Ph.D. Course on *Vorticity, Vortical Flows and Vortex-Induced Vibrations*
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Bluff Body Wakes II: Transitions for other bluff body geometries

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Reading Material

Johnson, T.A. & Patel, V.C., Flow past a sphere up to a Reynolds number of 300, Journal of Fluid Mechanics, 378, 19-70, 1999.

Leweke, T. & Provansal, M., The flow behind rings: bluff body wakes without end effects, 288, 265-310, 288.

Sheard, G.J., Thompson, M.C., Hourigan, K., 2003. From spheres to circular cylinders: the stability and flow structures of bluff ring wakes. Journal of Fluid Mechanics 492, 147–180.

Williamson, C.H.K., Vortex Dynamics in the Cylinder Wake, Annual Review of Fluid Mechanics, 28, 477-539, 1996.

Lecture Objectives

Learn:

Variations of geometries on the circular cylinder and sphere geometries

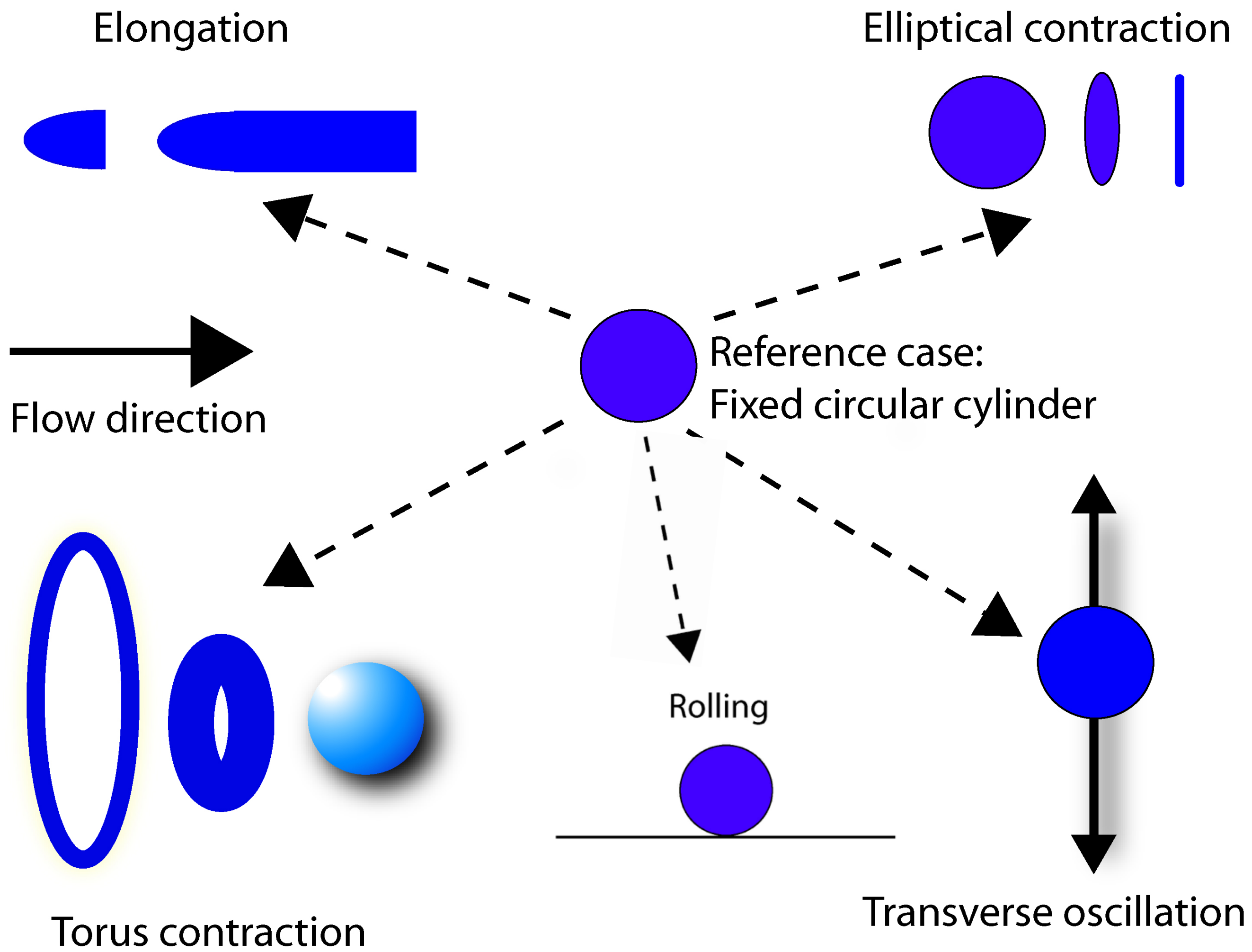
Effect of geometries on the instabilities and transitions in the wakes

Low Reynolds number instabilities and transition to turbulence

Overview

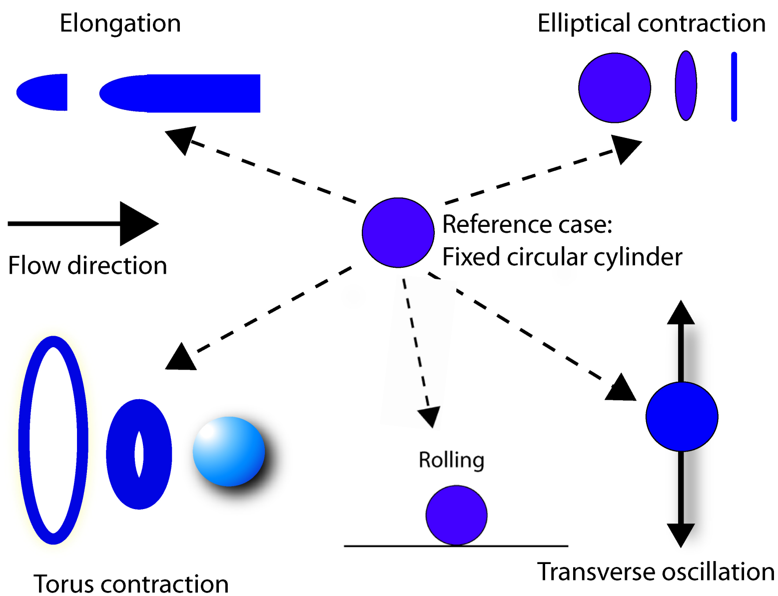
- **Transition between spheres and cylinders**
  - Numerical & experimental studies
  - Bifurcations in the flow past rings
- **Conclusions**

Variations on the Generic Fixed Circular Cylinder

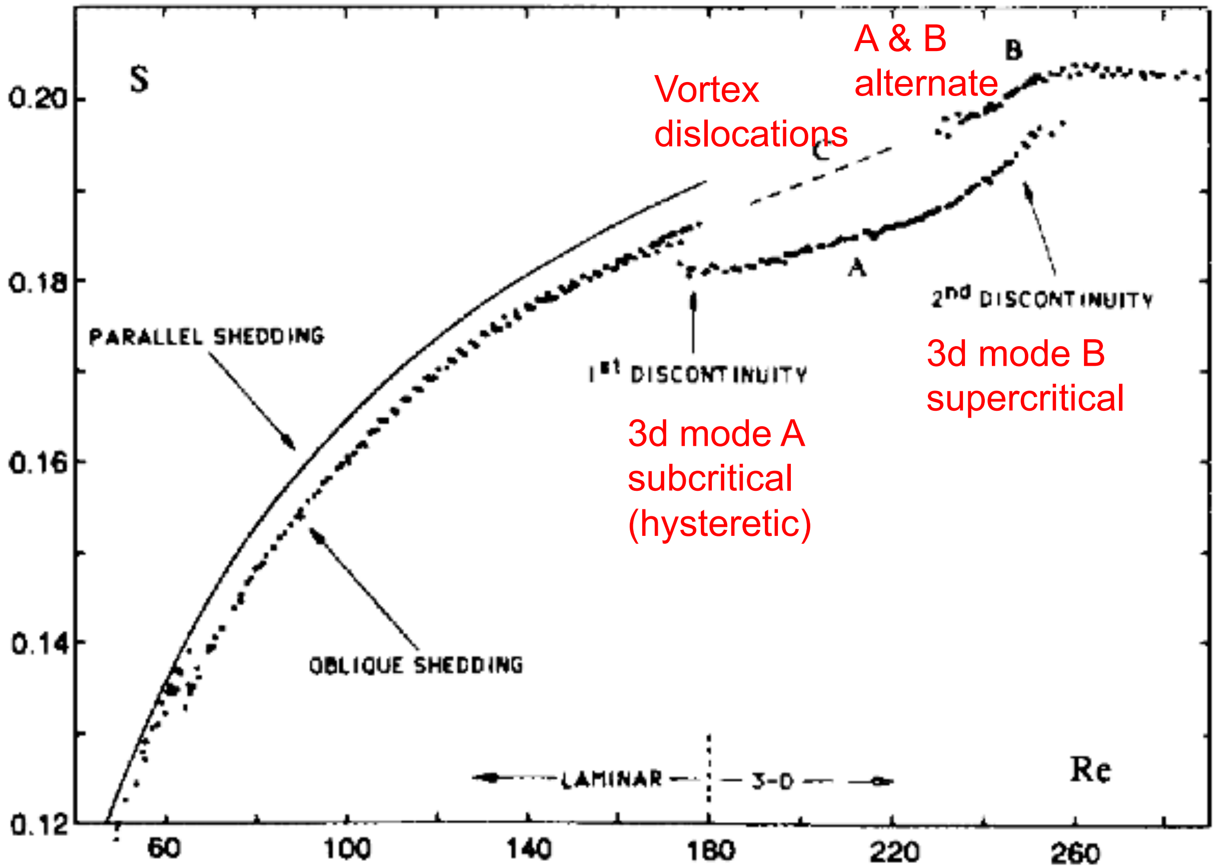


Independent Parameters

- The primary difference between the generic fixed cylinder (and sphere) flows and those studied here is that the former has only one independent parameter, Re
- However, the flow past tori, elliptical cylinders, elongated cylinders, rolling and oscillating cylinders each have two control parameters
- The second independent parameter being the aspect ratio, which can be varied, or the oscillation amplitude (at fixed f), or the rotation frequency for a “rolling” body



Discontinuities in St vs Re



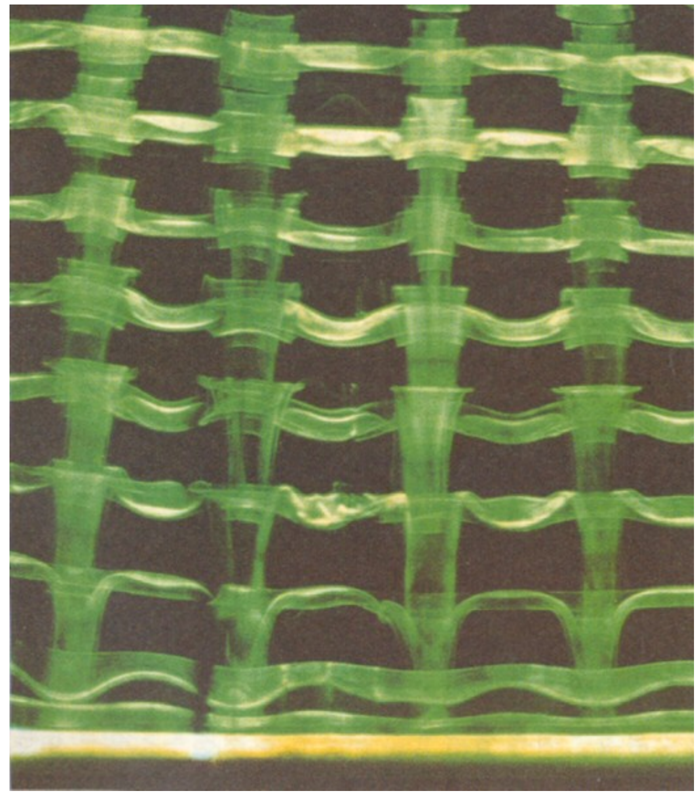
Strouhal number vs Reynolds number

Williamson (PoF, 1988)

The flow past spheres & circular cylinders

Mode A instability in the wake behind a circular cylinder at Re = 200

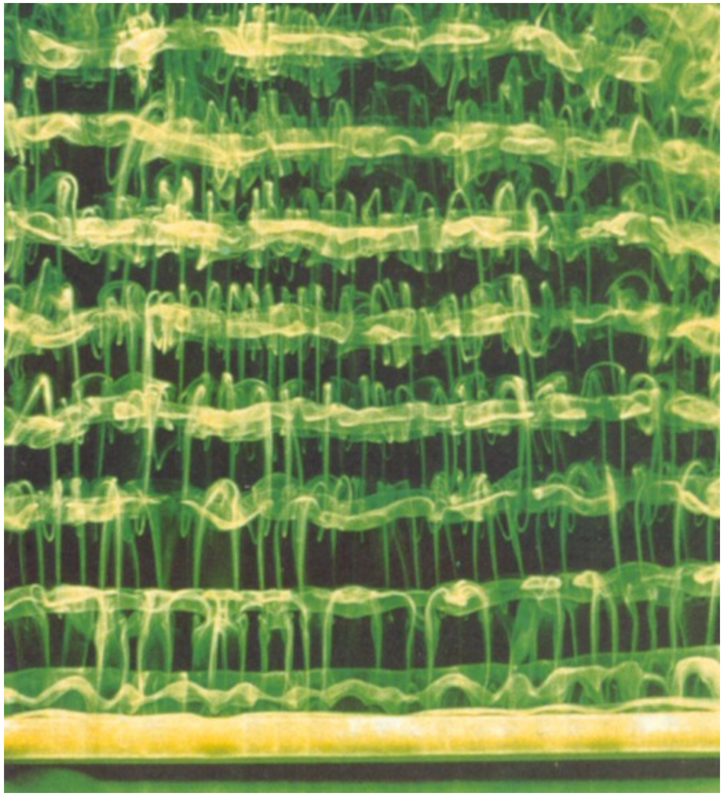
Williamson (1996)



The flow past spheres & circular cylinders

Mode B instability in the wake behind a circular cylinder at Re = 270

Williamson (1996)

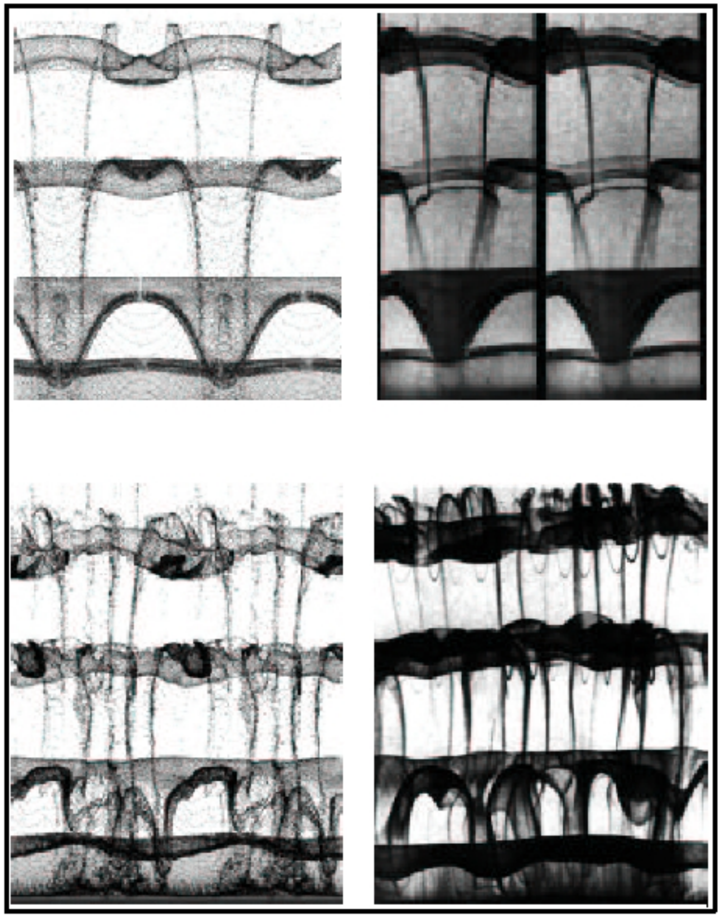


Numerical and experimental comparison

Mode A

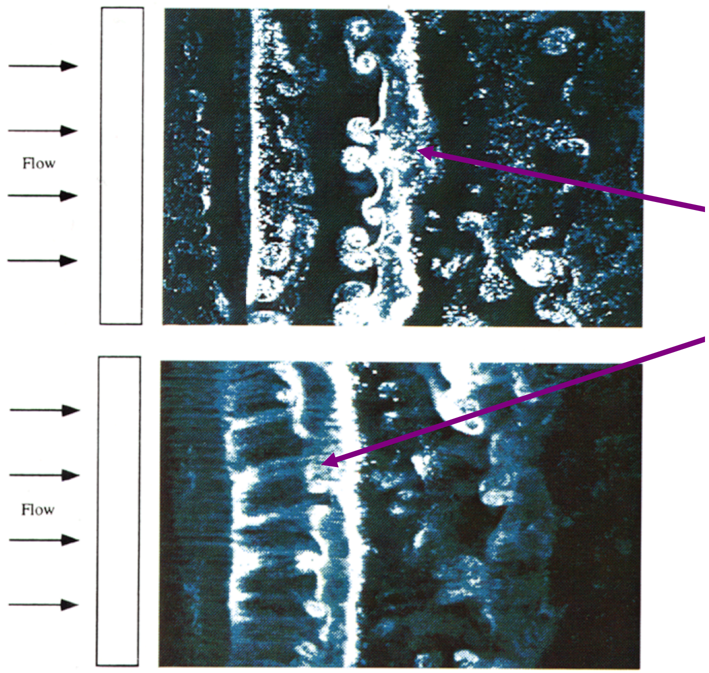
Williamson (1996)
Thompson, Hourigan
& Sheridan (1994, 1996)

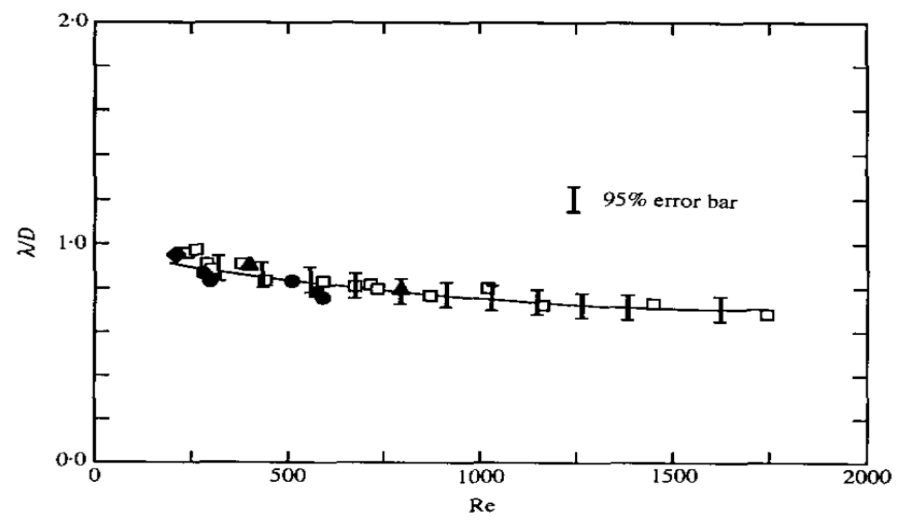
Mode B



Mode B persists to higher Re

- **Wake structures at Re = 1000**



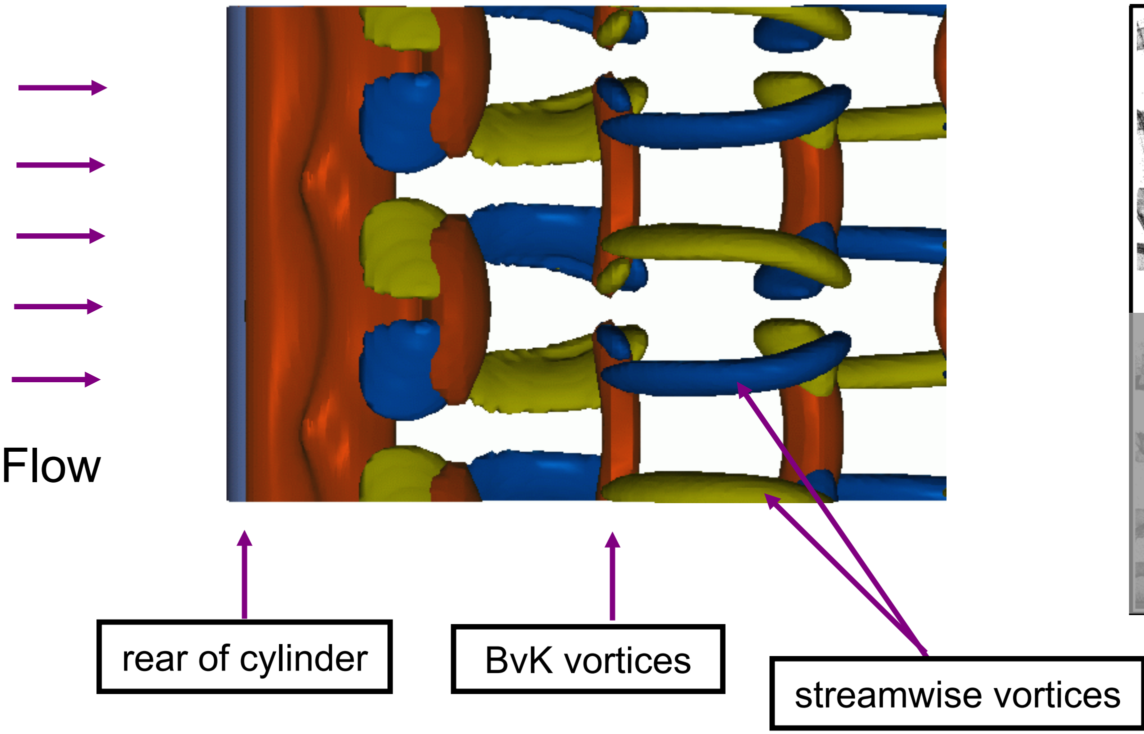


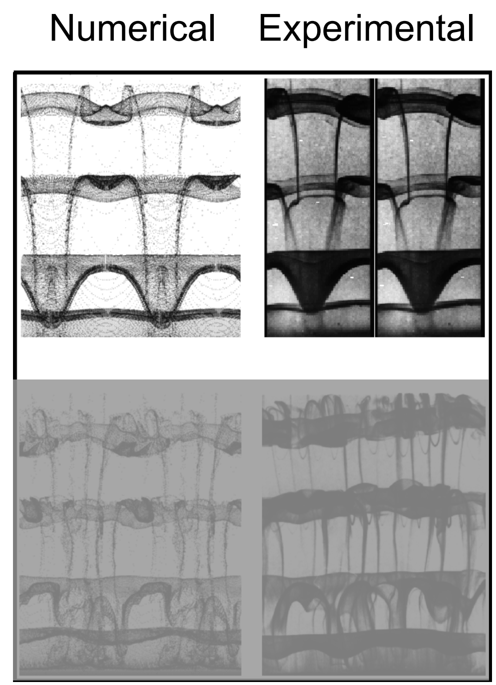
Persistence of mode B in turbulent wake

Wu, Sheridan, Soria, Welsh (1995)

3D transition mode symmetries

- **Mode A**



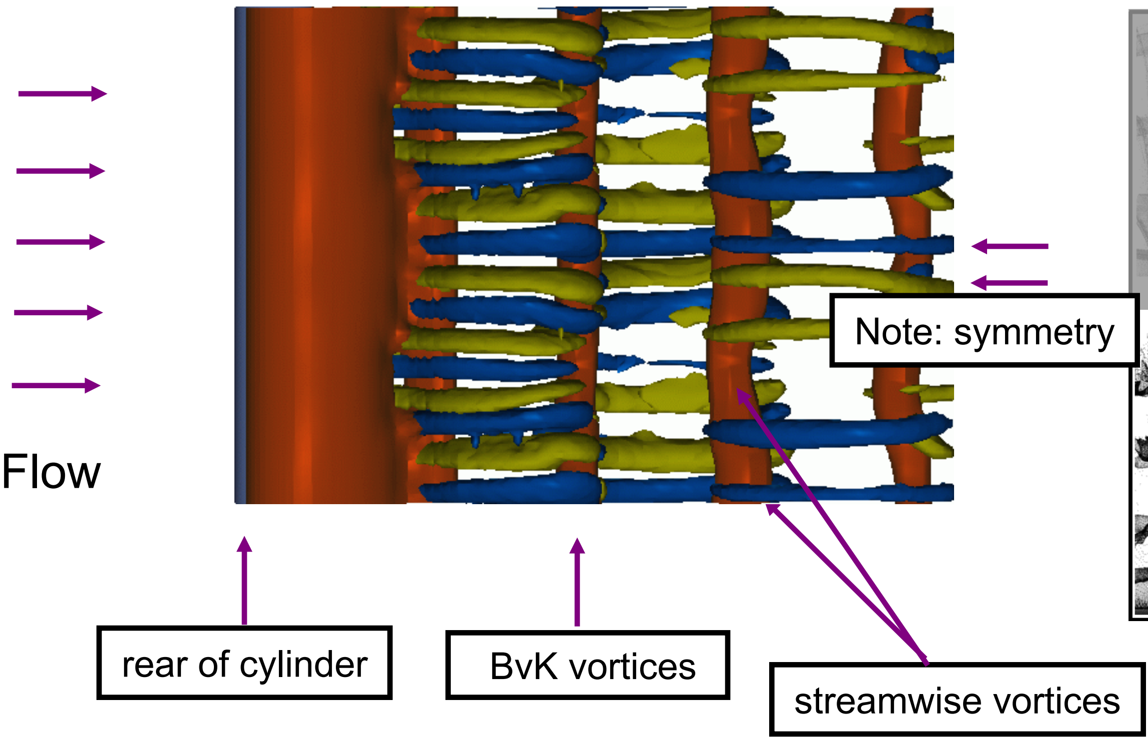


Streamwise vortices change sign every half cycle

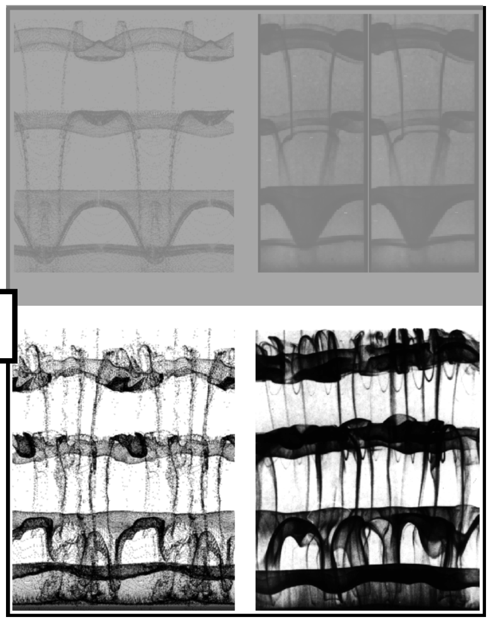
Williamson 1988, 1996,
Barkley & Henderson 1995
Thompson et al. 1996

3D transition mode symmetries

- **Mode B**



Numerical Experimental

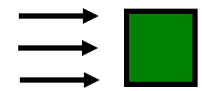


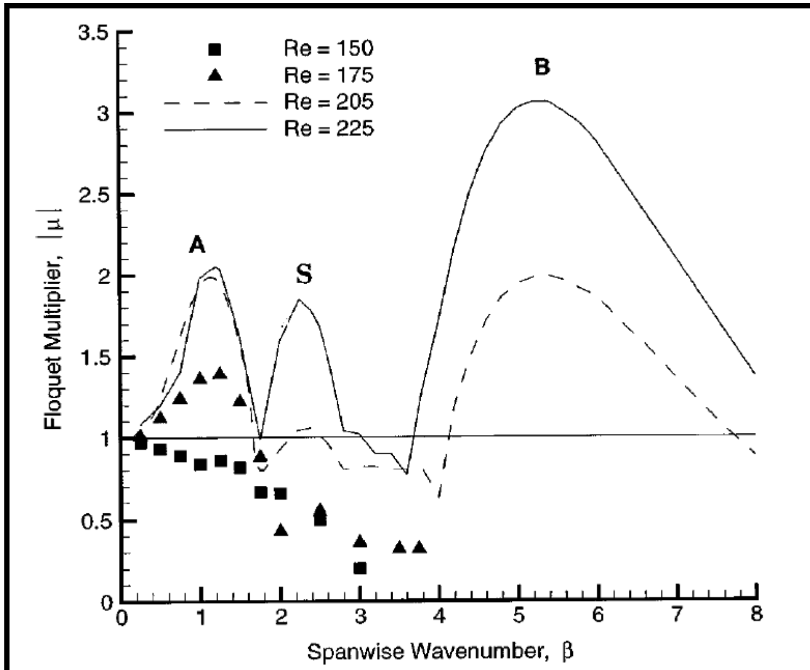
Streamwise vortices keep same sign

Williamson 1988, 1995
Thompson et al. 1996

Is this a generic turbulence transition scenario?

- **Square cross-sectioned cylinders**
  - Robichaux, Balachandar & Vanka (1999)



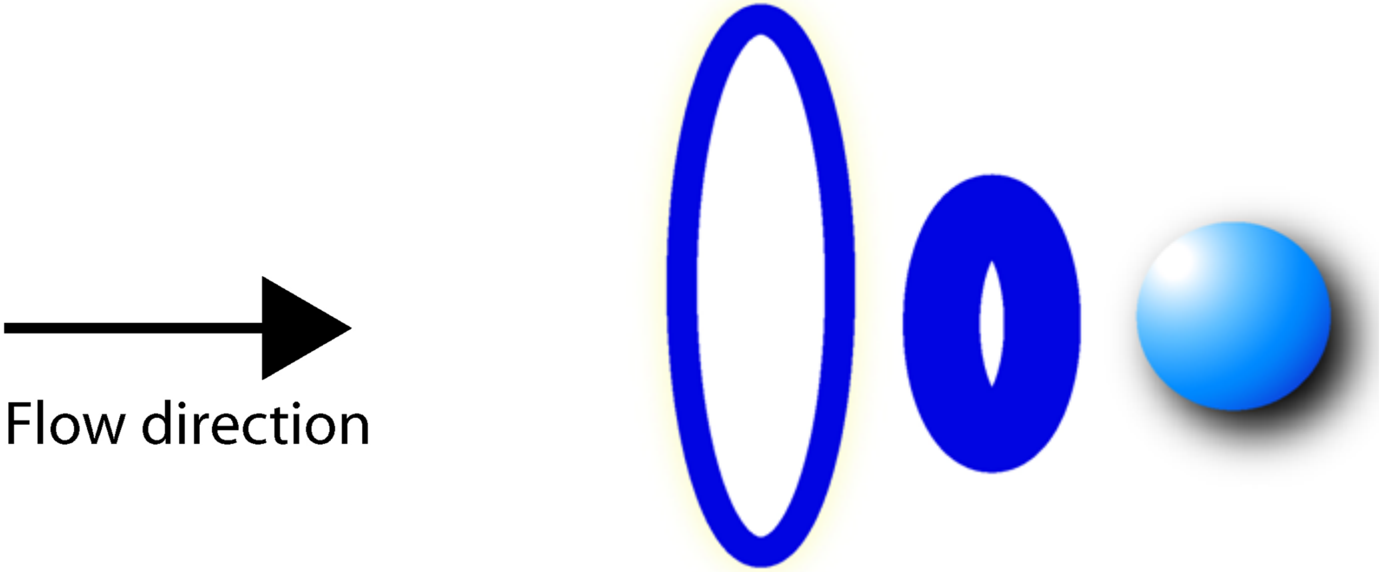


Mode	Re_2 Circle	Re_2 Square	λ Circle	λ Square
A	188	162±12	3.96	5.22
B	259	190±14	0.82	1.2
S	⋯	200±5	⋯	2.8
C	377	⋯	1.8	⋯

- Same instability modes
- Same sequence of transitions
- *"Subharmonic" mode (S) later shown to be not a true subharmonic*

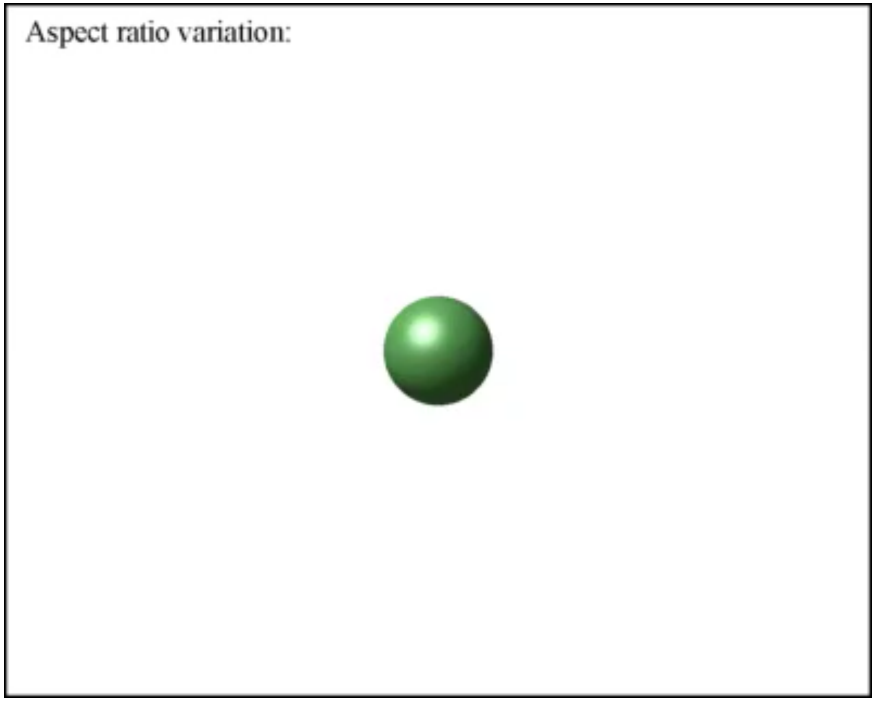
(Blackburn & Lopez 2001)

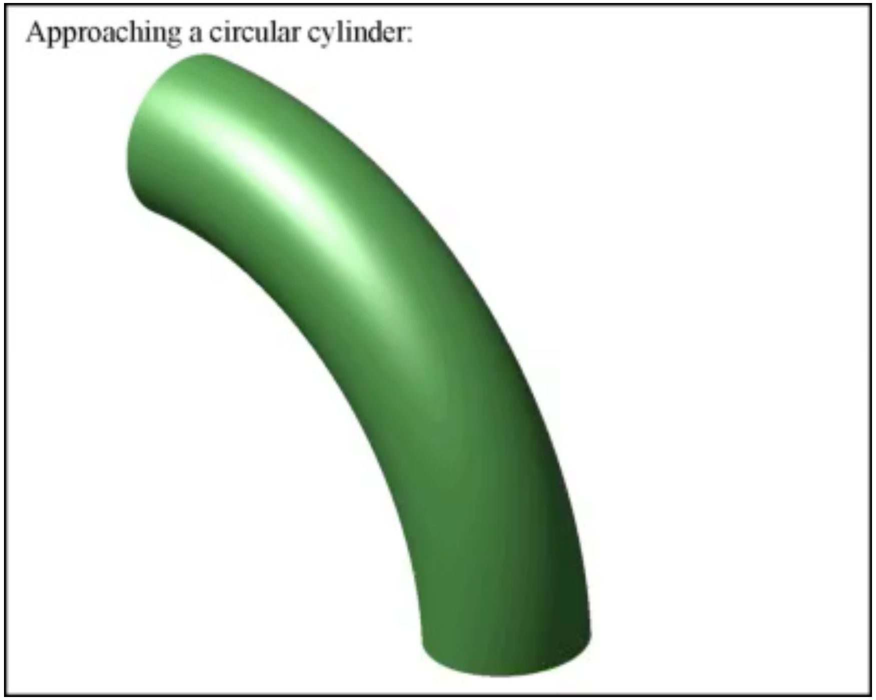
Tori



Linking spheres & cylinders with rings

- **Describes a sphere at the lower limit of aspect ratio:**

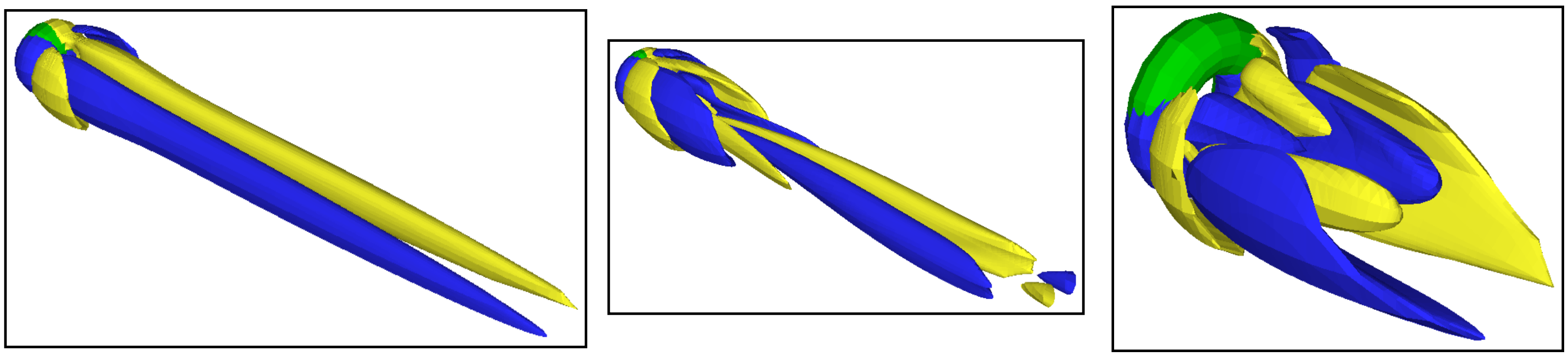




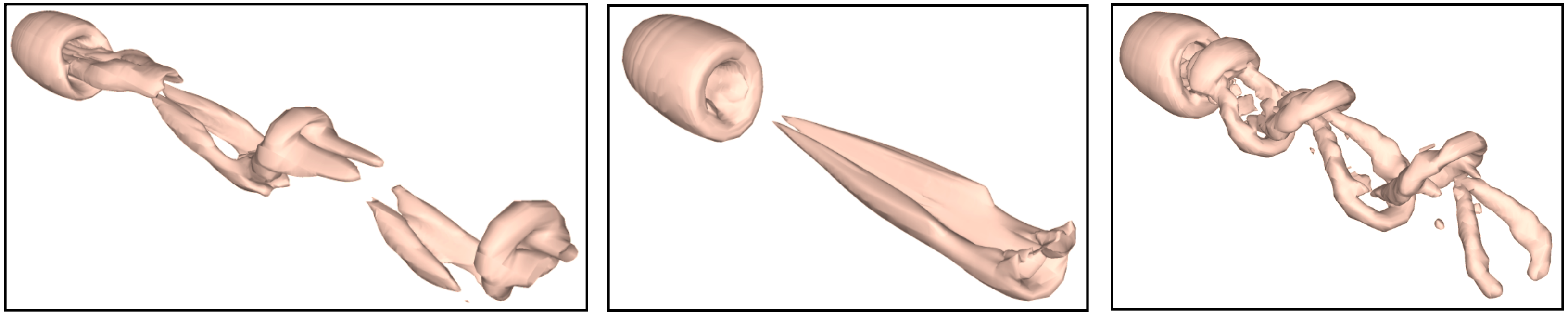
- **And a circular cylinder at the upper limit**

Linking spheres & cylinders with rings

- **Wakes behind rings with $A_R < 3.9$:**

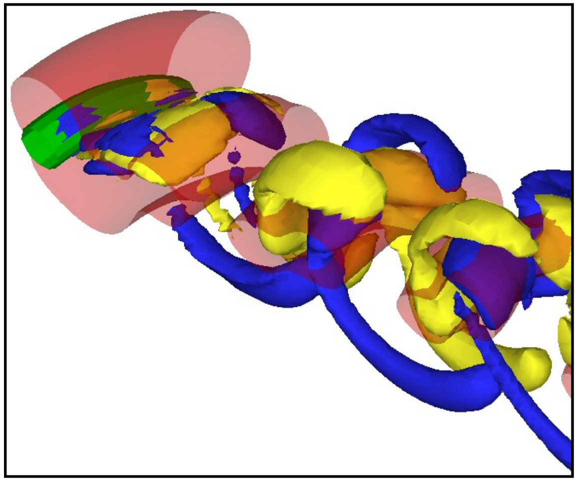


Non-axisymmetric bifurcation prior to development of unsteady flow

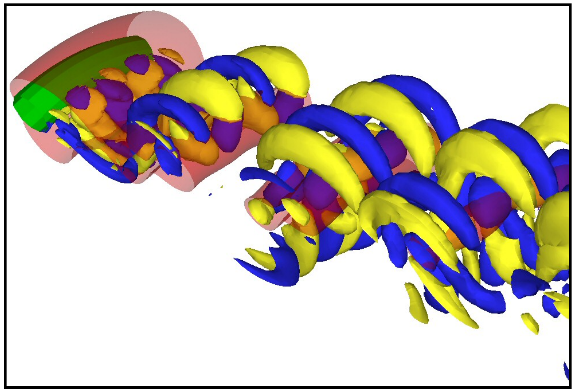


Linking spheres & cylinders with rings

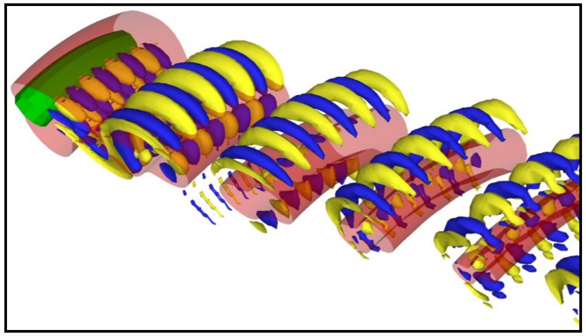
- **Wakes behind rings with A_R > 3.9:**
  - Hopf bifurcation leads to axisymmetric vortex street
  - Three distinct non-axisymmetric instability modes found



Mode A
Re = 200, A_R = 10
$\lambda_d \approx 4d$



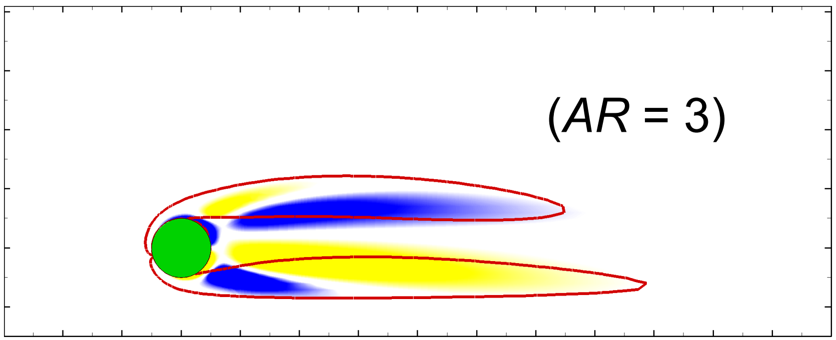
Mode C
Re = 235, A_R = 10
$\lambda_d \approx 1.6d$



Mode B
Re = 280, A_R = 10
$\lambda_d \approx 0.8d$

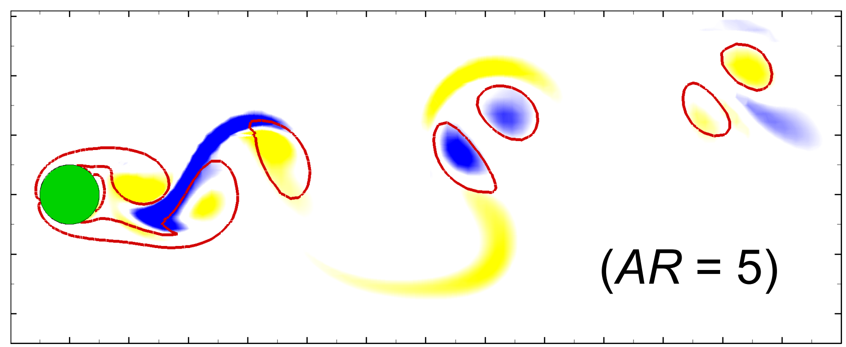
Linking spheres & cylinders with rings

- **Major topological change in the wake at approximately A_R = 3.9:**



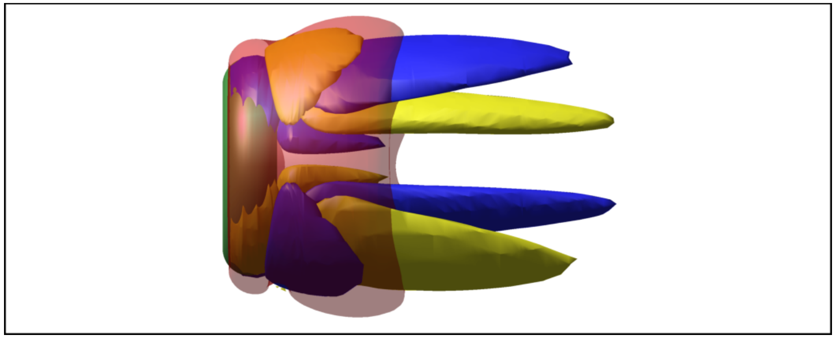
Predicted instability with azimuthal mode number *m* = 2
Subcritical bifurcation
Sphere wake first bifurcates through a supercritical regular bifurcation

Predicted instability with azimuthal mode wavelength = 1.6*d*
Supercritical bifurcation → "Mode C"
Cylinder wake first bifurcates through subcritical "Mode A" instability



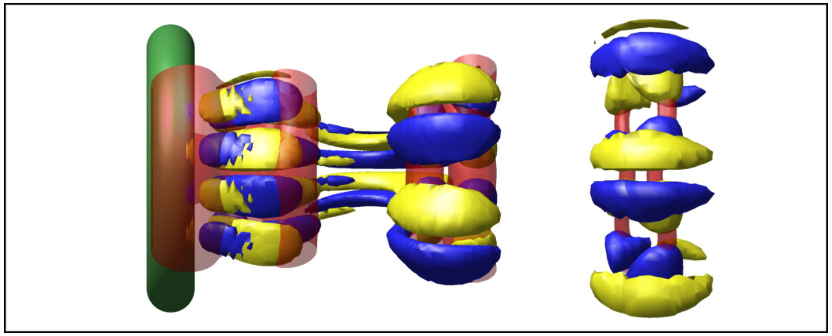
Linking spheres & cylinders with rings

- **Major topological change in the wake at approximately A_R = 3.9:**



Steady three-dimensional wake at *Re* = 115, A_R = 3
3D transition occurs before Hopf bifurcation

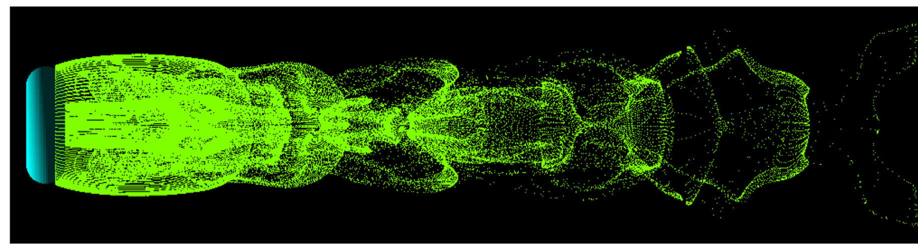
Periodic three-dimensional wake at *Re* = 170, *AR* = 5
3D transition occurs after Hopf bifurcation



Linking spheres & cylinders with rings

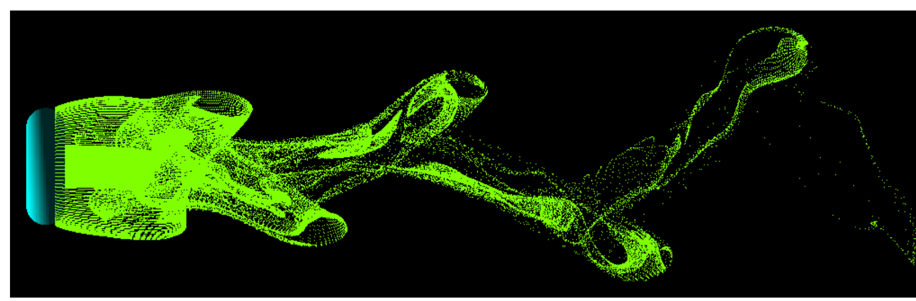
- **Change in azimuthal mode number of non-axisymmetric instabilities between A_R = 2 & 3**

$A_R = 2$, $Re = 150$



$A_R = 2$: Mode number $m = 1$, consistent with sphere wake

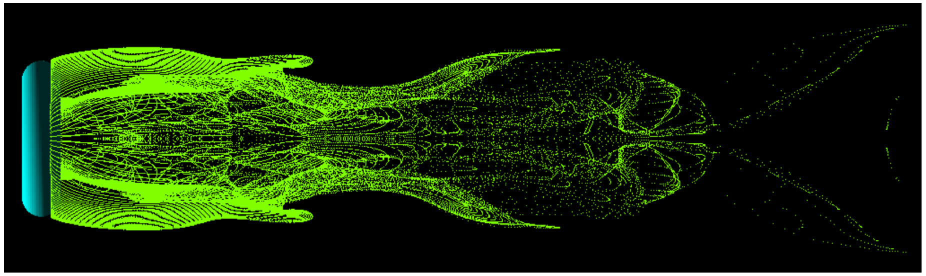
Familiar hairpin shedding observed



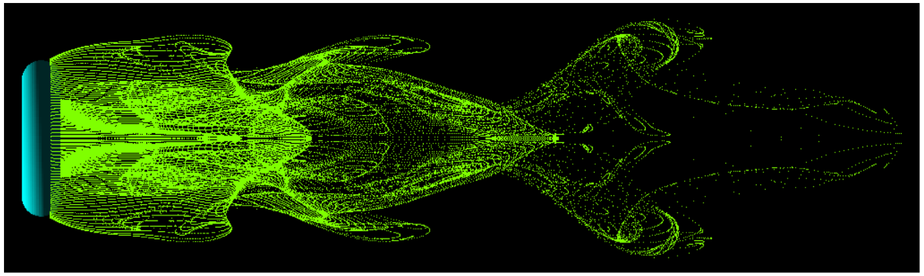
Linking spheres & cylinders with rings

- **Change in azimuthal mode number of non-axisymmetric instabilities between A_R = 2 & 3**

A_R = 3, Re = 138

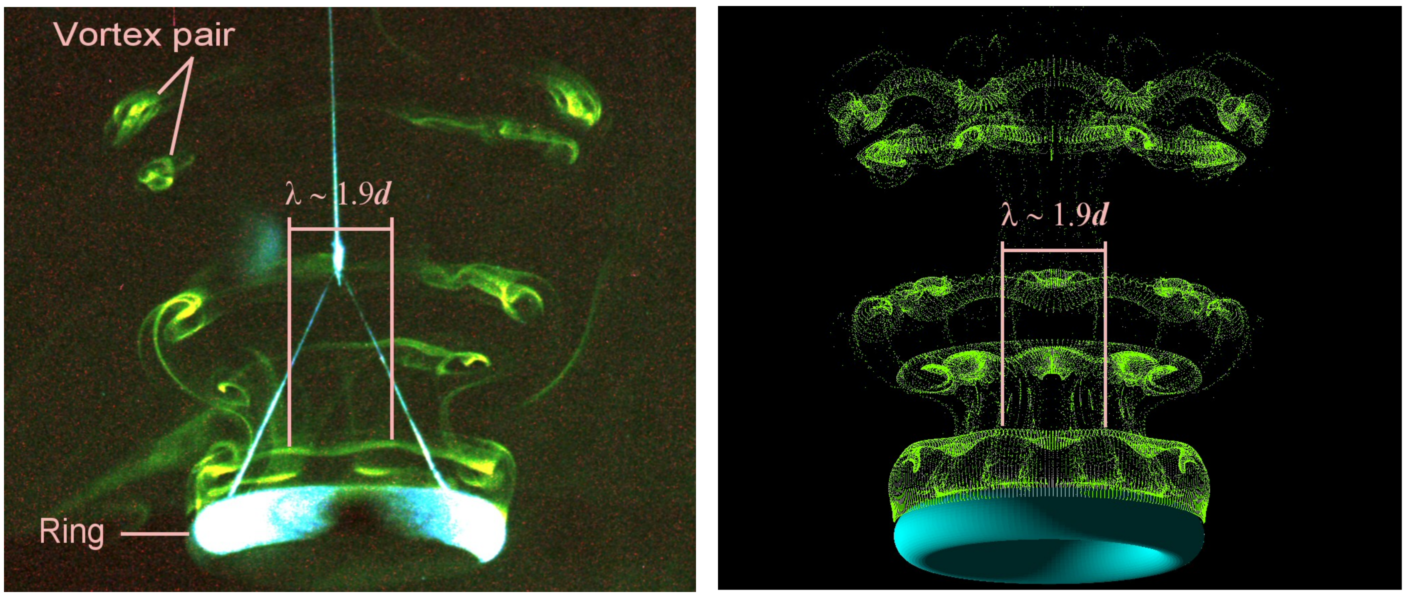


A_R = 3: Mode number m = 2



Linking spheres & cylinders with rings

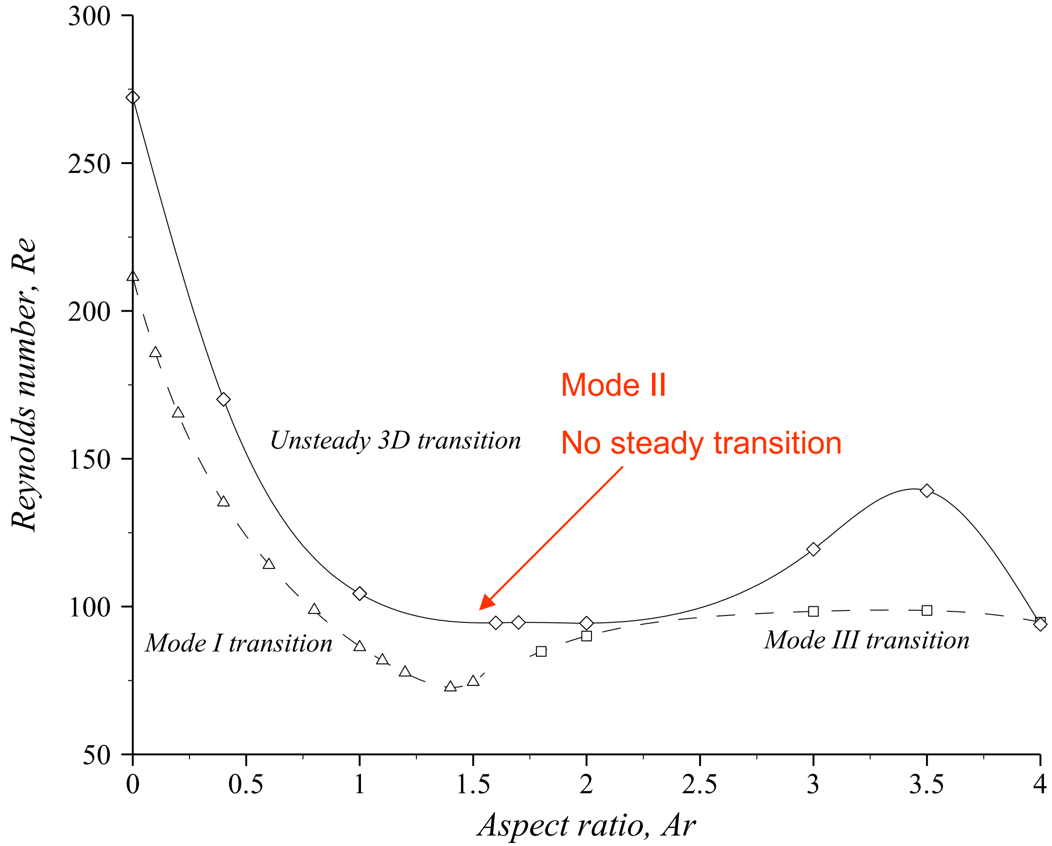
- **Onset of Mode C at A_R=5**



A_R = 5, *Re* = 200

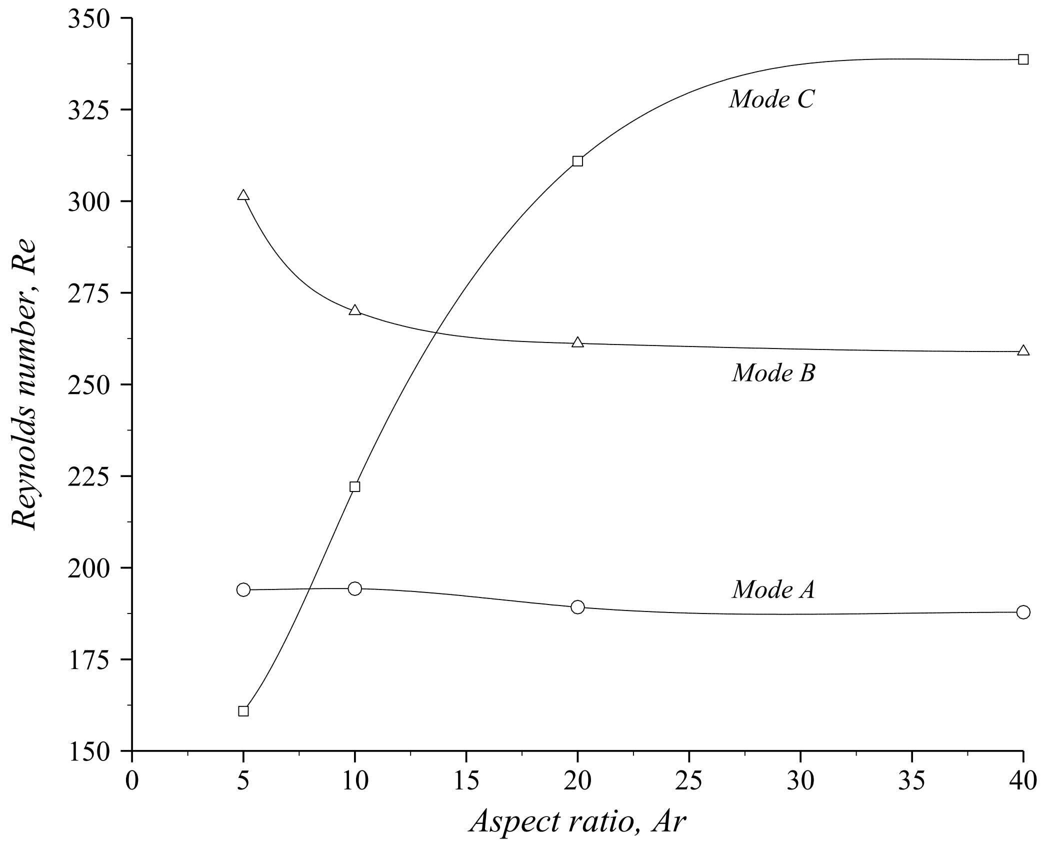
Possible experimental verification of the existence of the “Mode C” instability

Critical Reynolds numbers for the transitions to the three-dimensional vortex shedding modes



AR < 4

Critical Reynolds numbers for the transitions to the three-dimensional vortex shedding modes



AR >4

Conclusions

- **Steps to turbulence?**

AR<3.9:

Different 3D modes first then unsteady

AR>3.9:

Unsteady first then different order of modes A, B & C

- **Rings offer wide parameter range**

2D Wakes of various modified cylinders

Stationary Circular Cylinder

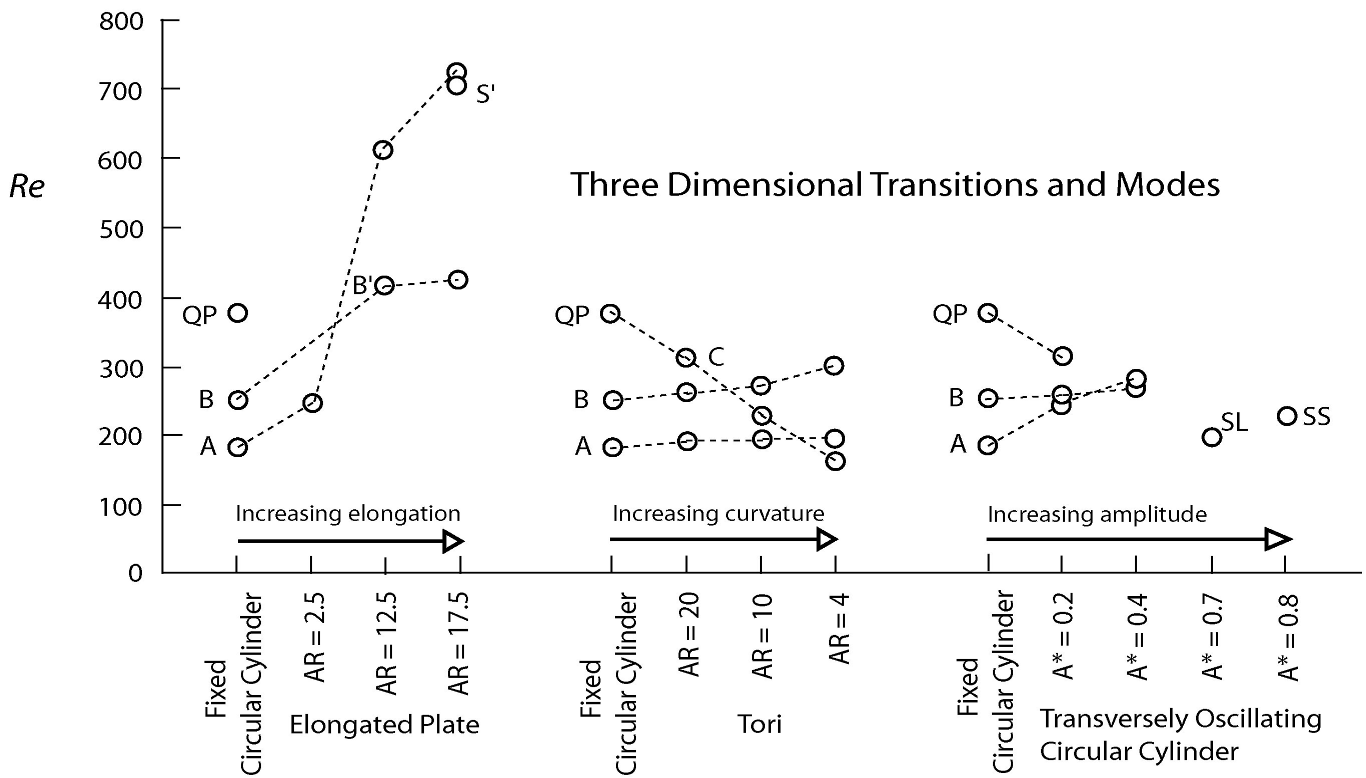
Stretched cylinder

Bent cylinder

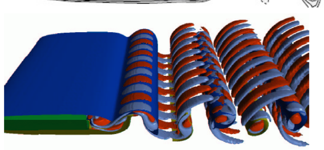
Rocking cylinder

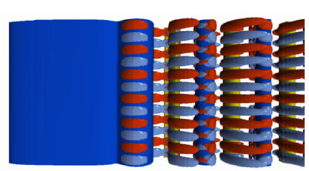
Rolling cylinder

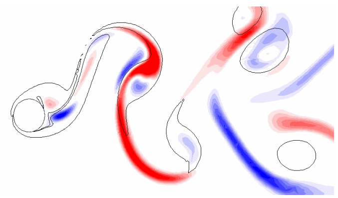
Summary of 3-d Wake Transitions for Elongated Plate, Tori, and Oscillating Cylinder



Bluff Body Case







Conclusions

- **Fixed circular cylinder is a generic case but ….**
- **Modes A, B, C can come in different orders for other cases**
- **Plus new modes are found**
- **Has implications for transition to turbulence (period doubling, etc)**