New Phenomena in Vortex-Induced Vibrations

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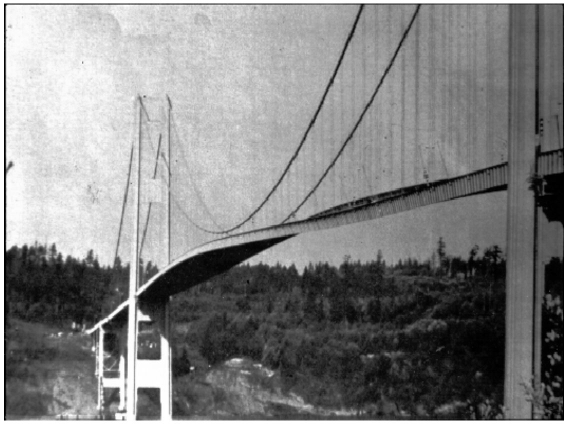
Motivation

Large vibrations of:

- Riser tubes bringing oil from the seabed
- Bridges and chimney stacks
- Heat exchangers
- Overhead power cables
- Many other applications



Tacoma Narrows Bridge

Hoover Diana Project
Exxon-Mobil

Generic -Universal Nature of Diverse VIV Systems

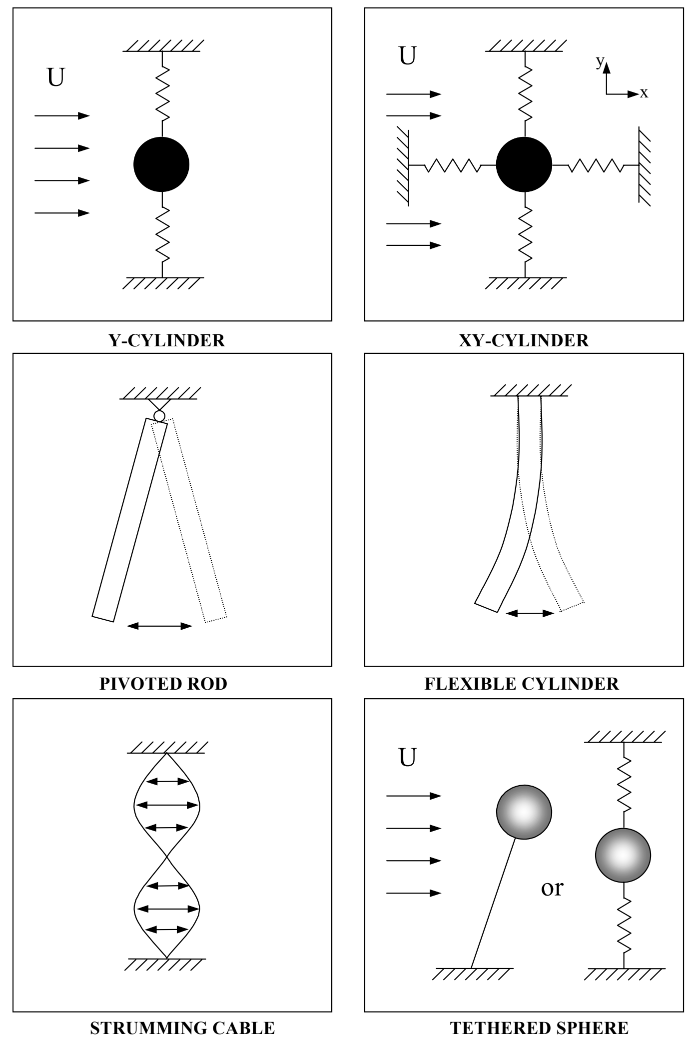
Paradigm for more complex systems

GENERIC PHENOMENA
Carry across to:

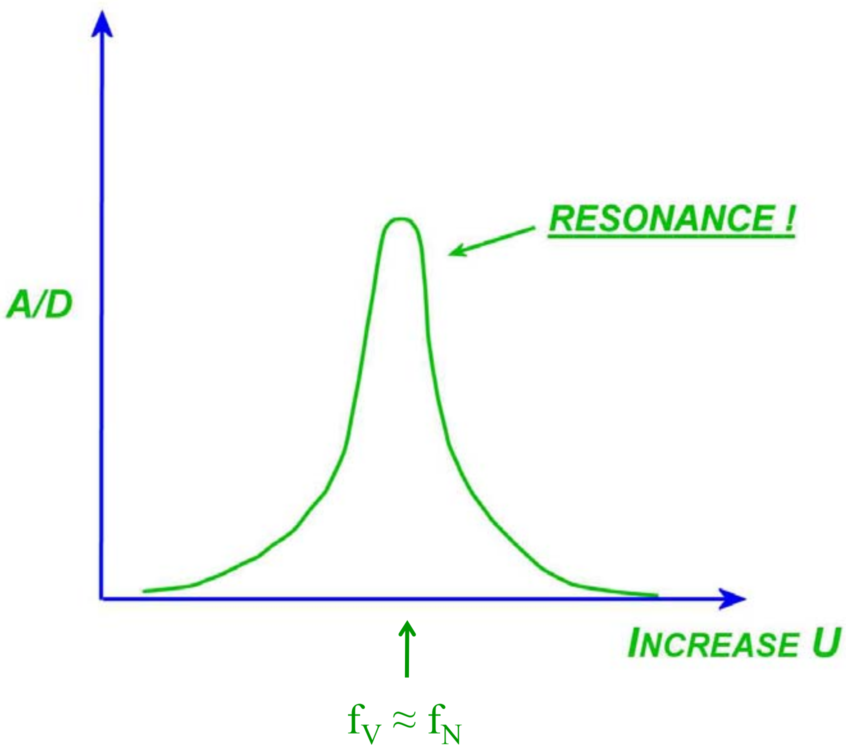
High Re

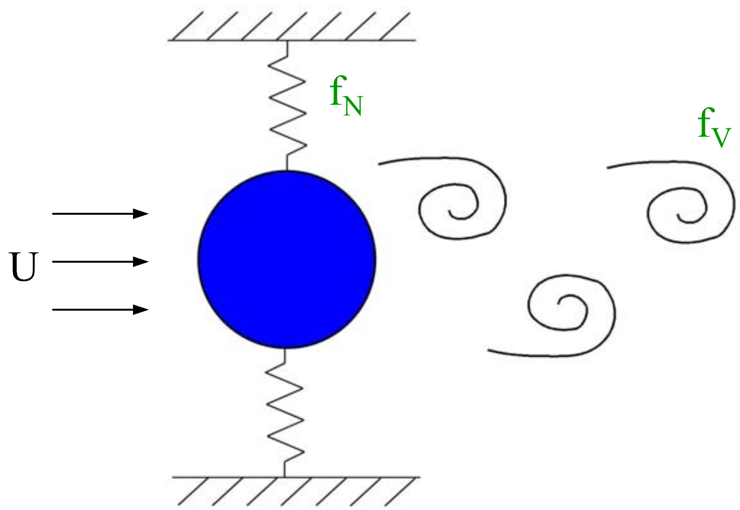
All VIV Systems

• MIT, Norway, Exxon



Does Resonance Look Anything Like This?





Parameters in the problem

- Flow speed U →

$$U^* = \frac{U}{f_N D}$$

↑ NORMALIZED VELOCITY

Expect resonant oscillation $f_V \approx f_N$

$$U^* = \frac{U}{f_N D} = \frac{U}{f_V D} = \frac{1}{S} \sim 5$$

- Oscillating mass m →

$$m^* = \frac{m}{displaced\ \ fluid\ mass}$$

↑ MASS RATIO

Air → m* is large ~ O(100)

Water → m* is small ~ 1-10

- Structural damping c →

$$\zeta = \frac{c}{critical\ damping}$$

↑ DAMPING RATIO

m*ζ = mass-damping parameter

VERY LOW VALUES HERE !

Typical VIV System

Equation of Motion:

$$m\ddot{y} + c\dot{y} + ky = F_{fluid}$$

Cylinder displacement: $y(t) = A \sin \omega t$

Fluid force: $F(t) = F_0 \sin(\omega t + \phi)$ ← ϕ IS VERY IMPORTANT !

Amplitude response

$$A^* = \frac{A}{D} = \frac{1}{(m^* + C_A)\zeta}\left[\frac{C_Y \sin\phi}{4\pi^3}\left(\frac{U^*}{f^*}\right)^2 f^*\right]$$

MASS-DAMPING PARAMETER: $(m^* + C_A)\zeta$

Frequency response

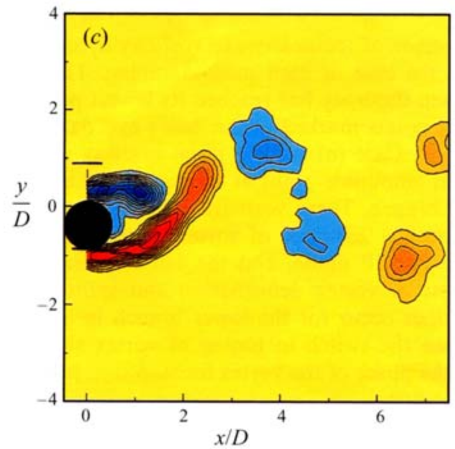
$$f^* = \frac{f}{f_N} = \sqrt{\frac{(m^* + 1)}{(m^* + C_{EA})}}$$

$$C_{EA} = \frac{1}{2\pi^3 A^*}\left(\frac{U^*}{f^*}\right)^2 C_Y \cos\phi$$

DEPENDS ON m*

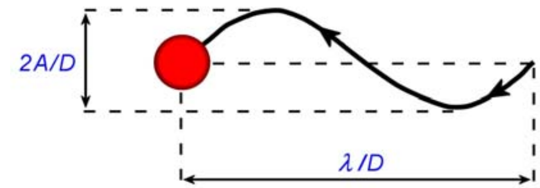
1

VIV Response Modes

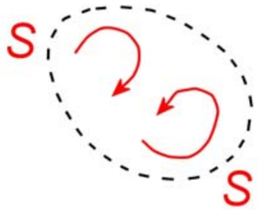


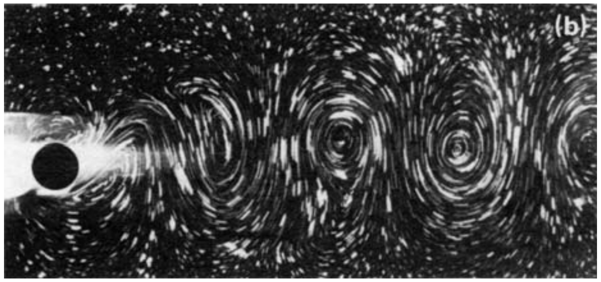
What is known about the wake vortex dynamics for a transversely oscillating cylinder

Williamson & Roshko (1988)



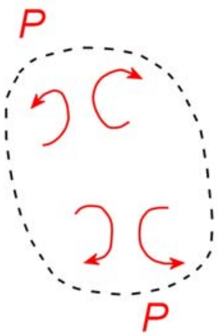
Example vortex wake modes





'2S' MODE

2 single vortices / cycle



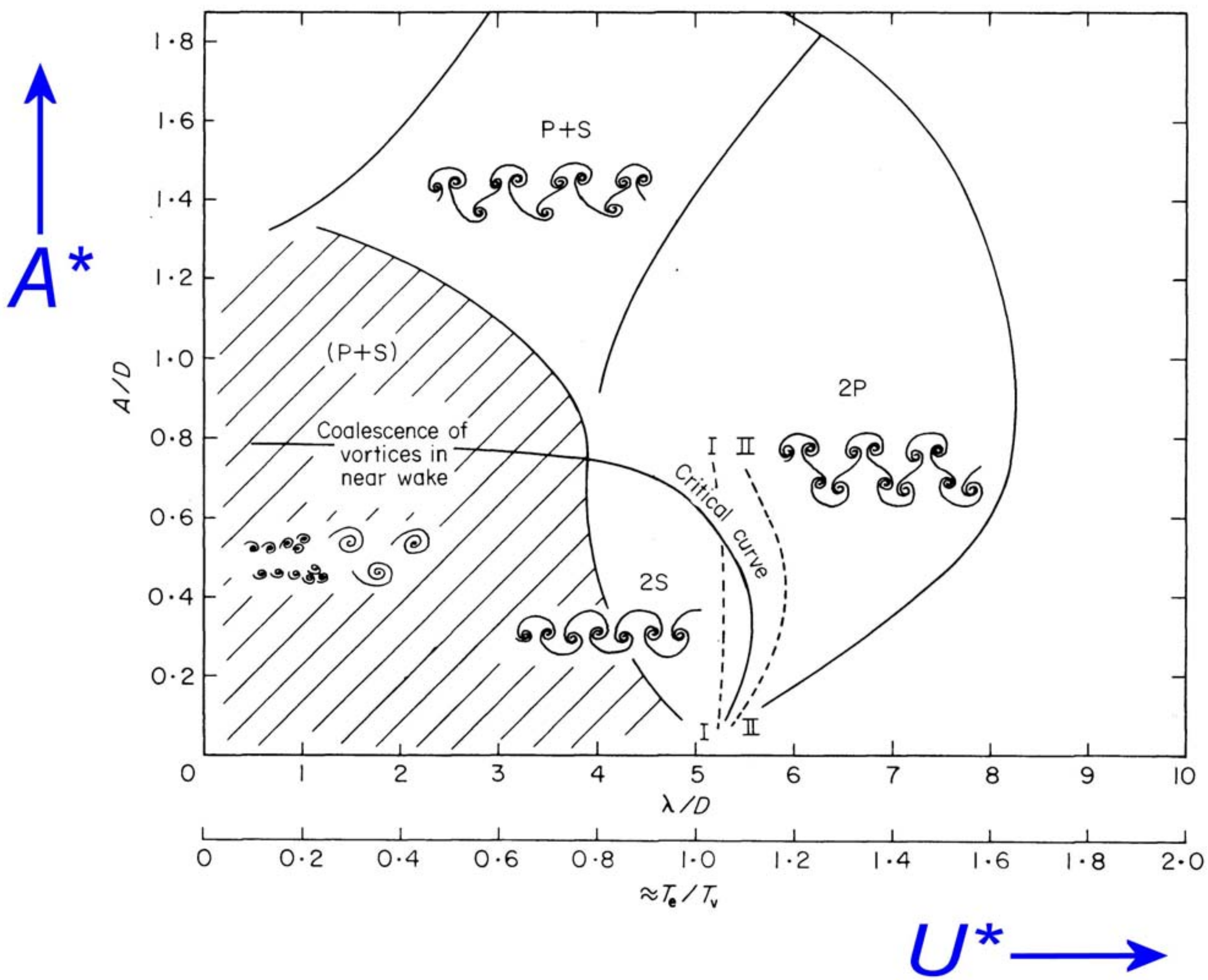
'2P' MODE

2 pairs of vortices / cycle

2P – Ongoren & Rockwell (1988) for in-line oscillations

Map of Wake Modes

Williamson & Roshko (1988)

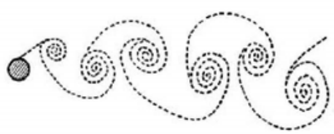


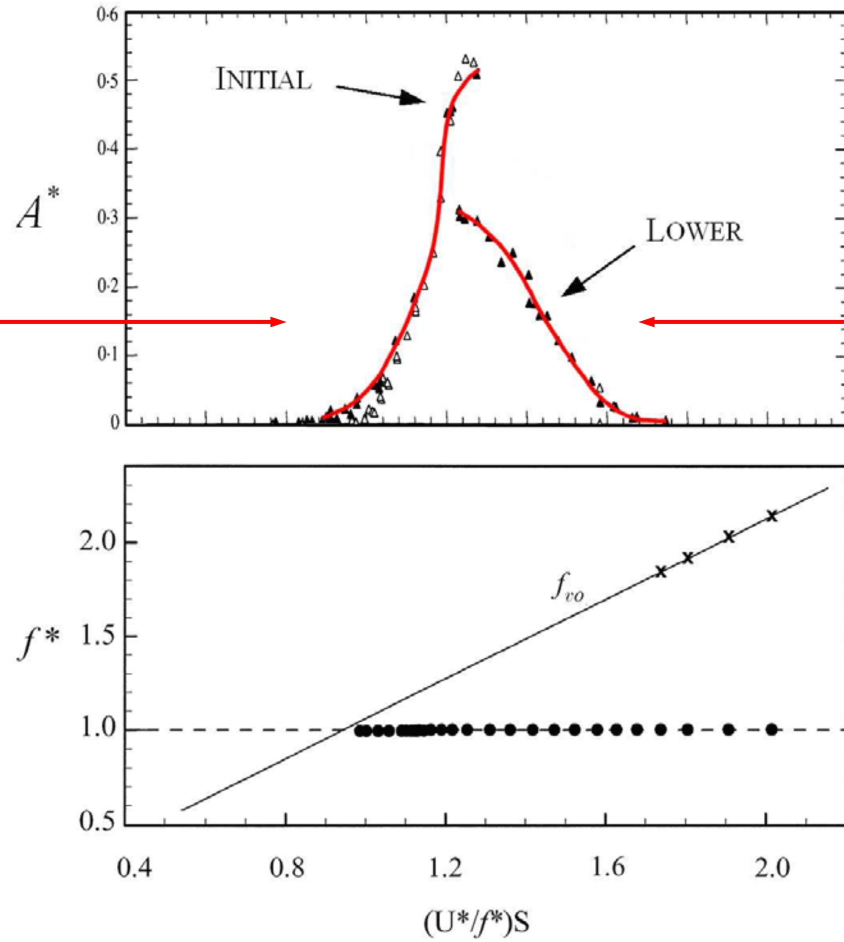
High Mass-Damping

2 Modes

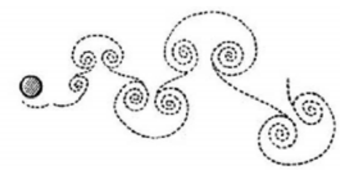
1 Discontinuity

‘2S’ Mode





‘2P’ Mode



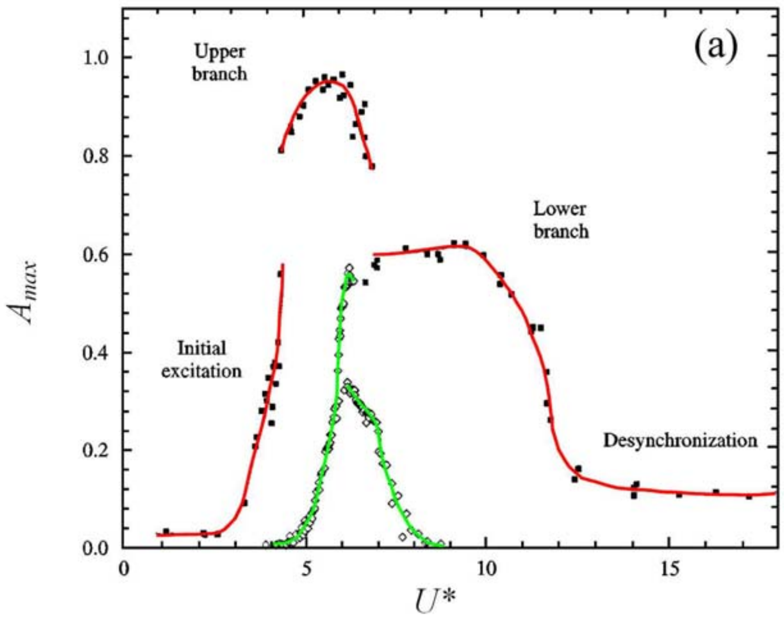
Experiments in AIR
m* ~ 100-200 → Feng (1968)
Brika & Laneville (1993)

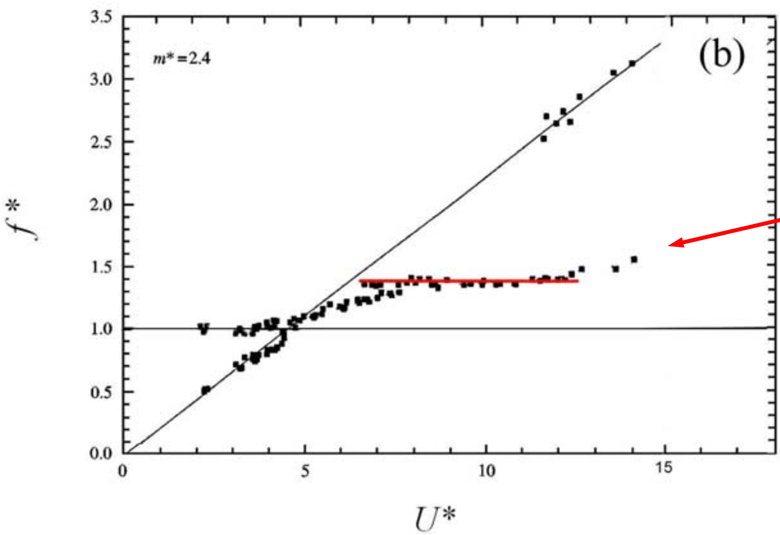
Low Mass-Damping

Experiments in WATER
$m^* \sim 5$

↓

Khalak & Williamson
(1996, 1999)





3 Modes

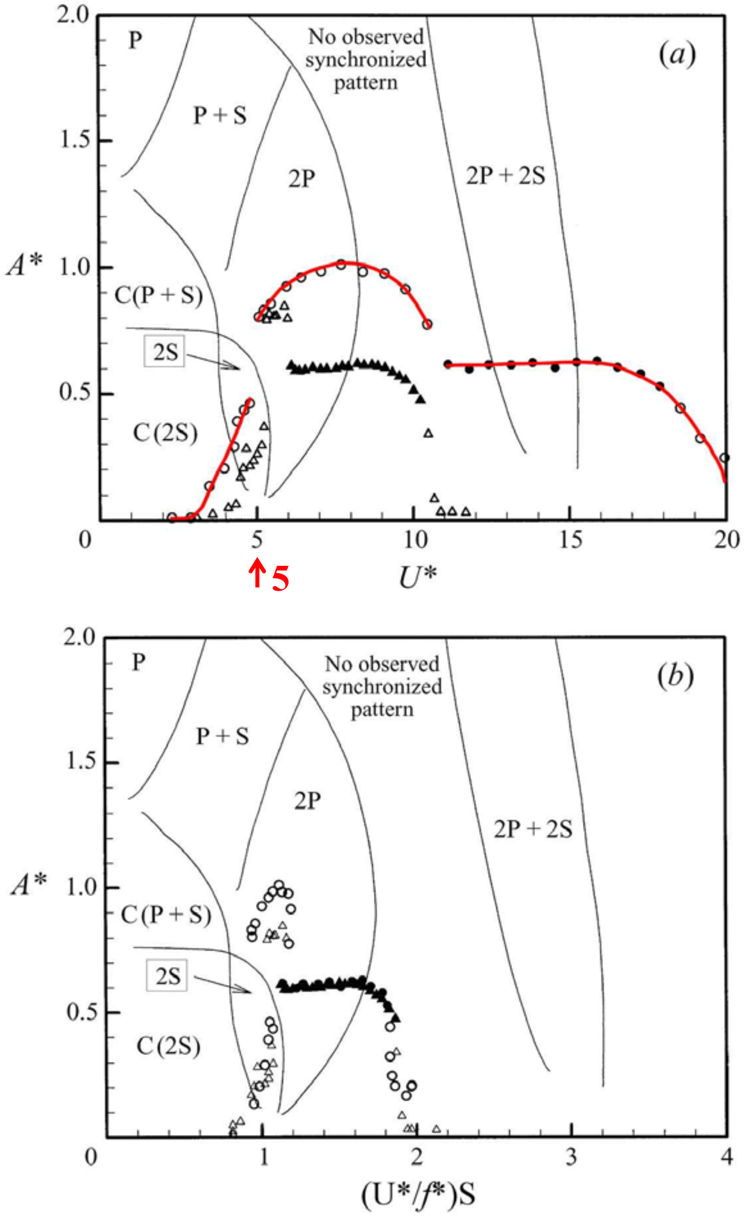
2 Discontinuities

- Large A*
- Wide regime of resonance

f* > 1.0 !!

Depart from classical resonance

Very Low m*



Very Wide Regime !

Collapses beautifully with:

$$\left(\frac{U^*}{f^*}\right)S = \frac{f_{vo}}{f}$$

Ratio of the 2 most basic frequencies

Suggests W-R Map:

Initial → 2S

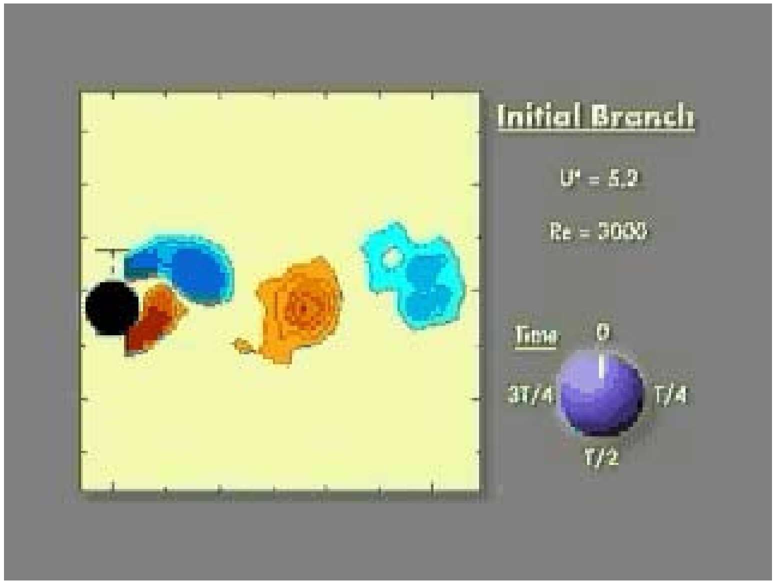
Upper → 2P

Lower → 2P

⇩

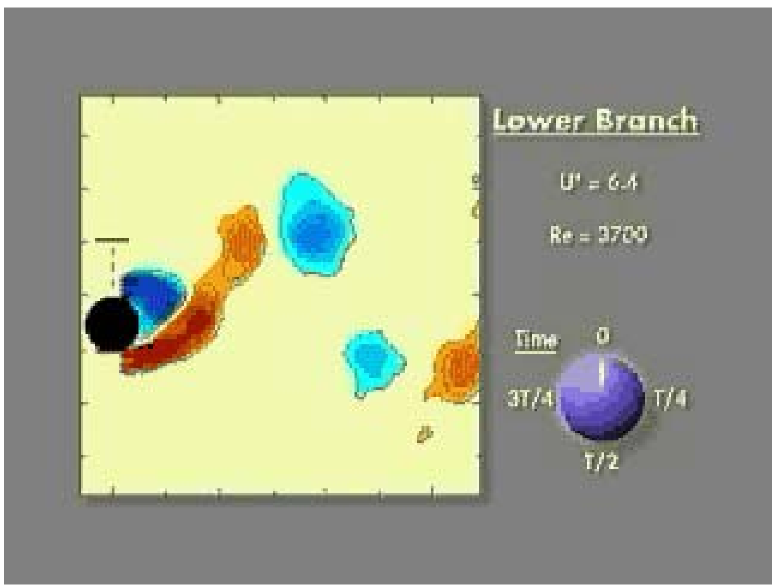
Now see VORTEX MODES !

Vortex Modes



Initial Branch

‘2S’



Lower Branch

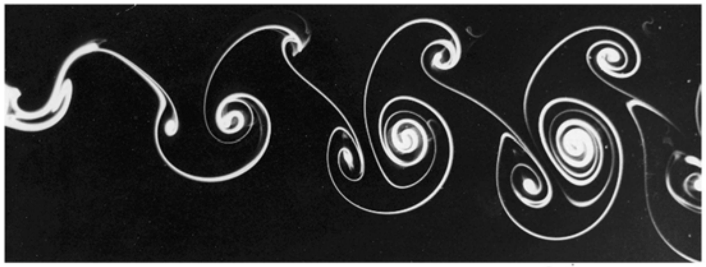
‘2P’

Seen effects:
 m*ζ, m*

See extreme later

2

Numerical Simulations & Laminar VIV

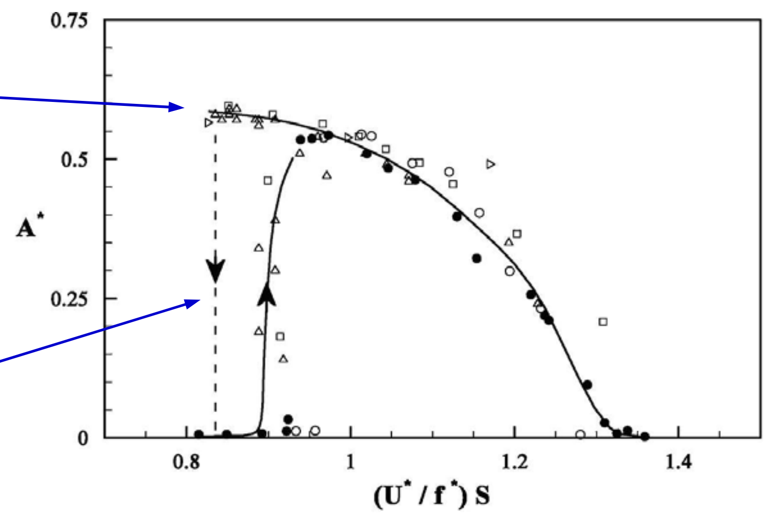


Compilation of Low-Re Results

$A^*_{peak} < 0.6$

Hysteresis

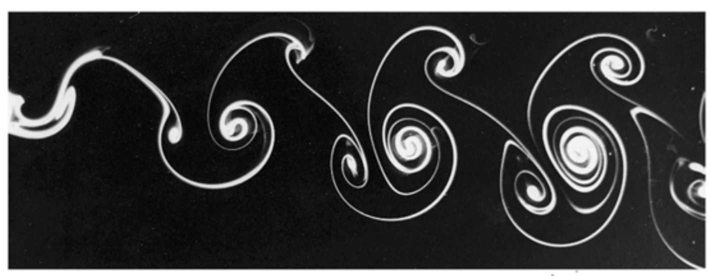
Consistent with



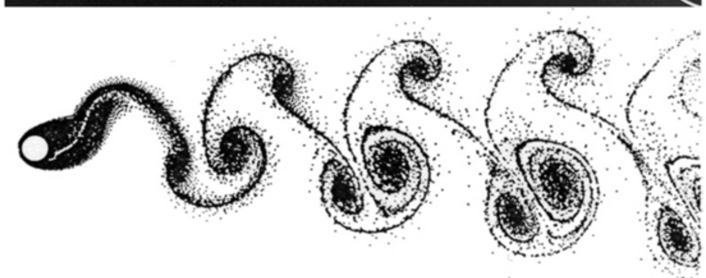
Anagnostopolous & Bearman (1992)
Anagnostopolous (1994)
Newman & Karniadakis (1997)
Shiels, Leonard, & Roshko (2001)
Wilden & Graham (2000)

Vortex mode changes to P+S

$A^* > 0.6$



Experiment



Numerical simulation

Ponta and Aref (2003)
Meneghini & Bearman (1995)

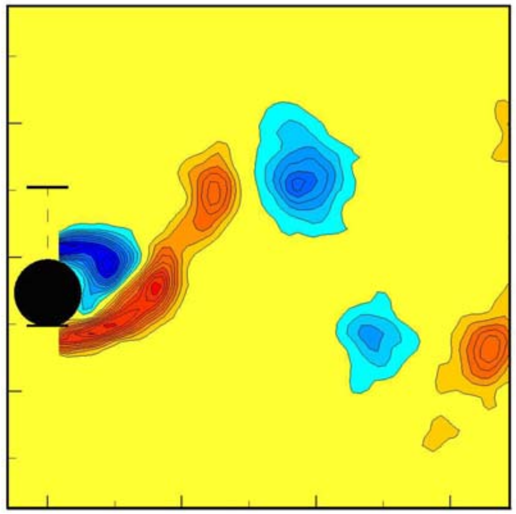
P+S mode must not be able to impart positive energy transfer

i.e. $C_y \sin \phi < 0$

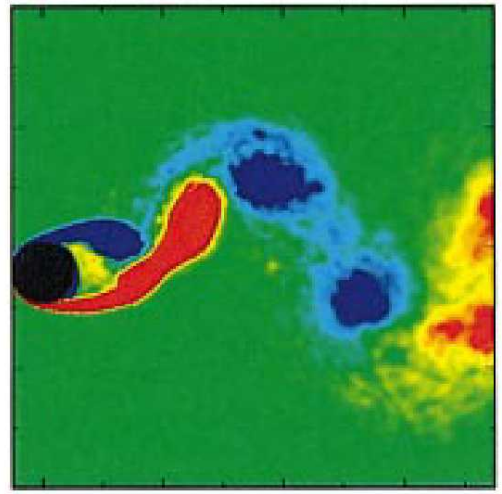
VIV Simulations

Govardhan & Williamson (2000)

Experiment



Blackburn et. al. (2001)
Lucor & Karniadakis (2005)



3D DNS

Challenges for CFD:

- Must use 3D simulations to produce:
  - '2P' mode
  - A* > 0.6
- Pushing up Re:
  - 1995 $Re_{max} \sim 200$ (Newman & Karniadakis)
  - 1999 $Re_{max} \sim 2000$ (Evangelinos & Karniadakis)
  - 2005 $Re_{max} \sim 3000 - 10{,}000$? (Lucor & Karniadakis………)
- LES:
  - Not yet good agreement with experiments or between LES studies.

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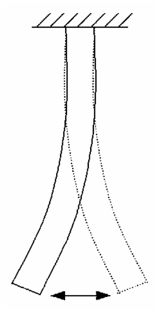
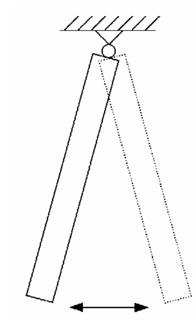
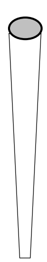
Flexible



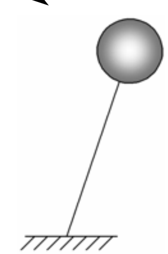
Pivoted



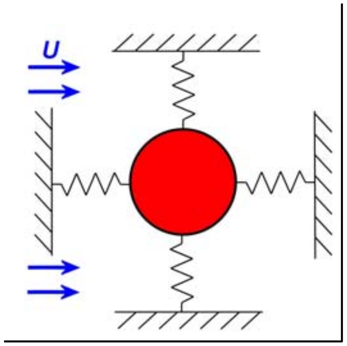
XY Motion & Complex Flows



Tapered



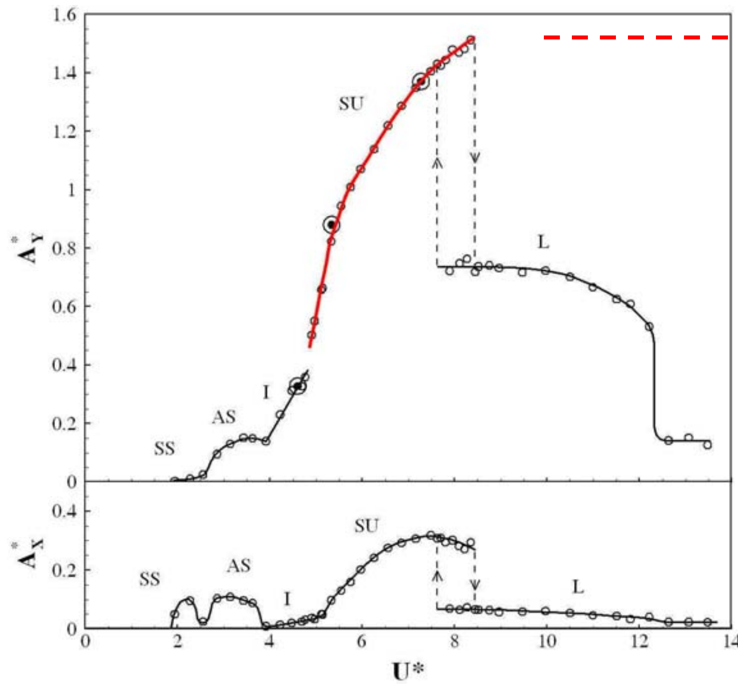
Tethered



X-Y Motion

Jauvtis & Williamson
JFM (2004)

$m^* < 6$

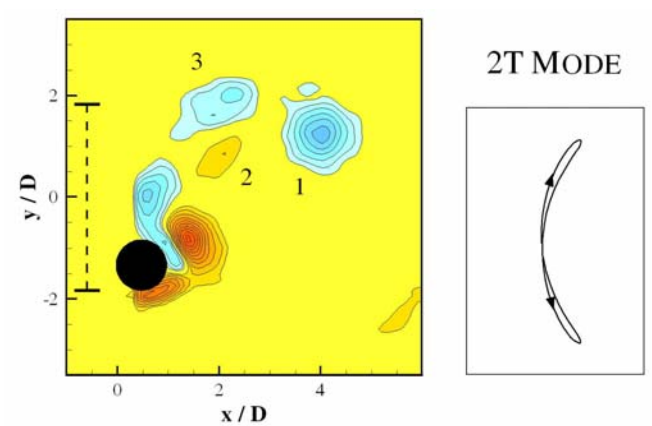


$A^* = 1.5$!

(Much bigger than Y-only)

Slight streamwise motion has dramatic effect !

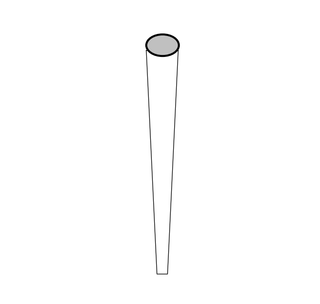
NOTE: Forced motion of Jeon & Gharib (2004)



Small change in ϕ due to vortex dynamics

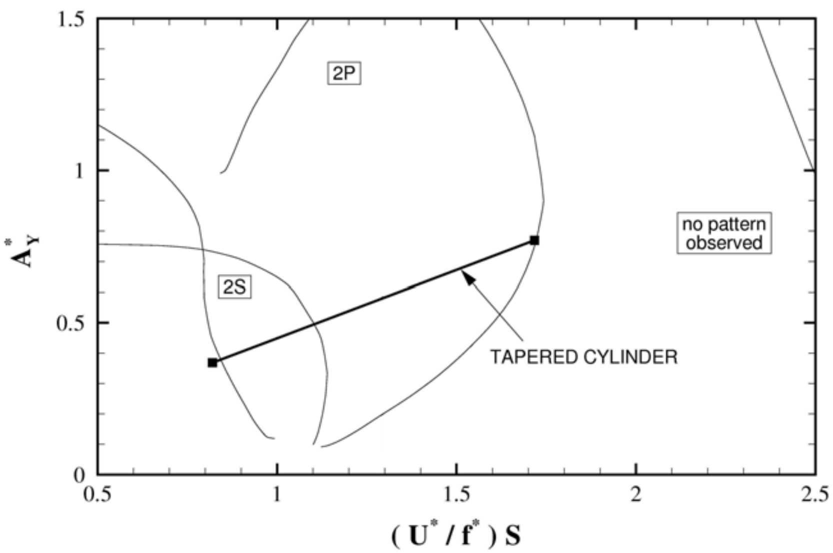
⇩

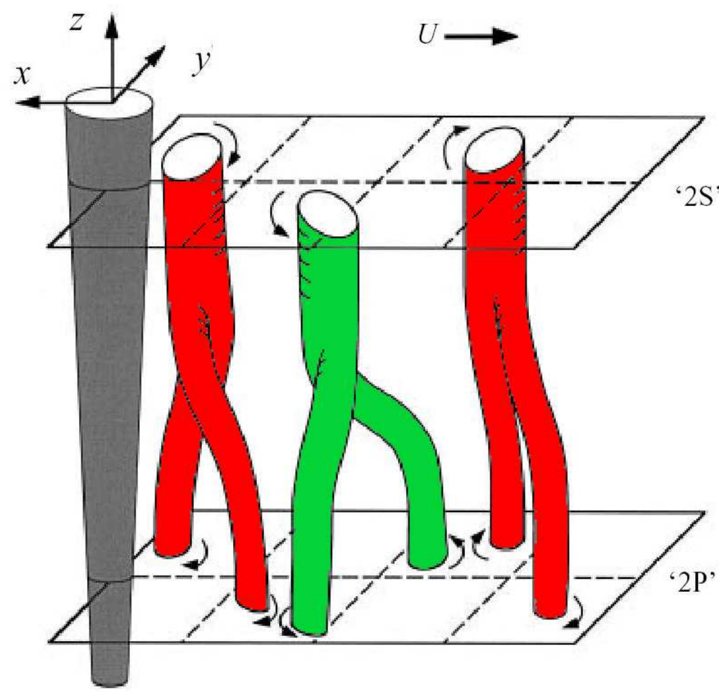
Big change in A*



Spanwise Variation of A*

Techet, Hover, &
Triantafyllou (1998)





Williamson-Roshko Map:

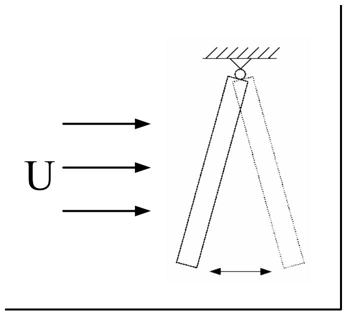
Suggests you can get 2S along part of span,
2P along other part of span

⇩

Relevant to Cable Dynamics

2S-2P Hybrid Mode

"Gumby"

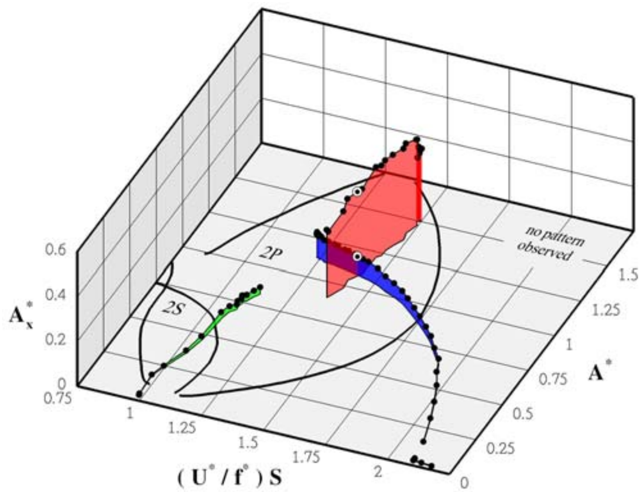


Pivoted Cylinder

Flemming & Williamson (2004)

Simplest case of spanwise amplitude variation

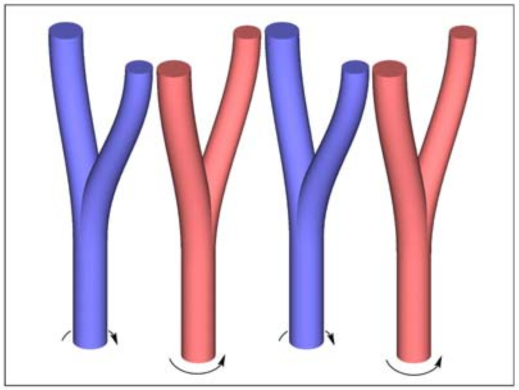
relevant to cable dynamics



Cross over of branches

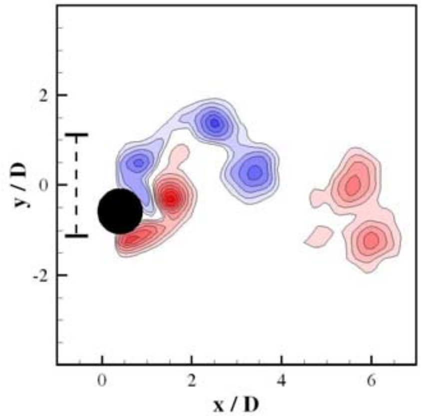
⇩

Need 3D W-R Map

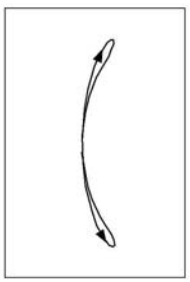


(a) 2S-2P Hybrid Mode

2S-2P Hybrid



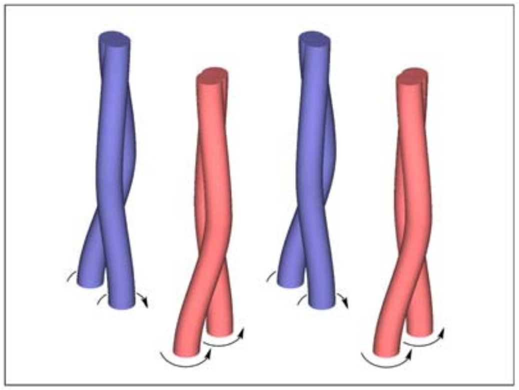
2C MODE



Biggest amplitude mode

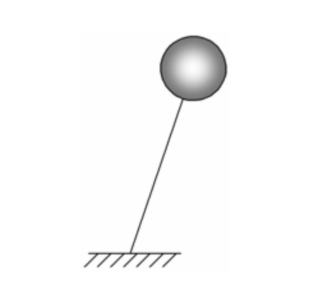
⇩

2C Mode



(b) 2C Mode

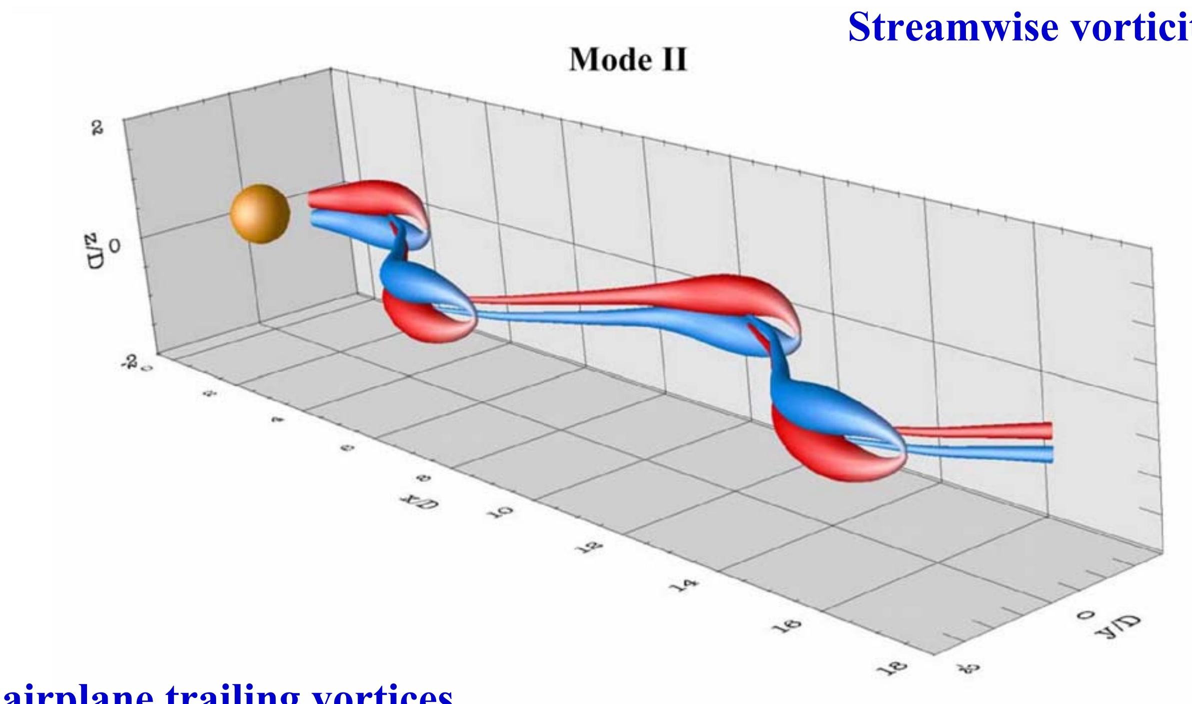
2C



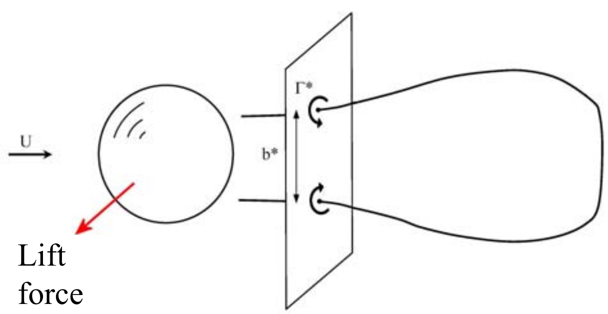
Sphere VIV

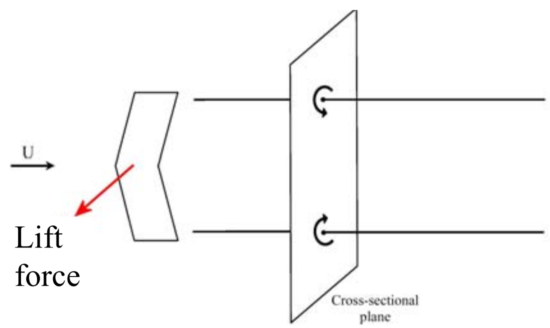
Govardhan & Williamson (2005)

Streamwise vorticity



Analogy to airplane trailing vortices





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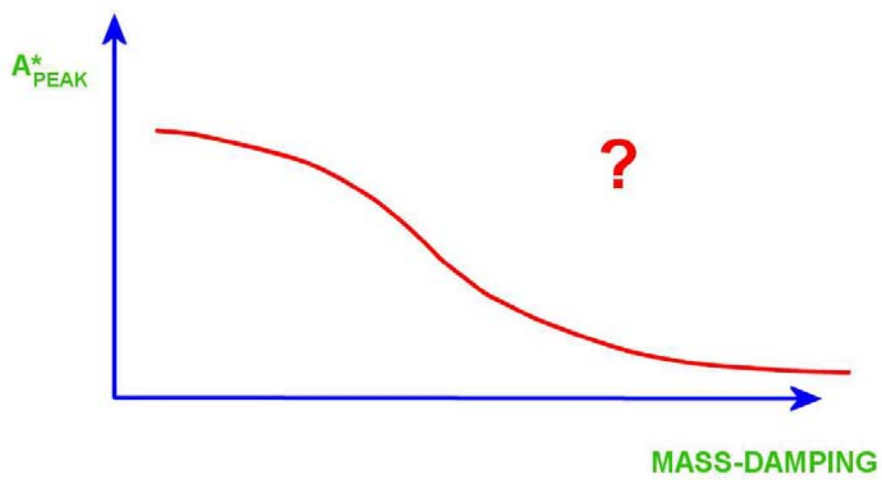
Griffin Plot



Perhaps the most basic question !

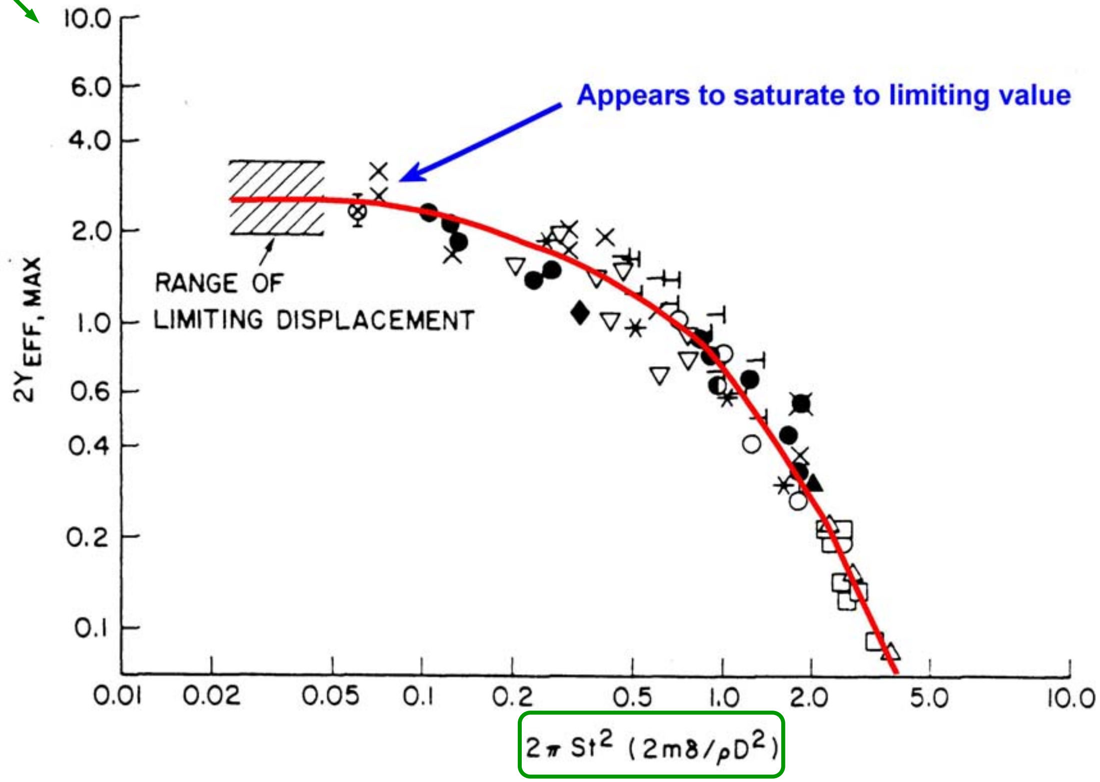
→ What is A^*_{peak}

Classical Griffin Plot

log-log

First extensive compilations of many studies

Griffin, et. al. (1975)

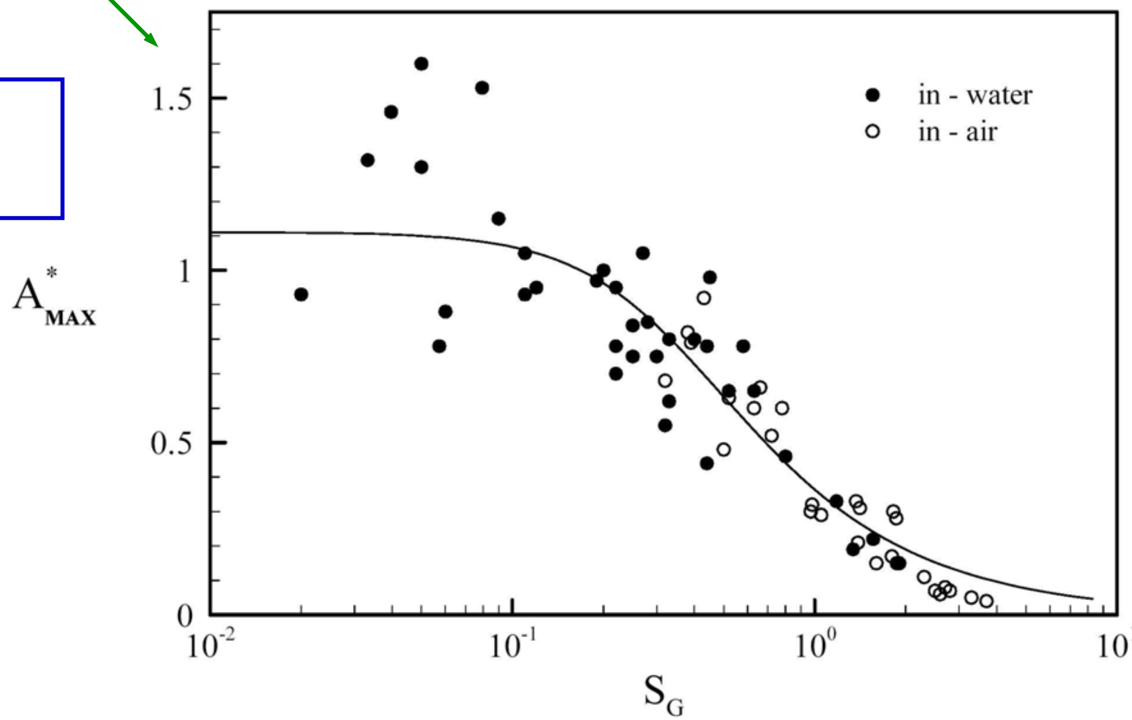


Skop-Griffin parameter

($m^* \zeta \cdot S^2$)

linear-log

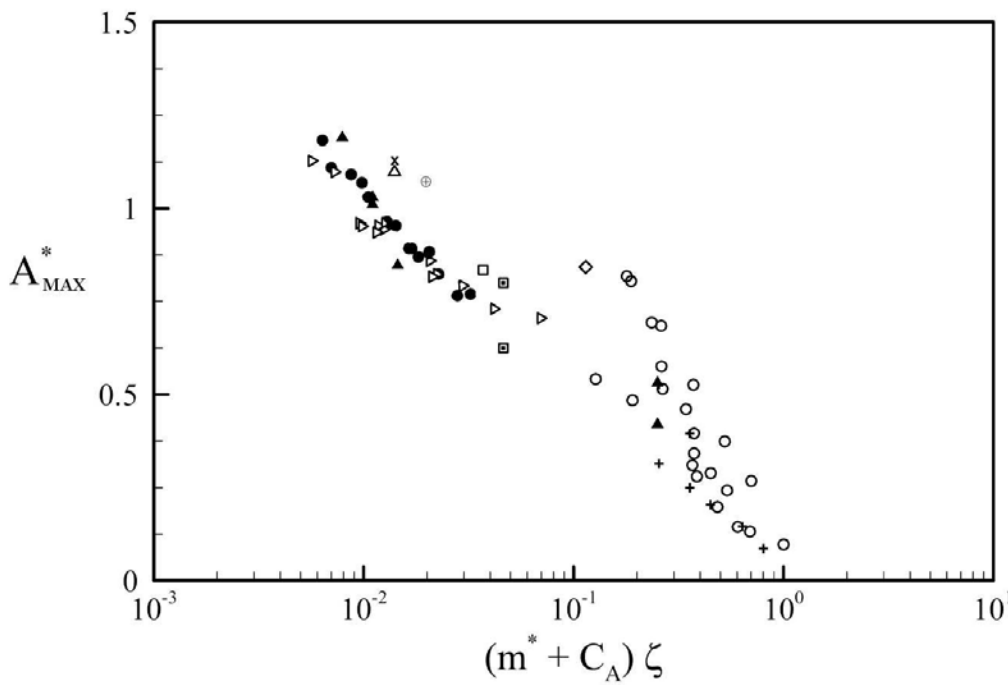
Big Scatter !



All Cases:

- Y – cylinders
- Pivoted bodies
- Flexible Cantilever
- ……… + others

Slightly Better Collapse



Cylinder y-motion only

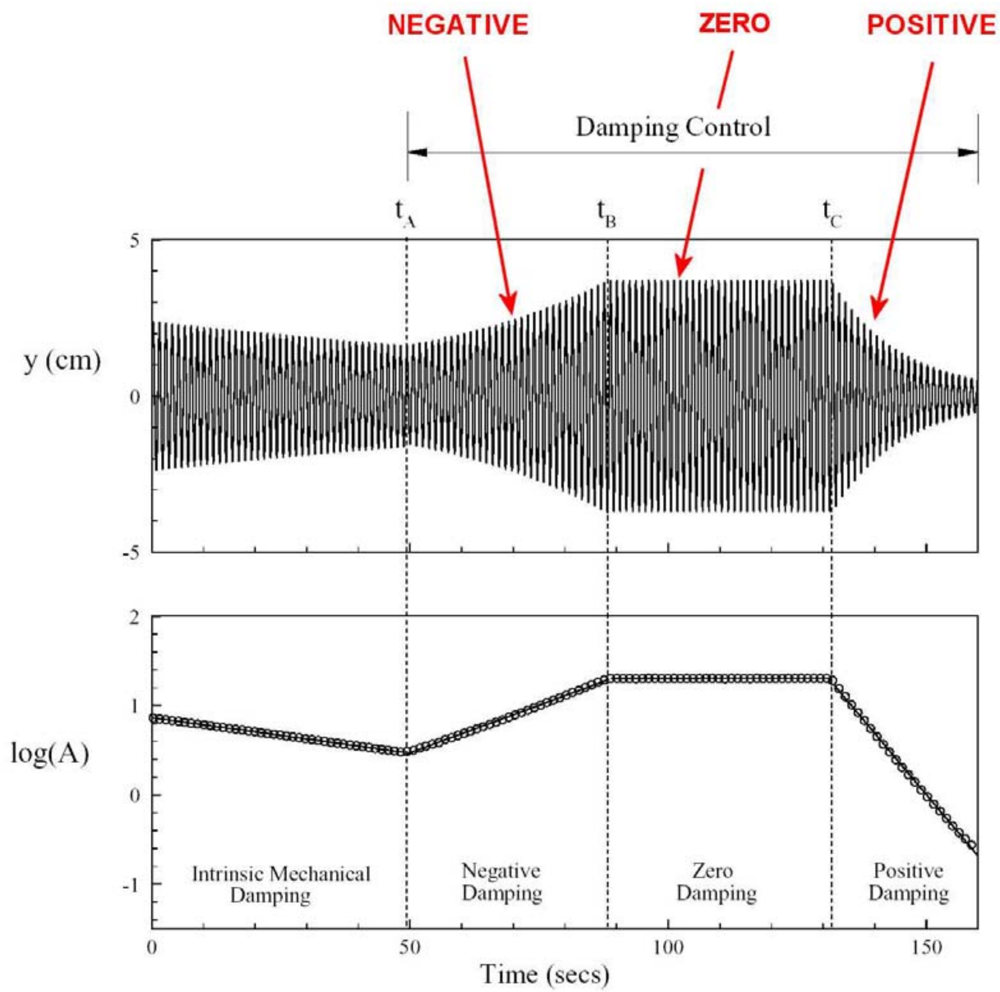
A^*_{PEAK} NOT SATURATED !

After 30 Years …

The Griffin Plot is not yet fully defined !

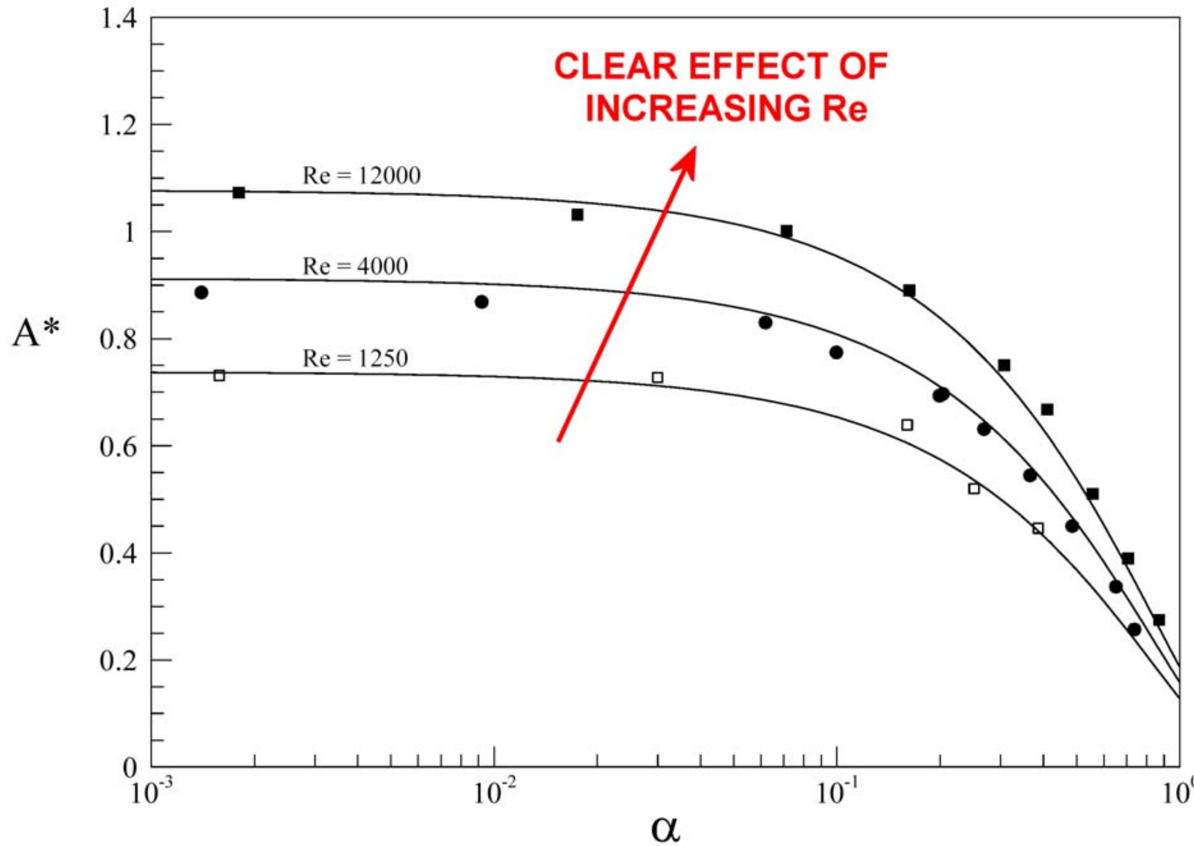
Even for the paradigm case !

Controlled Damping



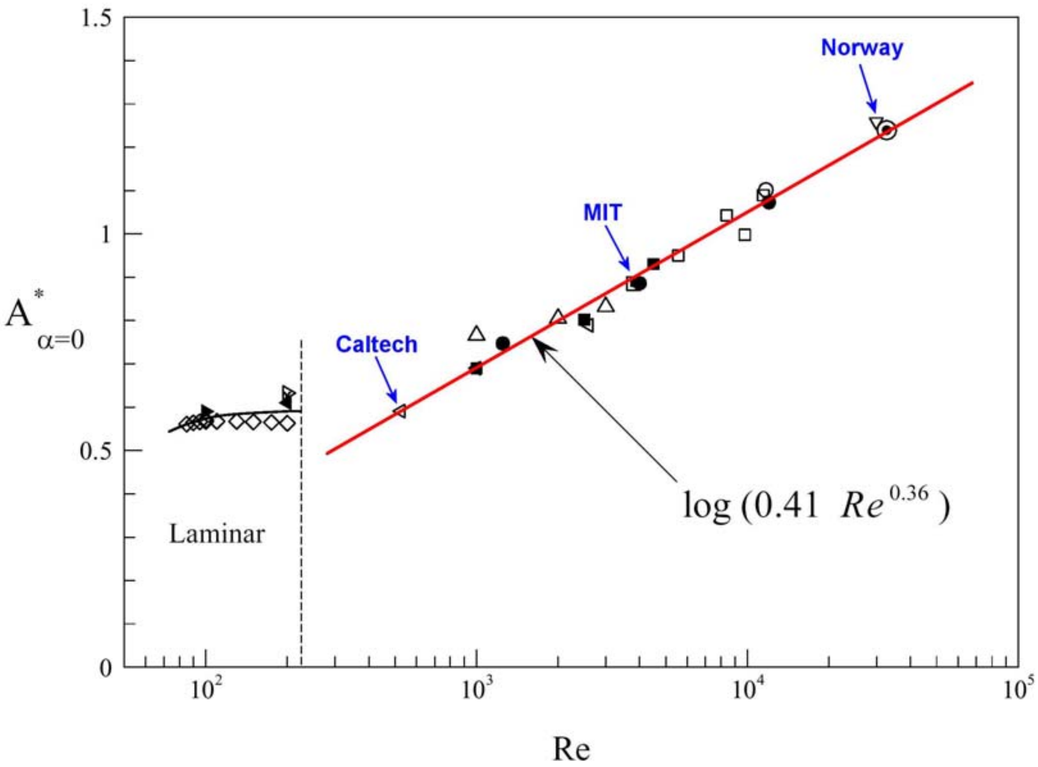
Damping Control Works !

Effect of Re



Note: curves look similar for each Re

Effect of Re



Good collapse of data:

$$A^*_{\alpha=0} = \log_{10}[0.41\ \mathrm{Re}^{0.36}]$$

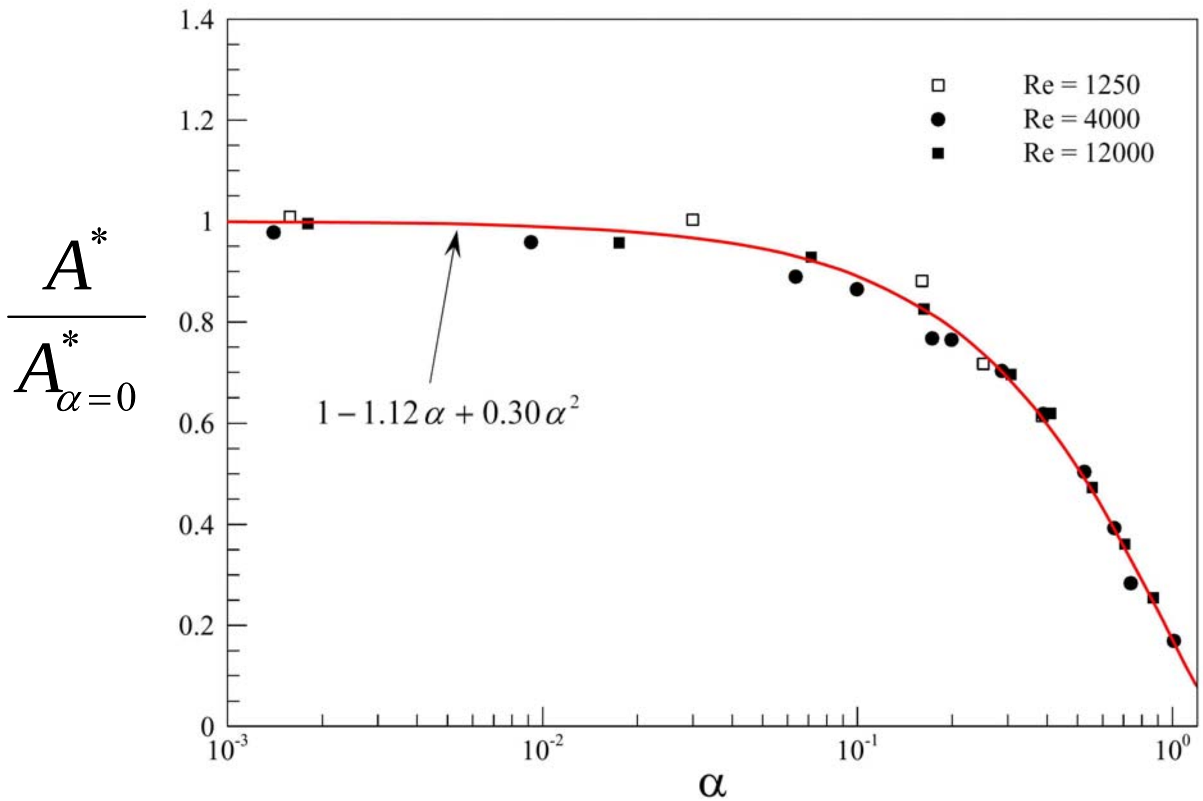
ALSO:

Klamo, Leonard, & Roshko (2005)

Independently find trend of amplitude increase with Re

(controlled damping)

The "Modified Griffin Plot"



We define:

$$A^*_{MODIFIED} = \frac{A^*}{A^*_{\alpha=0}}$$

⇒ Collapses our data well !

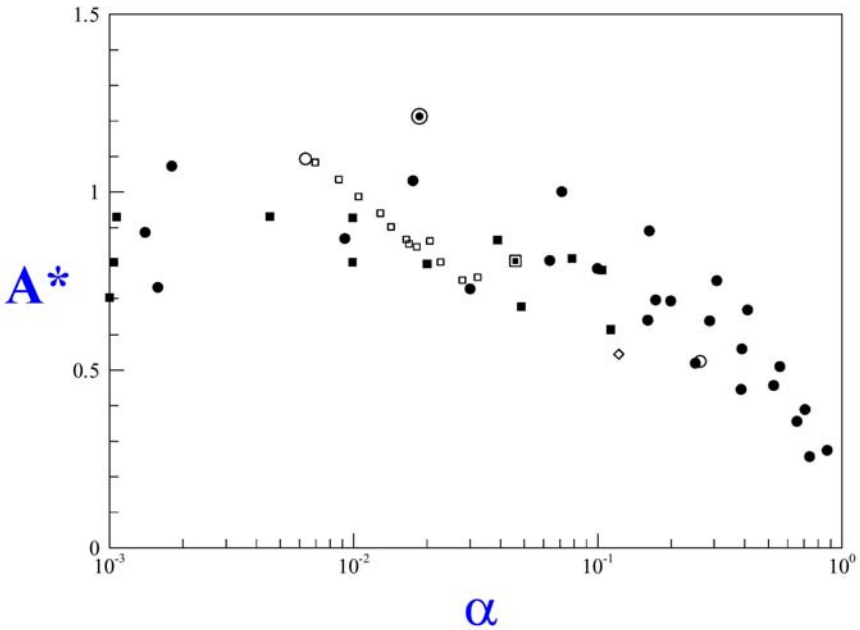
Can we now collapse

the large scatter in the classical Griffin plot

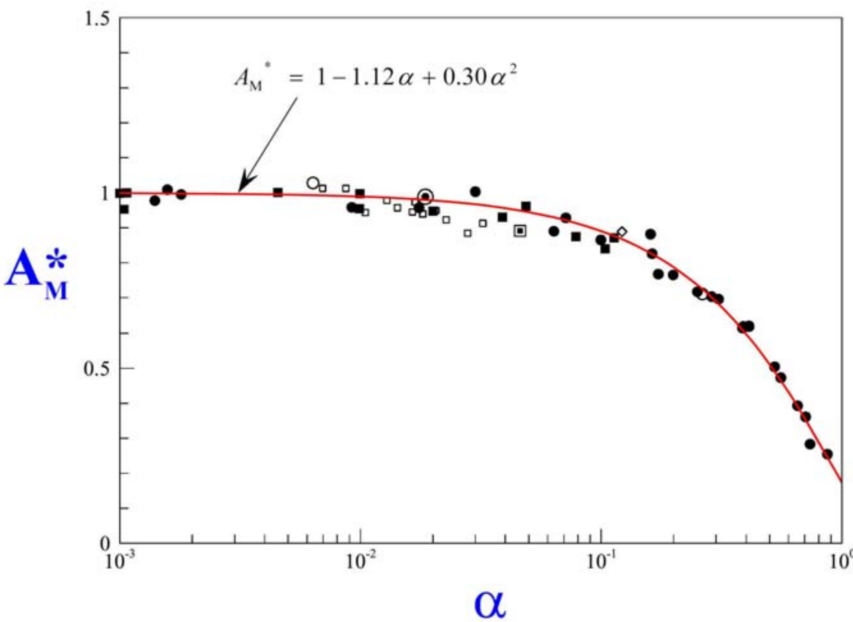
$$A^*_{MODIFIED} = \frac{A^*}{A^*_{\alpha=0}}$$ **?**

Take into account Re !

Griffin Plot



"Modified Griffin" Plot

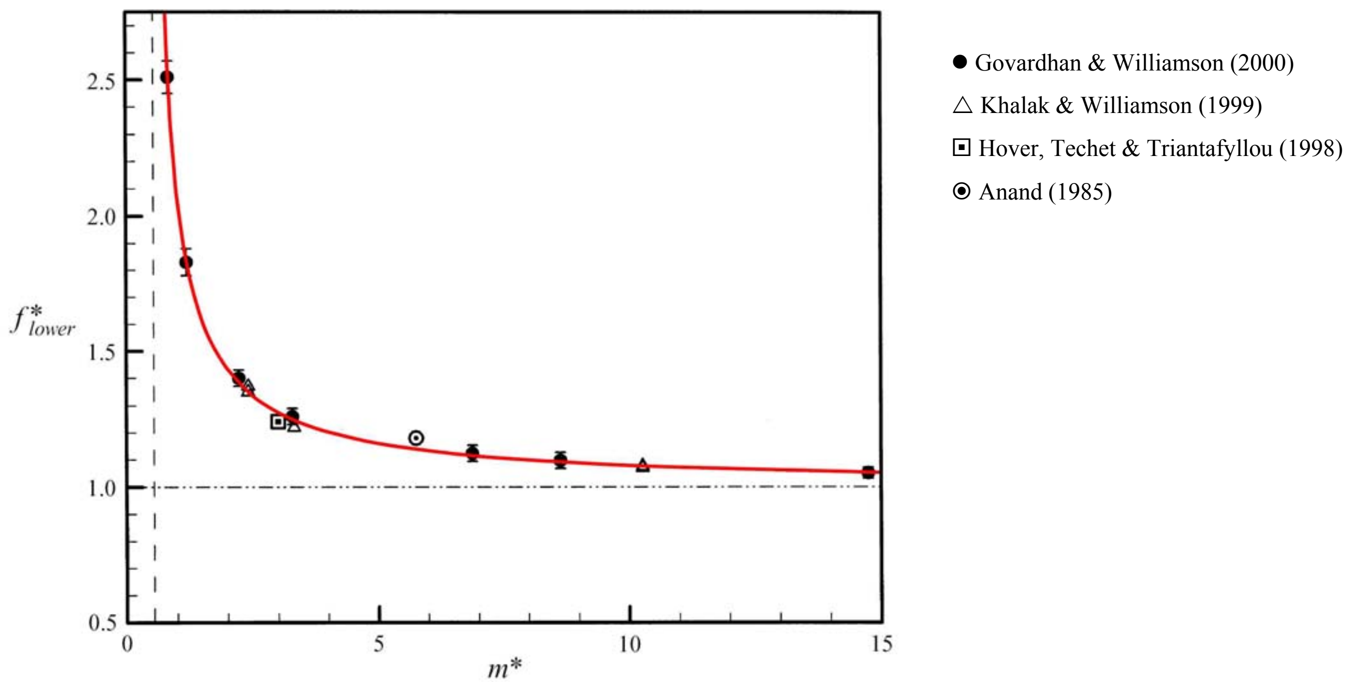


Data collapses onto a single curve !

5

Critical Mass

Equation for Oscillation Frequency



$$f^*_{LOWER} = \frac{f}{f_N} = \sqrt{\frac{(m^* + 1)}{(m^* + C_{EA})}}$$

Best fit : $C_{EA} = -0.54$

$$f^*_{LOWER} = \frac{f}{f_N} = \sqrt{\frac{(m^* + 1)}{(m^* - 0.54)}}$$

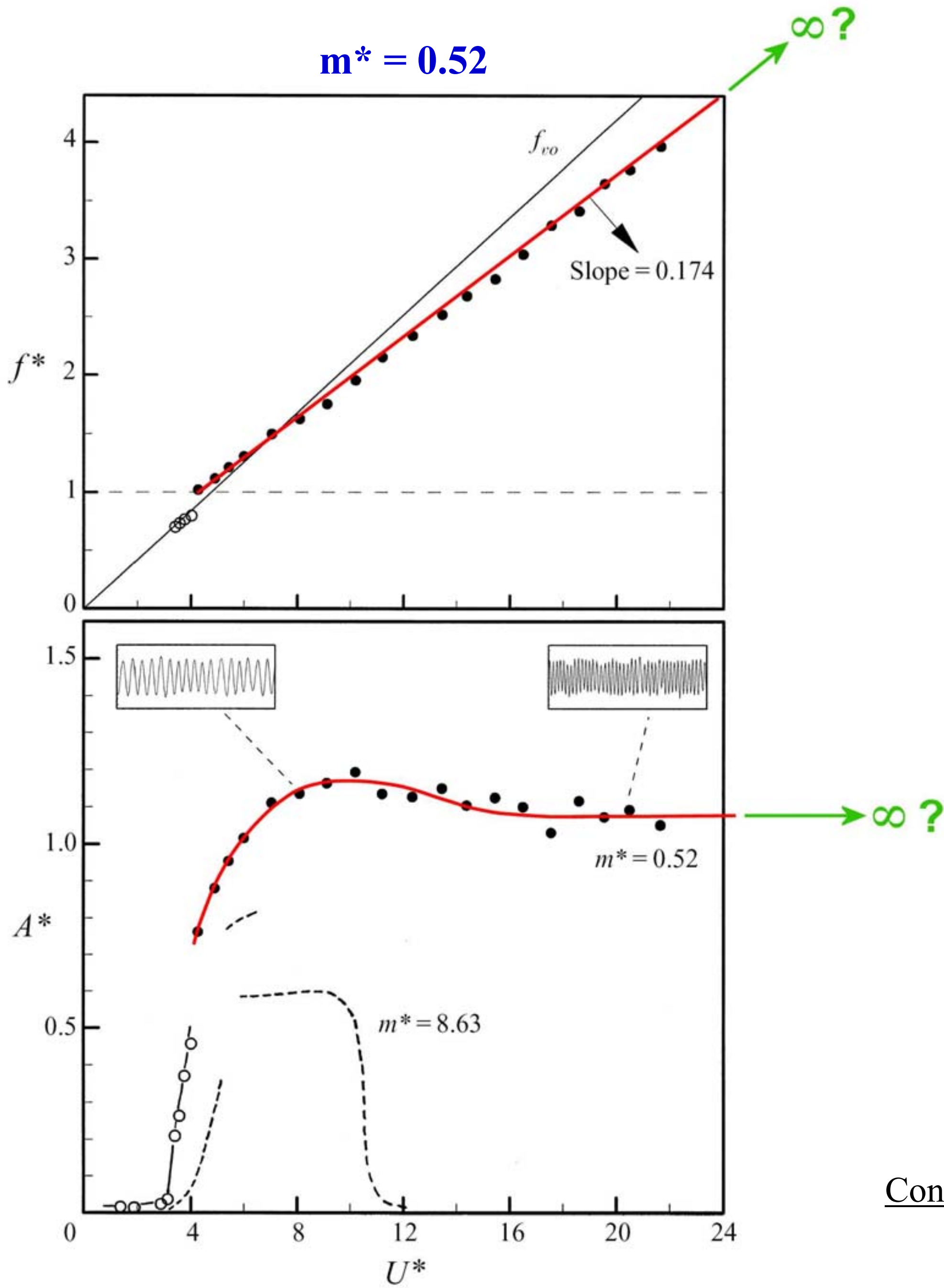
CRITICAL MASS RATIO

$m^*_{CRIT} = 0.54$

If **$m^* \rightarrow 0.54$**, $f^* \rightarrow \infty$

If **$m^* < m^*_{CRIT}$**,

- Lower branch does not exist
- Get stuck on upper branch



What if m* below critical ?

Radically different from classical resonance

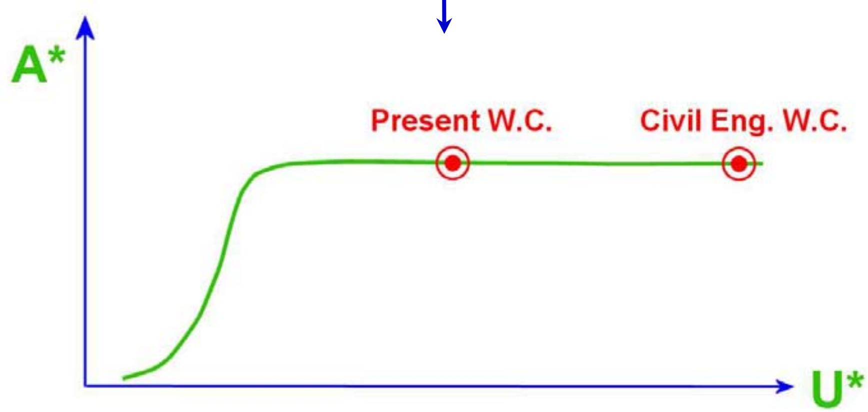
Consider : U* = 100 $f_{osc} \sim 17\, f_N$ Why not ?

U* = 500 $f_{osc} \sim 87\, f_N$

You are here

Get bigger / faster water channel

Reach much higher U*



Will not prove anything !

GO RIGHT TO INFINITY !

Infinite U*

$$U^* = \frac{U}{f_N\, D}$$

$U \rightarrow \infty$ **NO !**

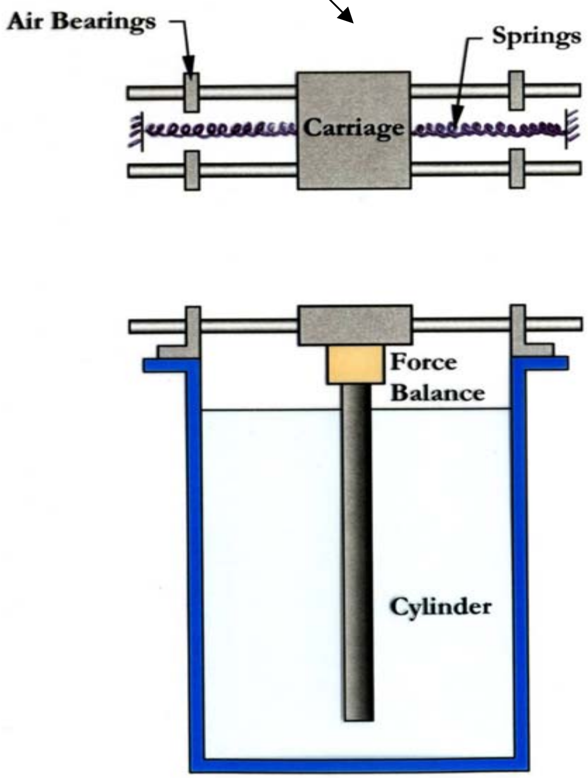
$D \rightarrow 0$ **NO !**

$f_N \rightarrow 0$ **YES !**

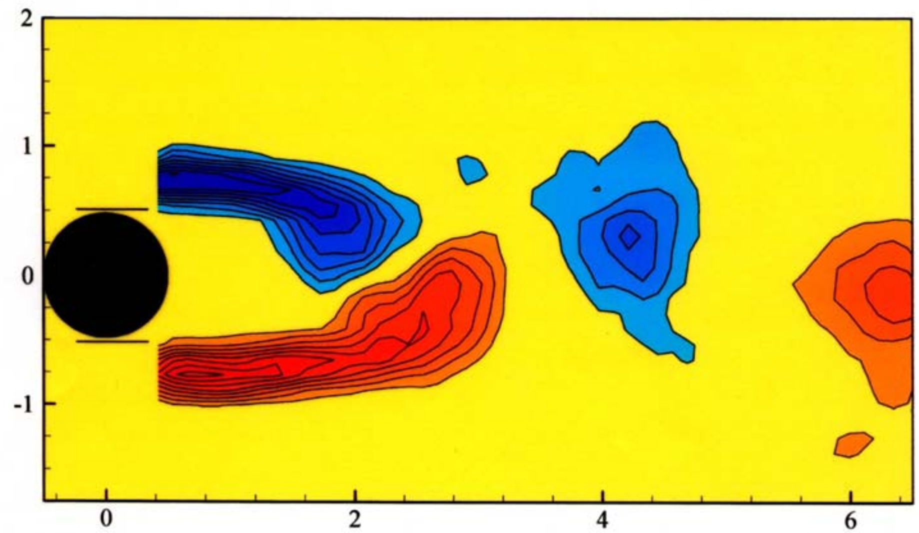
$$f_N \sim \sqrt{k/m} \;\; \ldots \;\; \underline{\text{make } k = 0}$$

REMOVE SPRINGS !

Remove springs !!!



m* = 1.7

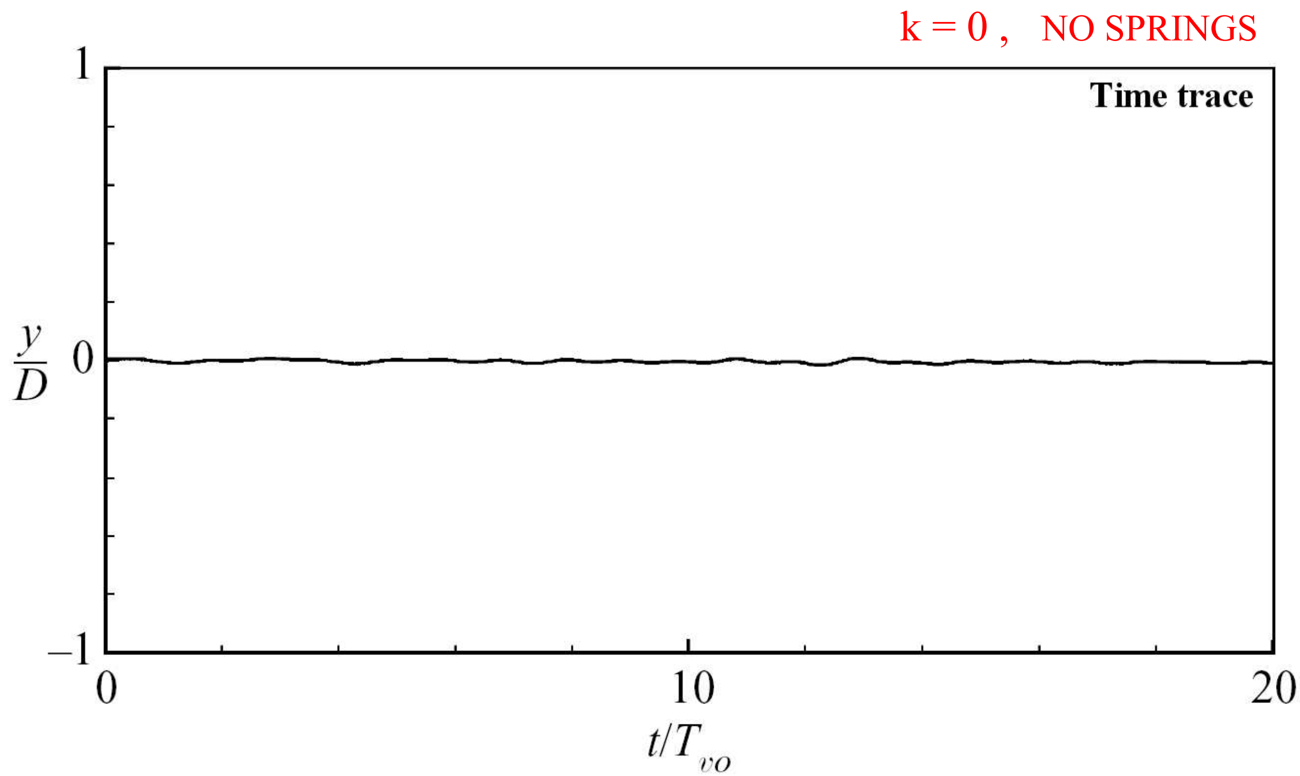


- Easily move with a feather
- Strong vortices……

Expect large vibrations

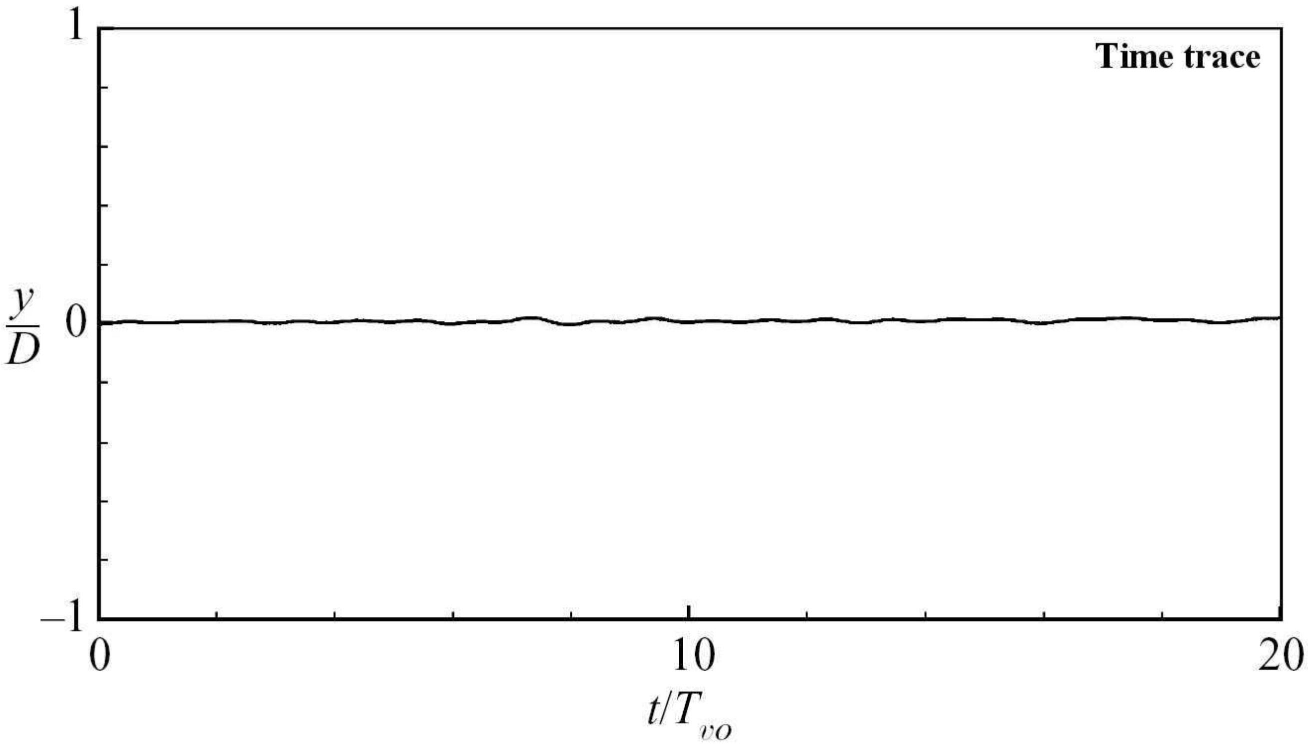
….Now what happens ???

m* = 1.7



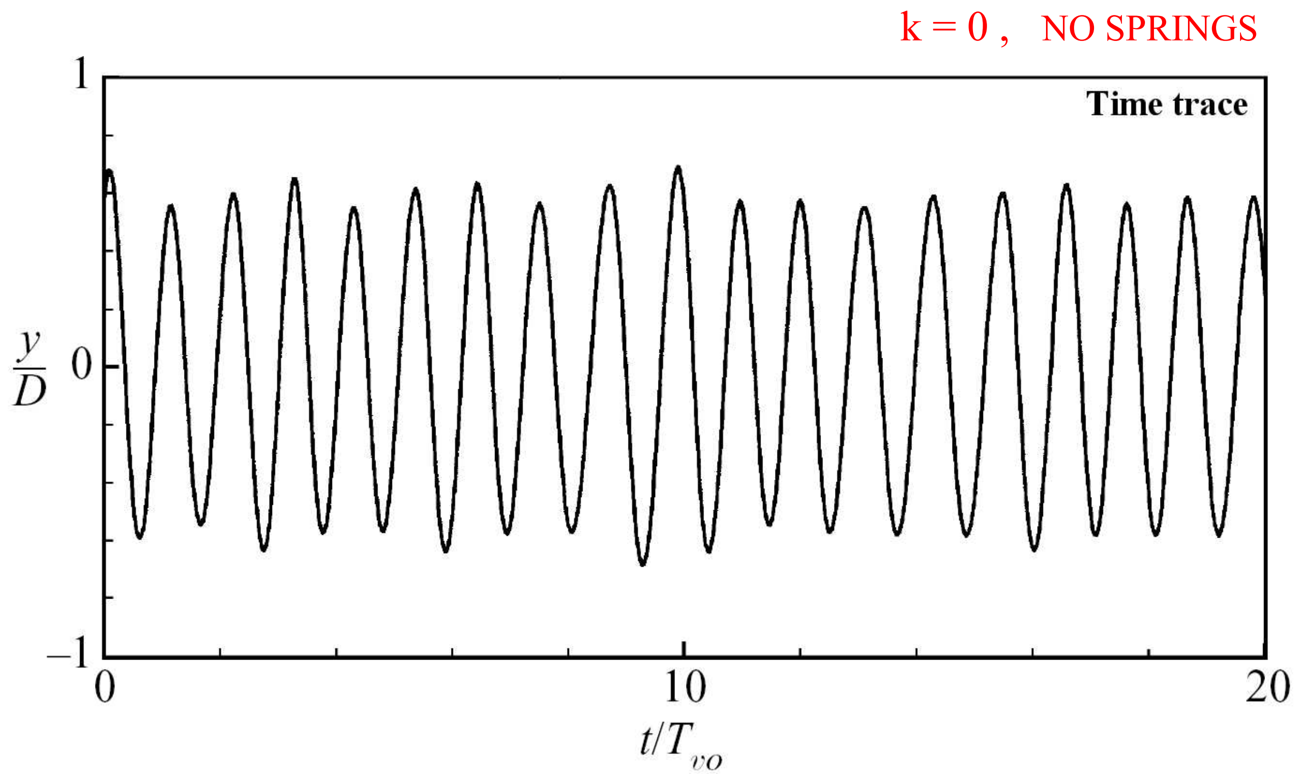
m* = 0.6

k = 0 ,   NO SPRINGS

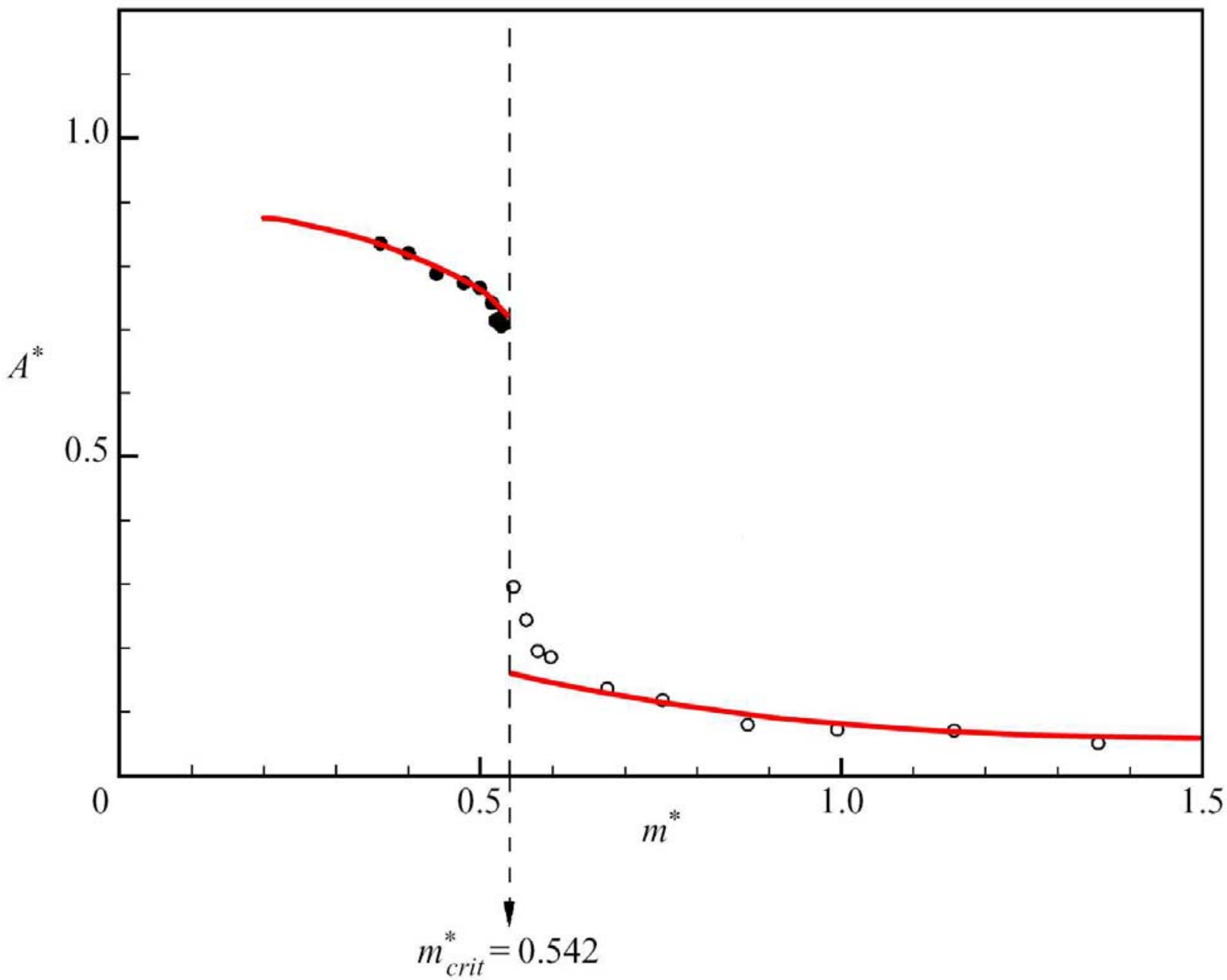


Now: Remove mass gradually

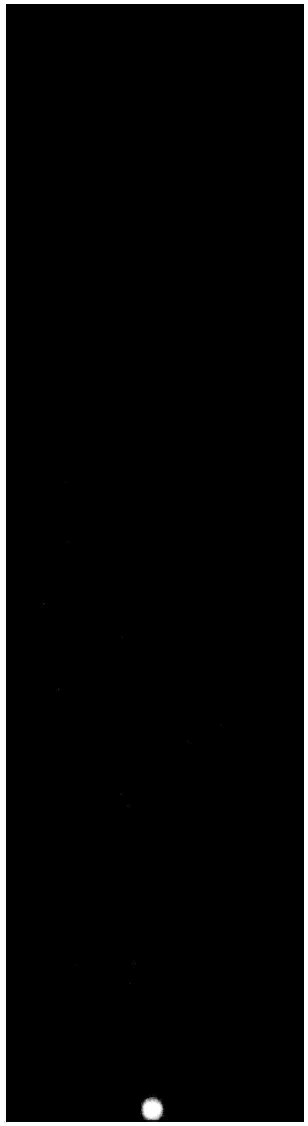
m* = 0.53



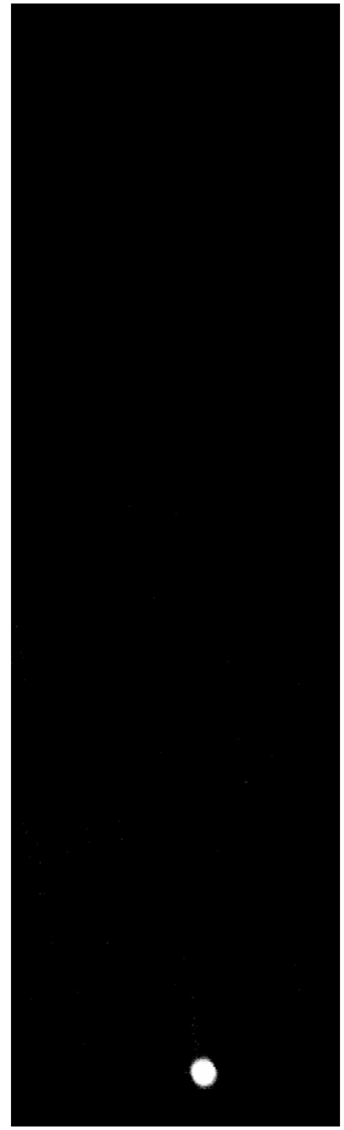
Experiments for INFINITE U*



Rising Cylinder Trajectories



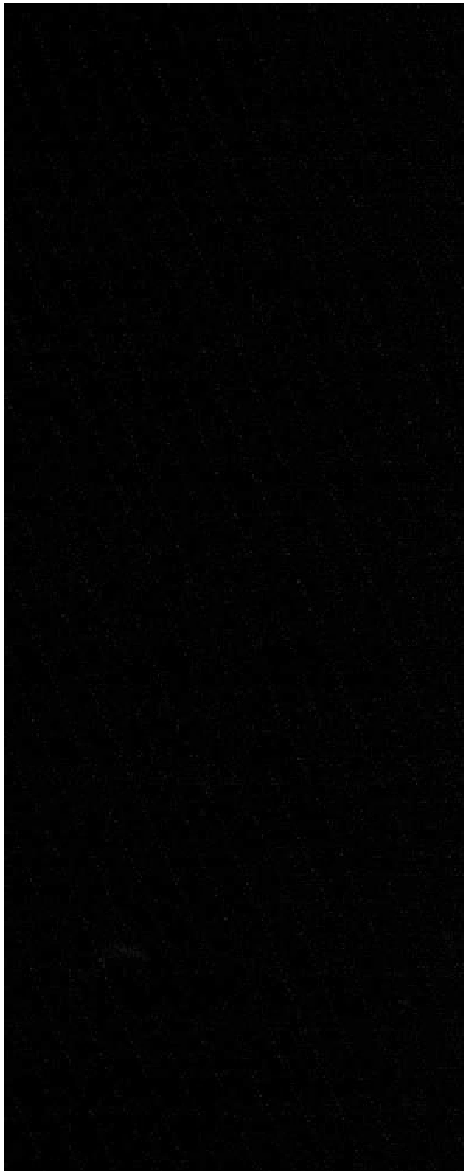
m* = 0.78

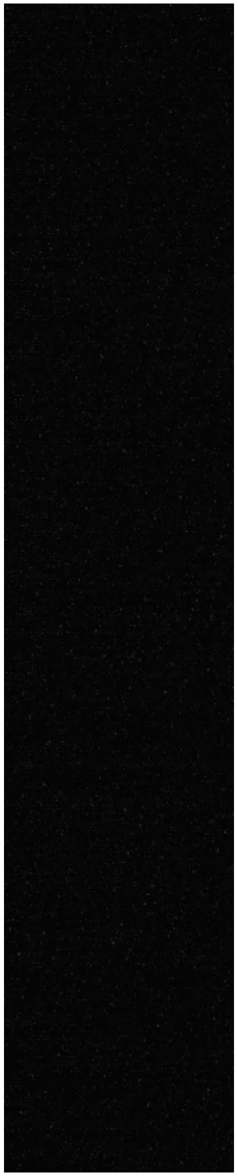


m* = 0.45

Vortex Dynamics Behind a Rising Sphere

m* = 0.08





Vortex Dynamics Behind a Rising Sphere

m* = 0.08