Ph.D. Course on *Vorticity, Vortical Flows and Vortex-Induced Vibrations*
Technical University of Denmark, Copenhagen, Denmark
vortex.compute.dtu.dk
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Bluff Body Wakes III: Effect of body rotation

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FLAIR
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Reading Material

Isolated Rotating Cylinder

Akoury, R.E., Braza, M., Perrin, R., Harran, G., Hoarau, Y., 2008. The three-dimensional transition in the flow around a rotating cylinder. Journal of Fluid Mechanics 607, 1–11.

Mittal, S., Kumar, B., 2003. Flow past a rotating cylinder. Journal of Fluid Mechanics 476, 303–334.

Prandtl, L., 1926. Application of the “Magnus Effect” to the Wind Propulsion of Ships. Technical memorandum, National Advisory Committee for Aeronautics.

Rao, A., Leontini, J., Thompson, M.C., Sheridan, J. & Hourigan, K., A review of rotating cylinder wake transitions, Journal of Fluid and Structures, *53*, 2 - 14, 2015.

Rao, A., Leontini, J., Thompson, M.C. & Hourigan, K., Three-dimensionality in the wake of a rotating cylinder in a uniform flow, Journal of Fluid Mechanics, 717, 1-29, 2013.

Rao, A., Leontini, J., Thompson, M.C. & Hourigan, K., Three-dimensionality in the wake of a rapidly rotating cylinder in uniform flow, Journal of Fluid Mechanics, 730, 379-391, 2013.

Radi, A., Thompson, M.C., Rao, A., Hourigan, K. & Sheridan, J., Experimental evidence of new three-dimensional modes in the wake of a rotating cylinder, Journal of Fluid Mechanics, 734, 567-594, 2013.

Isolated Rotating Sphere

Giacobello, M., Ooi, A., & Balachandar, S., Wake structure of a transversely rotating sphere at moderate Reynolds numbers. Journal of Fluid Mechanics, 621, 103-130, 2009.

Poon, E., Ooi, A., Giacobello, M., Iaccarino, G., & Chung, D., Flow past a transversely rotating sphere at Reynolds numbers above the laminar regime. *Journal of Fluid Mechanics, 759*, 751-781, 2014.

Williamson, C.H.K. & Govardhan, R., 2004 Vortex-induced vibrations. Annu. Rev. Fluid Mech. 36 (1), 413–455.

Lecture Objectives

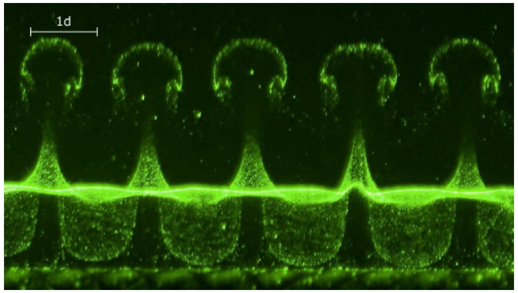
Learn:

Applications of rotating bodies

Magnus effect

Effect of body rotation on wakes of, and forces on, cylinders and spheres

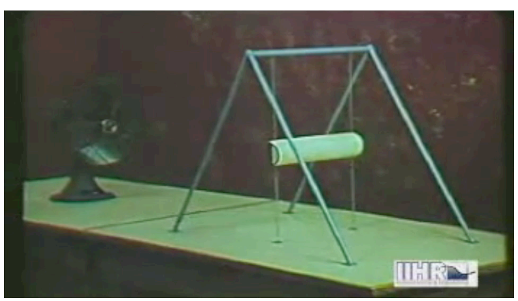
Outline of Presentation

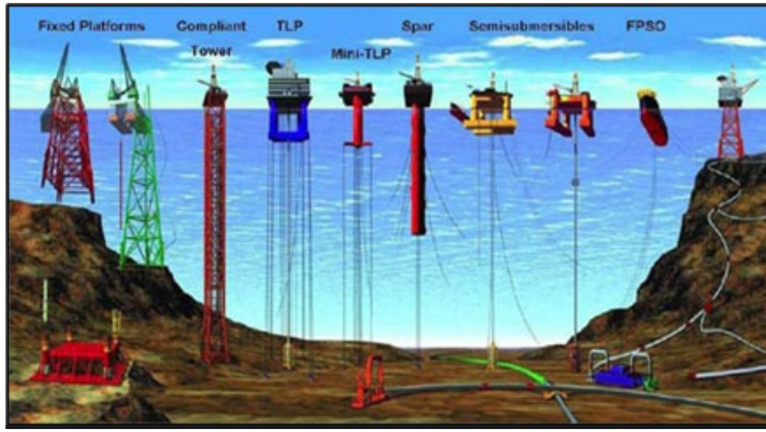


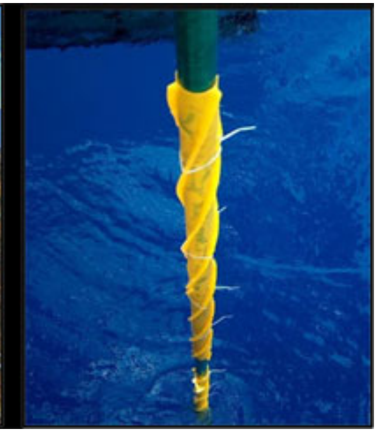
- Motivation
- Non-rotating cylinder/sphere, cross-flow: 2d/axisymmetric & 3d modes
- Rotating cylinder, no cross-flow
- Rotating cylinder/sphere in cross-flow: Varying rotation rate and Reynolds number
- Applications: Flettner rotors, ball sports, wind turbines
- Conclusions

Many applications for FSI and *non-rotating* bodies

- Offshore marine industry
- Wind engineering
- Heat exchangers
- Aerospace
- Tethered bodies
- etc







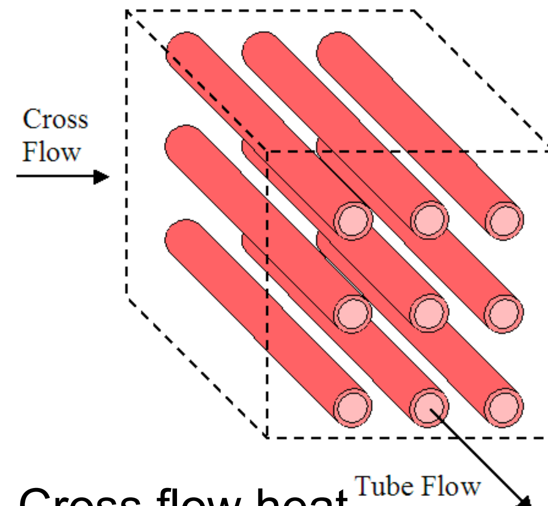
Ocean engineering applications, such as marine risers, oil platforms and mooring lines

web.mit.edu/towtank/www/viv.html

Tall buildings

(Imperial Tower – Mumbai)

http://gizmodo.com/how-this-116-story-skyscraper-will-confuse-the-wind-508206826



Cross flow heat exchangers

www.real-world-physics-problems.com/heat-exchanger.html

..and for *rotating* bodies

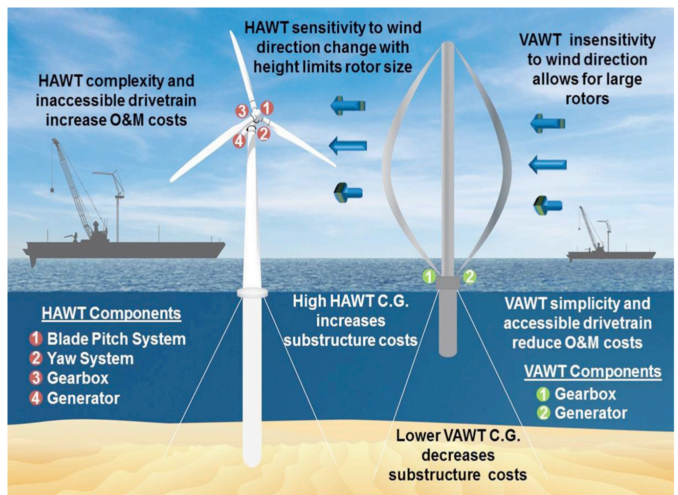
- Flettner rotors
- Wind turbines
- Sports balls
- Rolling particles
- etc

Flettner Rotor: Buckau (1924)

en.wikipedia.org/wiki/Rotor_ship

Flettner wings

www.youtube.com/watch?v=hlmvHfIAszo



Vertical axis wind turbines

www.offshorewind.biz/2012/07/31/usa-sandia-re-evaluates-vertical-axis-wind-turbines/

commons.wikimedia.org/wiki/File:Vertical_wind_turbine_near_US_Capitol.jpg

Non-spinning cylinder

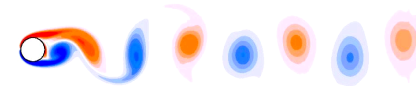
Isolated cylinder and sphere have important wake transitions at moderate Re

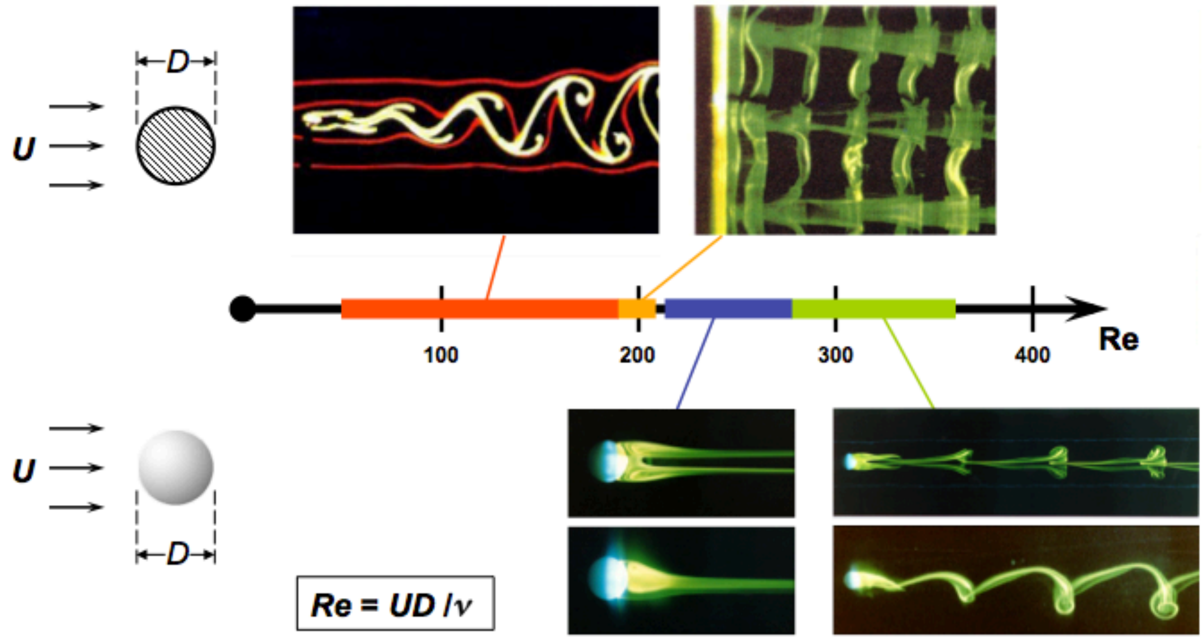
Cylinder

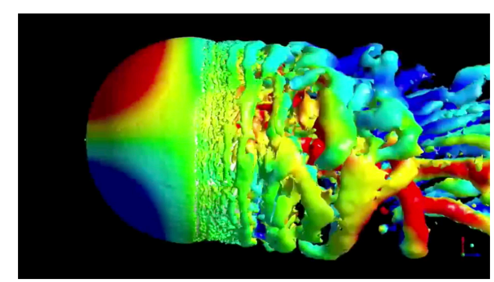
- Unsteady 2s at Re = 47
- 3d mode A at Re = 180
- 3d mode B at Re = 250

Sphere

- Steady asymmetrical at Re= 212
- Unsteady symmetrical at Re = 272 (Hopf)



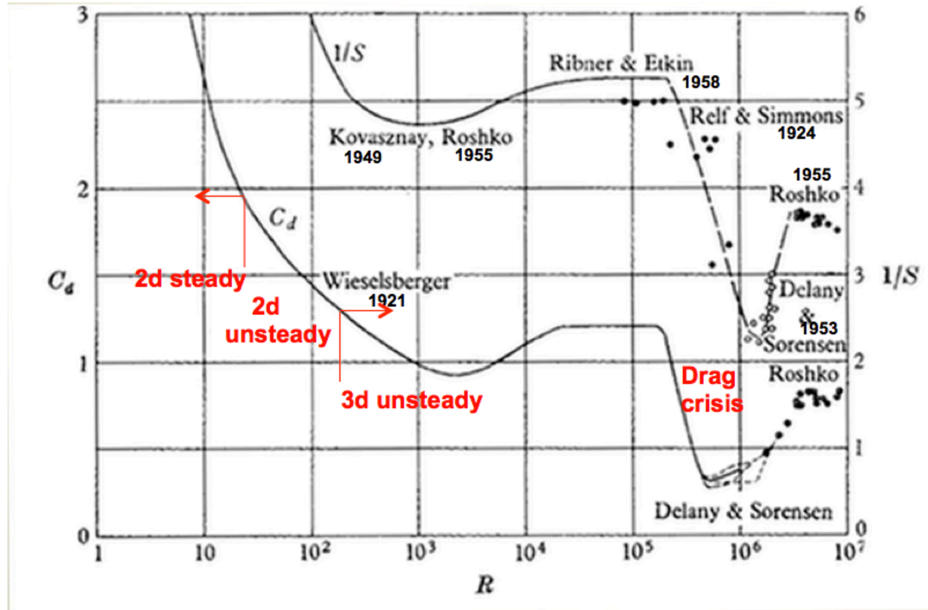




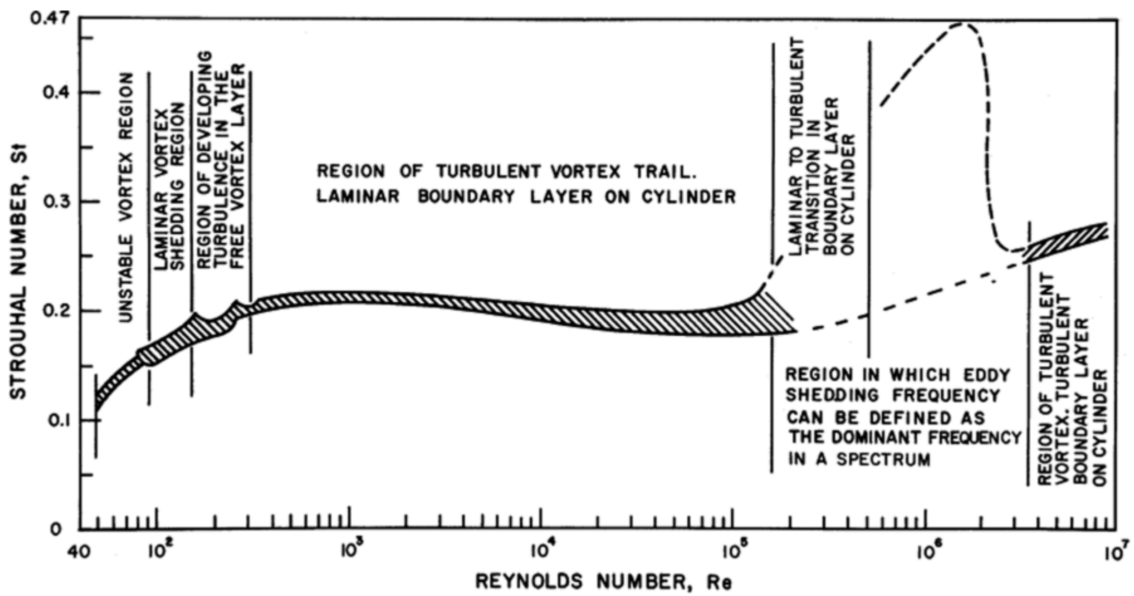
Battelle

Cylinder wake transitions

- Strouhal number and drag coefficient variation
- Initial transitions in low-moderate Re range



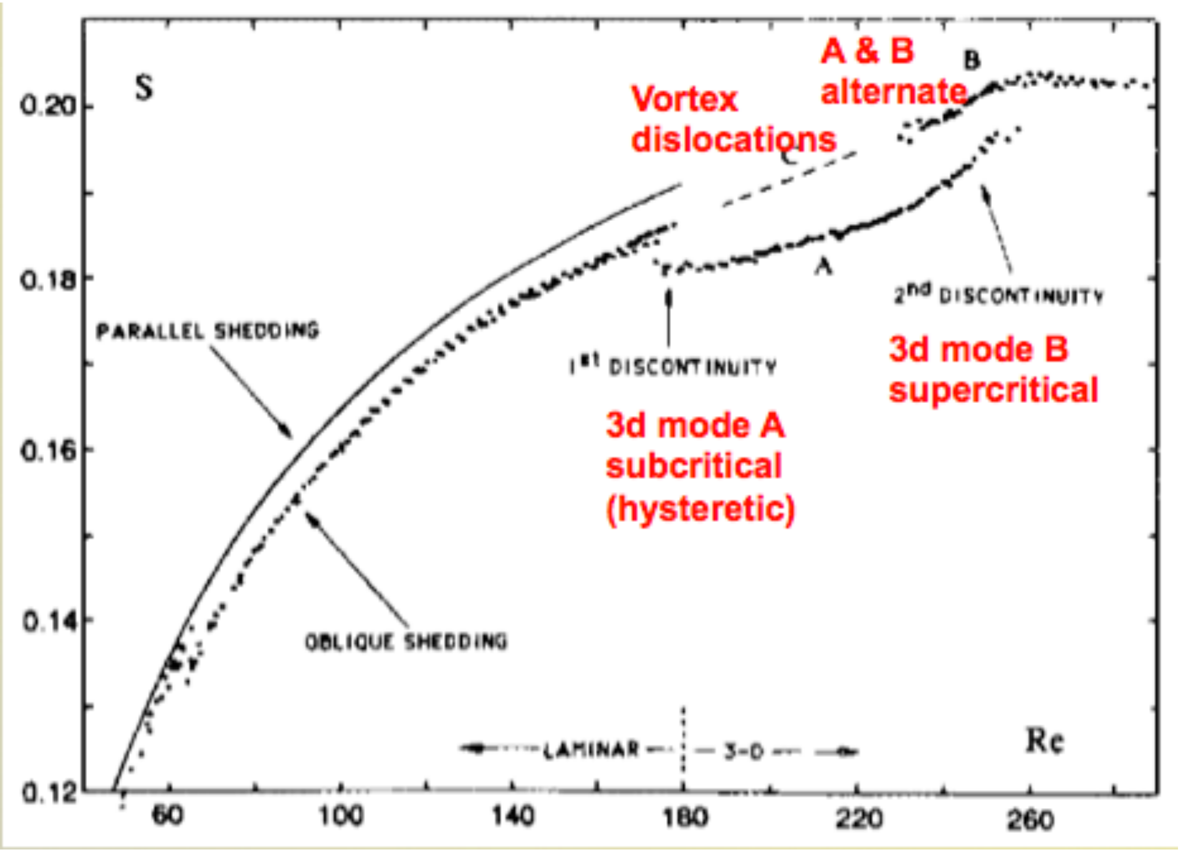
Drag coefficient and reciprocal of Strouhal number.
Roshko (JFM, 1961)



Strouhal number vs Reynolds number
appliedmechanicsreviews.asmedigitalcollection.asme.org

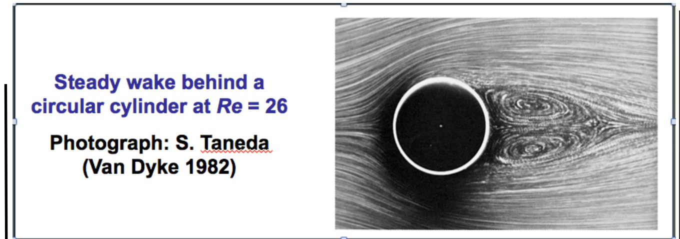
Cylinder wake transitions

- Strouhal number and drag coefficient variation
- Low Reynolds number transitions

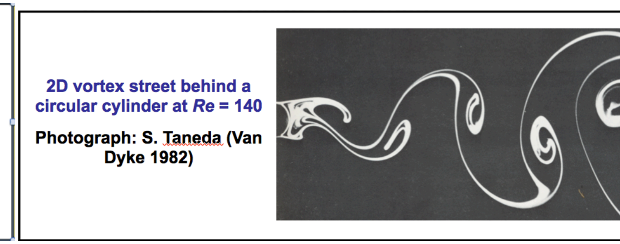


Strouhal number vs Reynolds number
Williamson (PoF, 1988)

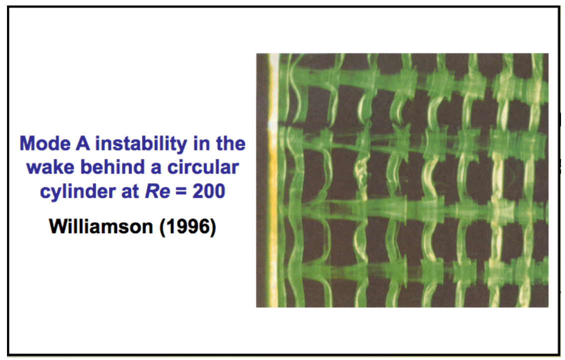
Cylinder: Major wake transitions as Reynolds number increases



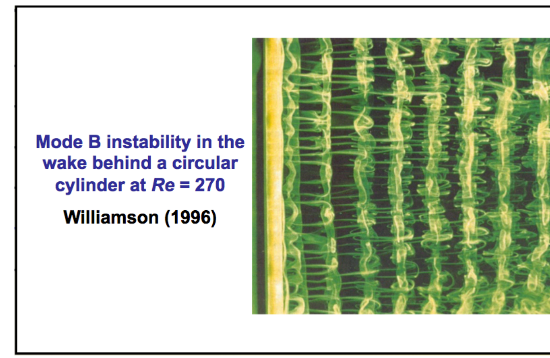
0 < *Re* < 47:
Steady 2D wake



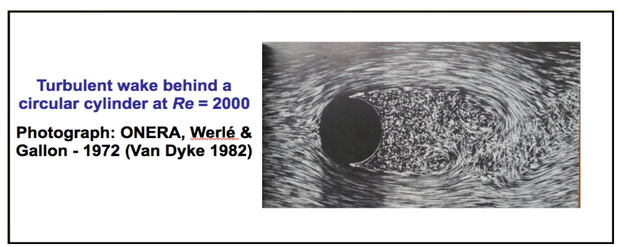
47 < *Re* < 180:
Periodic 2D vortex street



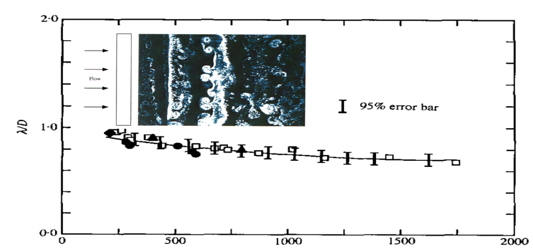
Re = 190: Subcritical Mode A instability ($\lambda_d \approx 4d$)



Re = 240: Mode B instability ($\lambda_d \approx 1d$)



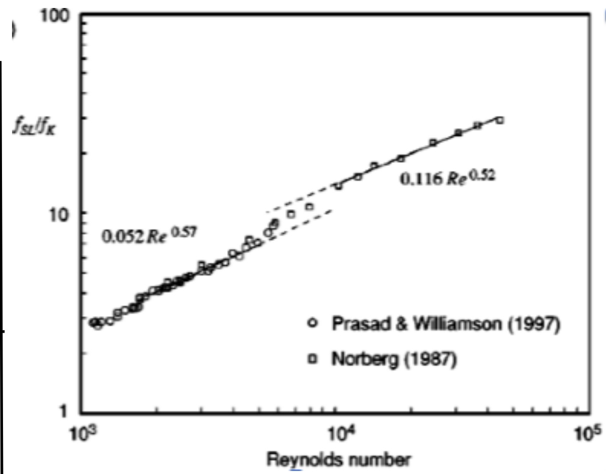
Re increasing: spatio-temporal chaos, rapid transition to turbulence



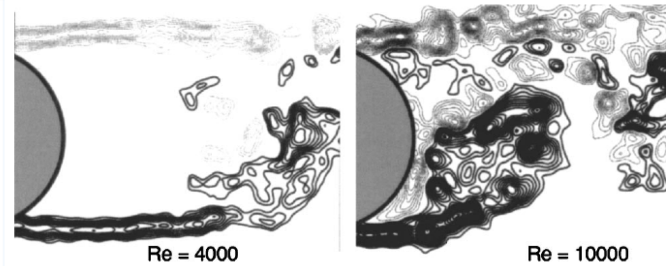
Persistence of mode B

Other cylinder wake transitions

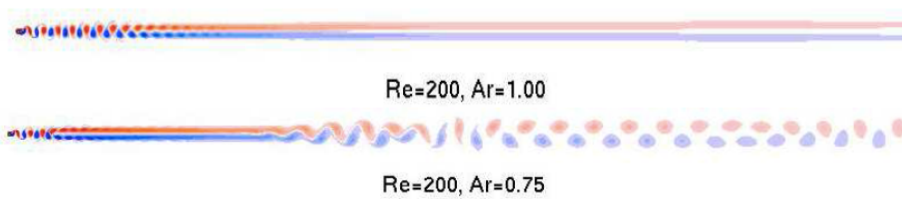
- Shear layer instability Re>10^2
- Far wake instability – wake relaminarises into double shear layer
- Drag crisis at Re ≈ 2×10^5

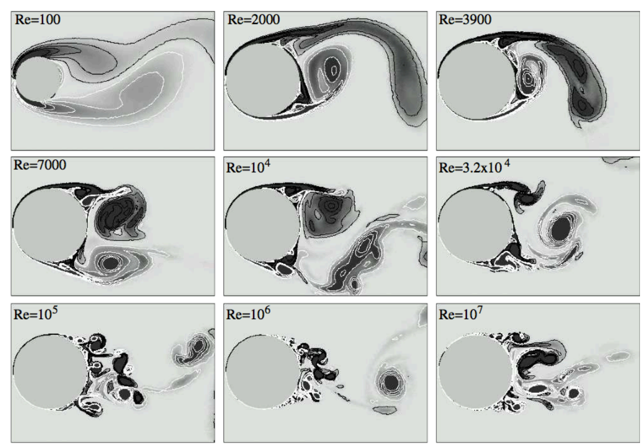


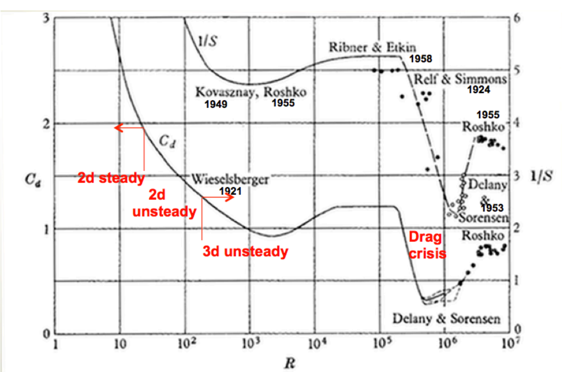
Thompson & Hourigan, PoF, 2005



N. Saelim and D. Rockwell, private comm. (2004)



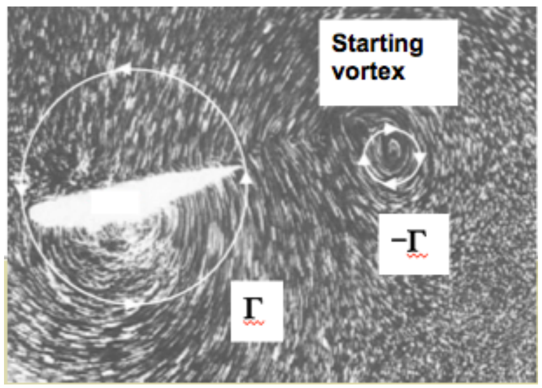


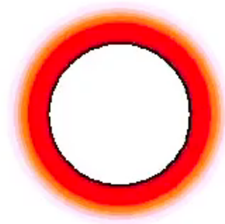


Spinning cylinder

Spinning cylinder generates net vorticity, starting vortex

- Spin a cylinder and vorticity generated diffuses to infinity
- Add a uniform flow and a starting vortex is formed
- Net lift results, similar to an airfoil

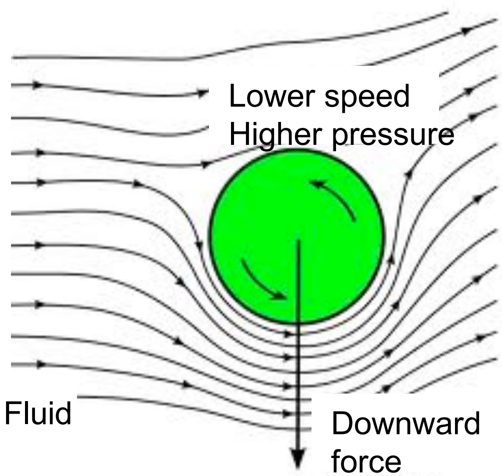




Impulsively spin a cylinder in still fluid

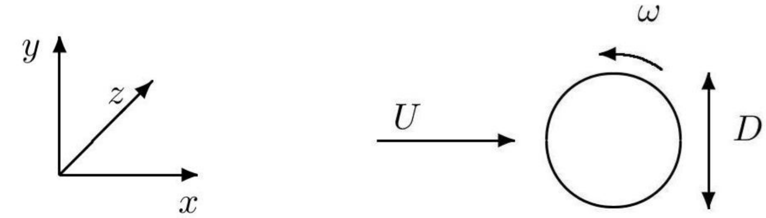
Add a cross flow and spin the cylinder

Magnus Effect – provides lift



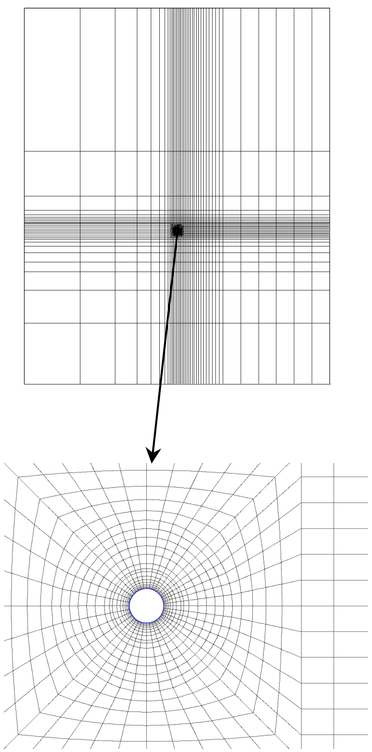
www.aviation-for-kids.com/the-magnus-force.html

CFD Methods



Reynolds number Re = UD/ν

Rotation rate $\alpha = \omega D/2U$



Spectral Element Method

The incompressible Navier-Stokes (N-S) equations are solved in 2-d and 3-d.
An in-house numerical solver employing a spectral element technique was used.
The computational domain consisted of quadrilateral macroelements with internal node points.
Fractional time-stepping technique was used to integrate the pressure, advection and diffusion terms of the N-S equation.

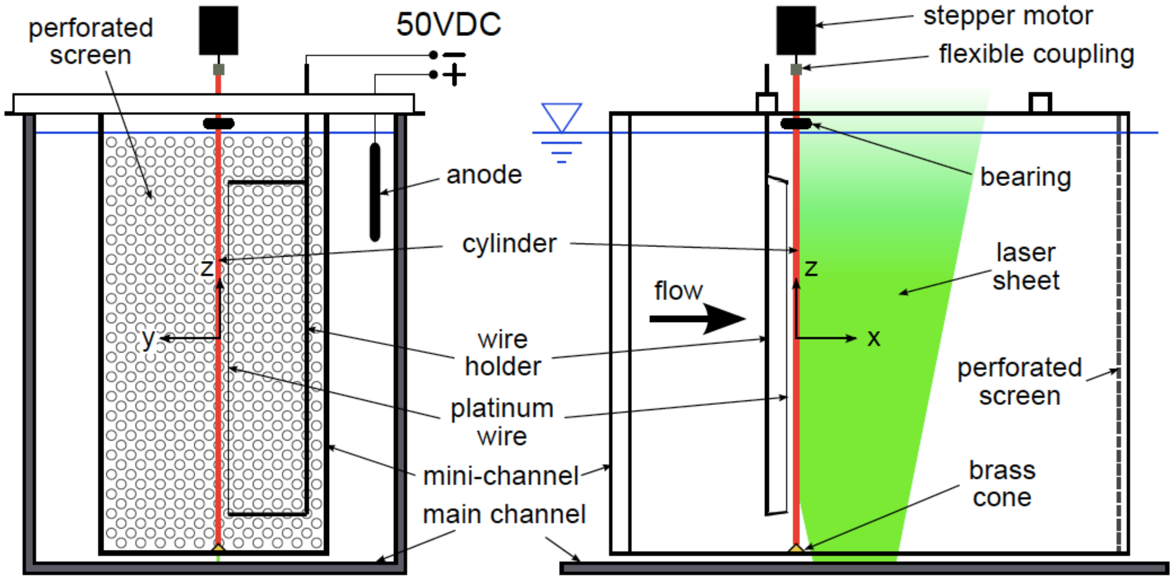
Stability analysis

The Floquet multiplier (μ)

$|\mu| < 1$, stable
$|\mu| = 1$, neutrally stable
$|\mu| > 1$, unstable

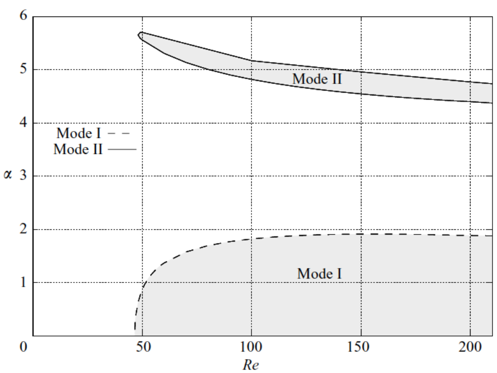
μ real & positive: 3d mode and base flow synchronous (A & B)
μ complex: if base flow periodic, 2^{nd} freq => quasi-periodic 3d flow
if base flow steady, 3d flow is periodic
μ real & negative: subharmonic mode

Water Channel

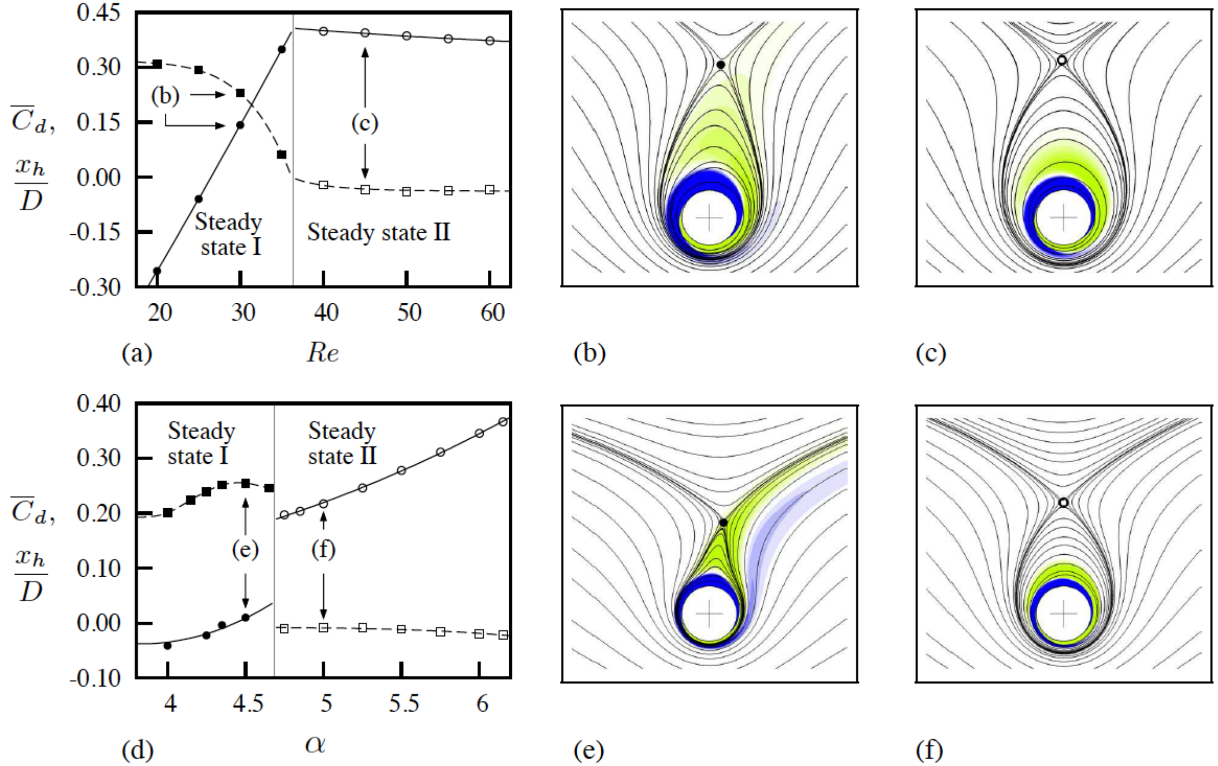


Water channel set up (FLAIR)

Rotating Cylinder – 2 Steady States

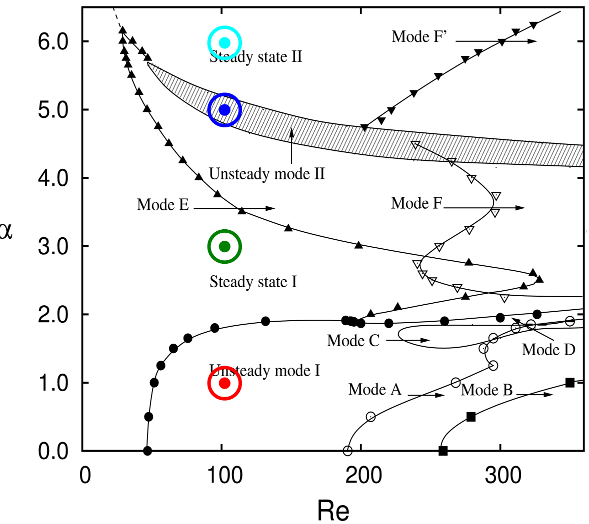


α = 6.15



Re = 200

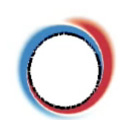
Rotate Cylinder & Add Flow 2d States



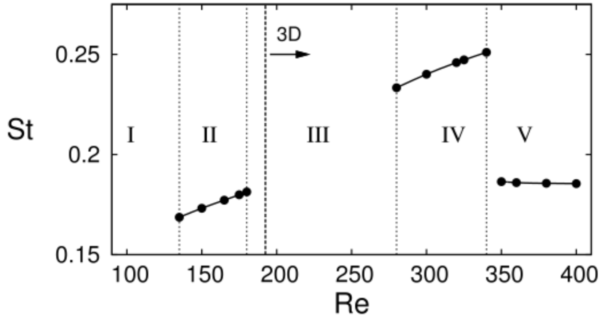
Re = 100, α = 1

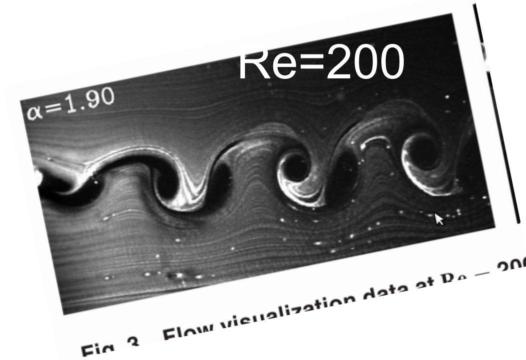
Re = 100, α = 3

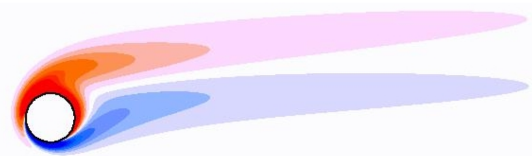
Re = 100, α = 5



Re = 100, α = 6



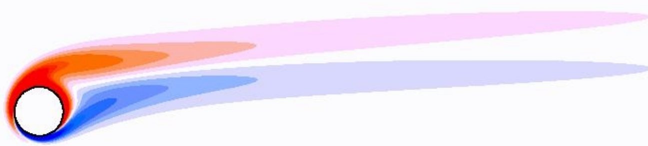




Re=50

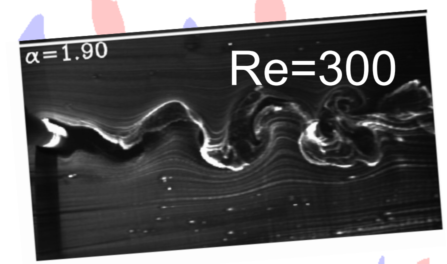
Re=250

Kumar et al, JFE, 2011

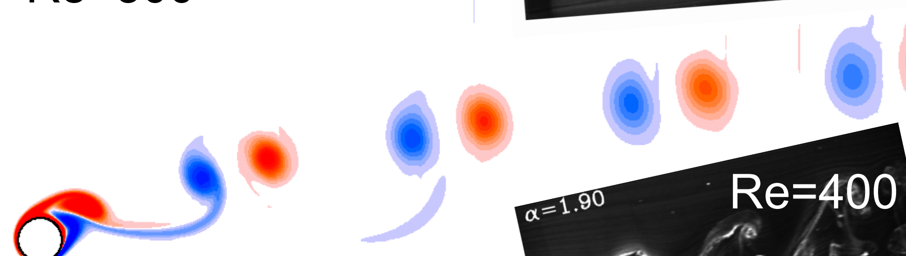


Re=100

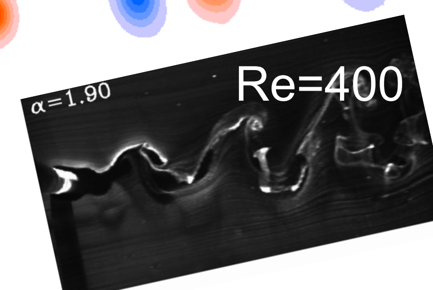
Re=300



Re=180

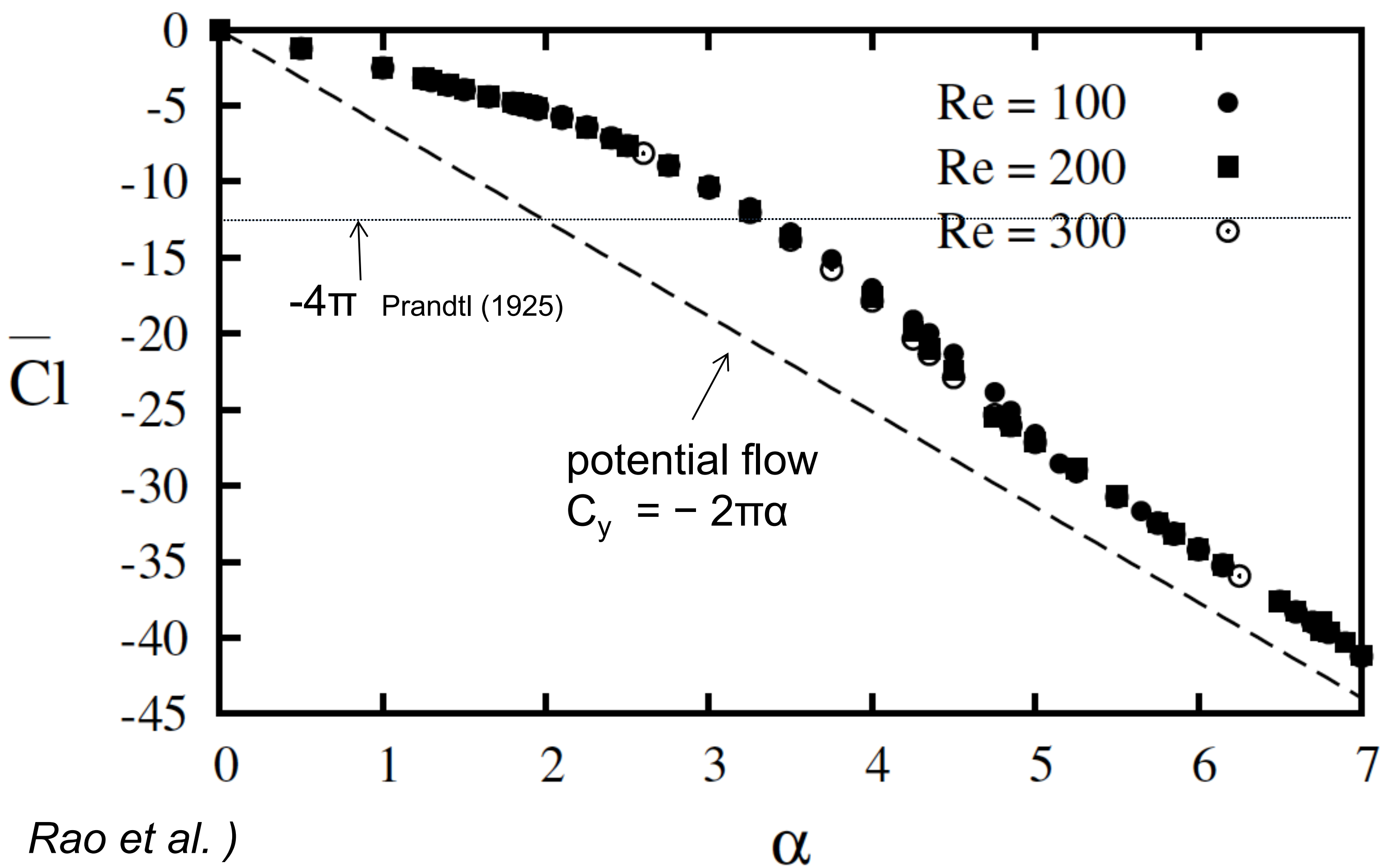


Re=400



MONASH University

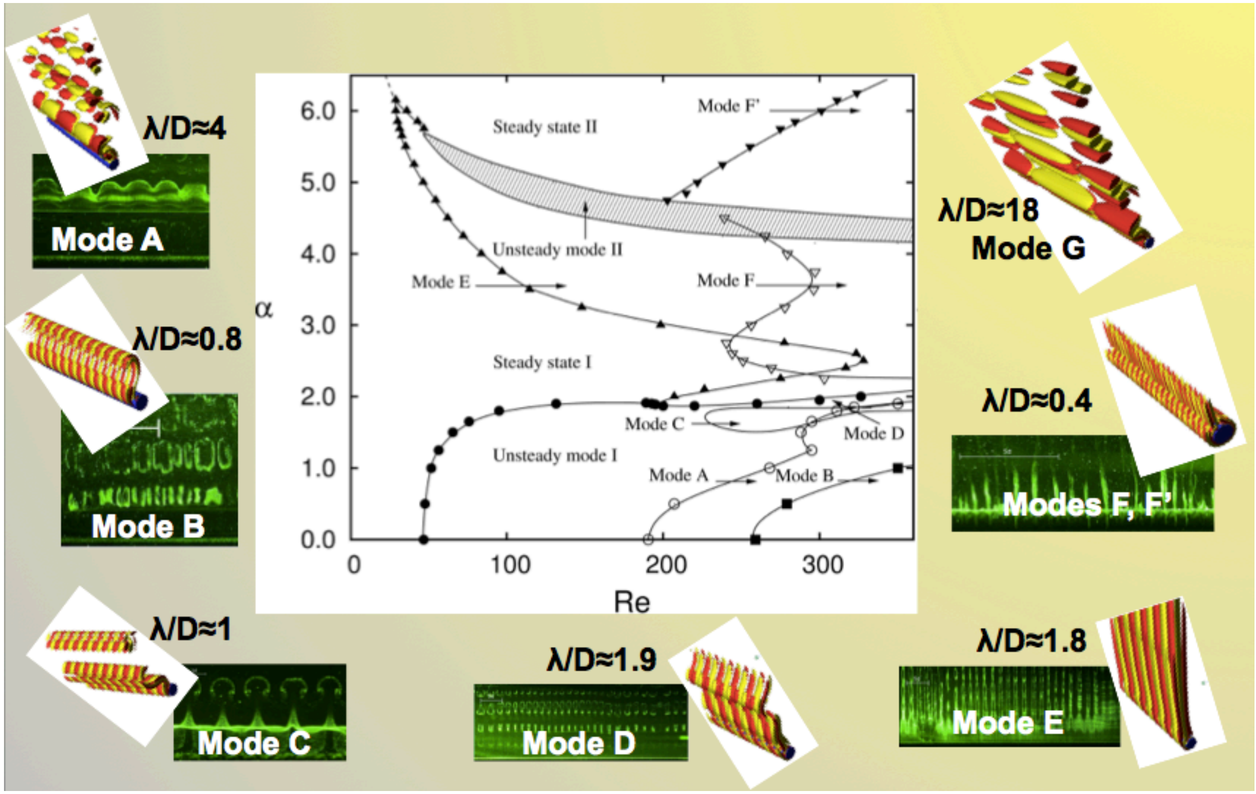
Predicted lift force coefficient

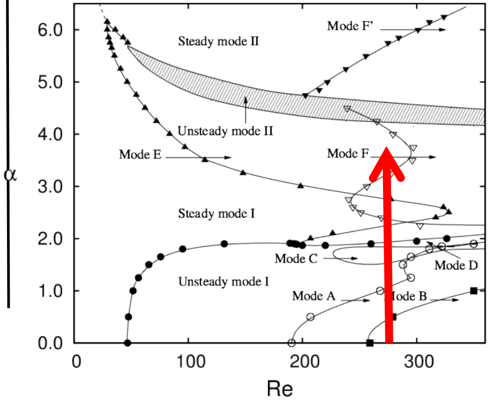


Rao et al.)

3d Transition Parameter Map

- Without rotation: modes A & B
- Increasing rotation adds many new 3d modes
- Flow becomes steady as α > 2, then unsteady again for α ≈ 4-5, then steady again
- Movie shows modes as α increases from 0 to 4, at Re = 275



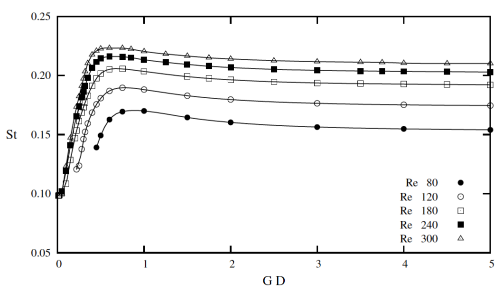


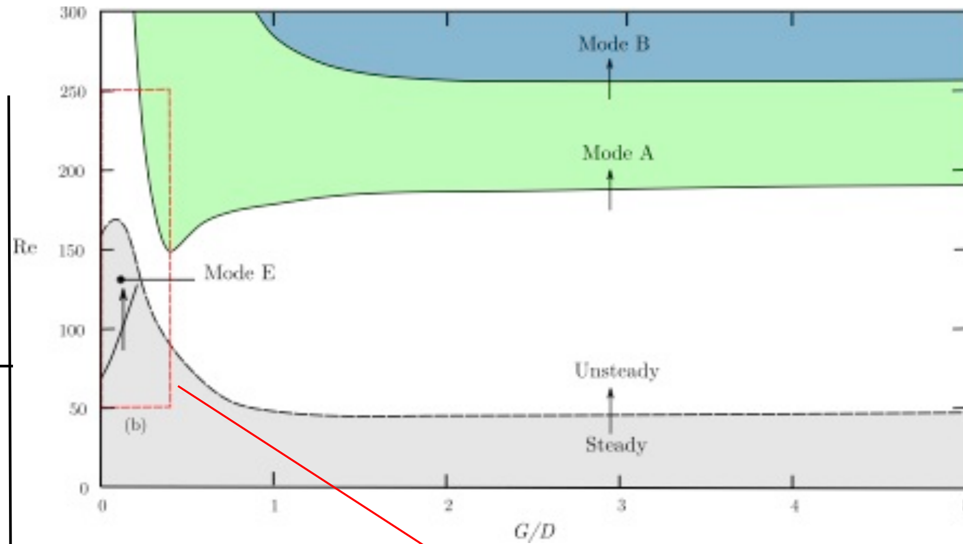
Re = 275

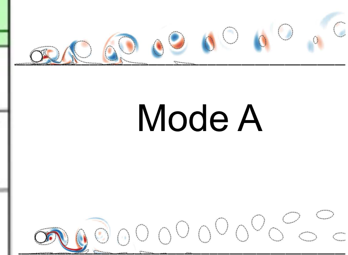
Effect of a wall on wake structure and transitions

α = 0 (sliding cylinder)

Mode	λ/D	Nature of μ	Gap height	Base flow
A	$\simeq 4$	Real and positive	$\gtrsim 0.25D - \infty$	Unsteady
B	$\simeq 0.8$	Real and positive	$\gtrsim 0.85D - \infty$	Unsteady
C′	$\simeq 1.25$	Real and negative	$\simeq 0.22D - 0.28D$	Unsteady
C*	$\simeq 1.5$	Real and negative	$\simeq 0.28D - 0.35D$	Unsteady
E	$\simeq 6$	Real and positive	$0 - 0.2D$	Steady

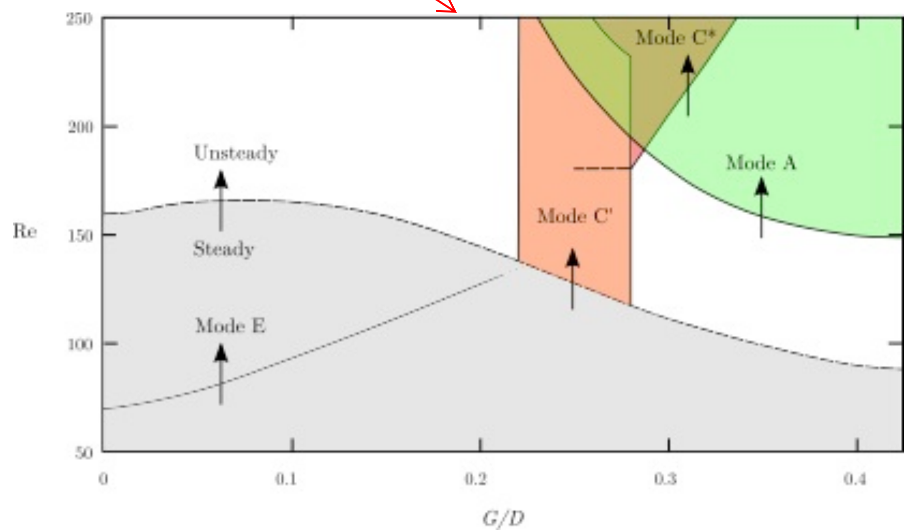


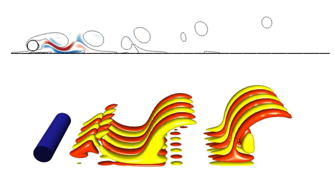




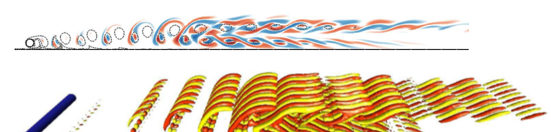
Mode A

Mode B



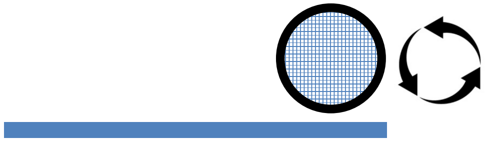


Mode C'

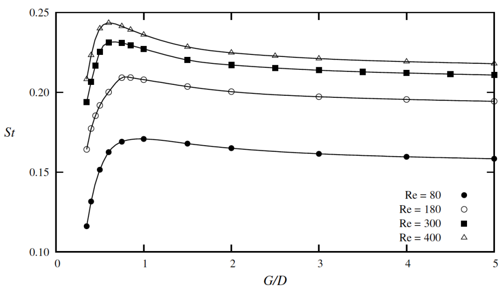


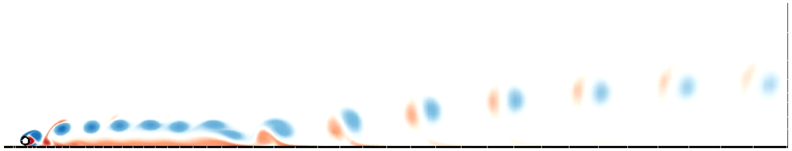
Mode C*

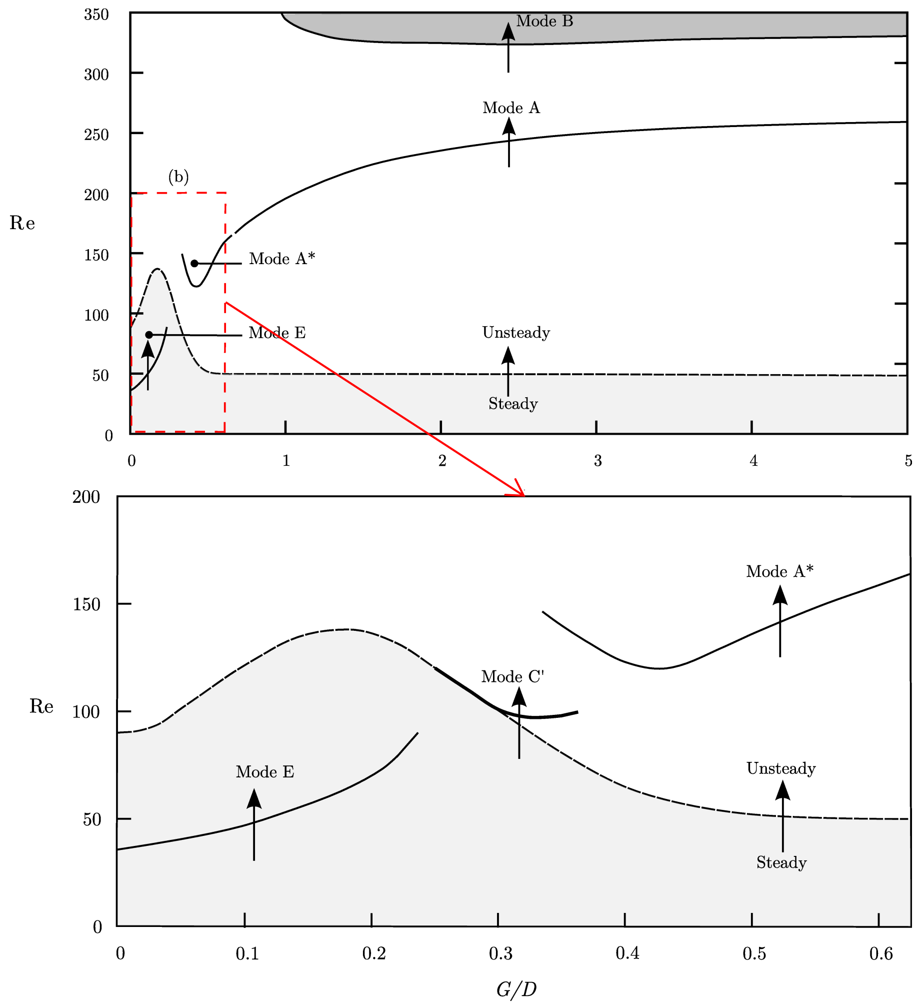
α = +1 (prograde rolling cylinder)

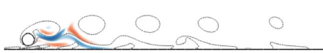


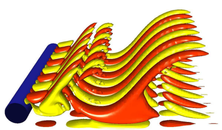
Mode	λ/D	Nature of μ	Gap height	Base flow
A	$\simeq 4$	Real and positive	$\gtrsim 0.75D - \infty$	Unsteady
A*	$\simeq 4$	Real and positive	$\simeq 0.35D - 0.6D$	Unsteady
B	$\simeq 0.8$	Real and positive	$\gtrsim 1D - \infty$	Unsteady
C′	$\simeq 2$	Real and negative	$\simeq 0.25D - 0.35D$	Unsteady
E	[8 – 14]	Real and positive	$0 - 0.22D$	Steady



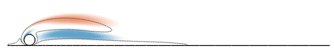


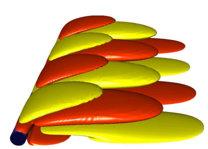






Mode C’

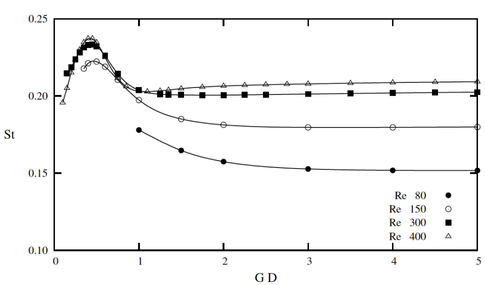


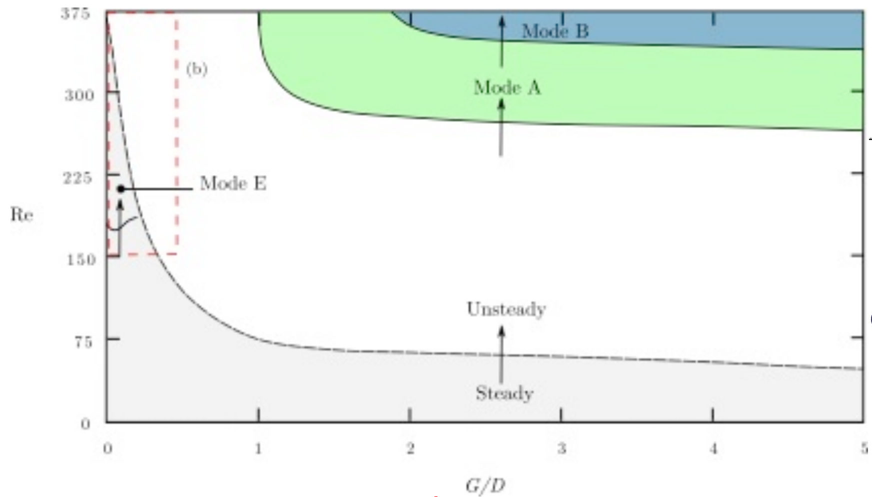


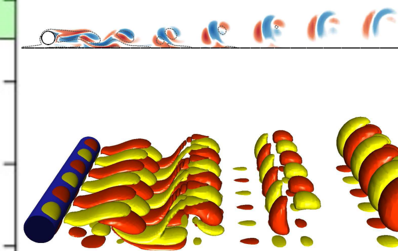
Mode E

α = -1 (retrograde spin cylinder)

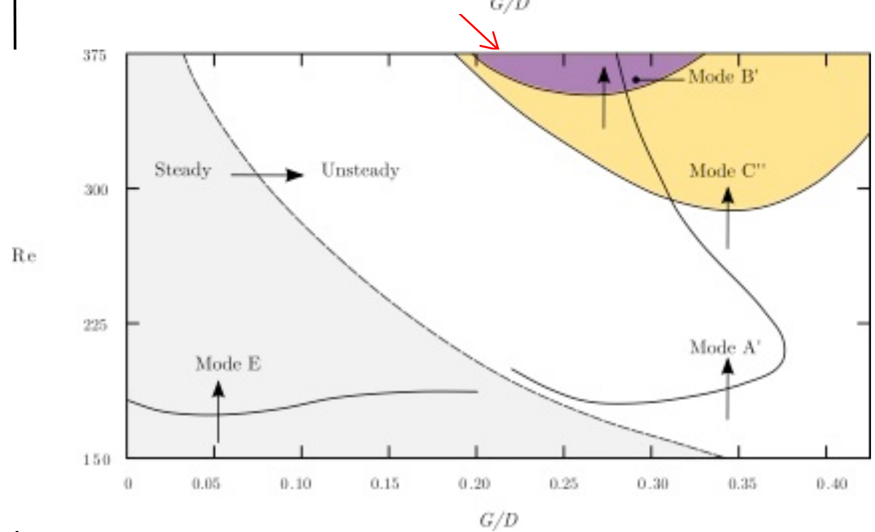
Mode	λ/D	Nature of μ	Gap height	Base flow
A	$\simeq 4$	Real and positive	$\gtrsim 1D - \infty$	Unsteady
A′	$\simeq 2.4$	Real and positive	$\simeq 0.22D - 0.37D$	Unsteady
B	$\simeq 0.8$	Real and positive	$\gtrsim 1.75D - \infty$	Unsteady
B′	$\simeq 0.77$	Real and positive	$\simeq 0.22D - 0.32D$	Unsteady
C″	$\simeq 1.5$	Real and negative	$\gtrsim 0.22D - 0.45D$	Unsteady
E	$\simeq 2.4$	Real and positive	$0 - 0.2D$	Steady

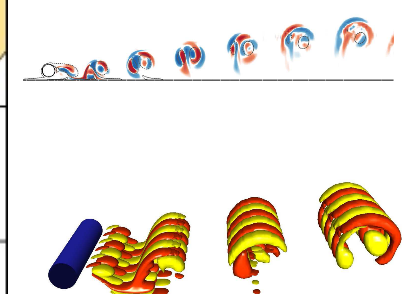




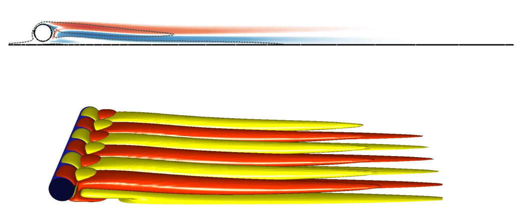


Mode A’

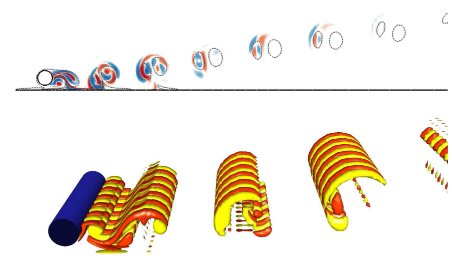




Mode C’’



Mode E



Mode B’

SPHERES

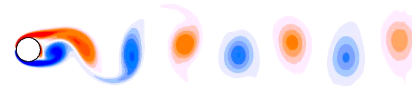
Isolated cylinder and sphere have important wake transitions at moderate Re

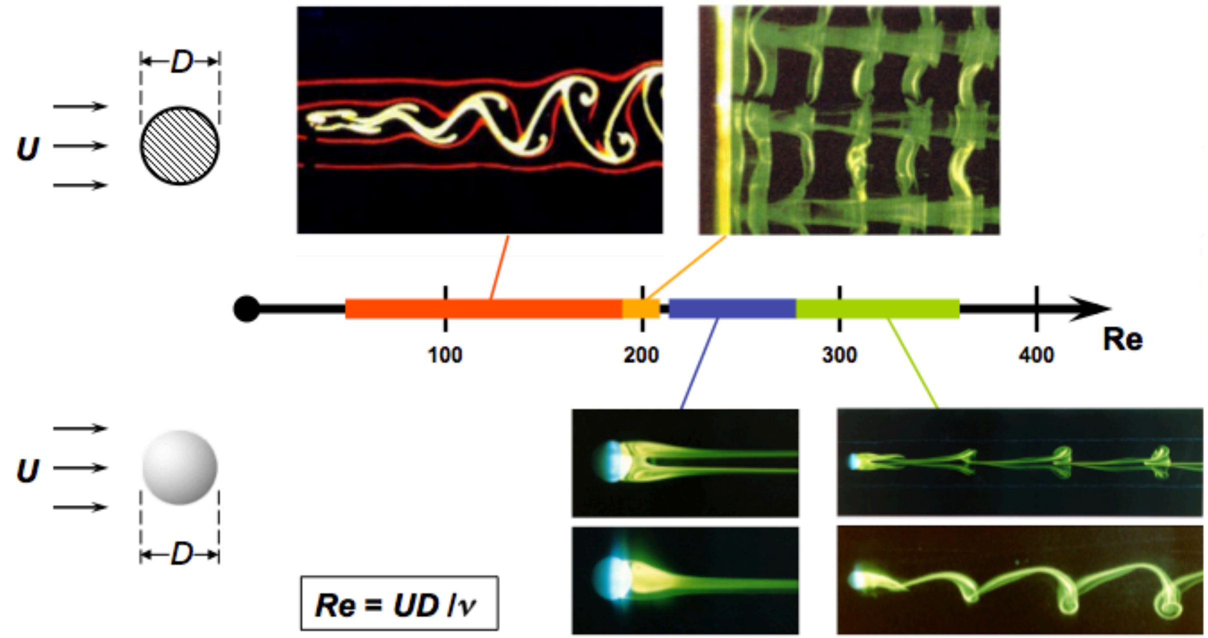
Cylinder

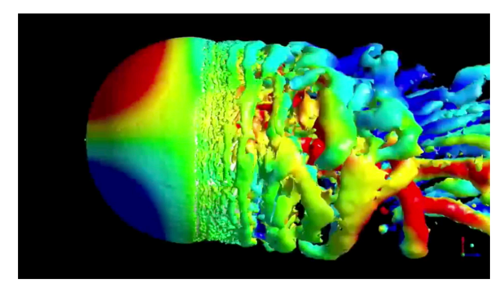
- Unsteady 2s at Re = 47
- 3d mode A at Re = 180
- 3d mode B at Re = 250

Sphere

- Steady asymmetrical at Re= 212
- Unsteady symmetrical at Re = 272 (Hopf)



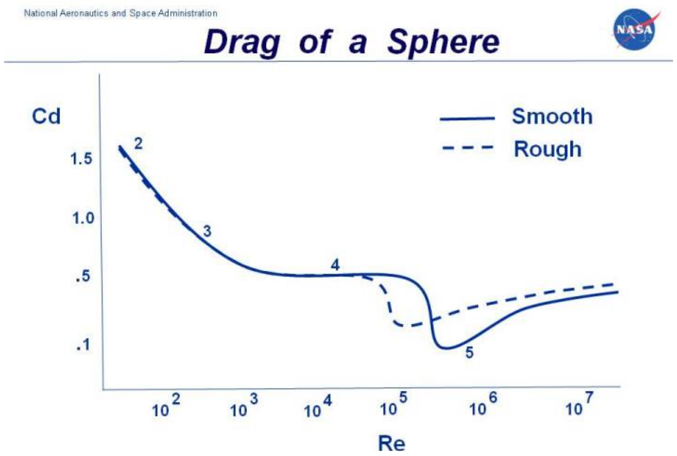




Battelle

Sphere wake transitions

- Strouhal number and drag coefficient variation
- Initial transitions in low-moderate Re range



Drag coefficient and reciprocal of Strouhal number.
NASA

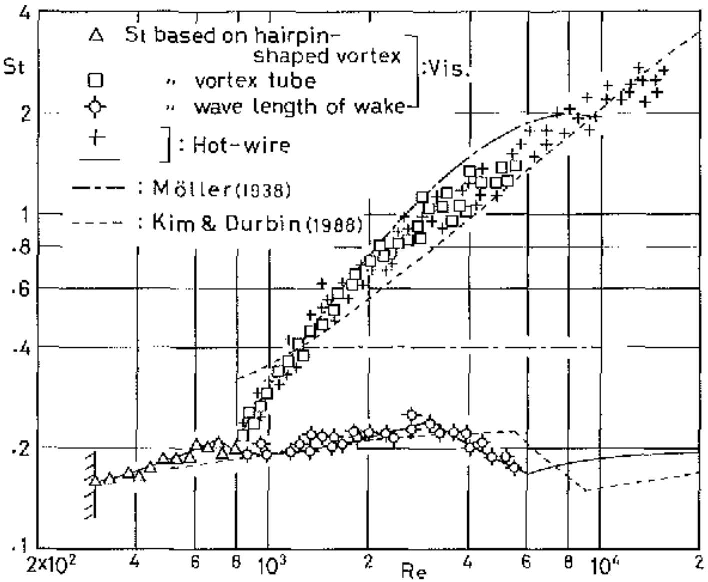


Fig. 4 Distribution of low-mode and high-mode Strouhal number versu

Strouhal number vs Reynolds number
Sakamoto &Haniu, *J. Fluids Eng* 112(4), 386-392 (Dec 01, 1990)

Non-Rotating spheres

- Johnson & Patel, JFM, 1999.

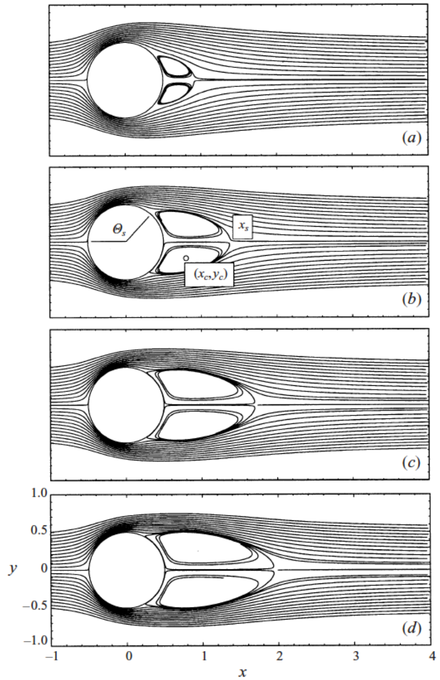


FIGURE 3. Computed axisymmetric streamlines past the sphere: (a) $Re = 50$; (b) $Re = 100$; (c) $Re = 150$; (d) $Re = 200$.

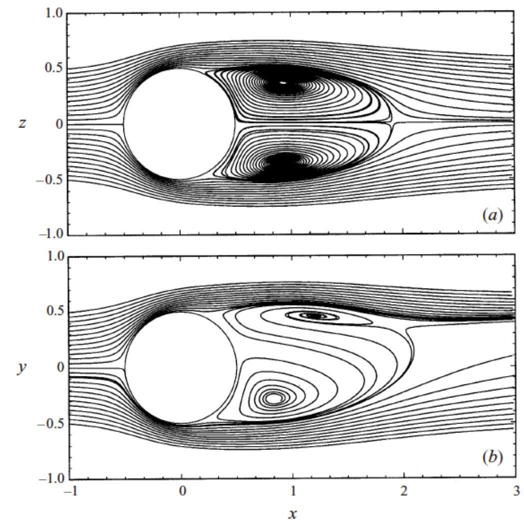


FIGURE 11. Streamlines of projected velocity vectors at $Re = 250$ in (a) the (x, z)-plane; (b) the (x, y)-plane.

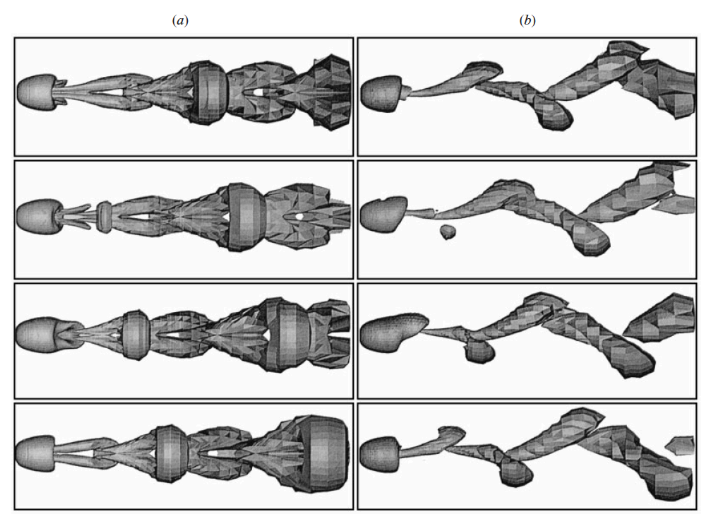


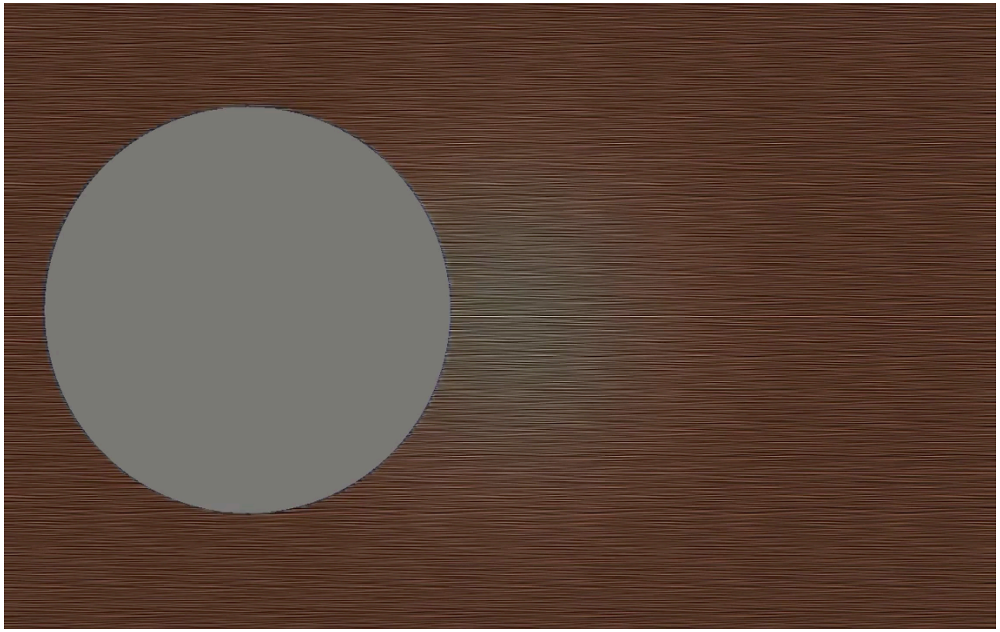
FIGURE 30. Vortical structure at $Re = 300$ at every quarter period: (a) x, z view; (b) x, y view.

Non-Rotating spheres

- Wake at Re=300

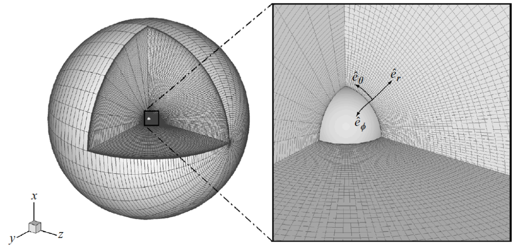
Non-Rotating spheres

- Wake at Re=10,000



Rotating spheres

- Giacaobello et al., JFM, 2009.



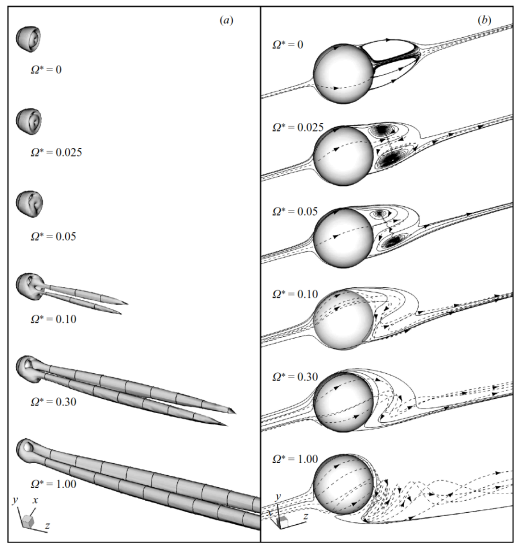


FIGURE 6. (*a*) Vortical structures and (*b*) three-dimensional streamline patterns for $Re = 100$.

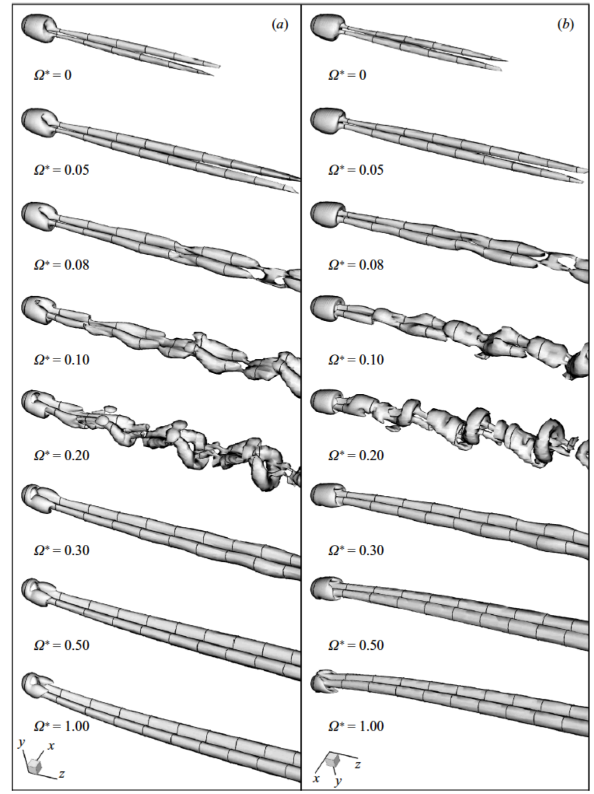


FIGURE 7. Instantaneous vortical structures for $Re = 250$: (*a*) and (*b*) look down on the wake from the retreating and advancing side of the sphere, respectively.

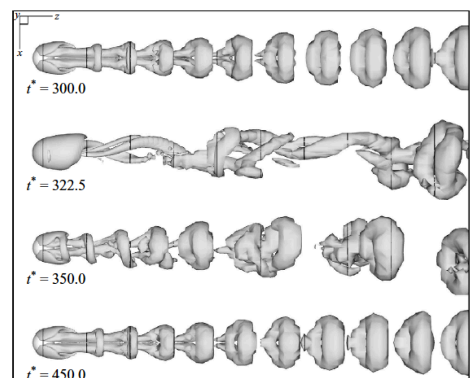
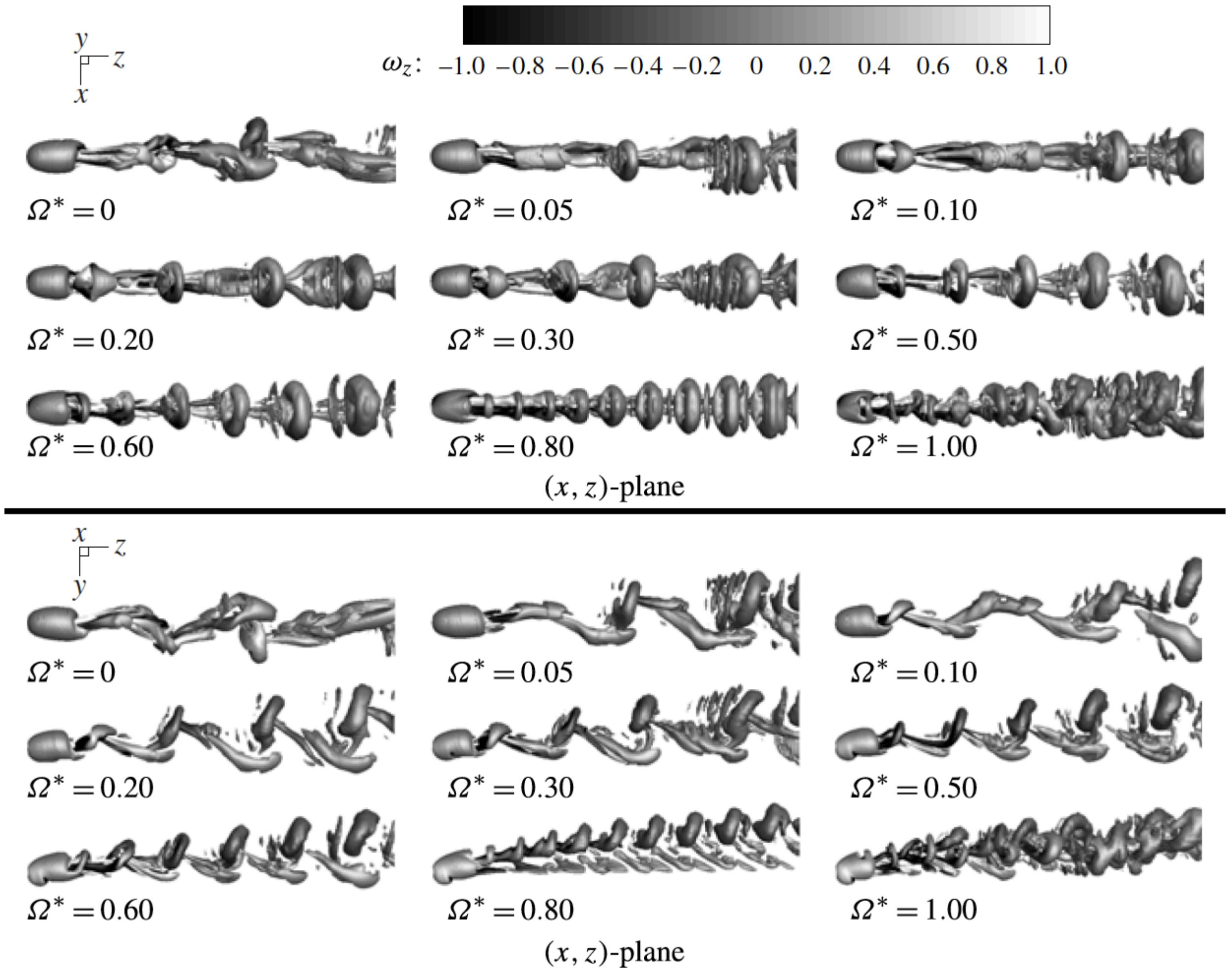


FIGURE 14. Effect of symmetry breaking perturbation for $Re = 300$ and $\Omega^* = 1.00$. The time sequence begins with the statistically steady flow for transversely rotating sphere at $t^* = 300.0$. This is followed by streamwise rotation for $300.0 < t^* \leqslant 322.5$ and transverse rotation for $t^* > 322.5$. Vortical structures are identified by plotting isosurfaces of $\lambda_2 = -8 \times 10^{-4}$.

Rotating spheres

- **Re = 500**
- **Variation of wake with increasing spin rate**
- **Streamwise vorticity plotted (λ_2)**

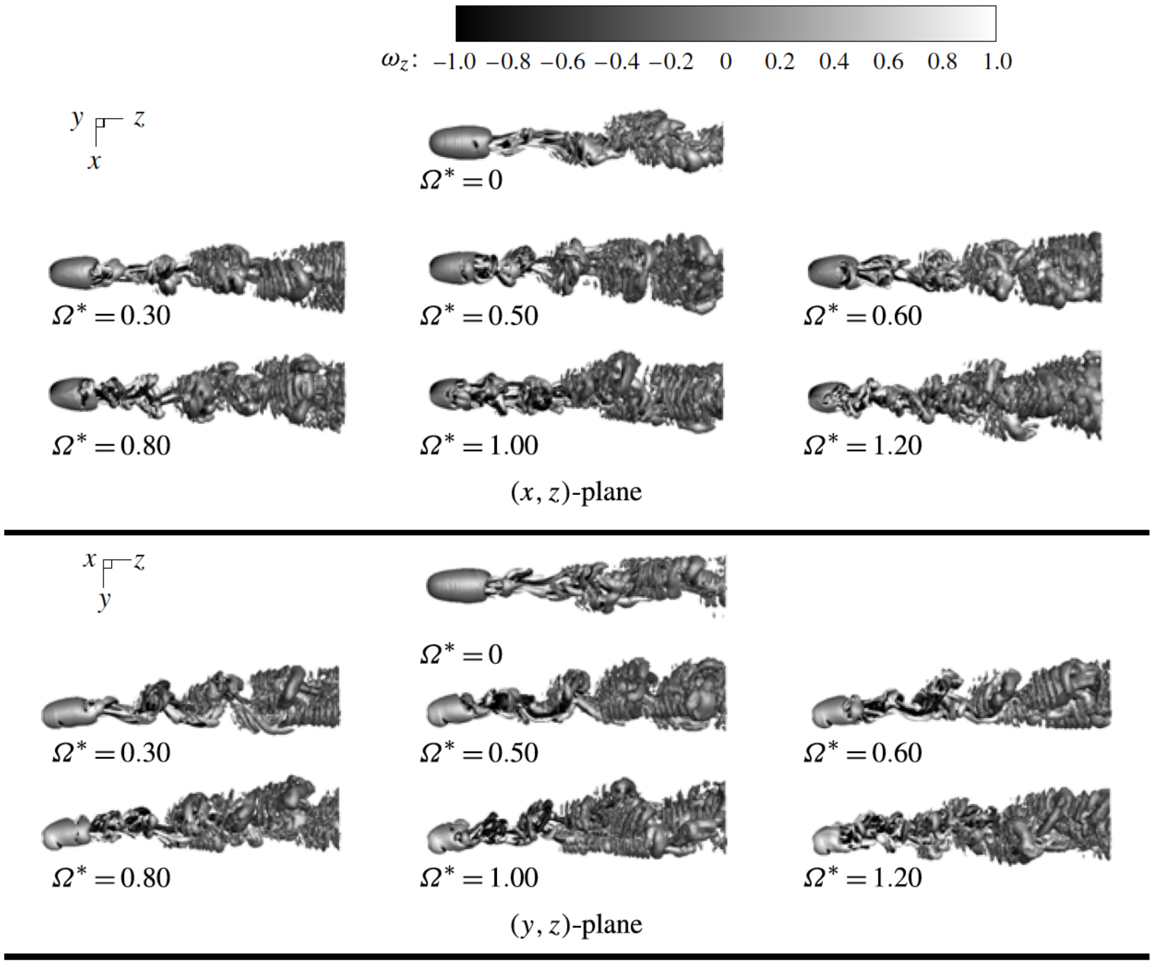
Poon et al., 2015.



Rotating spheres

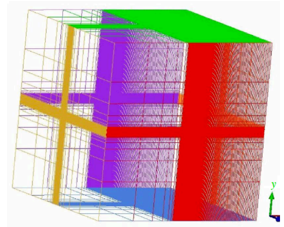
- Re = 1000
- Variation of wake with increasing spin rate
- Streamwise vorticity plotted (λ_2)

Poon et al., 2015.



Rotating spheres

- State of wake can change if computed for longer times for $\boldsymbol{\alpha}$ = 1 and 1.5.
- Rajamuni et al., JFM, 2018a
- Re = 300
- cf Giacobello et al., 2009.



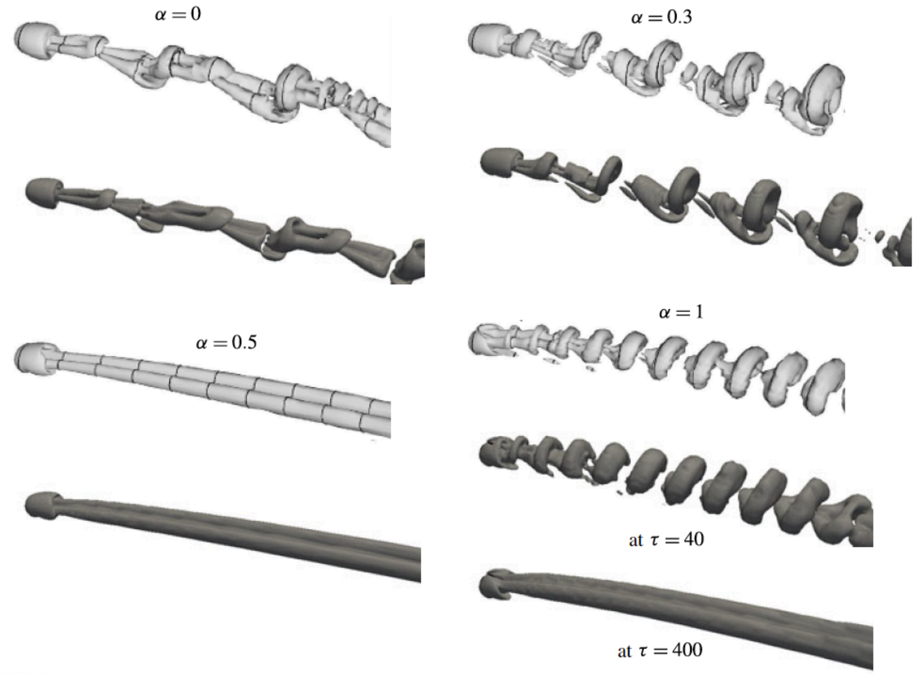


FIGURE 4. Wake structures of a rigidly mounted and transversely rotating sphere for $\alpha = 0$, 0.3, 0.5 and 1. Light grey structures are the results of Giacobello *et al.* (2009); dark structures are the results of the present study identified using the method of Jeong & Hussain (1995) at $\lambda_2 = -5 \times 10^{-4}$. For $\alpha = 1$, the wake structure varied with the time. Initially, the flow was unsteady as shown at $\tau = 40$, but for longer simulation time, the flow became stable with a double-threaded wake structure, as shown at $\tau = 400$, where $\tau = tU/D$ is the non-dimensional time.

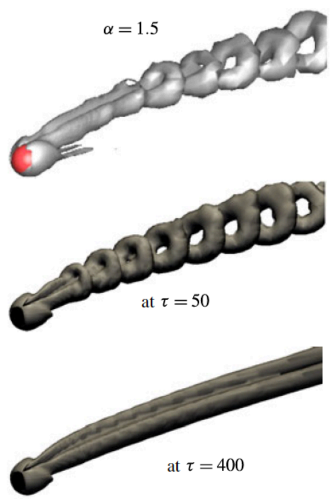


FIGURE 5. (Colour online) Comparison of wake structures of a rigidly mounted and transversely rotating sphere for $\alpha = 1.5$ with Dobson *et al.* (2014) (the dark structure). The light structures are the results of the present study.

Applications of rotating cylinders/spheres

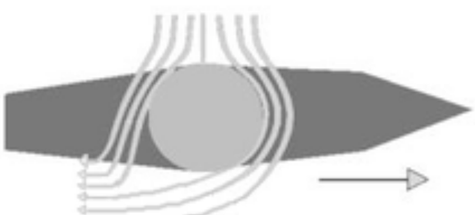
- Sails
- Wings
- Sports
- Wind turbines

Flettner Rotors – rotating round sails provide propulsion

•

http://www.youtube.com/watch?v=__8-QSXgupA

Flettner Rotor Ship 1920



http://www.youtube.com/watch?v=2pQga7jxAyc

Flettner Rotors – rotating round wings provide lift

Anton Flettner's Rotor Aircraft (1930)

Rotating Cylinder Helicopter Rotor

Nathan Phillips
Undergraduate Thesis

Ryerson University
Department of Aerospace Engineering
April 2006

http://www.youtube.com/watch?v=hlmvHfIAszo

Sports – Magnus effect is important

- Many sports take advantage of Magnus Effect: tennis, golf, table tennis, football, baseball, cricket, etc
- Magnus effect on ball
- “Impossible” Goal

http://www.youtube.com/watch?feature=player_detailpage&v=3ECoR__tJNQ

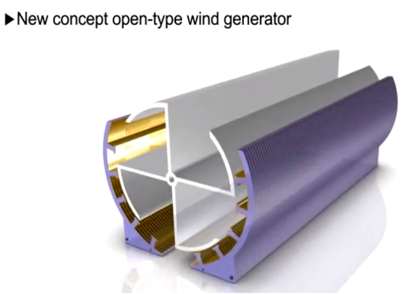
Roberto Carlos

Wind Turbines - Transverse Axis

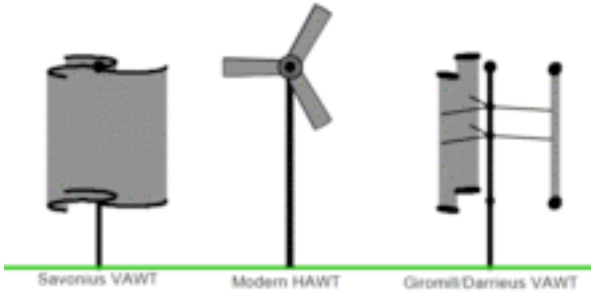
- Cylinder (chimney) suffers FSI oscillations

- Add rotation, and larger oscillations over wide velocity range

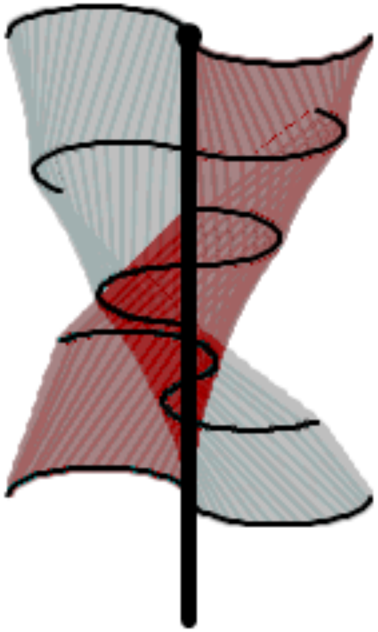
- Rotation can cause high bending moments on blades & shaft of turbines



http://www.youtube.com/watch?v=BybfndSoluY#t=17



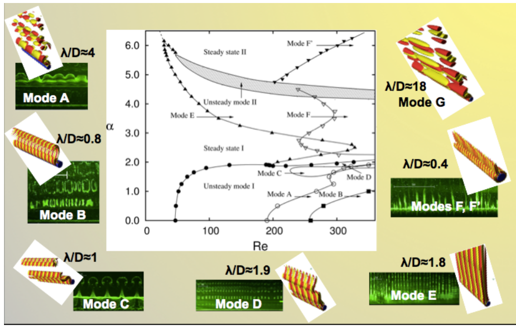
http://en.wikipedia.org/wiki/Wind_turbine



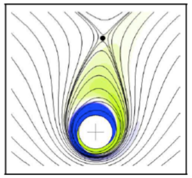
Conclusions

Rotation of a cylinder in a flow:

1. Introduces many new wake transitions



2. Can suppress vortex shedding

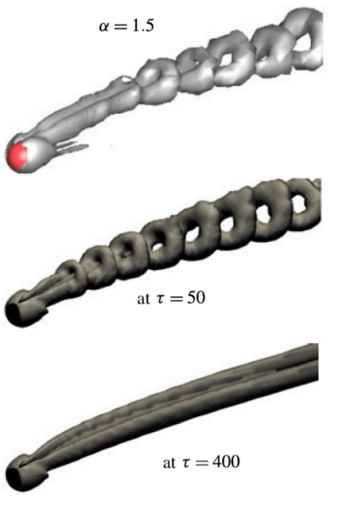


3. Increase dramatically lift and reduce drag

Conclusions

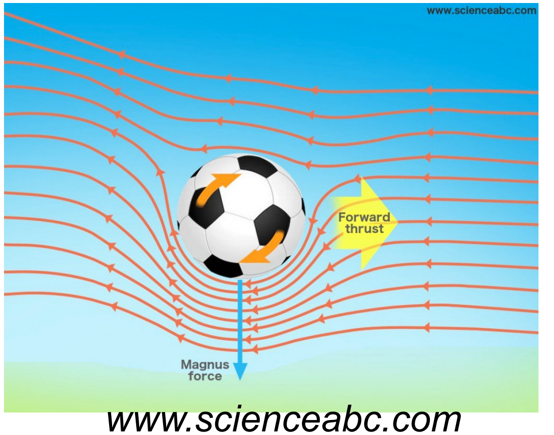
Rotation of a sphere in a flow:

1. Alters the wake structure



2. Can suppress vortex shedding

3. Produces a net lift force



www.scienceabc.com

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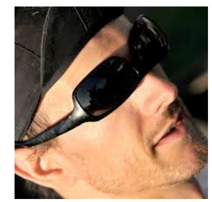
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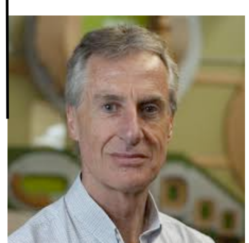
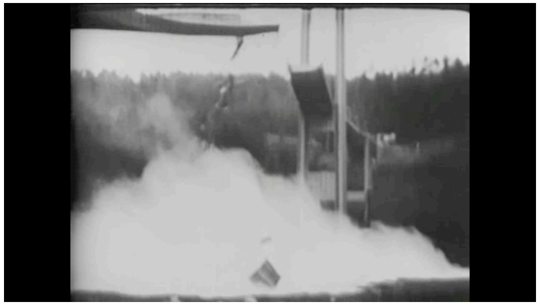
Swinburne University

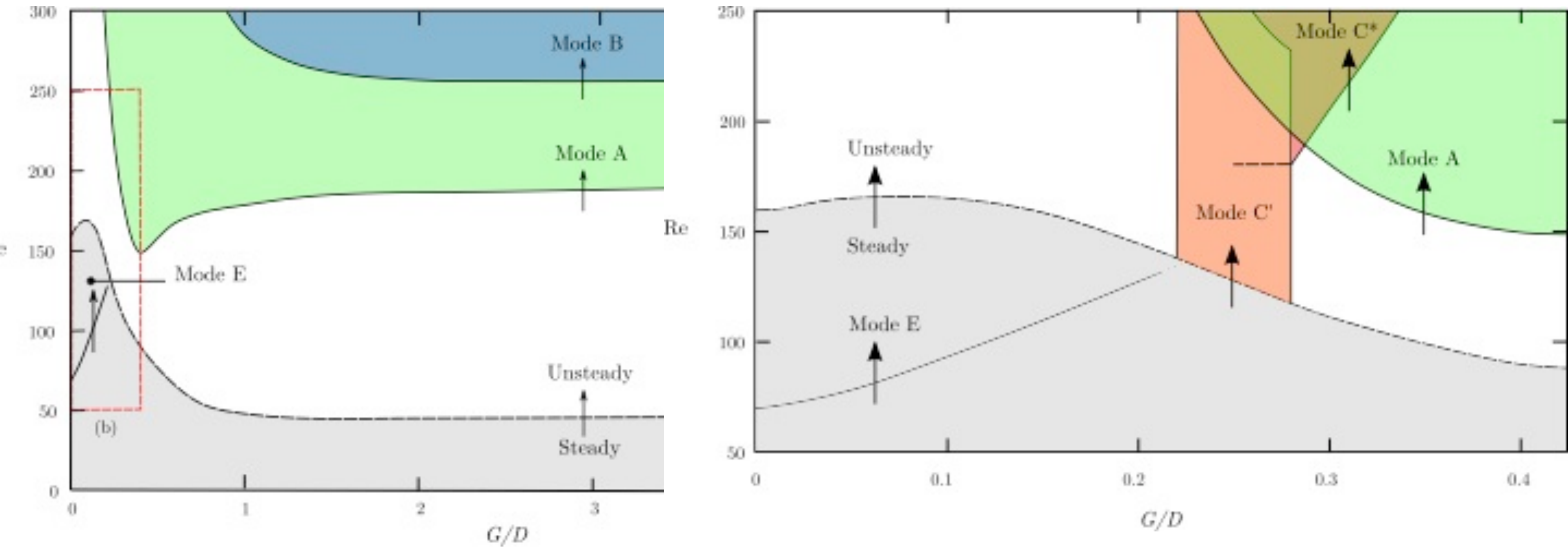

Prof Mark Thompson

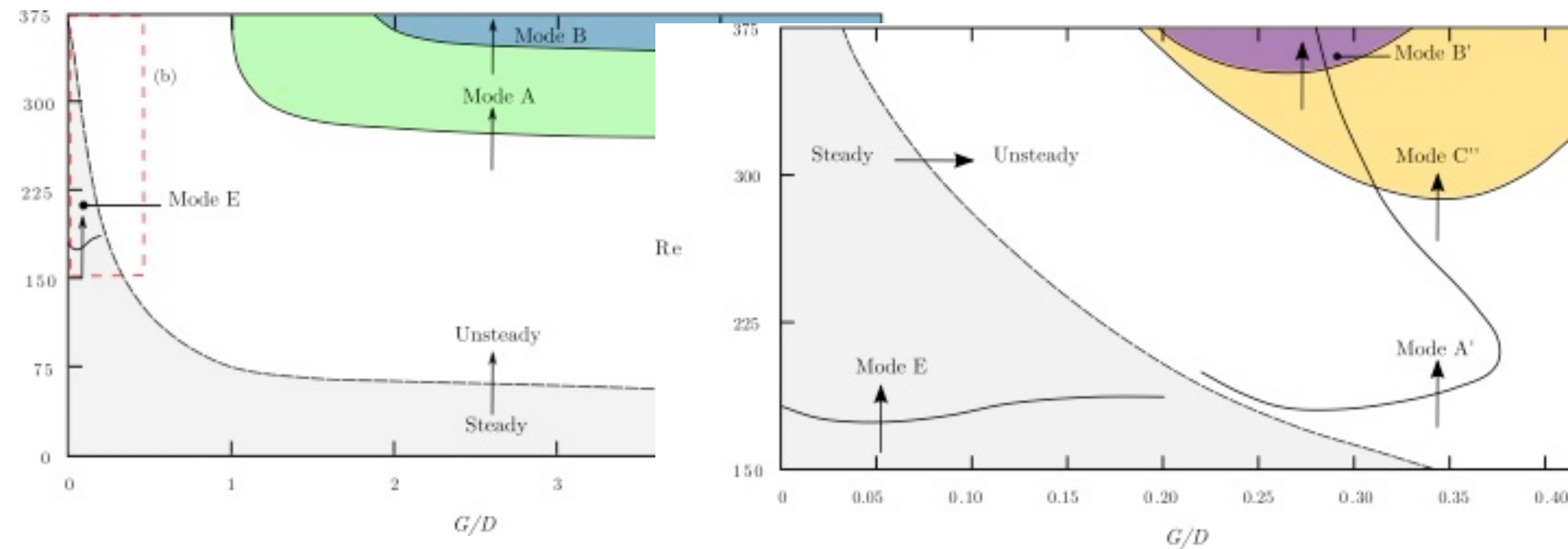

Dr David Lo Jacono
IMFT, Toulouse


Prof John Sheridan

Thank you



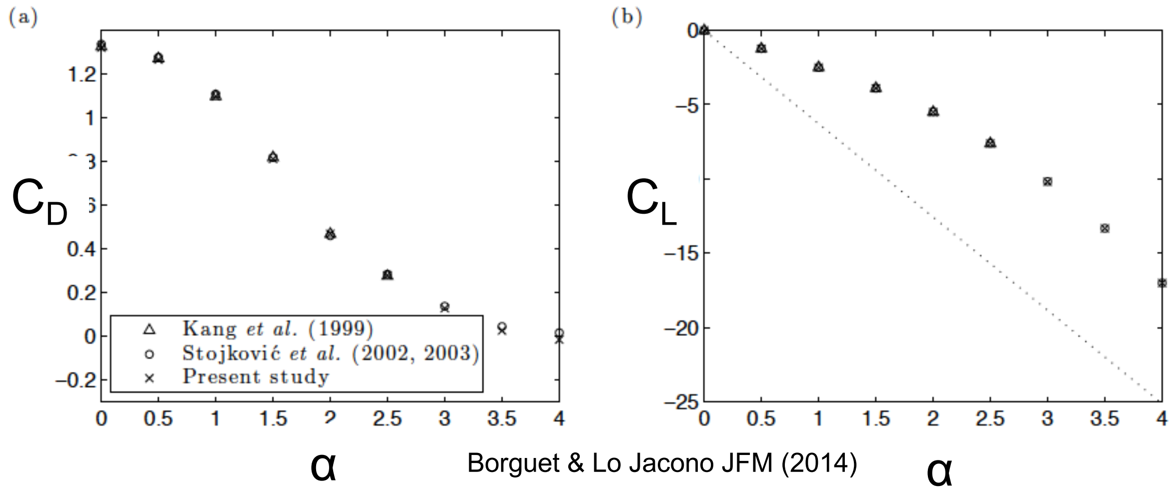

Mode B
Mode A
Mode E
Unsteady
Steady
(b)
Re
G/D
Mode C*
Mode C'
Mode A
Unsteady
Steady
Mode E
G/D


Mode B
Mode A
(b)
Mode E
Unsteady
Steady
G/D
Re
Mode B'
Steady
Unsteady
Mode C''
Mode A'
Mode E
G/D

Fluid-Structure Interaction

- Faster rotation =>
- Low (even negative!) drag
- High lift
- Elastically mount =>
- Larger oscillations
- Wide range of velocities

Fixed



Borguet & Lo Jacono JFM (2014)

Elastically mounted