Ph.D. Course on *Vorticity, Vortical Flows and Vortex-Induced Vibrations*
Technical University of Denmark, Copenhagen, Denmark
vortex.compute.dtu.dk
August 26-30, 2019

Fluid-Structure Interactions II: Spheres and Cubes

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Reading Material

Bearman, P., Vortex shedding from oscillating bluff bodies, Annual Review of Fluid Mechanics, 16, 195-222, 1984.

Behara, S. & Sotiropoulos, F., Vortex-induced vibrations of an elastically mounted sphere: the effects of Reynolds number and reduced velocity. J. Fluids Struct. 66, 54–68, 2016.

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Sareen, A., Zhao, J., Lo Jacono, D., Sheridan, J., Hourigan, K., & Thompson, M., Vortex-induced vibration of a rotating sphere. Journal of Fluid Mechanics, 837, 258-292, 2018.

Sareen, A., Zhao, J., Sheridan, J., Hourigan, K., & Thompson, M., Vortex-induced vibrations of a sphere close to a free surface. Journal of Fluid Mechanics, 846, 1023-1058, 2018.

van Hout, R., Krakovich, A. & Gottlieb, O., Time resolved measurements of vortex-induced vibrations of a tethered sphere in uniform flow. Phys. Fluids 22 (8), 087101, 2010.

Williamson, C.H.K. & Govardhan, R., Dynamics and forcing of a tethered body in a fluid flow, J. Fluids Struct., 11, 293-305, 1997.

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Lecture Objectives

Learn:

Applications of flow-induced vibrations

Vortex-induced vibration of the generic sphere

Effect of type of sphere support (spring, tether)

Effect of aspect ratio on the FIV of spheroids

Galloping for a cube

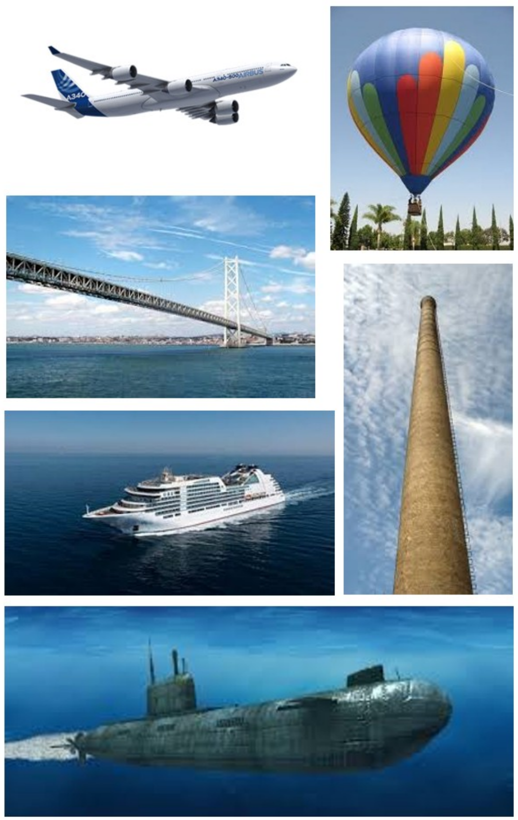
Outline of Lecture

- **Introduction and Motivation**
- **Non-rotating spheroid**
    - **Fixed**
    - **Flexibly mounted**
    - **FIV for different aspect ratio**
- **Non-rotating cube**
    - **Fixed**
    - **Flexibly mounted**
    - **FIV for different orientation angles**
- **Summary and Conclusions**

Introduction and Motivation

Flow-Induced Vibration (FIV) is a vibration phenomenon of structures induced from the surrounding fluid.

- **Vortex-induced vibration**
- **Galloping**



Examples of FIV

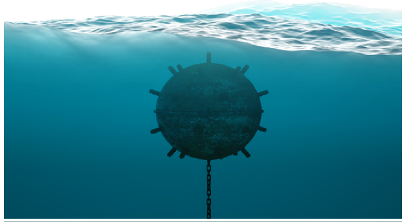
- **Bridges**
- **Chimney stacks**
- **Air craft**
- **Vessels**
- **Submarines**
- **Tethered structures**

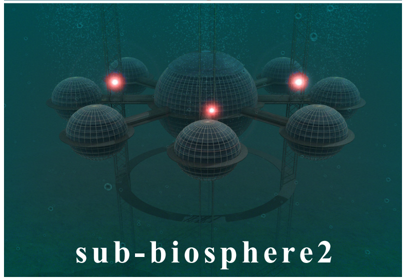
Introduction and Motivation contd...

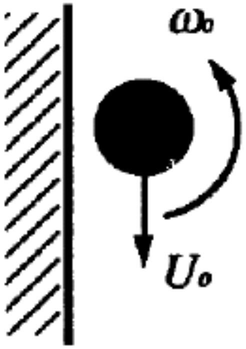
- A fatigue damage or catastrophic structural failure can occur.
- FIV is a critical consideration for many Engineering systems.
- Limited knowledge is available for spheroidal or cube structures.

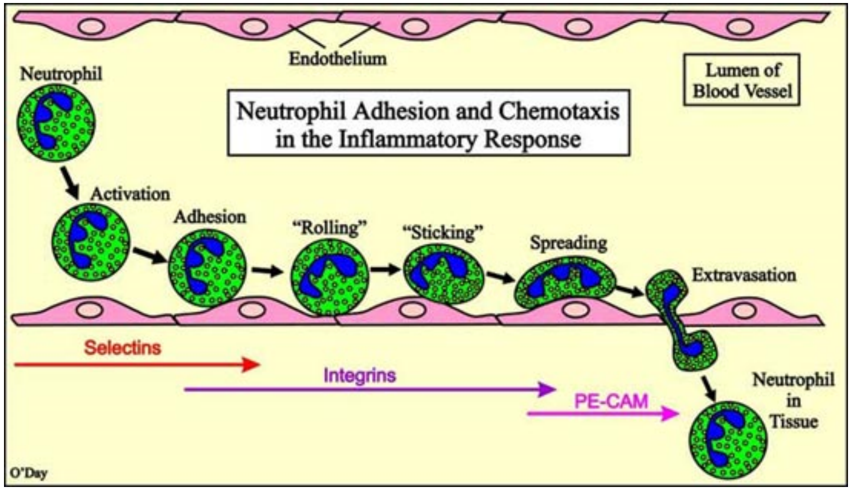
Why study FIV of a spheroid or cube?

- FIV: serious cause of structural fatigue
- Underwater mines
- Marine buoys
- Floating power generation equipment
- Small scale sphere-surface interactions



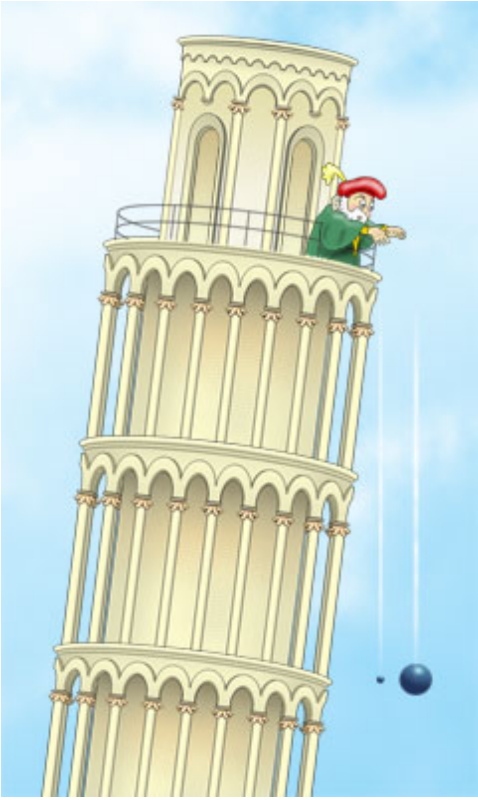






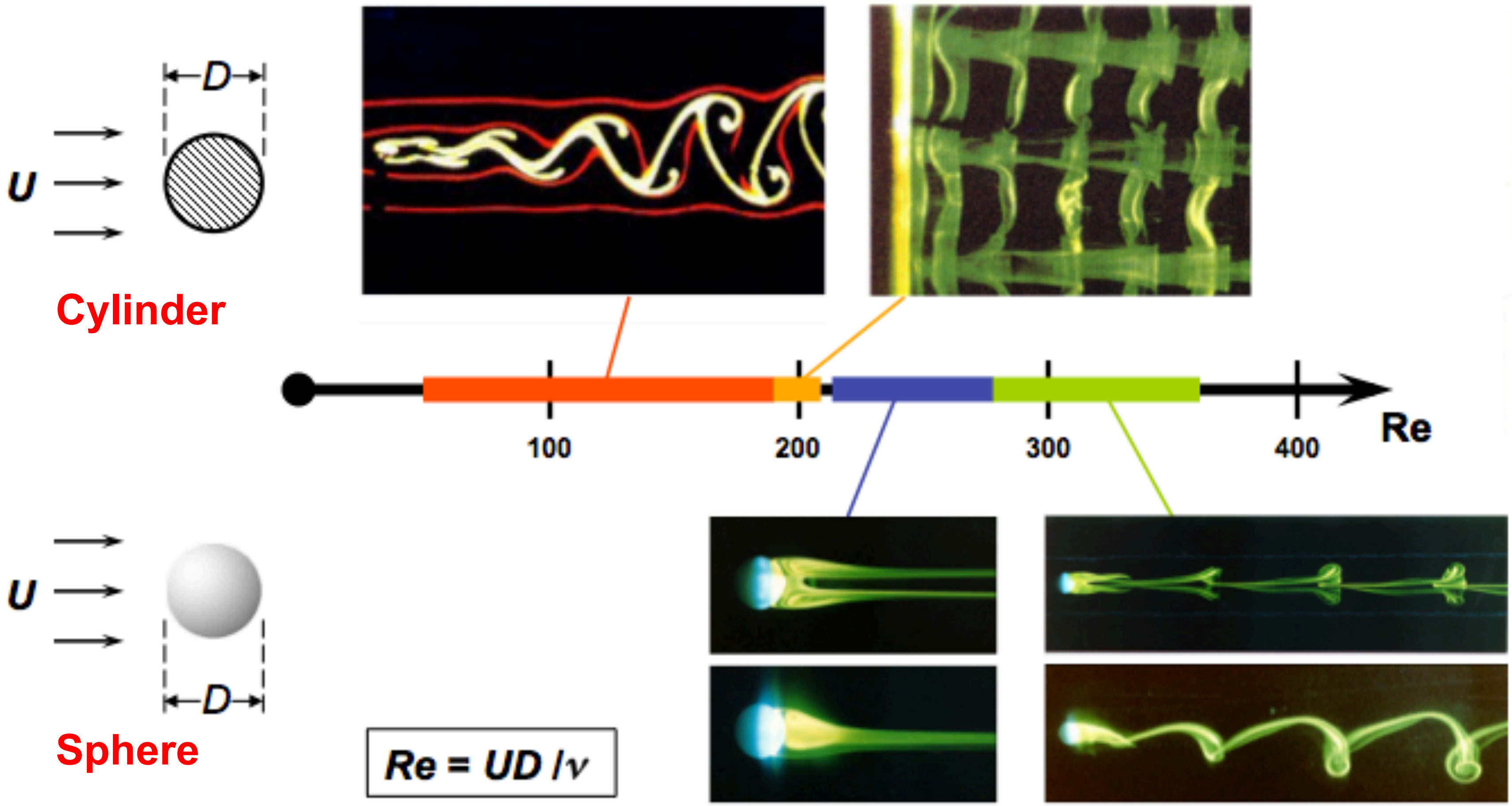
Sphere: Most basic 3D prototype.
Cuboid: Generic shape (with galloping?)

Galileo – falling & rolling spheres



In 1604, Galileo's inclined plane experiment, where he measured the distance a ball rolled down a ramp in each unit of time.

Wake Transitions Fixed Sphere



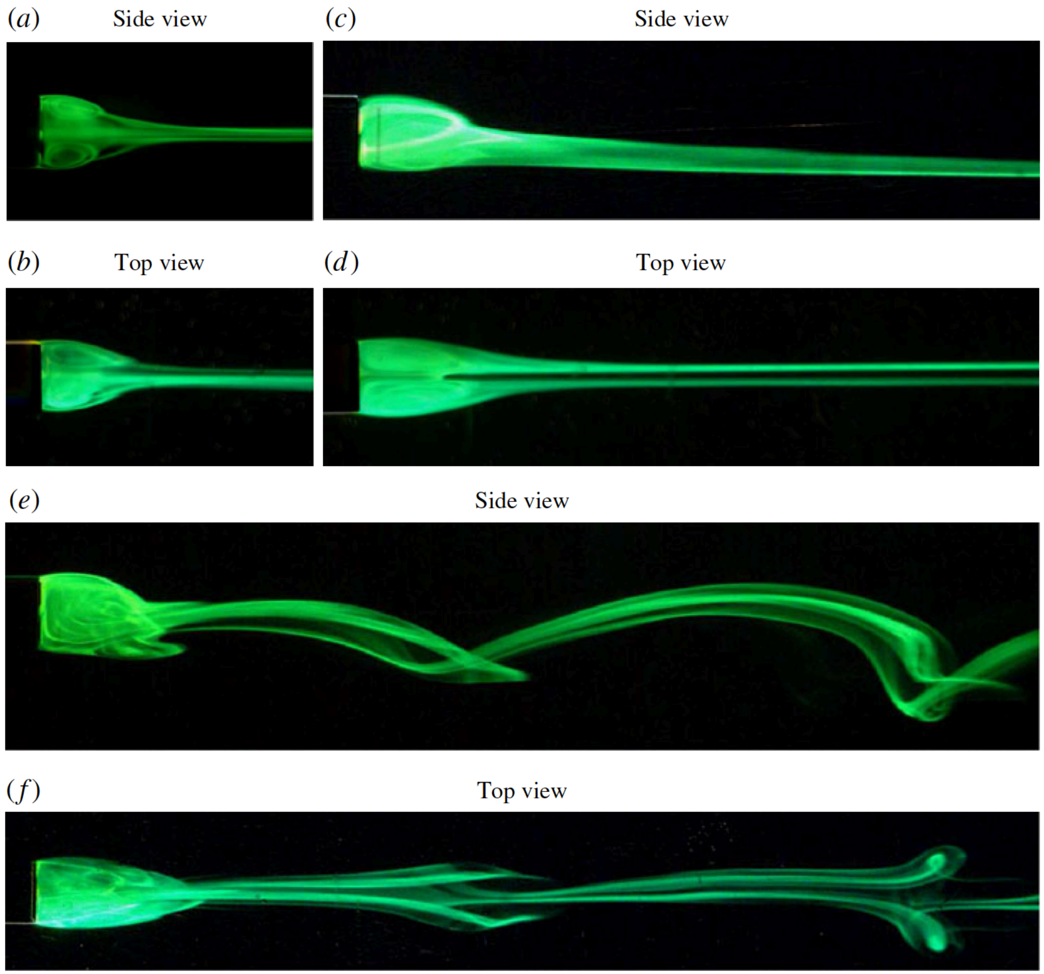
Wake Transitions Fixed Cube

Visualisations patterns of three consecutive regimes (Klotz et al., 2014).
:

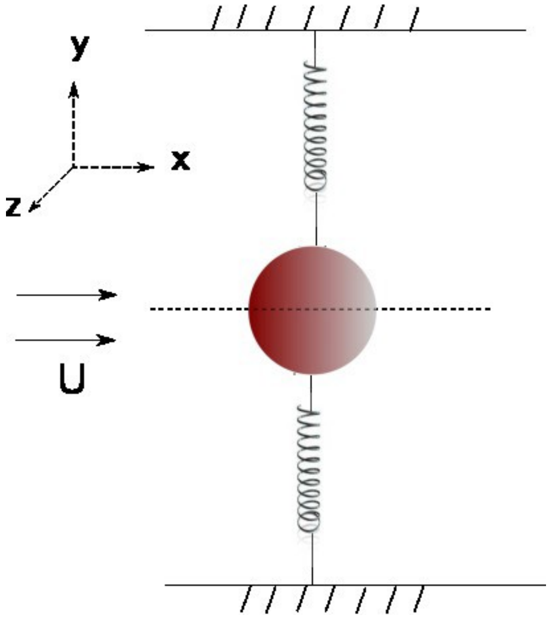
(c,d) the two counter-rotating vortices regime at Re = 250,

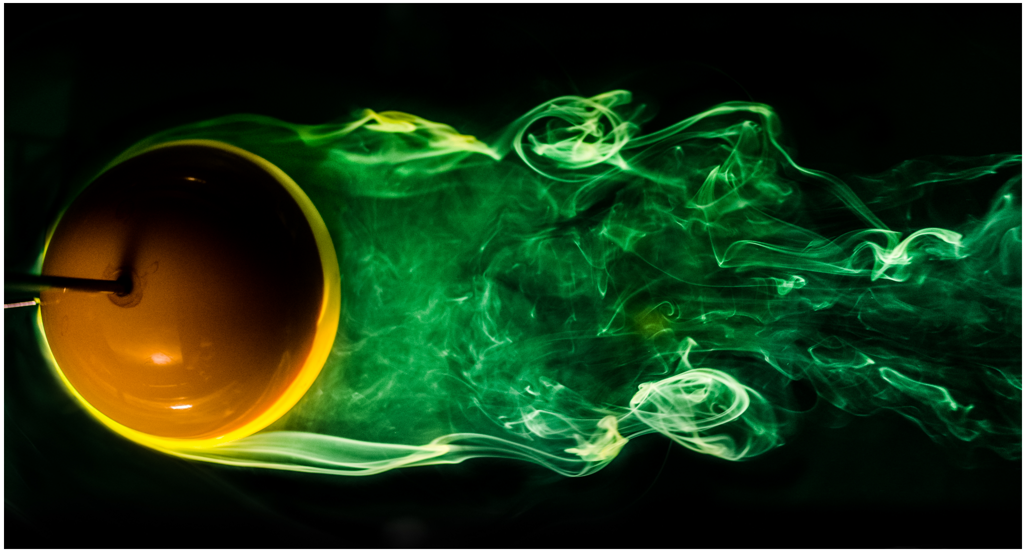
(a,b) the basic flow at Re = 100

(e, f)
the hairpin vortex shedding regime at Re = 300.



FIV: NON-ROTATING SPHERE





Literature: Does FIV occur for a sphere?

1. Govardhan & Williamson (1997, 2005)

2. Williamson & Govardhan (1997)

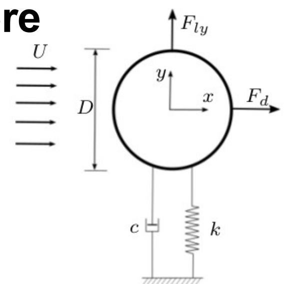
3. Jauvtis et al. (2001)

Four modes of sphere vibration (modes I–IV)

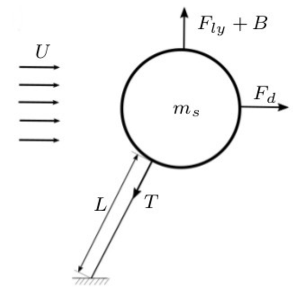
Modes I & II are VIV

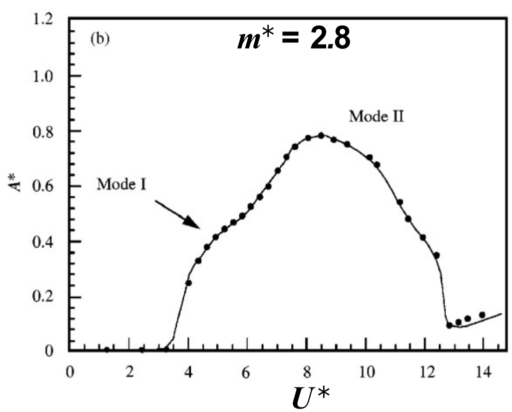
- Observed for $5 < U^* < 12$
- Smooth transition
- Two-sided hairpin loops

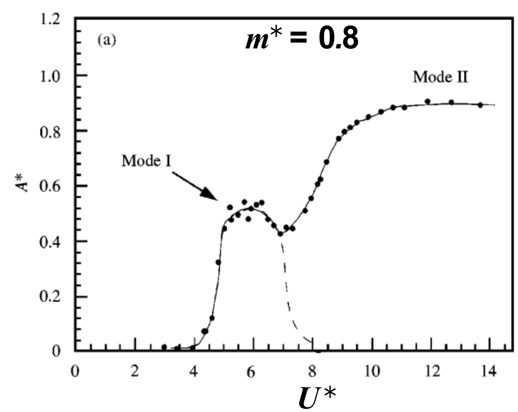
Elastically-mounted sphere sphere



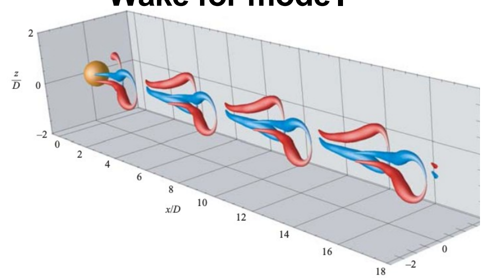
Tethered



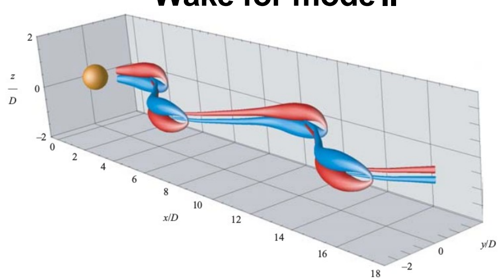




Wake for mode I



Wake for mode II



Modes III and IV vibration states

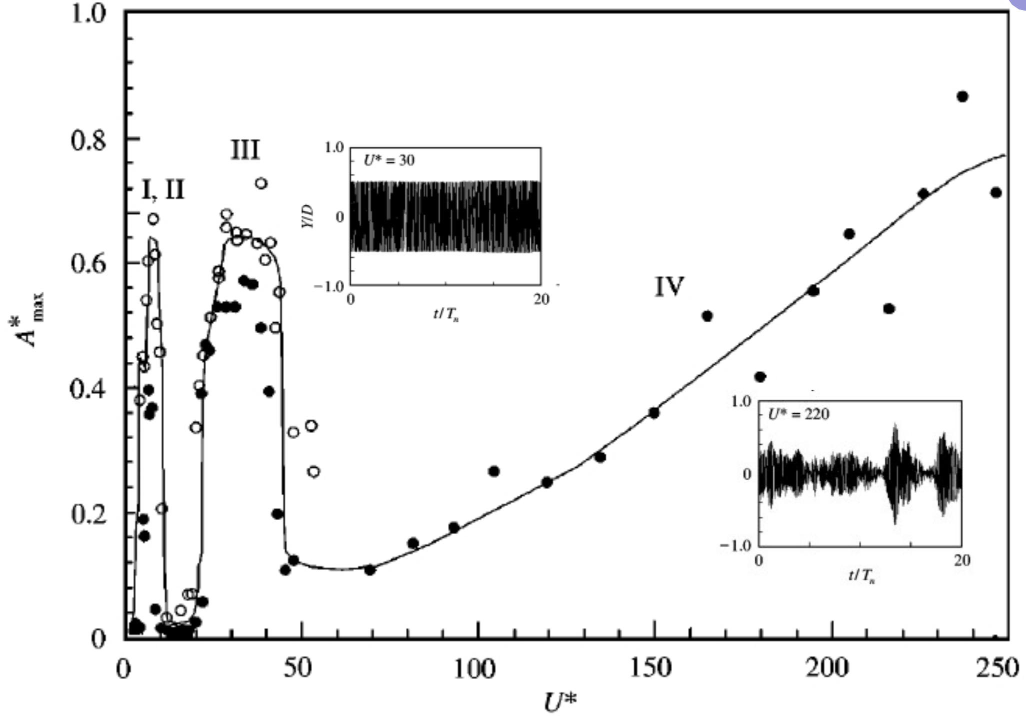
Mode III

- **Observed for** 20 < U^* < 40
  - Periodic vibration
  - Not a VIV
  - **$f = f_n$ and $f_{vo} >> f$**
  - Long vortical structures

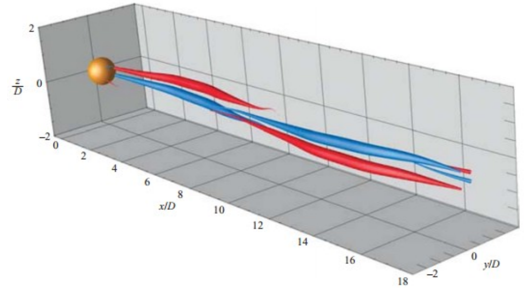
Mode IV

- **Observed for** U^* > 100
  - Intermittent bursts
  - Not a VIV

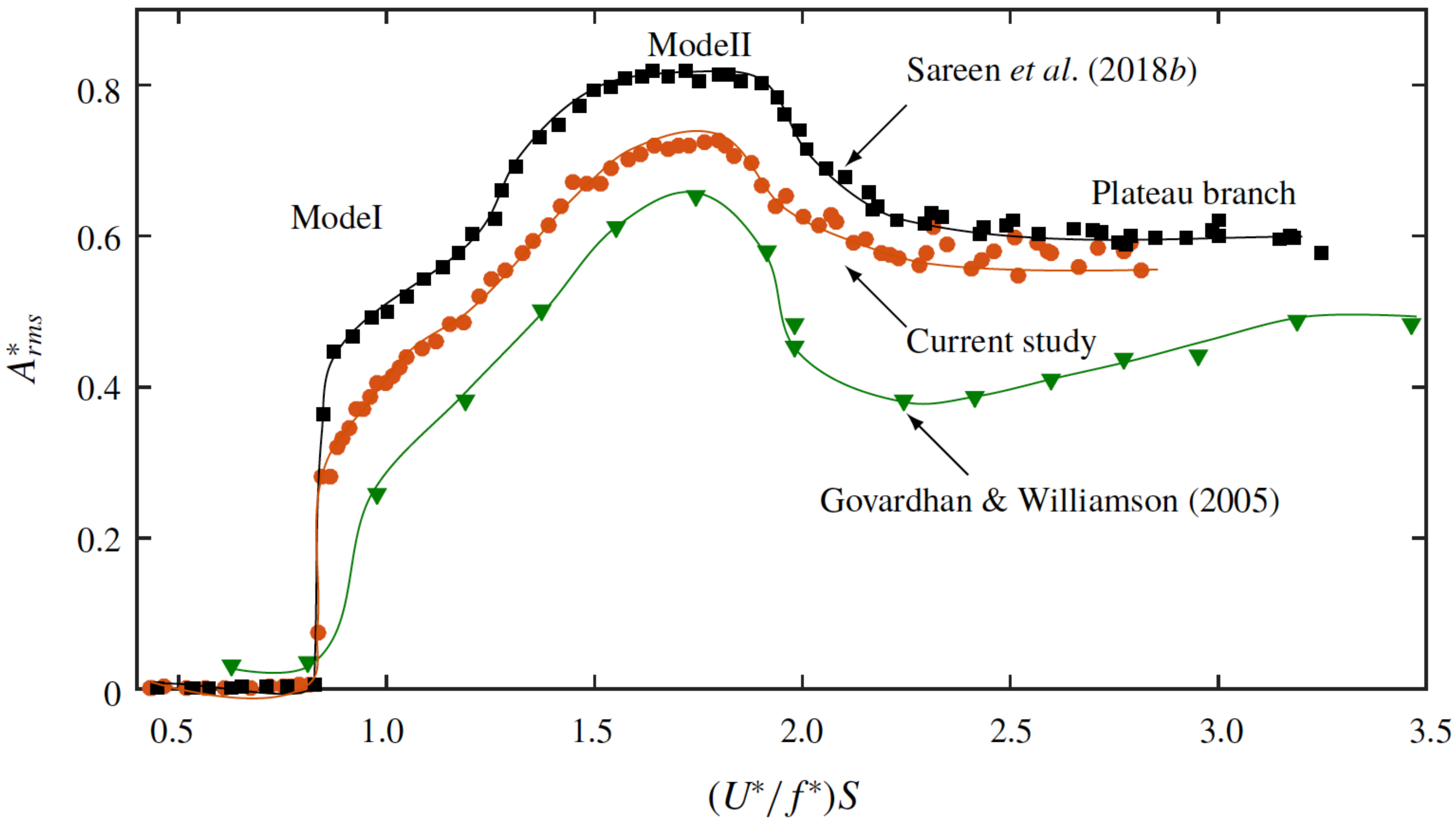
m^* = 80



Wake for mode III

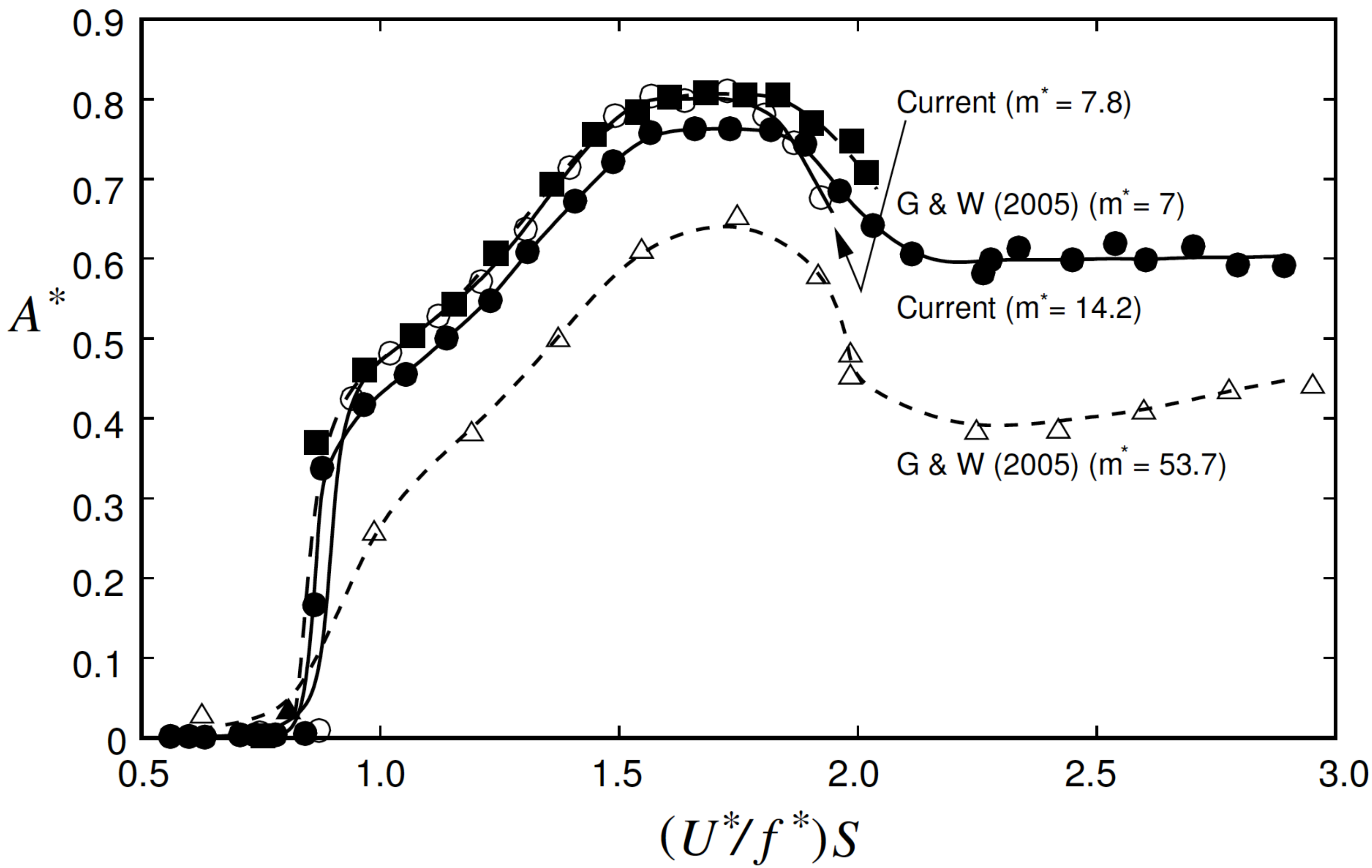


Lower mass damping ⇒ Larger vibrations



Sareen, A., Zhao, J., Lo Jacono, D., Sheridan, J., Hourigan, K., & Thompson, M., Vortex-induced vibration of a rotating sphere. Journal of Fluid Mechanics, 837, 258–292, 2018.

Lower mass ratio m* ⇒ Larger vibrations



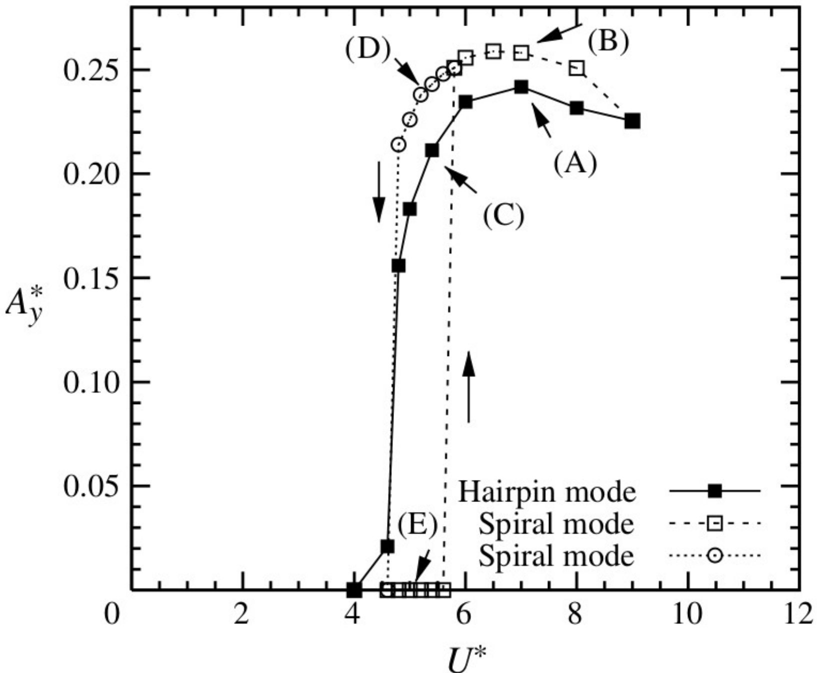
G&W: Govardhan & Williamson (2005)

Computational studies on VIV a sphere

Behara et al. (2011) and Behara and Sotiropoulos (2016) studied VIV of a sphere with 3 DOF at Re = 300.

- **Hairpin vortices**

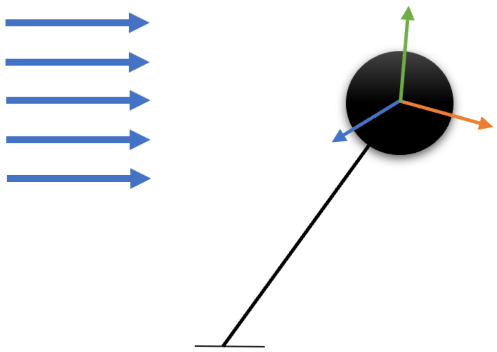
- **Spiral vortices**

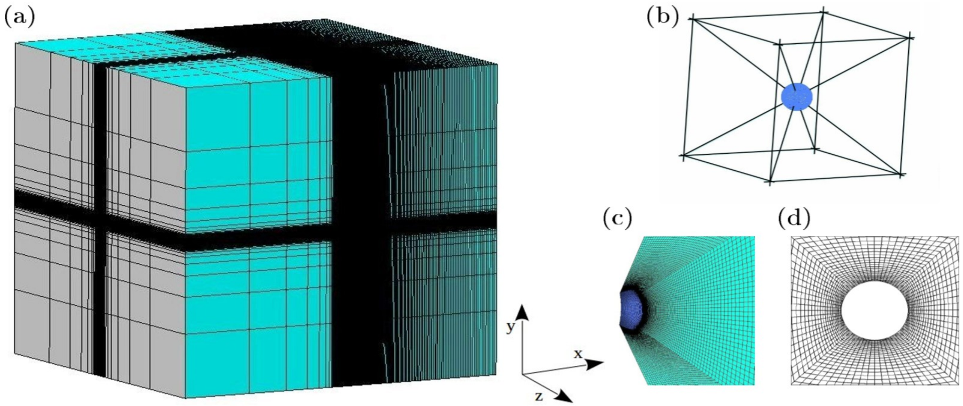


The reduced mass m_r = 2, ζ = 0, Re = 300

How current CFD solver works?

- Fluid is modeled in a reference frame attached to the centre of the sphere.
- A non-deformable mesh is used.
- The acceleration of the sphere appears in the momentum equation.
- The coupled system is solved using a predictor-corrector iterative method.

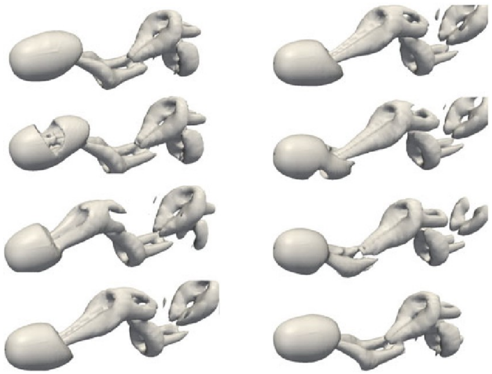




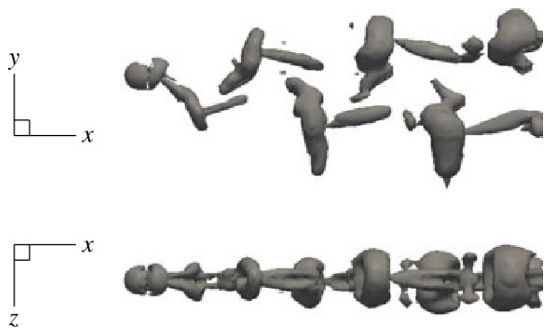
Rajamuni, M.M., Thompson, M.C. & Hourigan, K., Vortex-induced vibration of elastically-mounted spheres: A comparison of the response of three degrees of freedom and one degree of freedom systems, Journal of Fluids and Structures, in press.

FIV of an elastically-mounted sphere

Branch A: $Re = 300$

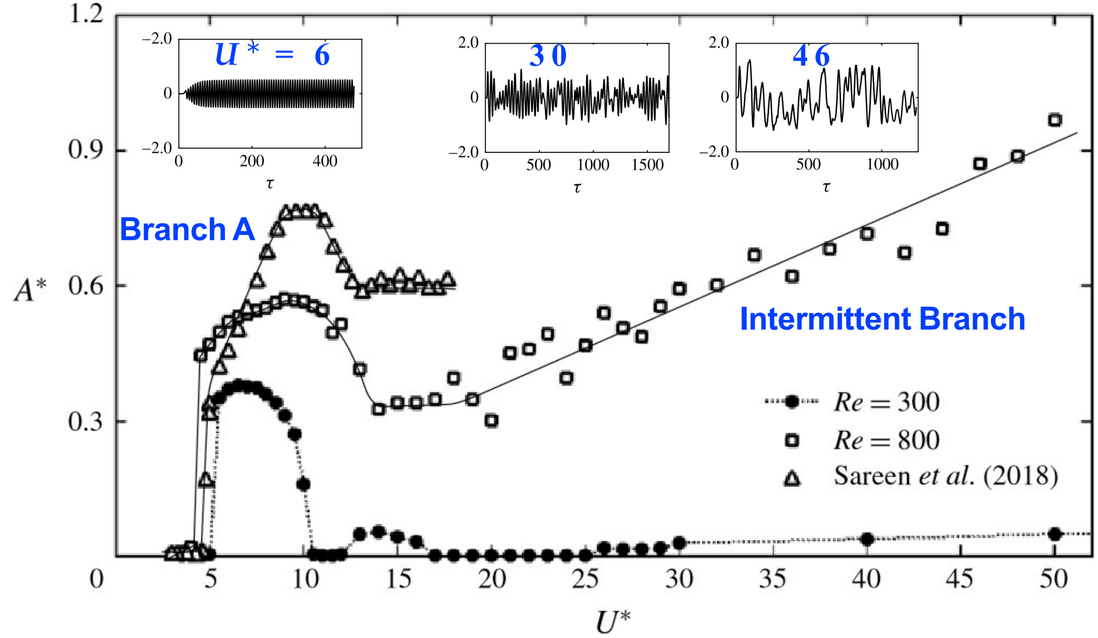


Branch A: $Re = 800$

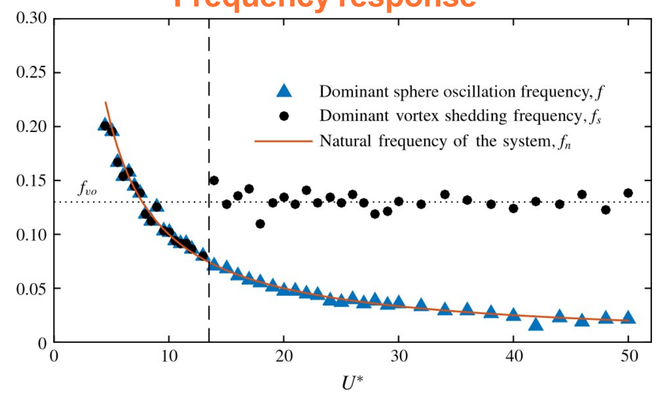


Intermittent Branch: $Re = 800$

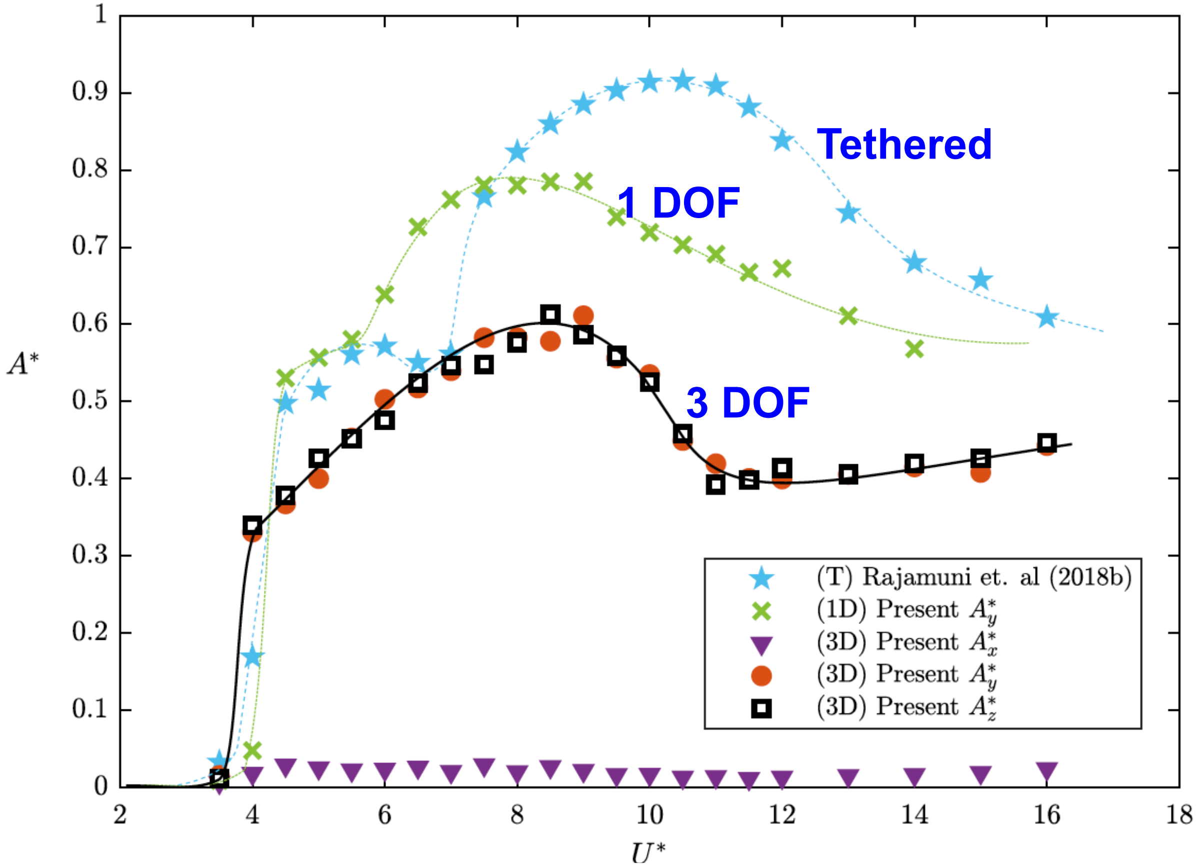
Amplitude response



Frequency response

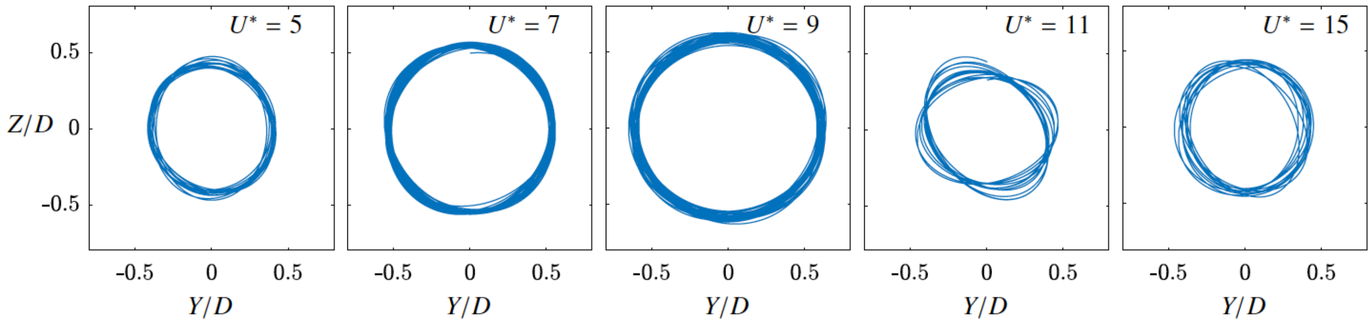


VIV: Tethered Sphere > 1 DOF Elastic > 3 DOF Elastic

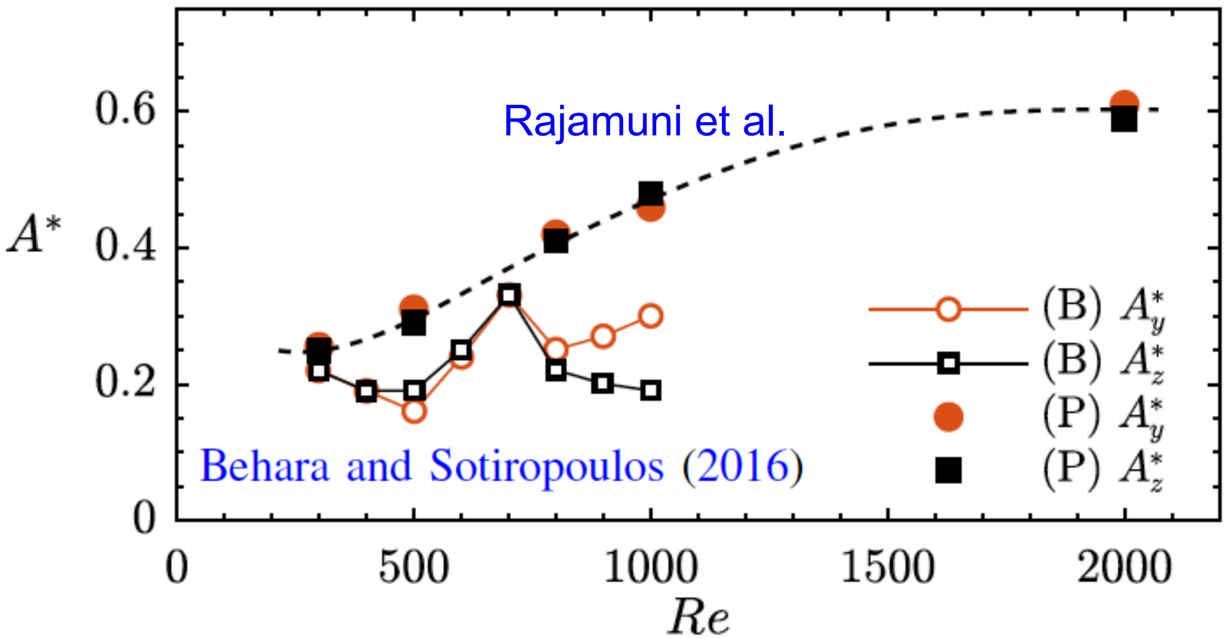


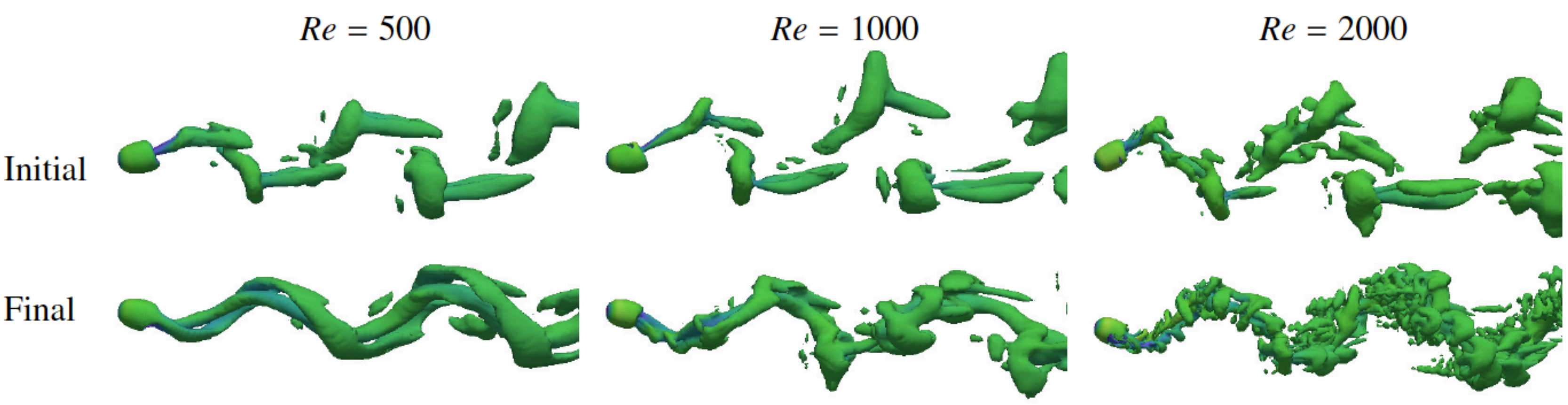
Re = 2000

3 DOF

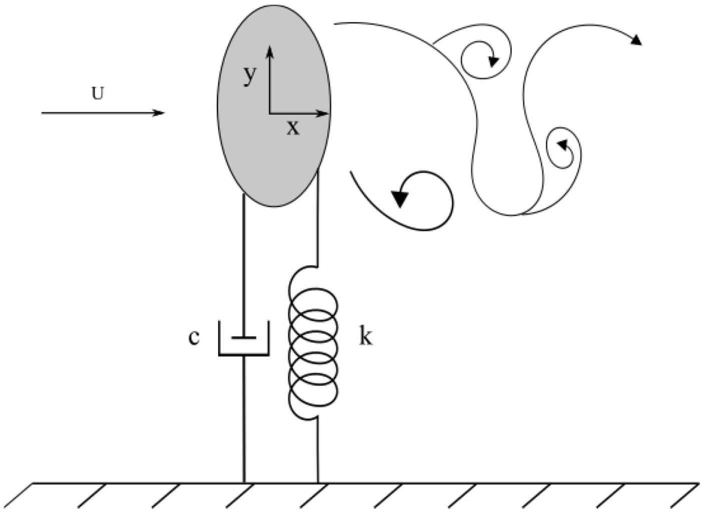


3DOF: VIV Amplitude increases with Re





FIV of Spheroids of different aspect ratios

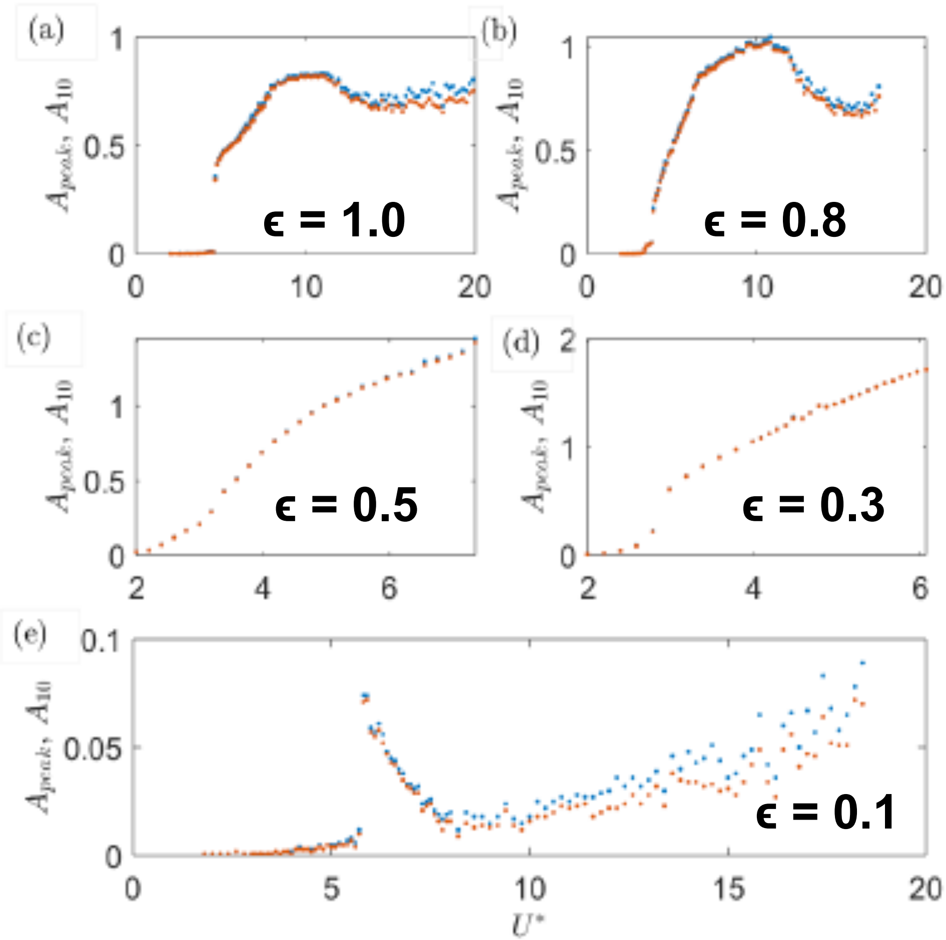


ϵ	U*	Re	$f_{recording}$ [Hz]
0.1	1.80 – 18.40	3090 - 31605	100
0.25	1.99-8.95	3438 - 15468	100
0.5	1.99 – 7.36	3397 - 12573	100
0.8	2.00-17.20	3262 - 28072	100
1.0	1.99-19.88	3208 - 32069	100

Aspect ratio ϵ = Horizontal diameter / Vertical diameter

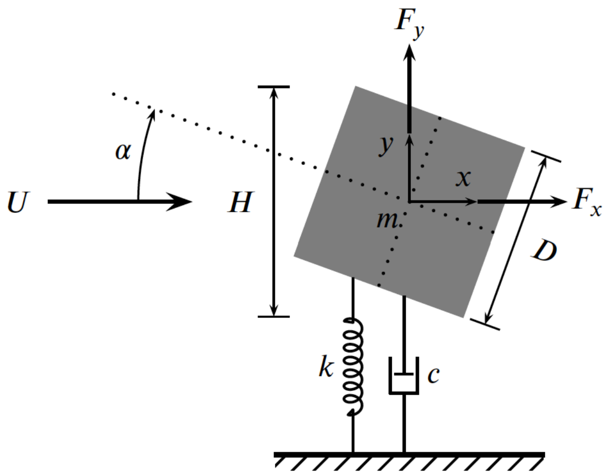
Zhao, J., Hourigan, K. & Thompson, M.C., unpublished

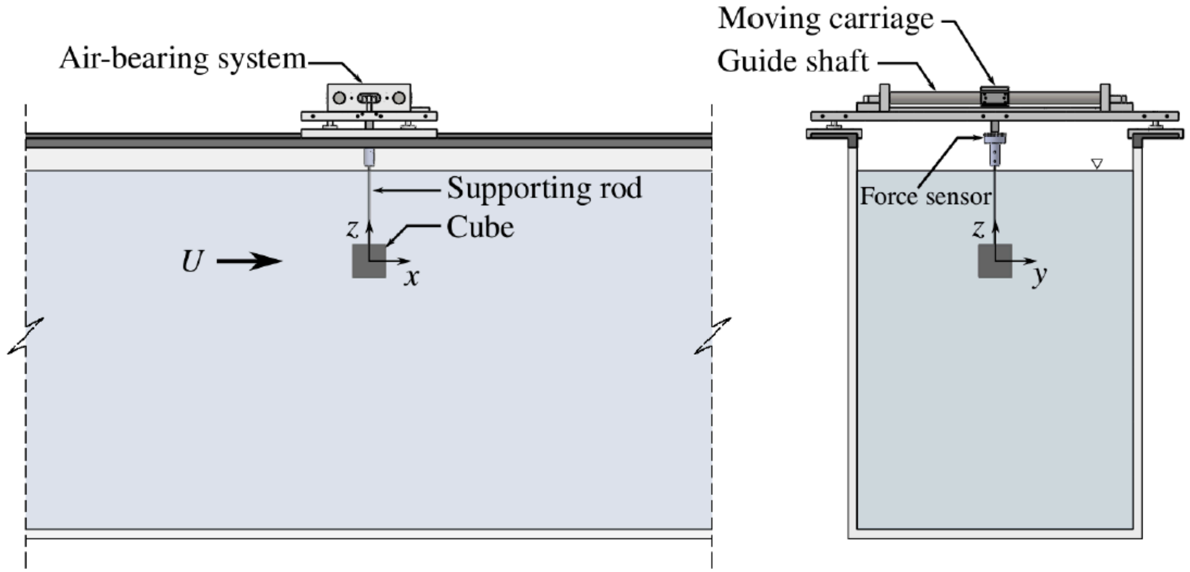
FIV amplitude increases as spheroid becomes thinner, then drops off



Plots representing the variation between the peak value of vibrational amplitude A_{peak} in comparison to the value of A^*_{10}

FIV of a Cube



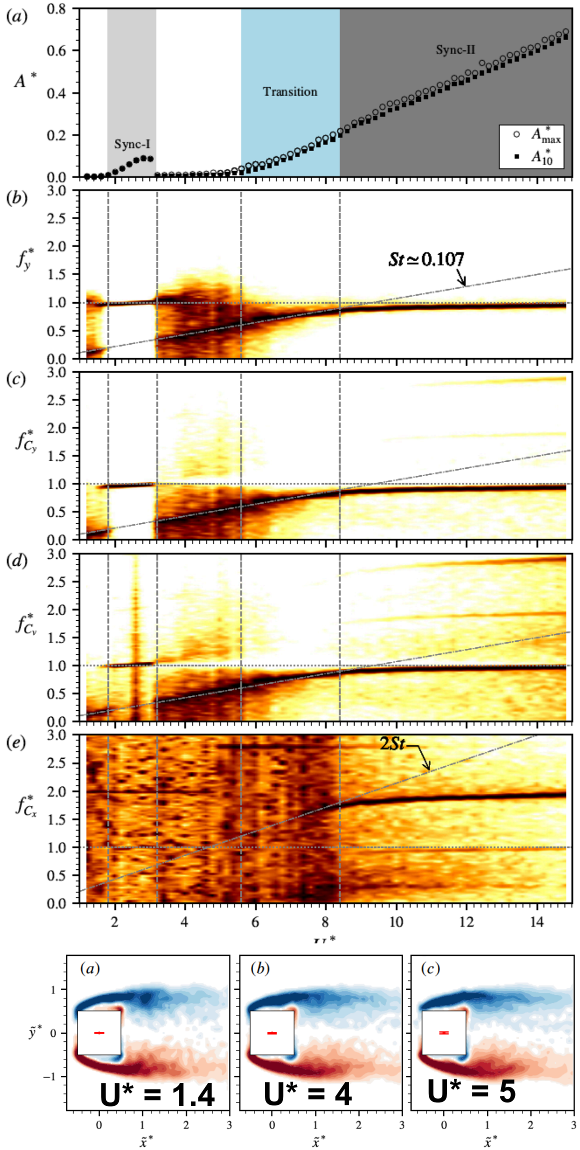


(*a*) Side view (*b*) Back view

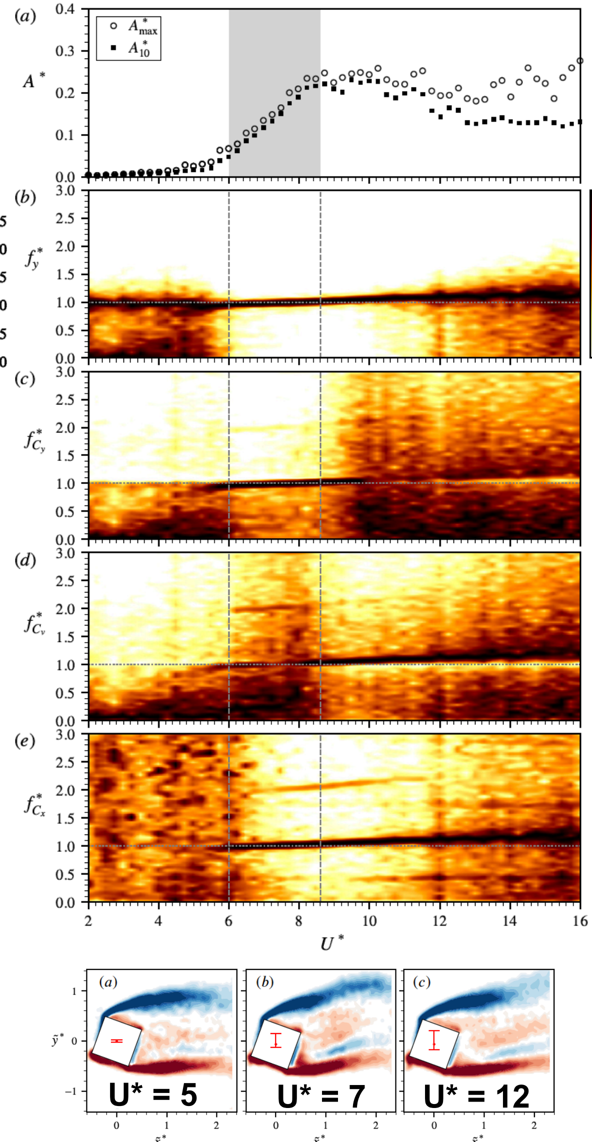
Zhao, J., Sheridan, J., Hourigan, K. & Thompson, M.C., Flow-induced vibration of a cube orientated at different incidence angles, Journal of Fluids and Structures, in press.

Effect on FIV of angle of attack α

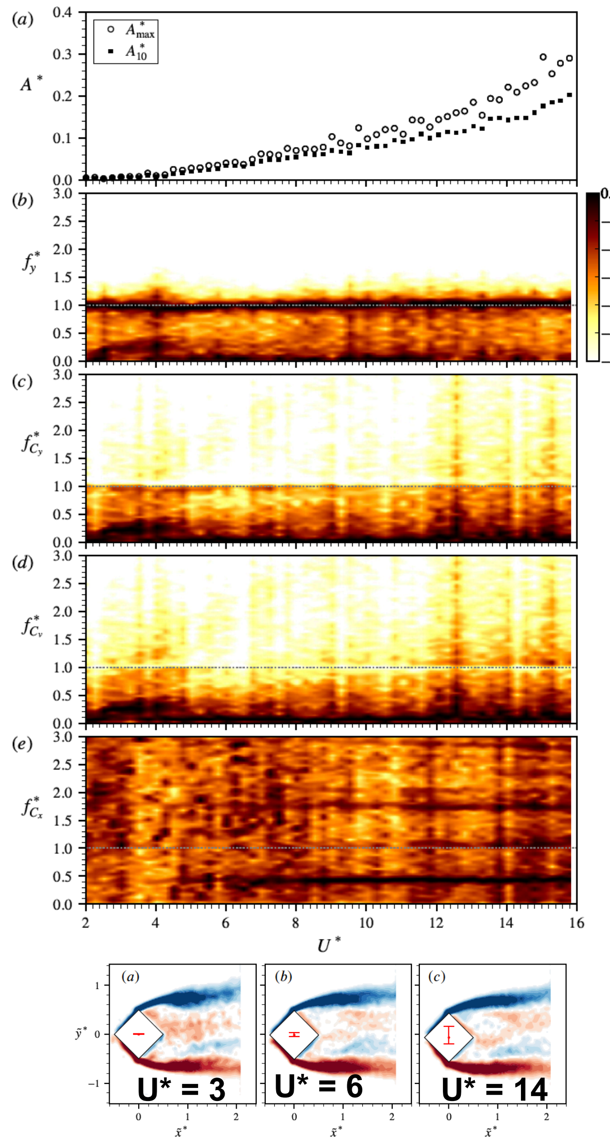
α = 0°



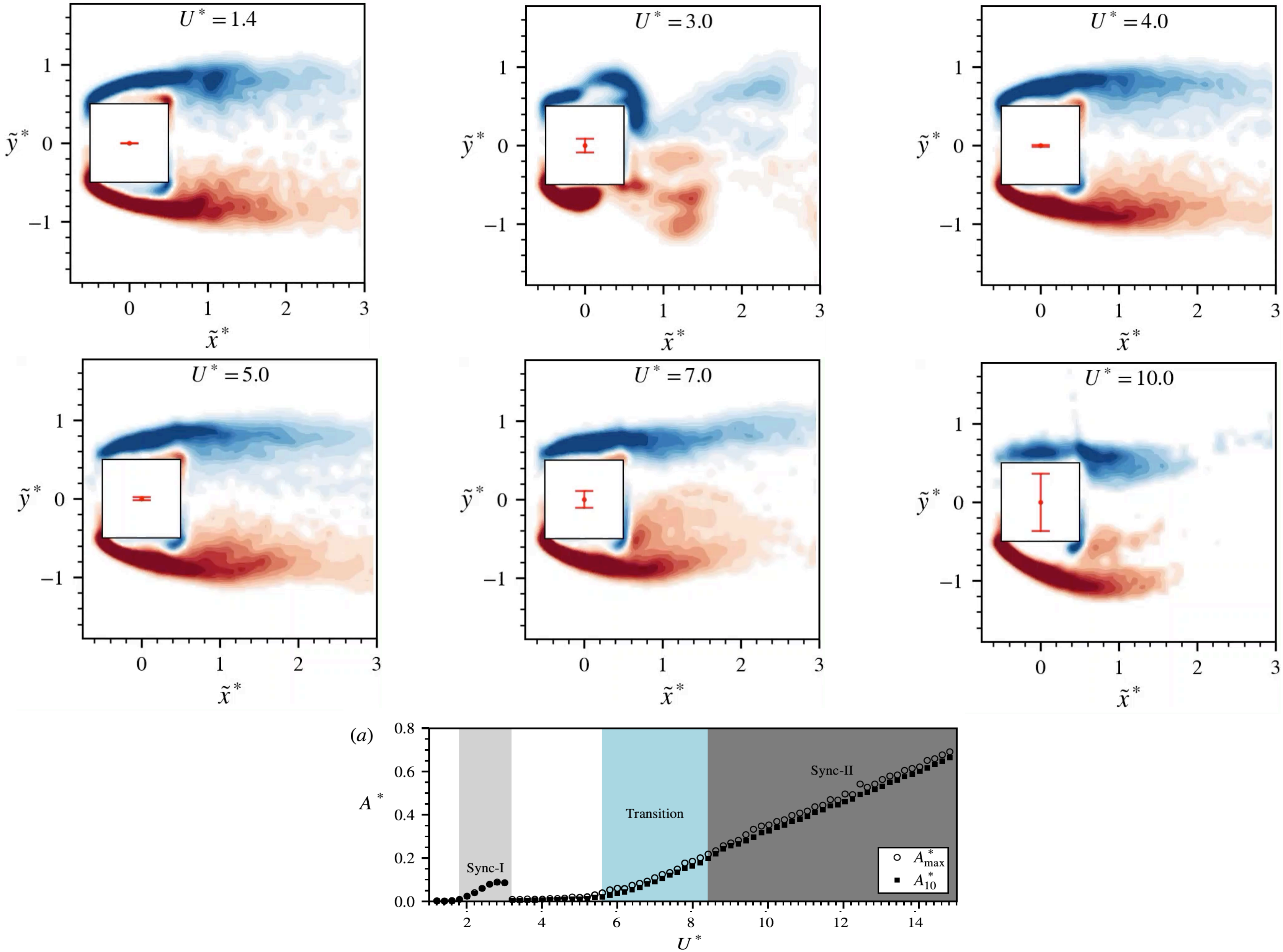
α = 20°



α = 45°



α = 0°: VIV, then Galloping as U^* increases



Synchonised FIV and impingement

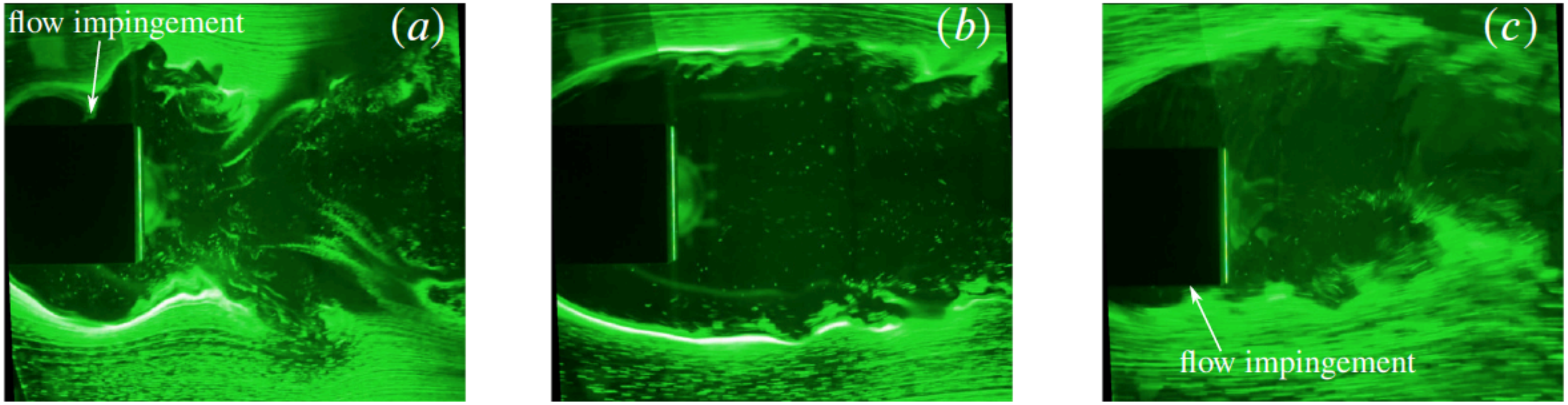
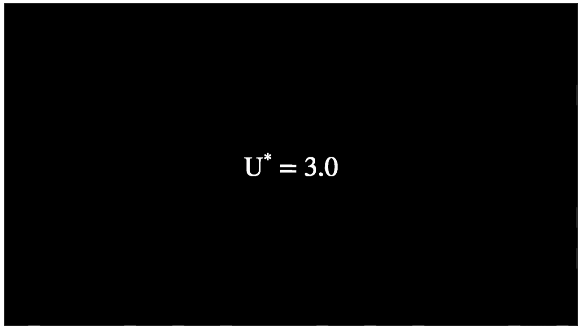
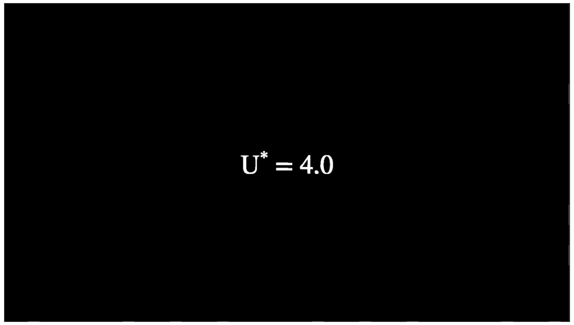
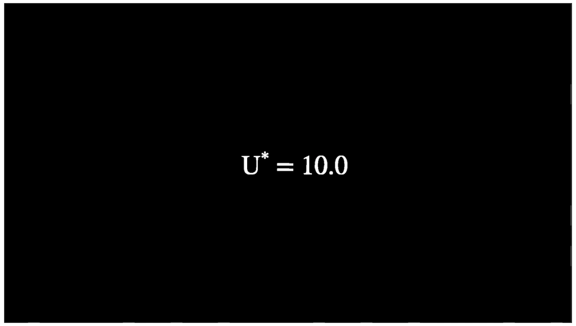


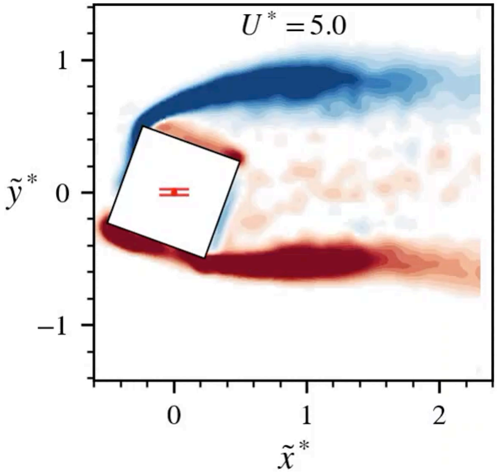
Figure 8: Hydrogen-bubble flow visualisations demonstrating flow impingement in the two synchronisation regions, compared with the negligible vibration region: (*a*) $U^* = 3.0$ (Sync-I), (*b*) $U^* = 4.0$ (non-vibration region) and (*c*) $U^* = 10.0$ (Sync-II) for $\alpha = 0°$. See supplementary movies 7 – 9.

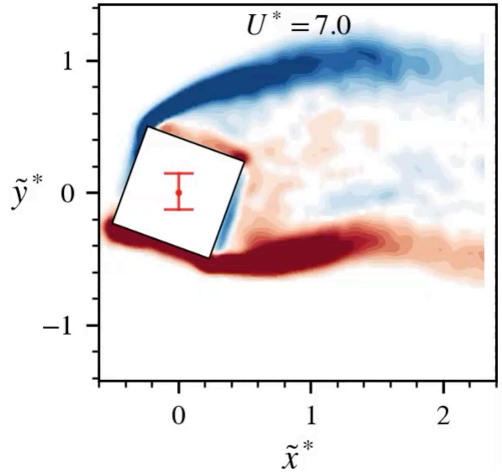


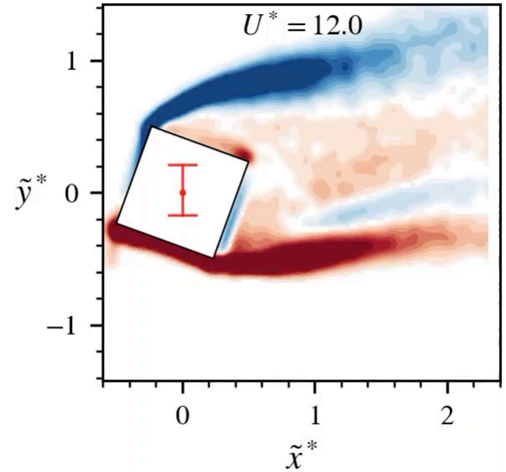


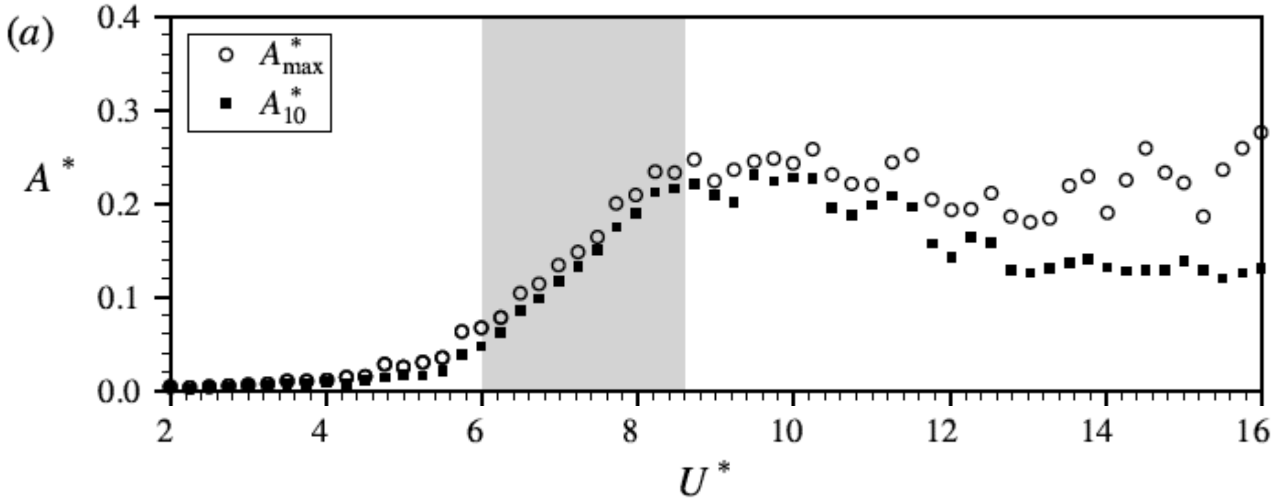


α = 20°: VIV but desynchronised

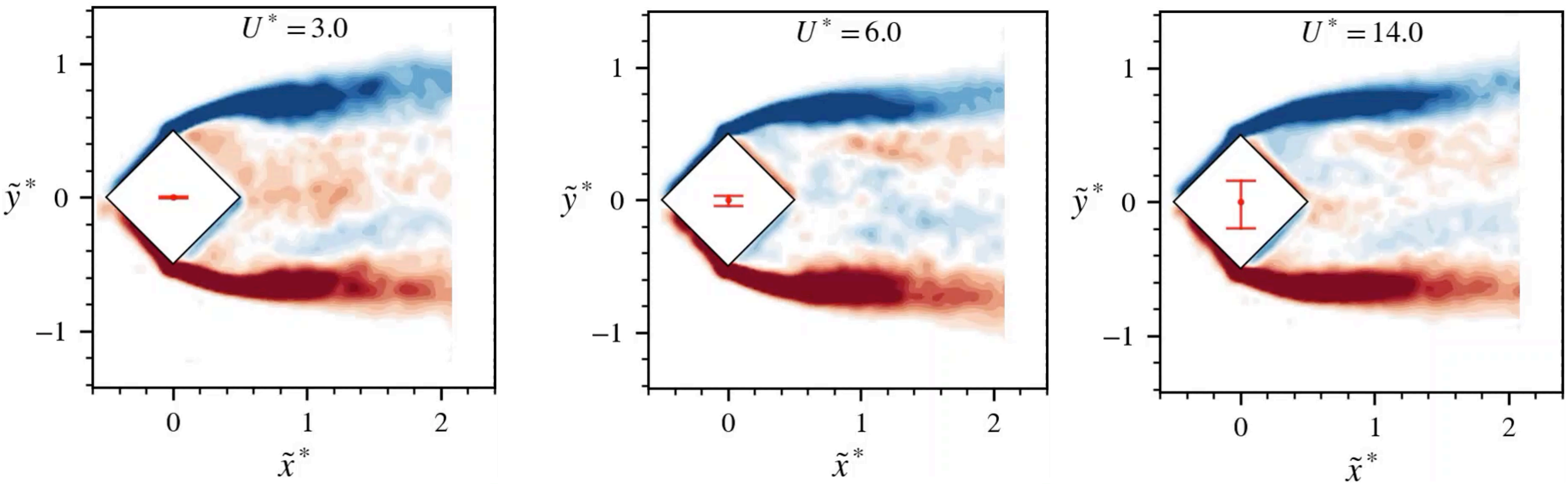


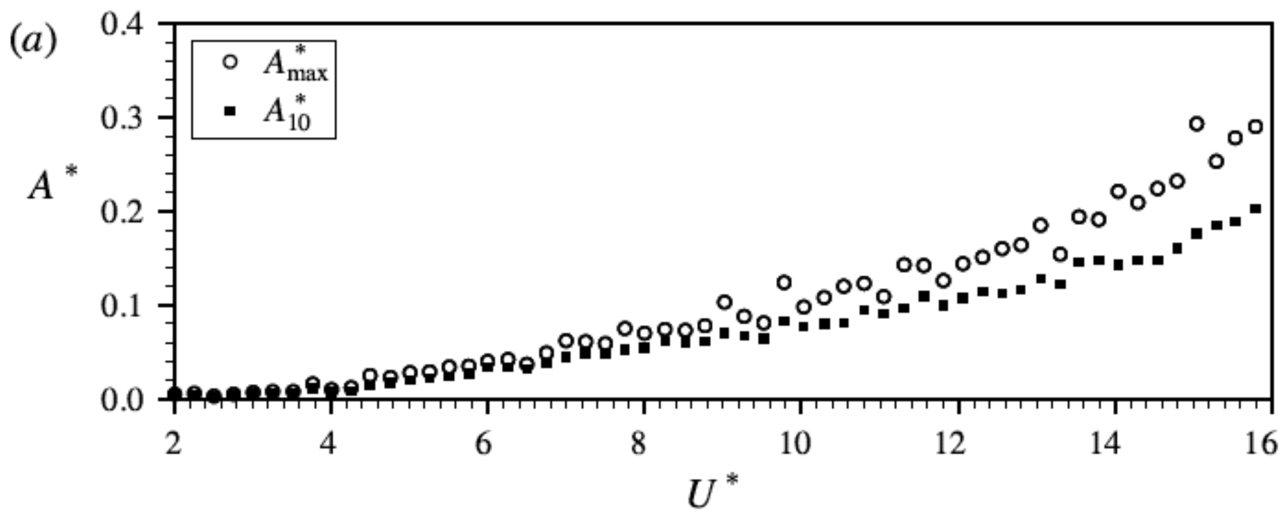






α = 45°: Small FIV desynchronised.





FIV differences between Cube and a Square Cylinder and with a Sphere

The transverse FIV response of a cube at $\alpha = 0^\circ$ is distinctly different from those of a square cylinder and a sphere.

Cf a **square cylinder**:

- the oscillating **cube** exhibits a distinctly different manner of vortex shedding,
    - where the two oppositely-signed shear layers appear to be well separated in the wake,
    - while the square cylinder displays a regular vortex shedding mode with the shear layers strongly interacting to form a vortex street

The VIV of a **sphere**

- exhibits a typical amplitude jump when the body vibration frequency is close to the vortex shedding frequency of the static body at $U* \approx 1/St \approx 5$.
- However, the **cube** exhibits an isolated lock-in region (Sync-I) at much lower reduced velocities, despite the fact that a second lock-in region occurs for $U* \geqslant 8.4$ when the body vibration frequency approaches the Strouhal vortex shedding frequency.
- From the wake measurement results, it is evident that the **mechanism** driving the body vibration of a **cube** is **differen**t from that of a **sphere**: the transverse vibration of a cube is strongly associated with the shear layers that separate from the leading edges and impinge on the lateral sides of the body, while the sphere vibration is due to a counter-rotating vortex pair in the wake.

Summary & Conclusions

Sphere

Fixed: Reviewed wake transitions: steady -> 3D -> unsteady hairpin

Flexibly mounted: Confirmed results of Govardhan & Williamson, effect of m*, Re

Surface trip wire: Different response depending on 2DOF or 3DOF for elastic support, and for tethering

Spheroid

Preliminary results: Significant effect on FIV of aspect ratio

Cube

0^{o} angle of attack: Both VIV and then Galloping observed as U* increases

Angle of attack increased (20^{o}, 45^{o}o): VIV becomes smaller and more desynchonised

Mechanism of FIV: Appears to be different to that for a sphere, shear layers more strongly interact