Suppression of 3D flow instabilities in tightly packed tube bundles

Nicholas Kevlahan

kevlahan@mcmaster.ca

Department of Mathematics & Statistics

McMaster University

SHARCNET™

Collaborators

Collaborators

- J. Wadsley (McMaster University, Canada)

Collaborators

- J. Wadsley (McMaster University, Canada)
- J. Simon (École MatMéca, France)
- N. Tonnet (École MatMéca, France)

Outline

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2. Goals

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4. Numerical method

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Introduction

Transition from 2D to 3D flow past an obstacle

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- Well understood for flow past a single tube.

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Transition from 2D to 3D flow past an obstacle

- Well understood for flow past a single tube.
- Not well understood for flow past a tightly packed tube bundle, e.g. spacing $P/D = 1.5$.

Introduction (cont.)

Transition from 2D to 3D flow past a single tube

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Transition from 2D to 3D flow past a single tube

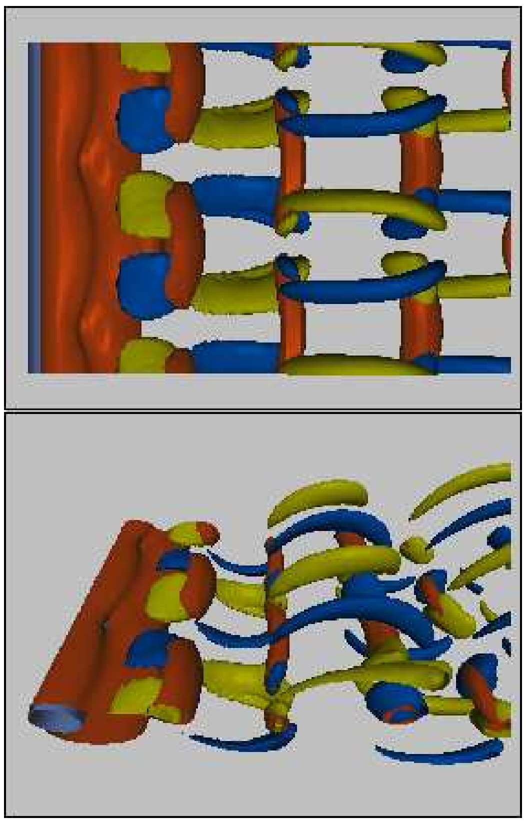
- Wake becomes 3D at $Re \approx 180$ via formation of streamwise vortices with a spacing of about three cylinder diameters (mode A instability)

Introduction (cont.)

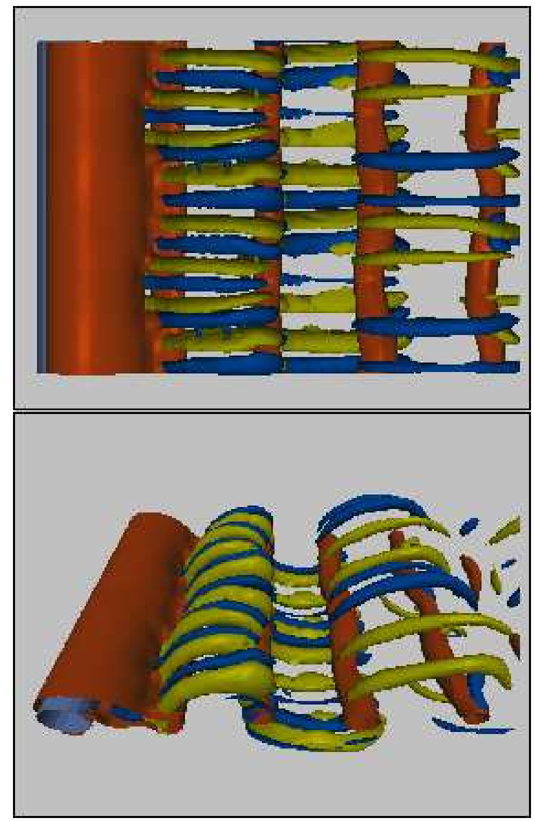
Transition from 2D to 3D flow past a single tube

- Wake becomes 3D at $Re \approx 180$ via formation of streamwise vortices with a spacing of about three cylinder diameters (mode A instability)
- At $Re \approx 230$ a second vortex mode appears (mode B instability), via the formation of irregular streamwise vortices with a spacing of one cylinder diameter (Williamson 1989)

Introduction (cont.)



Mode A instability at $Re = 210$



Mode B instability at $Re = 250$

(Thompson, Hourigan & Sheridan 1995)

Introduction (cont.)

- As Reynolds number increases further, the wake becomes increasingly complicated until it is completely turbulent.

Introduction (cont.)

What about tightly packed tube bundles?

Industrial heat exchanger

Introduction (cont.)

Transition from 2D to 3D flow past a tube bundle

Introduction (cont.)

Transition from 2D to 3D flow past a tube bundle

- Experiments appear to indicate that the flow and cylinder response remain roughly two-dimensional for $Re \gg 180$ (Weaver 2001).

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Transition from 2D to 3D flow past a tube bundle

- Experiments appear to indicate that the flow and cylinder response remain roughly two-dimensional for $Re \gg 180$ (Weaver 2001).
- Price et al (1995) find that Strouhal frequency and rms drag do not change with Reynolds number for $Re > 150$.

Introduction (cont.)

- Blevins (1985) demonstrated that acoustic forcing of an isolated cylinder at its Strouhal frequency is able to produce nearly perfect spanwise correlation of pressure for $20\,000 \leq Re \leq 40\,000$.

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  He conjectured that similar effects might be observed in tube bundles.

- This confirmed earlier work by Toebes (1969) showing cylinder vibration of $A/D \geq 0.125$ is required to enforce spanwise correlation.

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   - Is tight packing sufficient?
   - Is resonant tube motion effective in tube bundles?
   - Is tube motion amplitude large enough in tube bundles?
   - Does tube response remain 2D even if the flow is 3D?

Goals (cont.)

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    - What are the differences between 2D and 3D flows?
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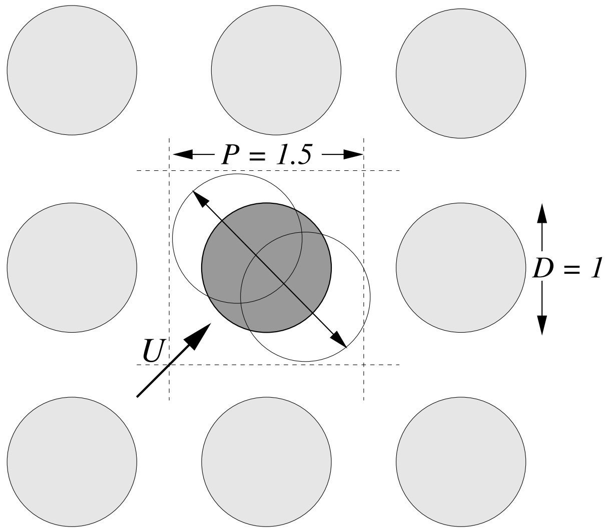
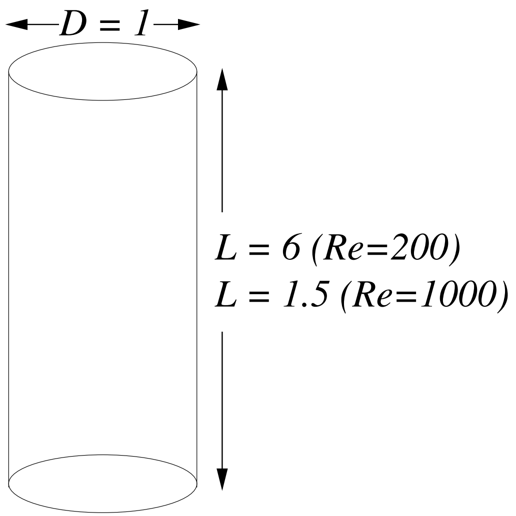
We consider flows at $Re = 200$ and $Re = 1\,000$ in rotated square tube bundles with $P/D = 1.5$.

Problem formulation





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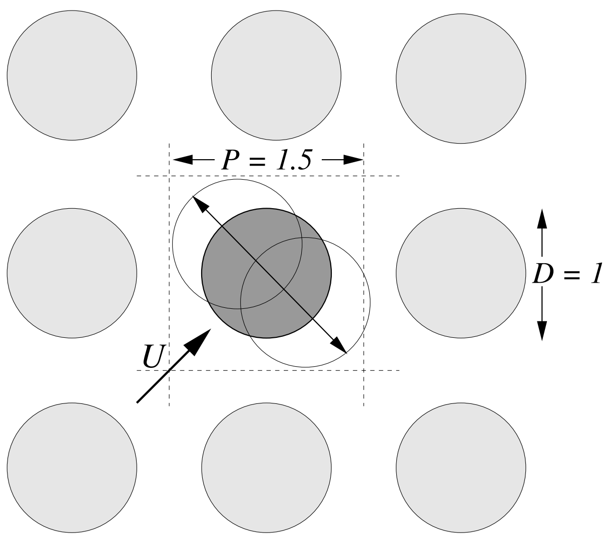
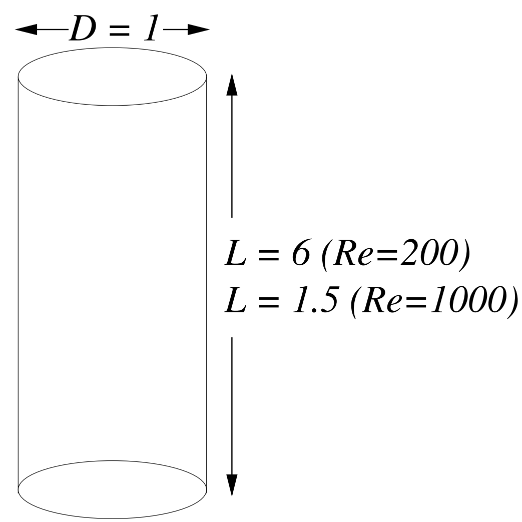
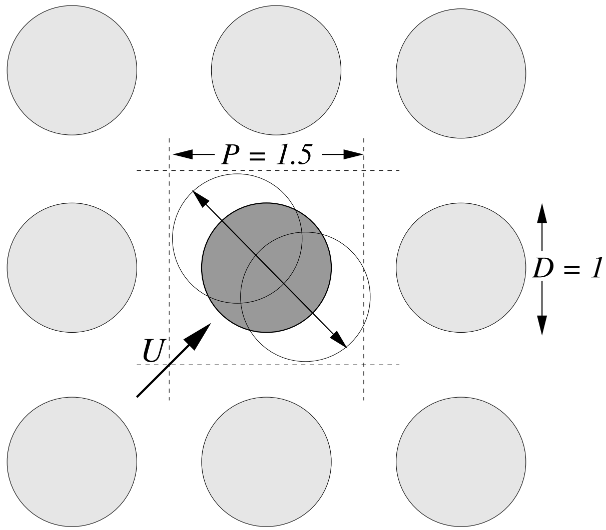
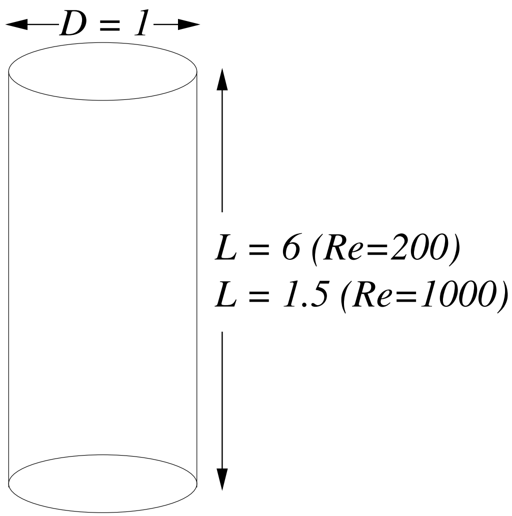




- Periodic boundary conditions.

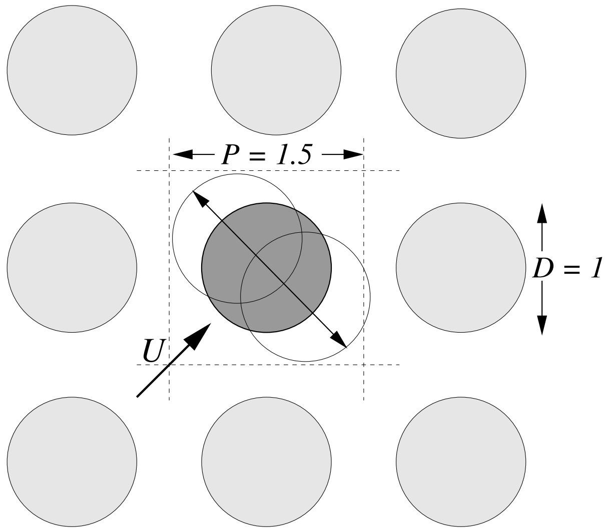
Problem formulation

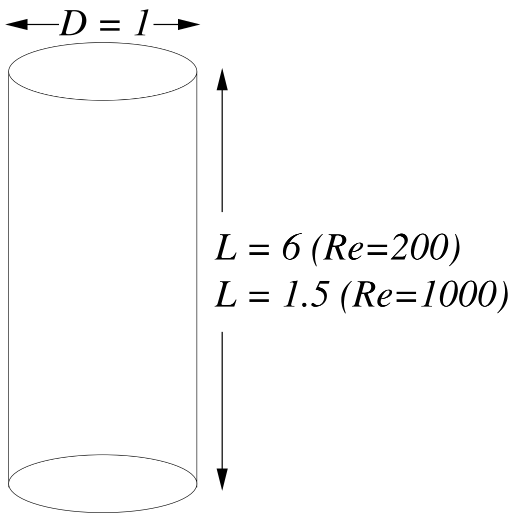




- Periodic boundary conditions.
- One tube in the periodic domain.

Problem formulation





- Periodic boundary conditions.
- One tube in the periodic domain.
- All tubes move in phase (extreme case).

Problem formulation (cont).

No-slip boundary conditions at tube surface

- Modelled by Brinkman penalization of Navier–Stokes equations.

$$\frac{\partial \boldsymbol{u}}{\partial t} + (\boldsymbol{u} + \boldsymbol{U}) \cdot \nabla \boldsymbol{u} \; + \; \nabla P = \nu \Delta \boldsymbol{u}$$

$$\nabla \cdot \boldsymbol{u} \; = \; 0$$

Problem formulation (cont).

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\begin{aligned}
\frac{\partial \boldsymbol{u}}{\partial t} + (\boldsymbol{u} + \boldsymbol{U}) \cdot \nabla \boldsymbol{u} \; + \; \nabla P &= \nu \Delta \boldsymbol{u} \\
& - \frac{1}{\eta} \chi(\mathbf{x}, t)(\boldsymbol{u} + \boldsymbol{U} - \boldsymbol{U}_o) \\
\nabla \cdot \boldsymbol{u} &= 0
\end{aligned}
$$

Problem formulation (cont.)

where the solid is defined by

$$\chi(\mathbf{x}, t) = \begin{cases} 1 & \text{if } \mathbf{x} \in \text{solid}, \\ 0 & \text{otherwise}. \end{cases}$$

- The upper bound on the global error of this penalization was shown to be (Angot et al. 1999) $O(\eta^{1/4})$.
- We observe an error of $O(\eta)$.

Problem formulation (cont.)

Cylinder response

- modelled as a damped harmonic oscillator

$$m\ddot{\mathbf{x}}_o(t) + b\dot{\mathbf{x}}_o(t) + k\mathbf{x}_o = \boldsymbol{F}(t),$$

Problem formulation (cont.)

Cylinder response

- modelled as a damped harmonic oscillator

$$m\ddot{\mathbf{x}}_o(t) + b\dot{\mathbf{x}}_o(t) + k\mathbf{x}_o = \boldsymbol{F}(t),$$

where the force $\boldsymbol{F}(t)$ is calculated from the penalization

$$\boldsymbol{F}(t) = \frac{1}{\eta}\int \chi(\mathbf{x},t)(\boldsymbol{u} + \boldsymbol{U} - \boldsymbol{U}_o)\,\mathrm{d}\mathbf{x}.$$

Numerical method

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1. Pseudo-spectral method for calculating derivatives and nonlinear terms on the periodic spatial domain.
2. Krylov time scheme for adaptive, stiffly stable integration in time.

Results

Cases:

Re	resolution	L	m_*	b_*	k_*	f
200	$128^2 \times 64$	6.0	5	0	249	0.98
1 000	$288^2 \times 96$	1.5	5	0	130	1.00

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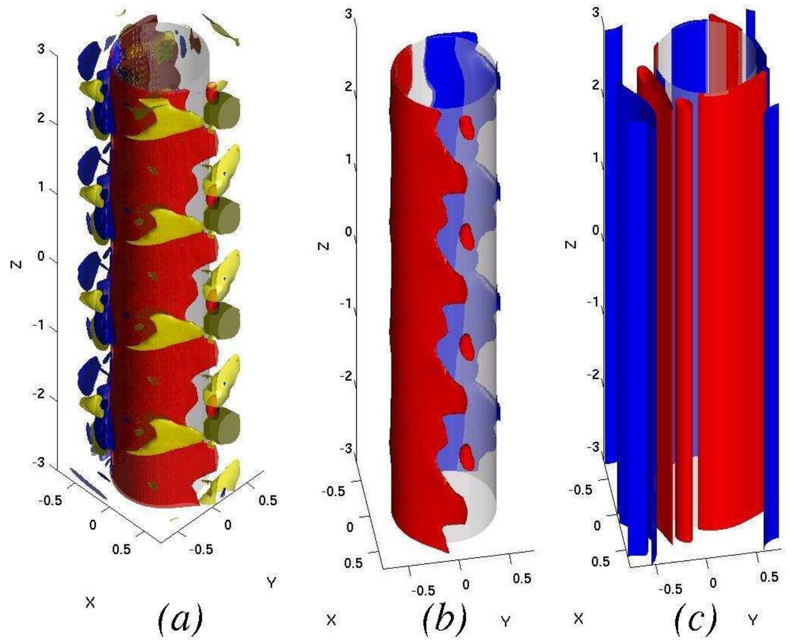
- Fixed and moving tube simulations are done for each case.
- Moving tubes are tuned to match the Strouhal frequency.
- 2D simulations are also done for each case.

$Re = 200$ results

Vorticity at $t = 15$

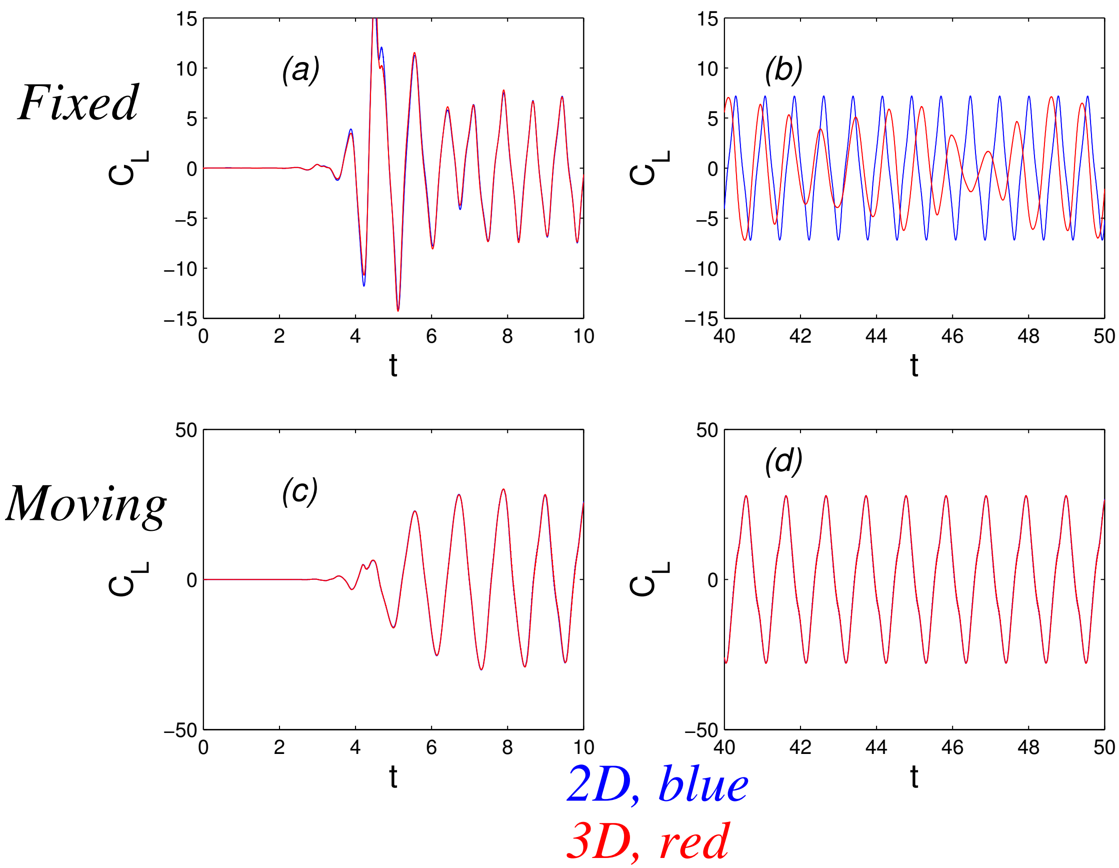


(a) Fixed cylinder, 3 components. (b) Fixed cylinder, spanwise vorticity.

(c) Moving cylinder, spanwise vorticity.

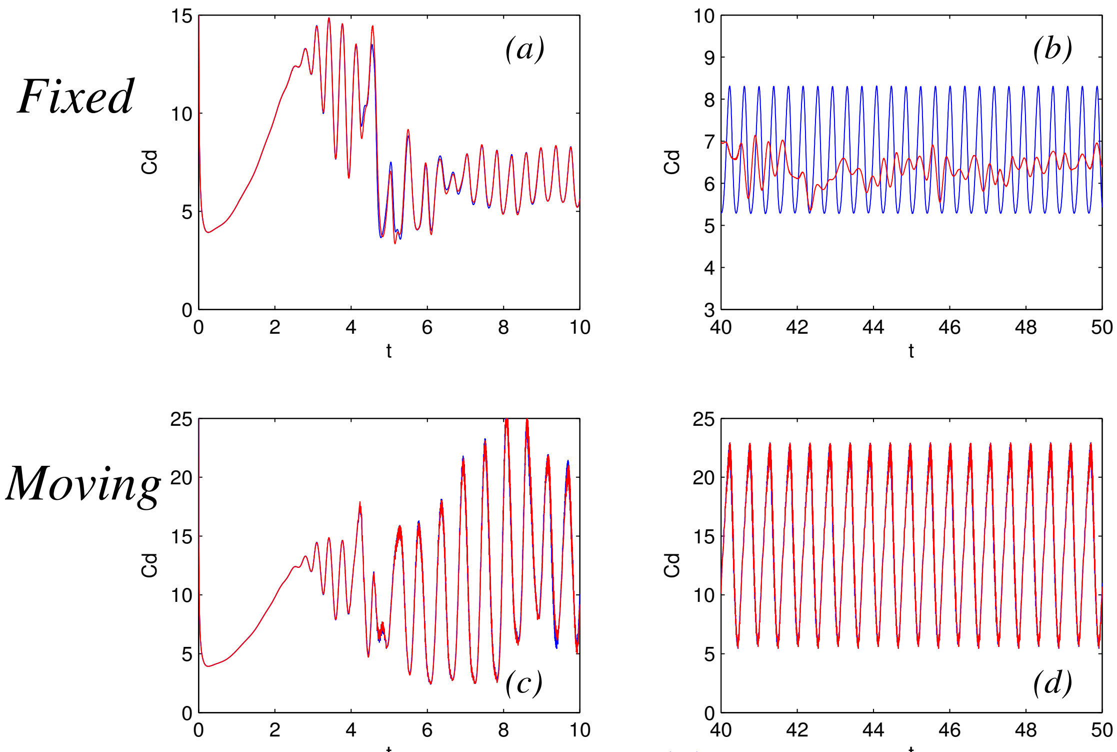
$Re = 200$ results (cont.)

Lift



$Re = 200$ results (cont.)

Drag

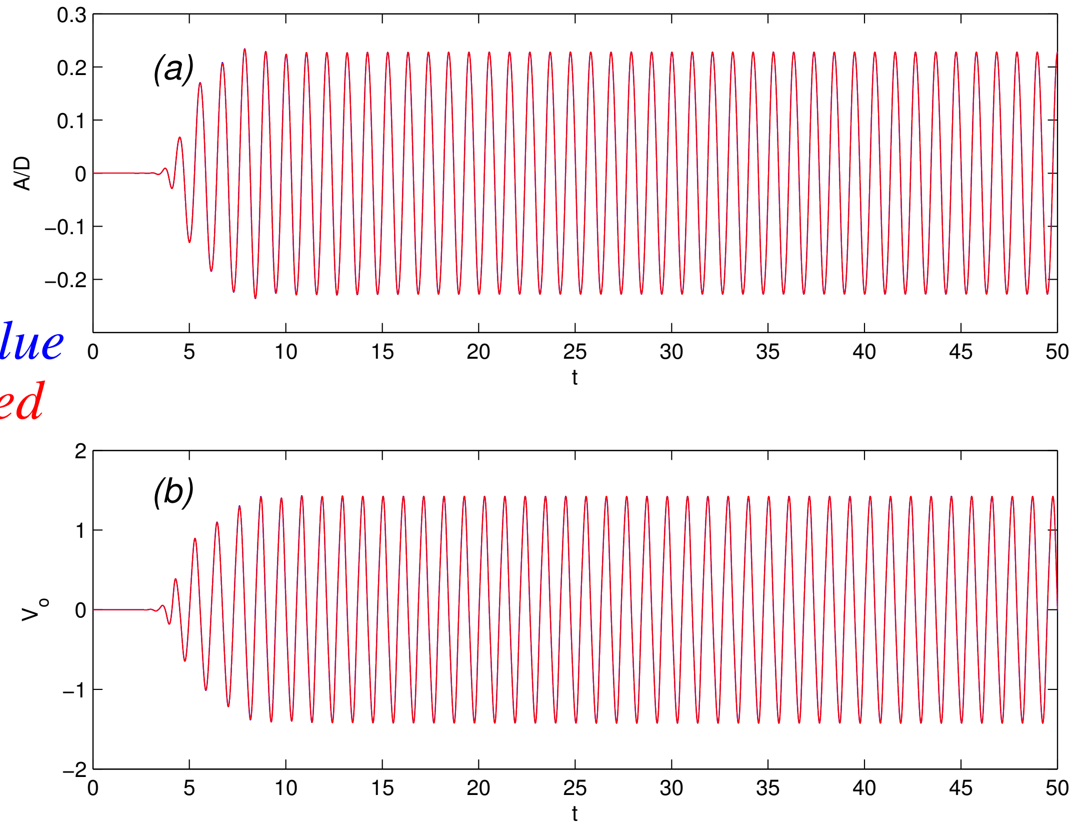


2D, blue
3D, red

$Re = 200$ results (cont.)

Cylinder motion

2D, blue
3D, red



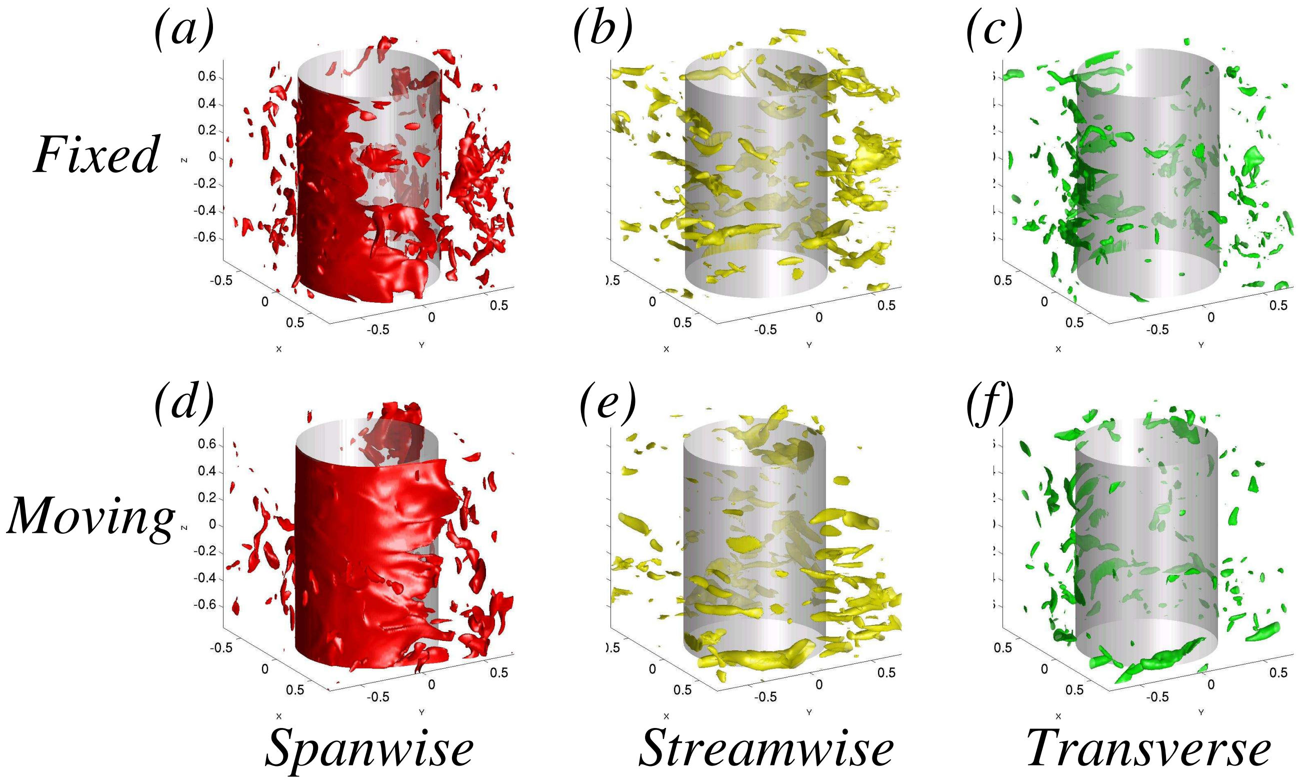
$Re = 200$ results (cont.)

Strouhal frequencies

Case	Peak frequency
2D, fixed	1.32
3D, fixed	1.18
2D, moving	0.95
3D, moving	0.95

$Re = 1\,000$ results

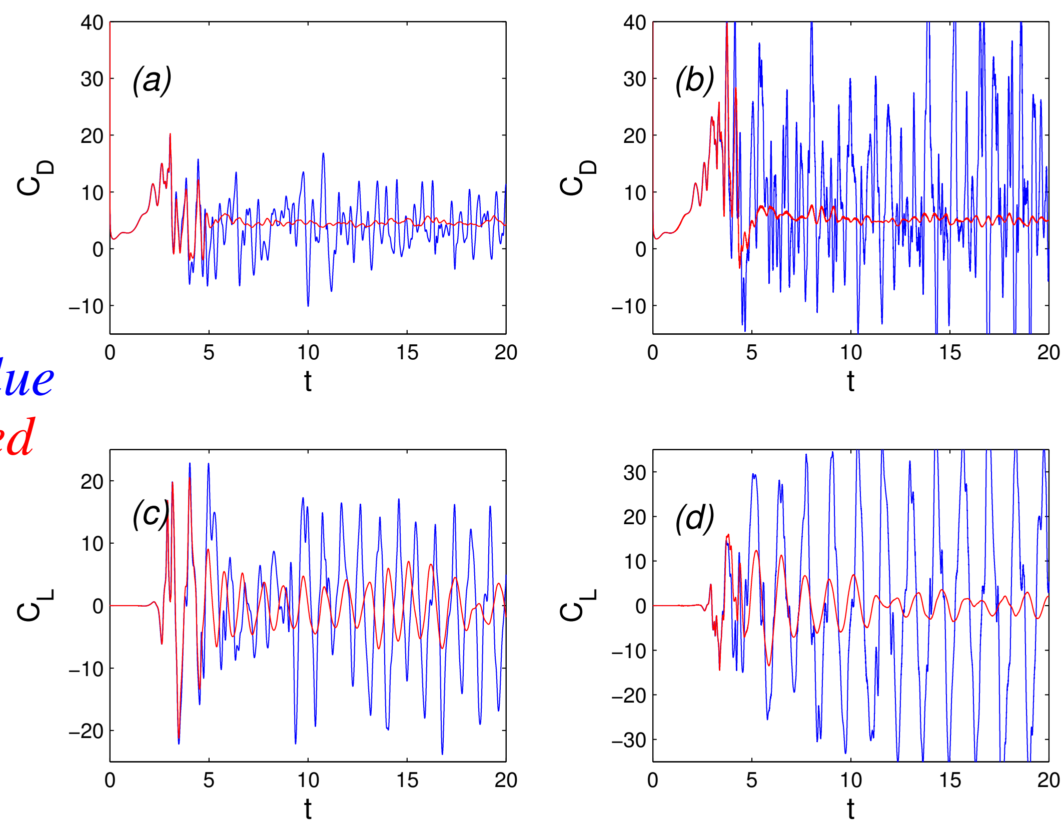
Vorticity at $t = 15$



$Re = 1\,000$ results (cont.)

Lift and drag

2D, blue
3D, red

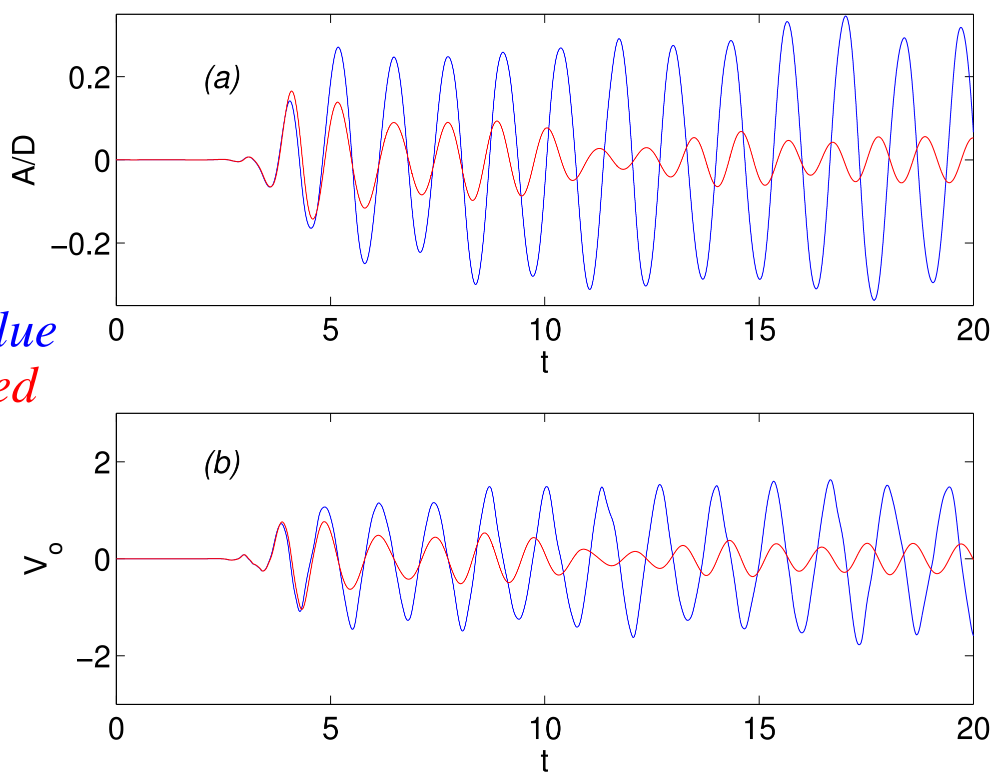


Fixed *Moving*

$Re = 1\,000$ results (cont.)

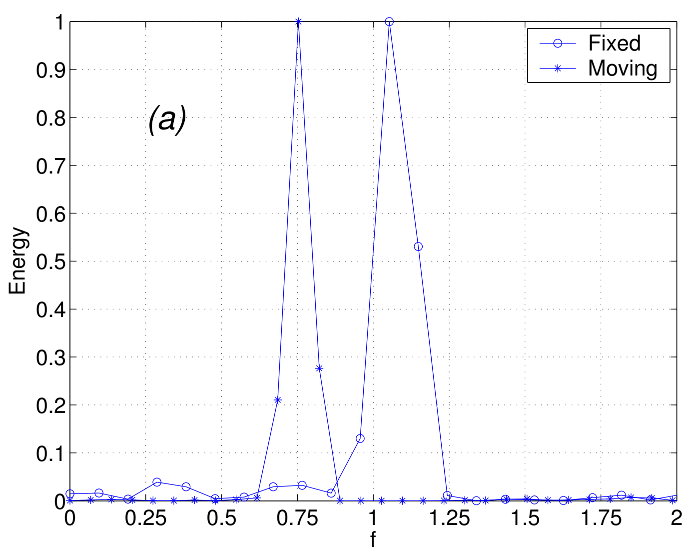
Cylinder motion

2D, blue
3D, red

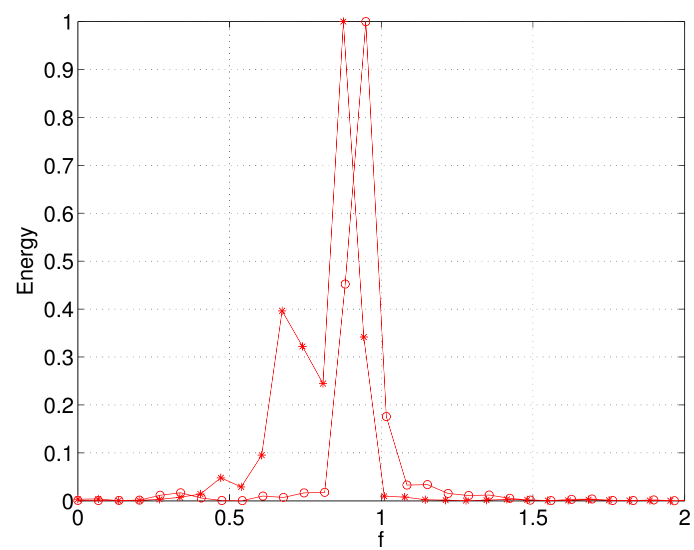


$Re = 1\,000$ results (cont.)

Lift spectra



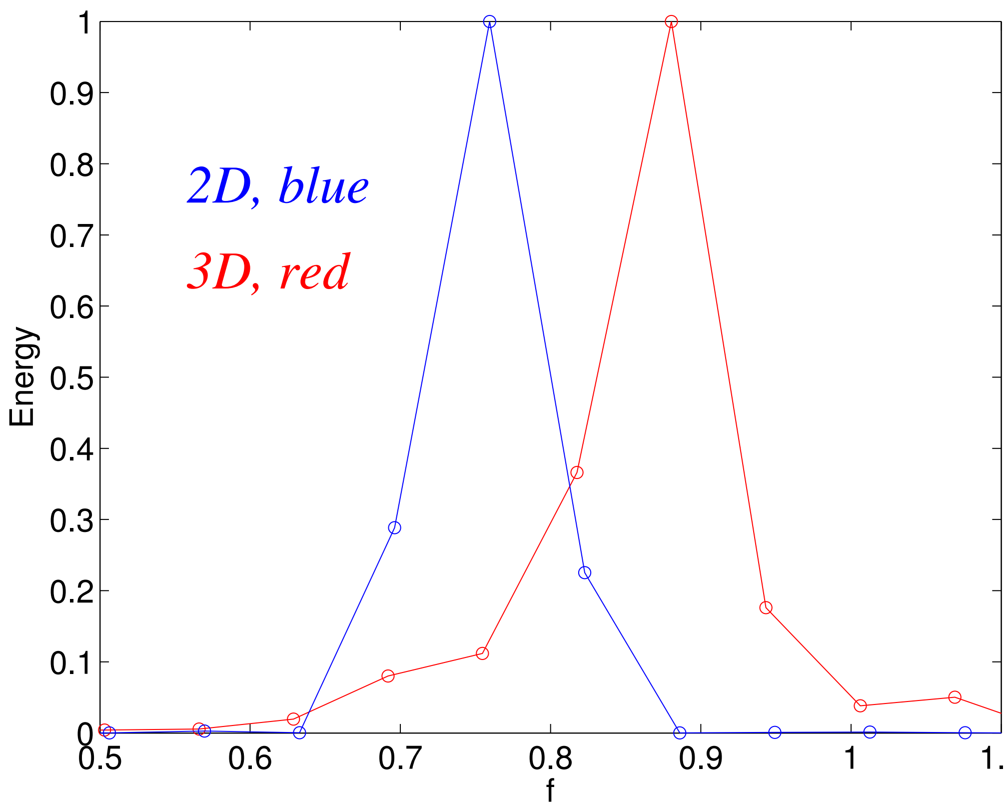
Two-dimensional



Three-dimensional

$Re = 1\,000$ results (cont.)

Spectra of cylinder oscillation



$Re = 1\,000$ results (cont.)

Strouhal frequencies

Case	Peak frequency
2D, fixed	1.06
3D, fixed	0.95
2D, moving	0.75
3D, moving	0.88, 0.68

Conclusions

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Conclusions

Suppression of 3D flow instabilities

1. At $Re = 200$ cylinder vibration suppresses 3D fluid instability ($A/D = 0.23 > 0.125$).
2. Tight packing alone does not suppress instability.
3. At $Re = 1\,000$ cylinder vibration is insufficient ($A/D \approx 0.05 < 0.125$) to suppress 3D fluid instability.
   However, the 2D and 3D Strouhal frequencies and cylinder response differ only slightly.

Conclusions (cont.)

Suppression of 3D flow instabilities (cont.)

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Suppression of 3D flow instabilities (cont.)

4. Moving cylinder has less effect at $Re = 1\,000$ than at $Re = 200$.

Conclusions (cont.)

Suppression of 3D flow instabilities (cont.)

4. Moving cylinder has less effect at $Re = 1\,000$ than at $Re = 200$.
5. Moving cylinder has less effect in 3D than in 2D.

Conclusions (cont.)

Effect of 3D vorticity compared with 2D flow

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1. Reduces lift amplitude by about three times.

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2. Reduces drag amplitude by about three times, and drag is always positive. In fact, drag is roughly constant.
3. Reduces cylinder amplitude by about two times.

$Re = 10^4, t = 3.5, P/D = 1.5$