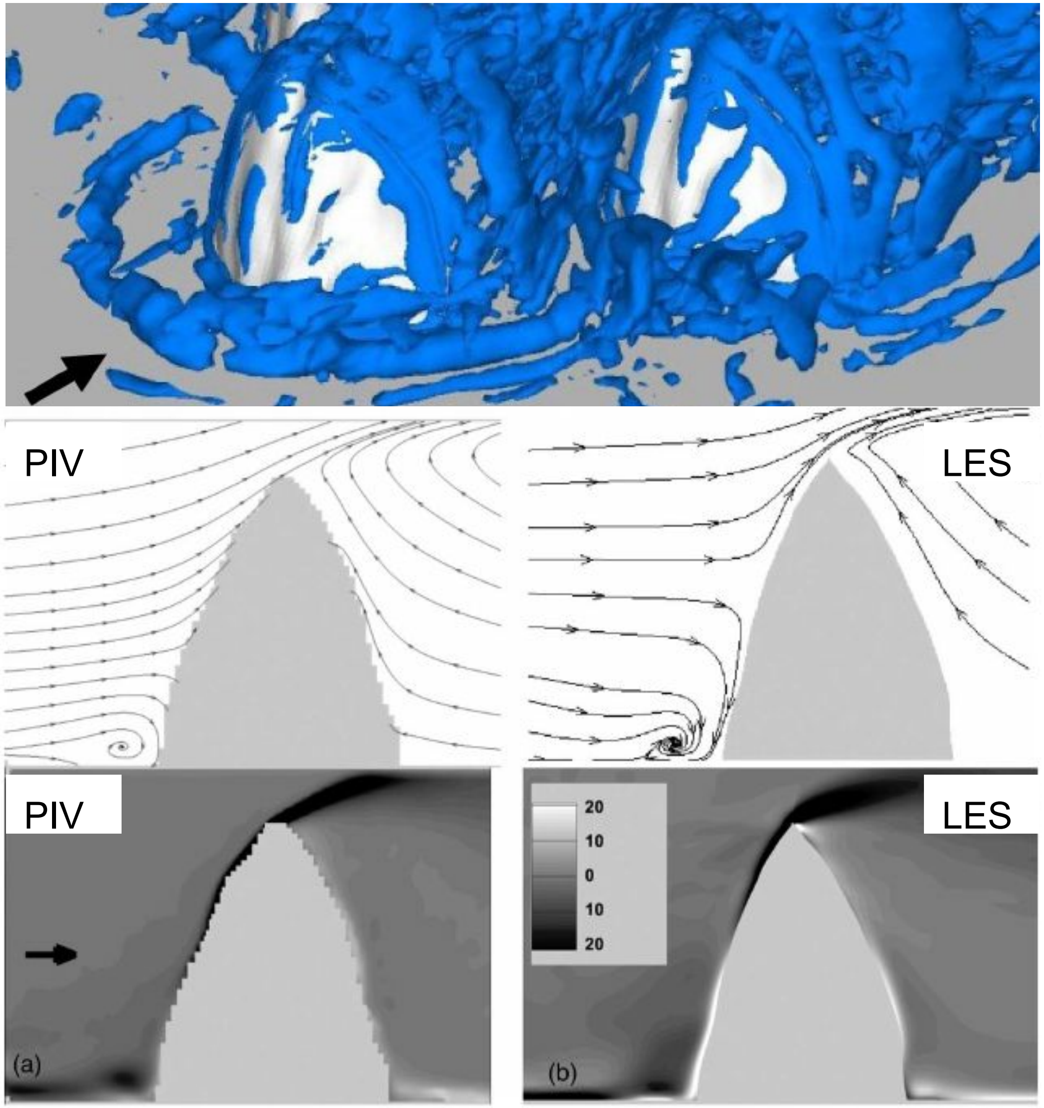




Exp methods: Example 2







Constantinescu et.al (2013)

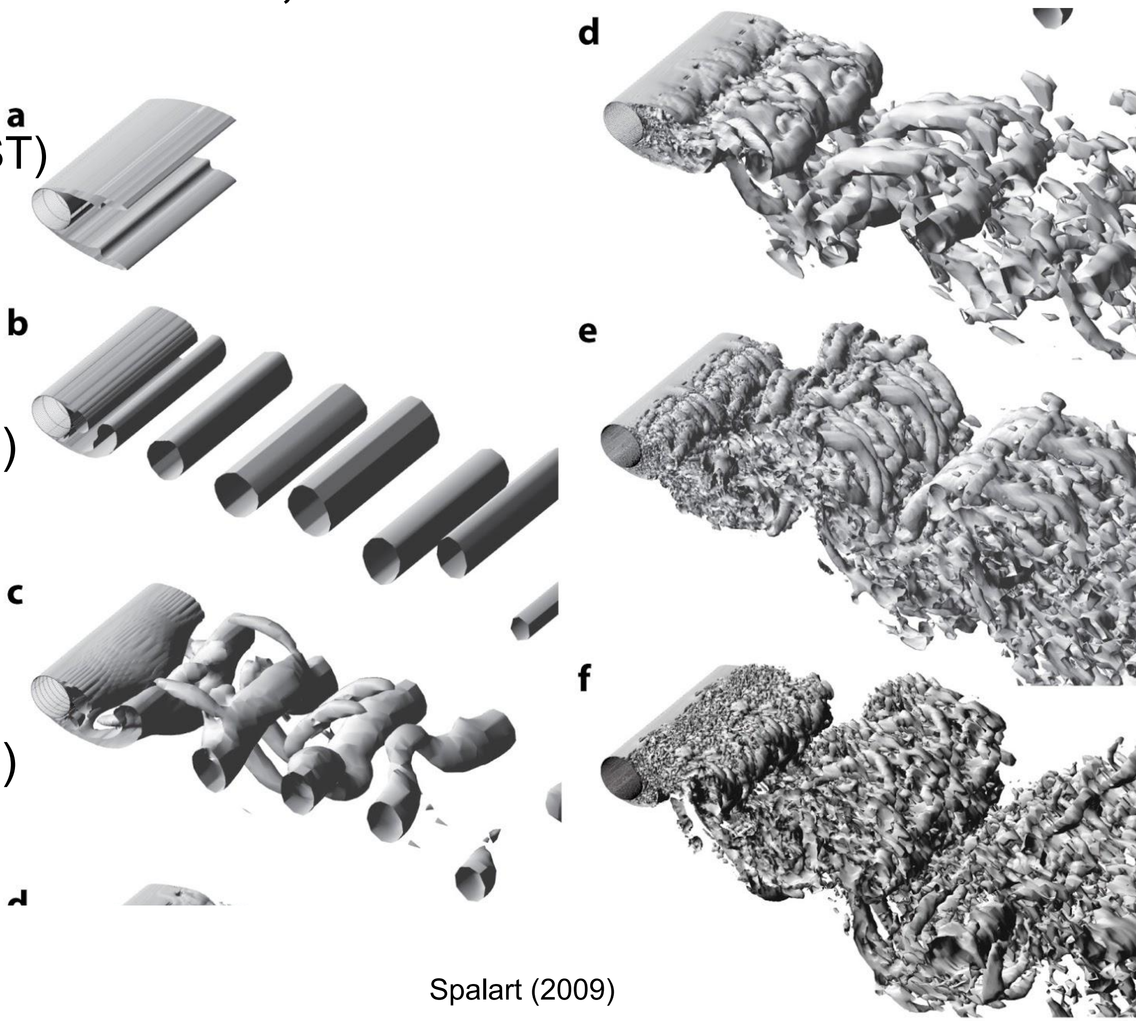
Turbulence Modeling Overview

- Direct Numerical Simulation (DNS)
  - Solve Navier-Stokes equations directly (no modeling)
  - Must resolve all turbulence scales on grid
- Reynolds-Averaged Navier-Stokes (RANS)
  - Decompose into mean and perturbation quantities, simplify
  - Model turbulence (typically with eddy viscosity relations)
- Unsteady RANS (URANS)
  - Global time stepping, capture unsteady behavior in mean flow
- Large Eddy Simulation (LES)
  - Solve large turbulent structures directly on grid (DNS)
  - Model small turbulence with subgrid-scale (SGS) model
- Detached Eddy Simulation (DES)
  - Hybrid RANS/LES: Use RANS near wall instead of SGS
- Scale Adaptive Simulation (SAS)
  - RANS-like model that adjusts with von Karman length-scale
  - Allows turbulent spectrum to develop (LES-like)

Simulation Comparisons

Vorticity isosurfaces over a circular cylinder

Experiment: Re=5e4, Cd=1.15-1.25



Steady RANS (SST)
Cd=0.78

2D URANS (SST)
Cd=1.73

3D URANS (SST)
Cd=1.24

Coarse DES (SA)
Cd=1.15

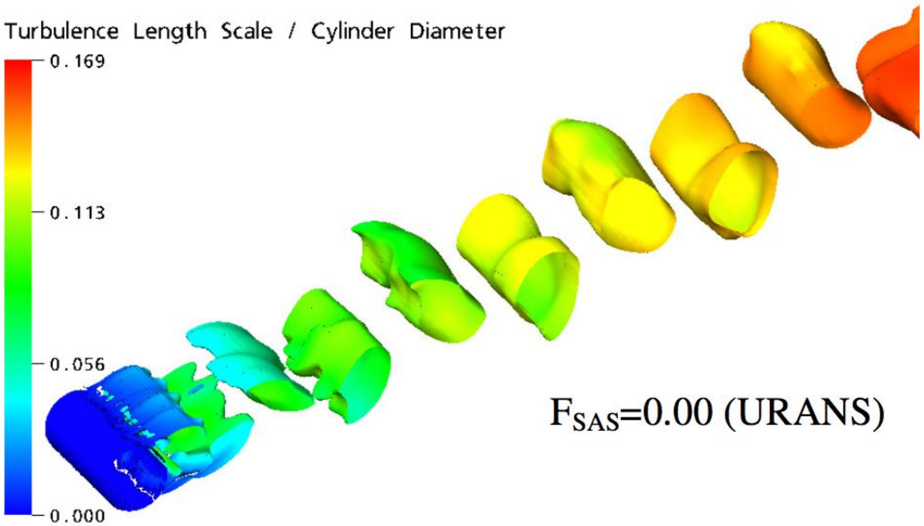
Fine DES (SA)
Cd=1.26

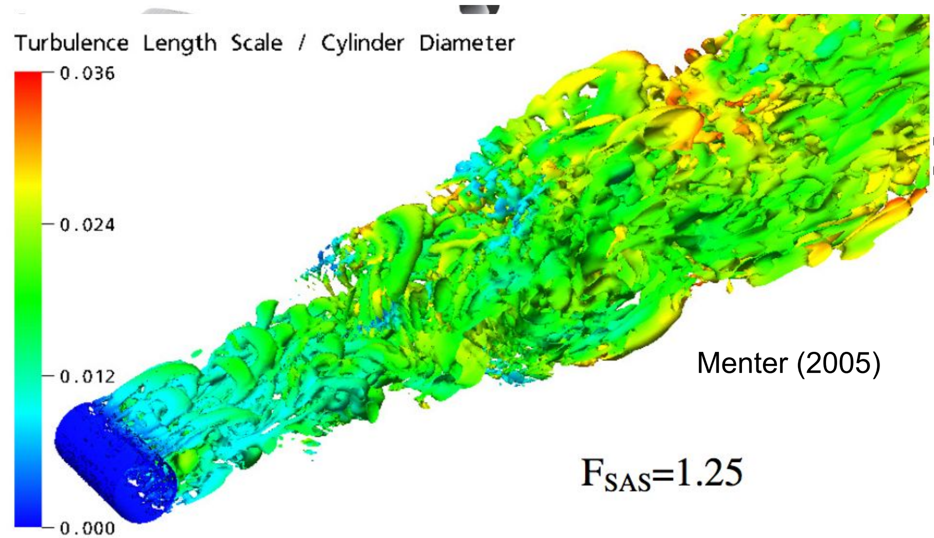
Fine DES (SST)
Cd=1.28

Spalart (2009)

Simulation Comparisons

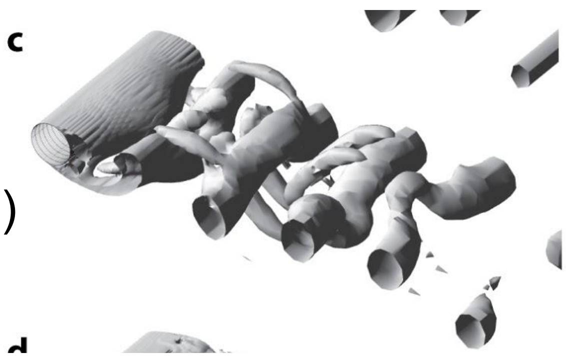
SAS attempts to avoid ambiguous grid dependencies of DES

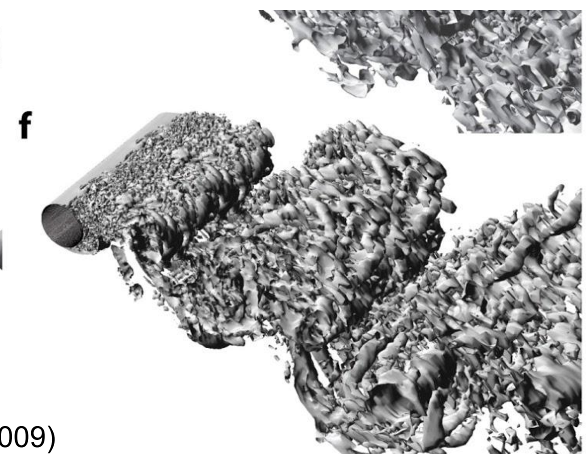




Menter (2005)

3D URANS (SST)
Cd=1.24



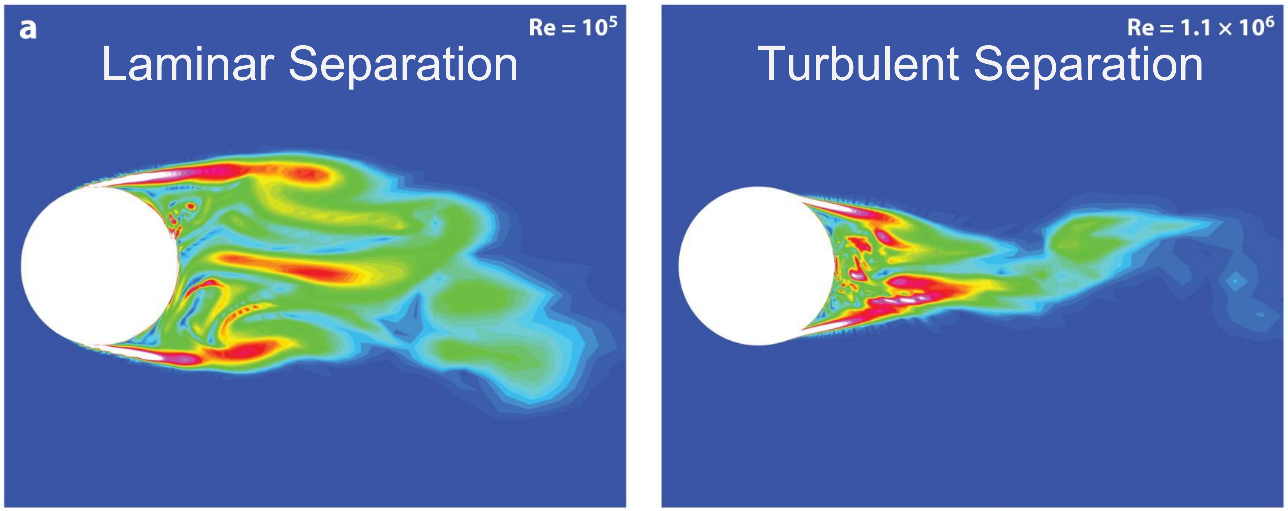


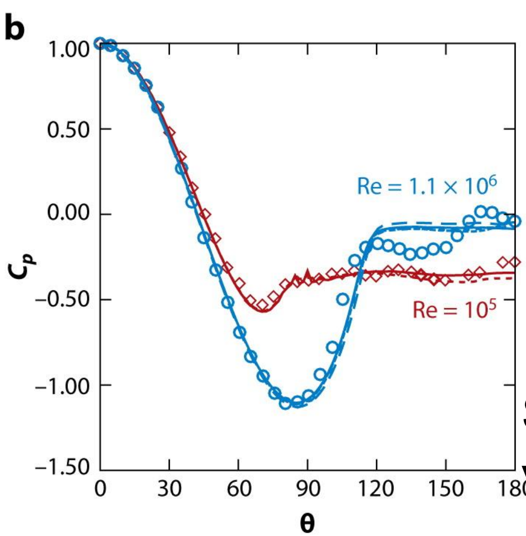
Fine DES (SST)
Cd=1.28

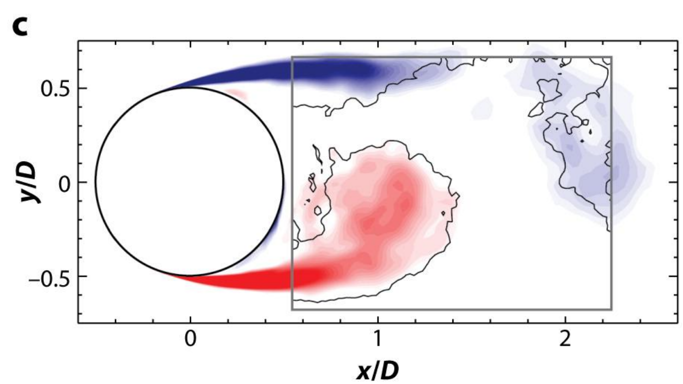
Spalart (2009)

Simulation Successes

DES flow over a sphere (controlled separation)







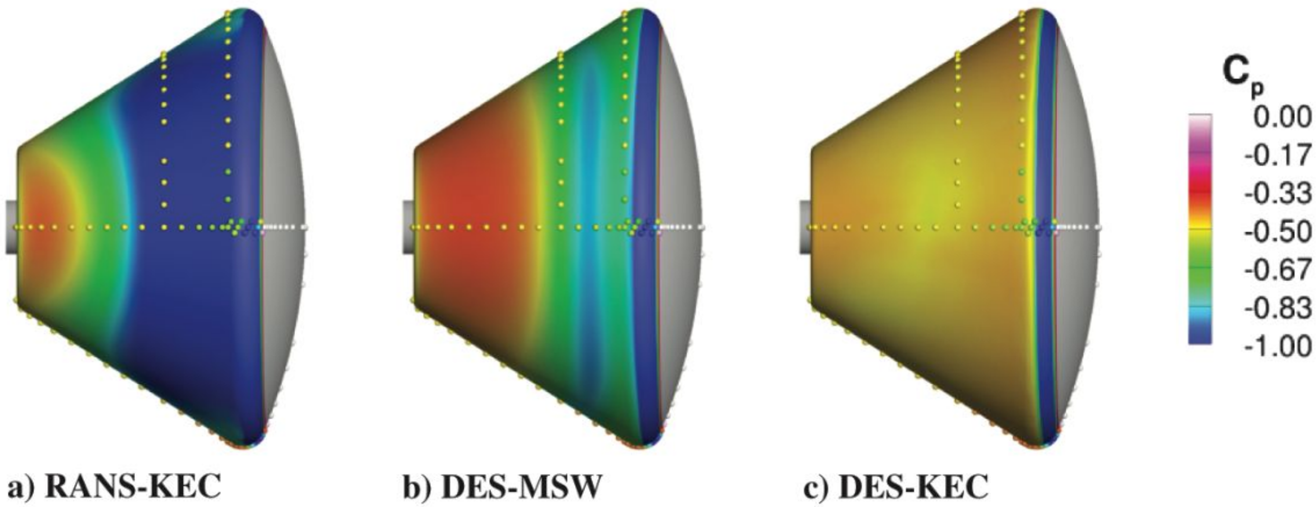
Surface pressure compared to experiment (left)

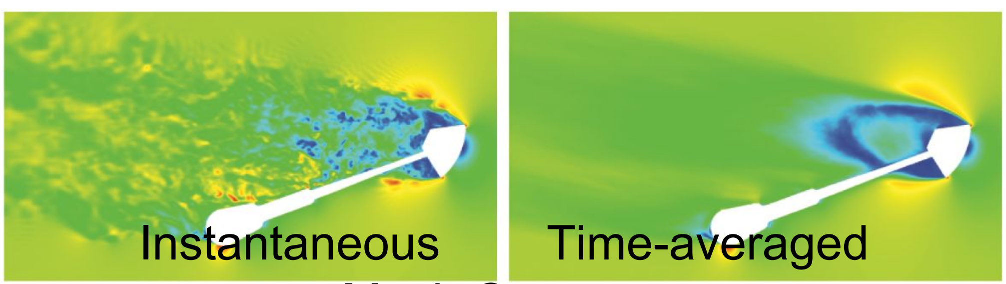
Vorticity contours compared to experiment (above)

DES vs URANS (Capsule)

- Wind Tunnel (dots) and URANS/DES (Schwing et al. 2009)
  - M=0.5, Re=5e6
- Surface pressure: DES (right) closer match than RANS

Capsule Surface Pressure Coefficient



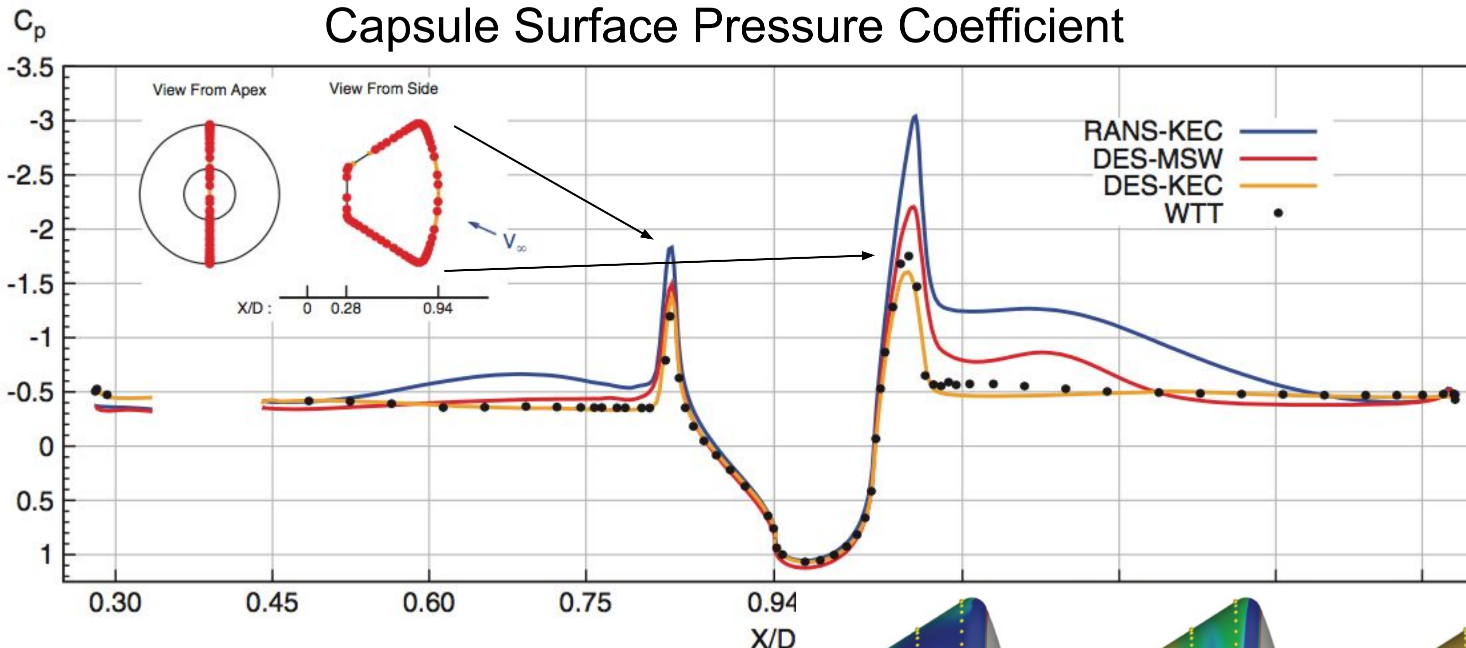


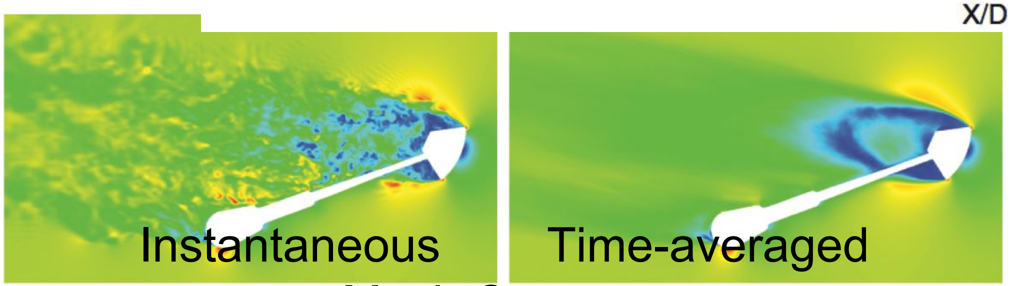
Mach Contours

DES vs URANS Cont.

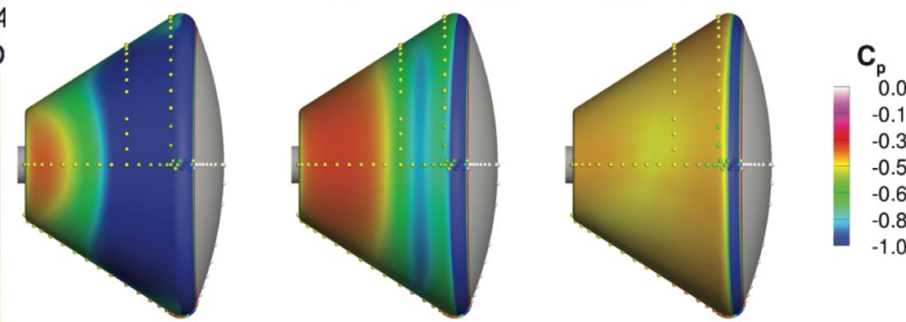
- DES outperforms URANS in suction peak/base pressure prediction: more correct drag integration
- But URANS more correctly predicts lift integration

Capsule Surface Pressure Coefficient



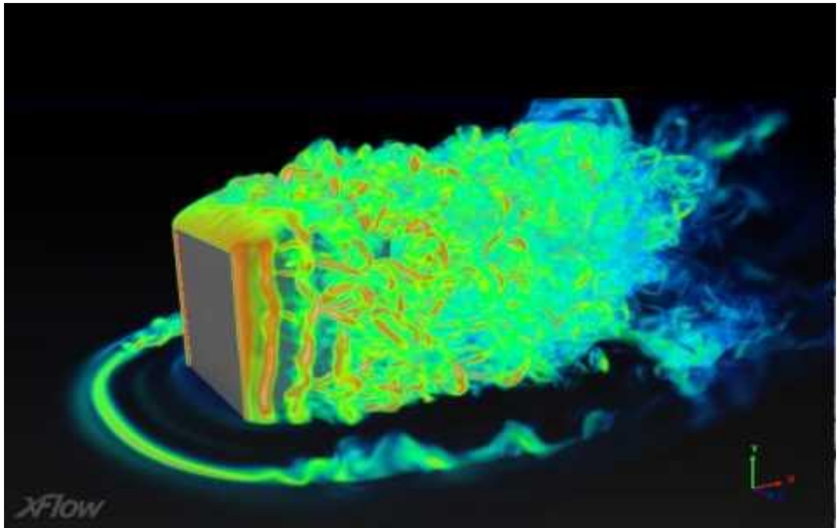


Mach Contours



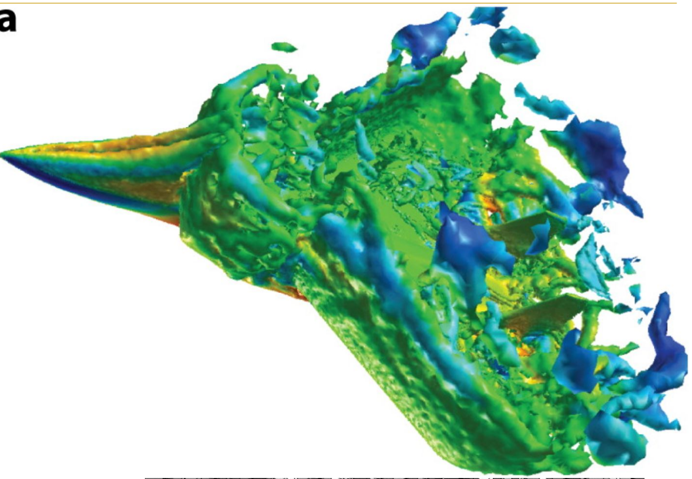
a) RANS-KEC b) DES-MSW c) DES-KEC

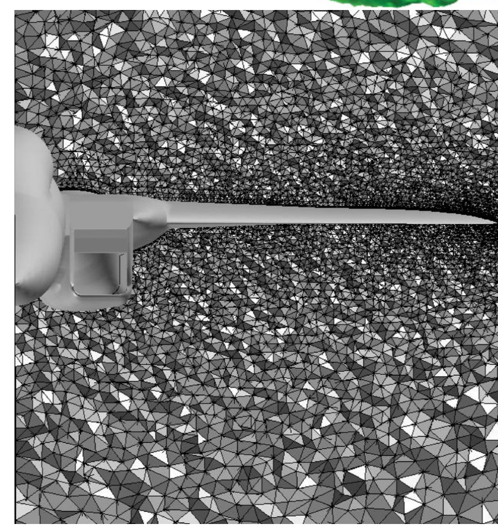
Other Complex Applications



LES of wall-mounted cube (Xflow)

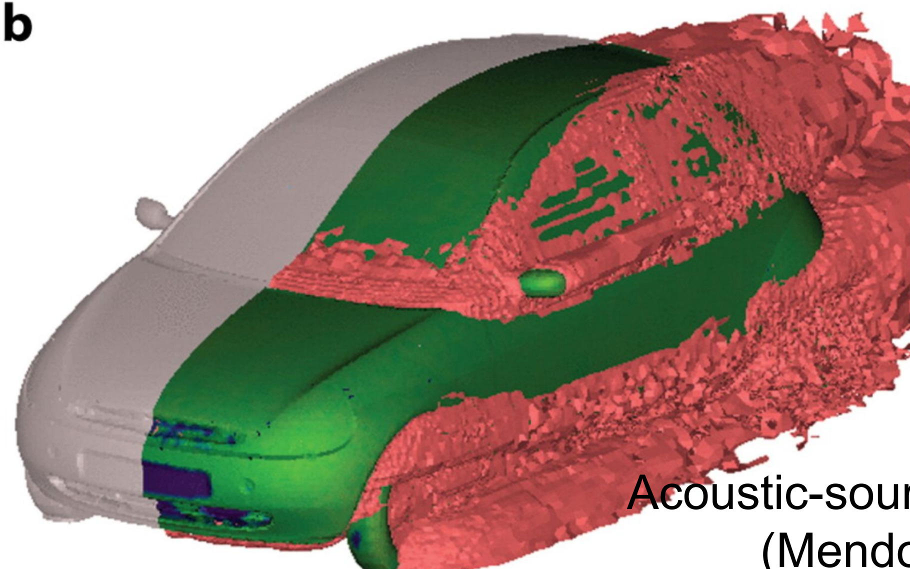
a





F-15 at AoA=65deg (vorticity)
(Forsythe et al. 2004)

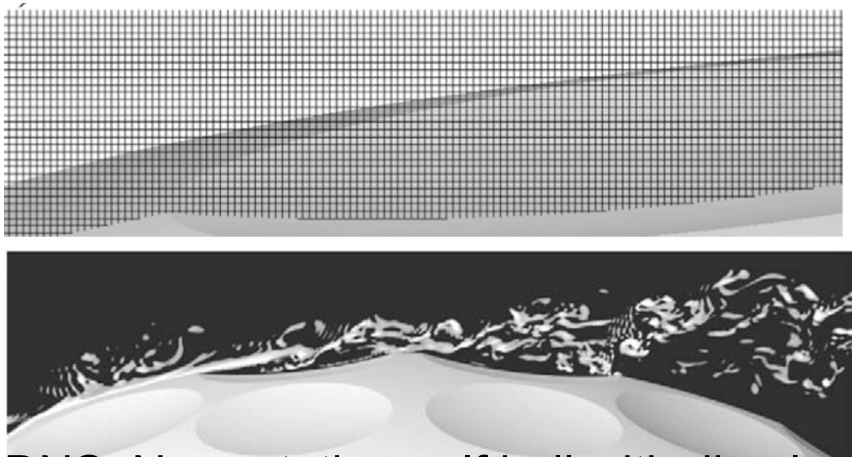
b



Acoustic-source isosurface over car
(Mendonca et al. 2002)

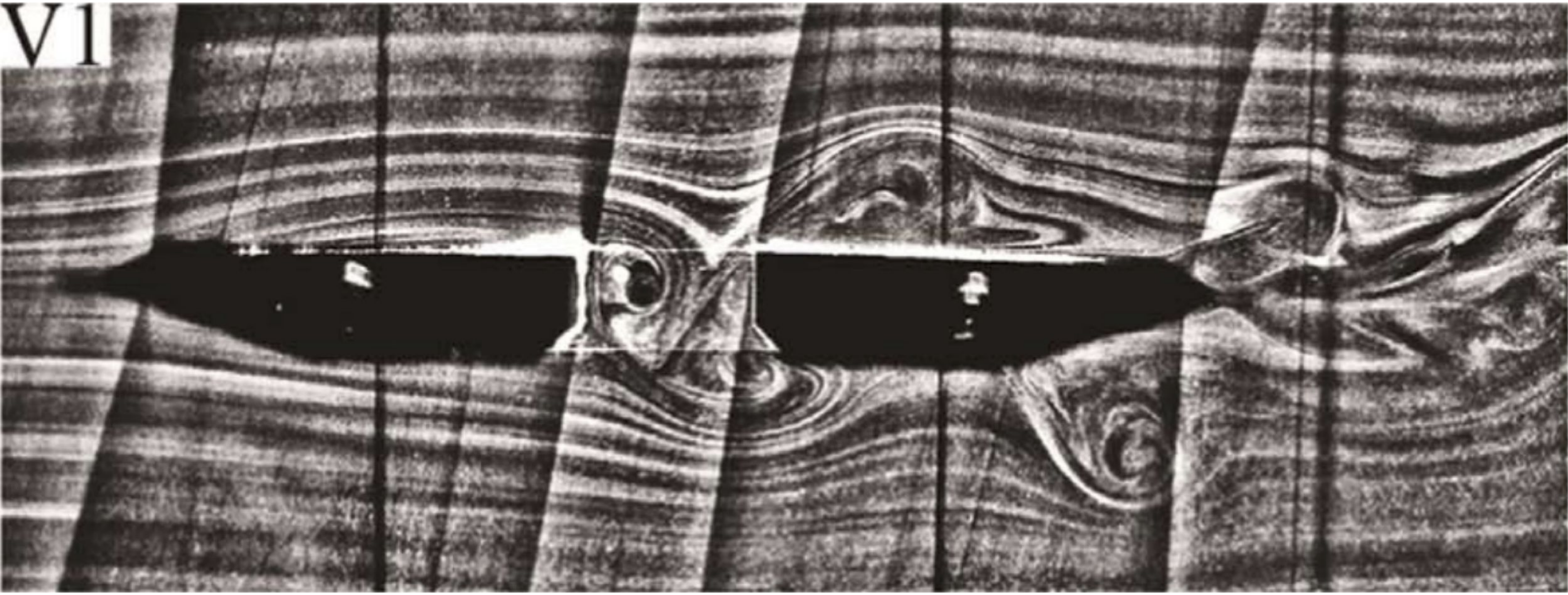
Current State: Bluff Body CFD

- URANS
  - + Least-expensive/most used in industry
  - + Good for averaged loads (lift more than drag)
  - - Unable to resolve true turbulence behaviour in all situations
- DES
  - + More accurate unsteady behavior/turbulence spectra
  - + “Functional” version of LES
  - - Order of accuracy unquantified (hybrid nature)
  - - Grid induced separation, not “plug-and-play”
- SAS:
  - + No grid induced separation
  - - Still modeling turbulence
- ~~DNS~~:
  - + No turbulence modeling
  - - Cost prohibitive grids



DNS: Non-rotating golf ball with dimples
Re=1.1e5 (Smith et al. 2010)

Questions?



Wind Tunnel Test of Bridge Span
(PIV)
(Yuan et al. 2017)

References

[1] Hunt, J., Kawai, H., Ramsey, S., Pedrizetti, G., and Perkins, R., "A review of velocity and pressure fluctuations in turbulent flows around bluff bodies," *Journal of Wind Engineering and Industrial Aerodynamics*, Vol. 35, 1990, pp. 49 – 85. doi:https://doi.org/10.1016/0167-6105(90)90210-4, URL `https://www.sciencedirect.com/science/article/pii/0167610590902104`.

[2] Zdravkovich, M., "Smoke obervations of the formation of a Kárman vortex street," *Journal of Fluid Mechanics*, Vol. 37, No. 3, 1968, pp. 491 – 496. doi:doi:10.1017/S0022112069000681, URL `https://www.cambridge.org/core/journals/journal-of-fluid-mechanics/article/smoke-observations-of-the-formation-of-a-karman-vortex-street/C9BFB26B8A755EAFFFA6ACC3C91800FB`.

[3] Gerrard, J. H., "The wakes of cylindrical bluff bodies at low Reynolds number," *Philosophical transactions of the Royal Society A*, Vol. 288, 1978, pp. 351 – 382. doi:https://doi.org/10.1098/rsta.1978.0020, URL `http://rsta.royalsocietypublishing.org/content/288/1354/351.article-info`.

[4] Zdravkovich, M. M., "Flow around Circular Cylinders; Volume 1. Fundamentals," *Journal of Fluid Mechanics*, Vol. 350, 1997, p. 375–378. doi:10.1017/S0022112097227291.

[5] Richardson, L. F., *Weather Prediction by Numerical Process*, Cambridge University Press, Cambridge, UK, 1922.

[6] Tanaka, S., Takahashi, K., Hosoi, J., and Uchida, M., "Bluff Body Flame Holder with Flow Entrainment Using Perforated Plate," *9th AIAA/ASME/SAE/ASEE Joint Propulsion Conference*, San Jose, CA, July 2013.

[7] Li, H., Sung, H., and Yang, V., "Large Eddy Simulation of Combustion Dynamics of Bluff Body Stabilized Flame," *49th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition*, Orlando, Florida, January 2011.

[8] Ross, J. C., Heineck, J. T., Burnside, N., Sellers, M. E., Halcomb, N., Garbeff, T., Yamauchi, G., and Kushner, L., "Comprehensive Study of the Flow Around a Simplified Orion Capsule Model," *31st AIAA Applied Aerodynamics Conference*, San Diego, CA, June 2013.

[9] Yuan, W., Laima, S., Chen, W., Li, H., and Hu, H., "Investigation on the vortex-and-wake-induced vibration of a separated-box bridge girder," *Journal of Fluids and Structures*, Vol. 70, 2017, pp. 145 – 161. doi:https://doi.org/10.1016/j.jfluidstructs.2017.01.015, URL `http://www.sciencedirect.com/science/article/pii/S0889974616304911`.

[10] Menter, F., and Egorov, Y., "A Scale Adaptive Simulation Model using Two-Equation Models," *43rd AIAA Aerospace Sciences Meeting and Exhibit, Aerospace Sciences Meetings*, Reno, NV, January 2005.

References

[11] Catalano, P., Wang, M., Iaccarino, G., and Moin, P., "Numerical simulation of the flow around a circular cylinder at high Reynolds numbers," *International Journal of Heat and Fluid Flow*, Vol. 24, No. 4, 2003, pp. 463 – 469. doi:https://doi.org/10.1016/S0142-727X(03)00061-4, URL `http://www.sciencedirect.com/science/article/pii/S0142727X03000614`, selected Papers from the Fifth International Conference on Engineering Turbulence Modelling and Measurements.

[12] Travin, A., Shur, M., Strelets, M., and Spalart, P., "Detached-Eddy Simulations Past a Circular Cylinder," *Flow, Turbulence and Combustion*, Vol. 63, No. 1, 2000, pp. 293–313. doi:10.1023/A:1009901401183, URL `https://doi.org/10.1023/A:1009901401183`.

[13] Spalart, P., "Strategies for turbulence modelling and simulations," *International Journal of Heat and Fluid Flow*, Vol. 21, No. 3, 2000, pp. 252 – 263. doi:https://doi.org/10.1016/S0142-727X(00)00007-2, URL `http://www.sciencedirect.com/science/article/pii/S0142727X00000072`.

[14] Spalart, P. R., "Detached-Eddy Simulation," *Annual Review of Fluid Mechanics*, Vol. 41, No. 1, 2009, pp. 181–202. doi:10.1146/annurev.fluid.010908.165130, URL `https://doi.org/10.1146/annurev.fluid.010908.165130`.

[15] Squires, K. D., "Detached-Eddy Simulation: Current Status and Perspectives," *Direct and Large-Eddy Simulation V*, edited by R. Friedrich, B. J. Geurts, and O. Métais, Springer Netherlands, Dordrecht, 2004, pp. 465–480.

[16] Mockett, C., Greschner, B., Knacke, T., Perrin, R., Yan, J., and Thiele, F., "Demonstration of Improved DES Methods for Generic and Industrial Applications," *Advances in Hybrid RANS-LES Modelling*, edited by S.-H. Peng and W. Haase, Springer Berlin Heidelberg, Berlin, Heidelberg, 2008, pp. 222–231.

[17] Menter, F. R., and Kuntz, M., "Adaptation of Eddy-Viscosity Turbulence Models to Unsteady Separated Flow Behind Vehicles," *The Aerodynamics of Heavy Vehicles: Trucks, Buses, and Trains*, edited by R. McCallen, F. Browand, and J. Ross, Springer Berlin Heidelberg, Berlin, Heidelberg, 2004, pp. 339–352.

[18] Schwing, A. M., and Candler, G. V., "Detached-Eddy Simulation of Capsule Wake Flows and Comparison to ind-Tunnel Test Data," *Journal of Spacecraft and Rockets*, Vol. 52, No. 2, 2015, pp. 439–449.

[19] Forsythe, J. R., Squires, K. D., Wurtzler, K. E., and Spalart, P. R., "Detached-Eddy Simulation of the F-15E at High Alpha," *Journal of Aircraft*, Vol. 41, No. 9, 2004, pp. 193–200.

[20] Mendonça, F., Allen, R., de Charentenay, J., and Lewis, M., "Towards Understanding LES and DES for Industrial Aeroacoustic Predictions," *International workshop on 'LES for Acoustics'*, DLR Göttingen, Germany, October 2002.

[21] Durbin, P. A., "Some Recent Developments in Turbulence Closure Modeling," *Annual Review of Fluid Mechanics*, Vol. 50, No. 1, 2018, pp. 77–103. doi:10.1146/annurev-fluid-122316-045020.

[22] Smith, C., Beratlis, N., Balaras, E., Squires, K., and Tsunoda, M., "Numerical investigation of the flow over a golf ball in the subcritical and supercritical regimes," *International Journal of Heat and Fluid Flow*, Vol. 31, No. 3, 2010, pp. 262 – 273. doi:https://doi.org/10.1016/j.ijheatfluidflow.2010.01.002, URL `http://www.sciencedirect.com/science/article/pii/S0142727X10000147`, sixth International Symposium on Turbulence and Shear Flow Phenomena.

References

[23] Cimarelli, A., Leonforte, A., and Angeli, D., "Direct numerical simulation of the flow around a rectangular cylinder at a moderately high Reynolds number," *Journal of Wind Engineering and Industrial Aerodynamics*, Vol. 174, 2018, pp. 39 – 49. doi:https://doi.org/10.1016/j.jweia.2017.12.020, URL `http://www.sciencedirect.com/science/article/pii/S0167610517304622`.

[24] Nakamura, Y., "Bluff-body aerodynamics and turbulence," *Journal of Wind Engineering and Industrial Aerodynamics*, Vol. 49, No. 1, 1993, pp. 65 – 78. doi:https://doi.org/10.1016/0167-6105(93)90006-A, URL `http://www.sciencedirect.com/science/article/pii/016761059390006A`.

Backup: Grids

Clockwise: reentry capsule (DES), non-rotating golf ball (DNS), Grid Induced Separation on airfoil (DES), Circular Cylinder (DES)