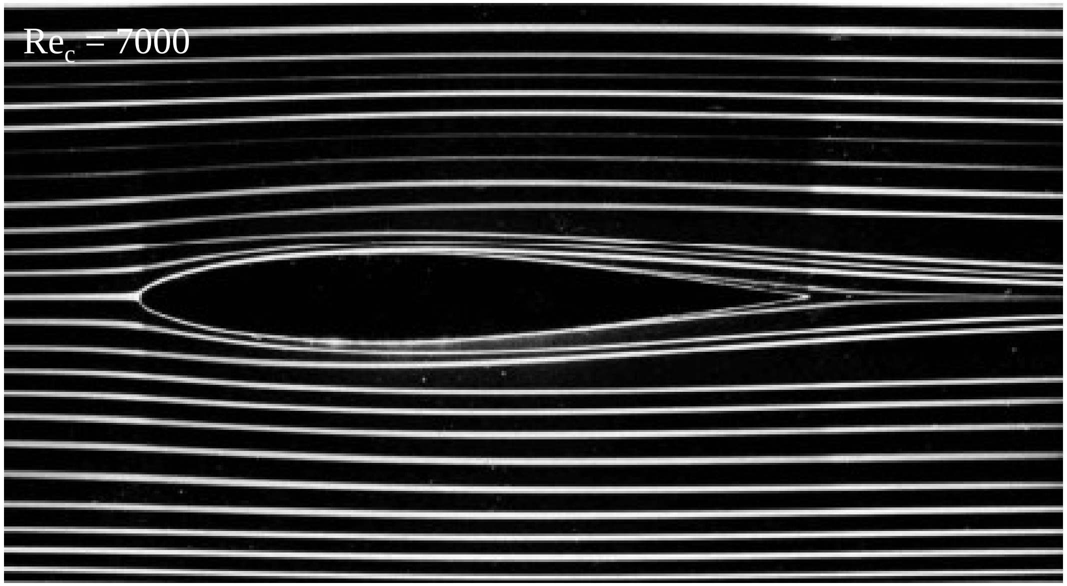
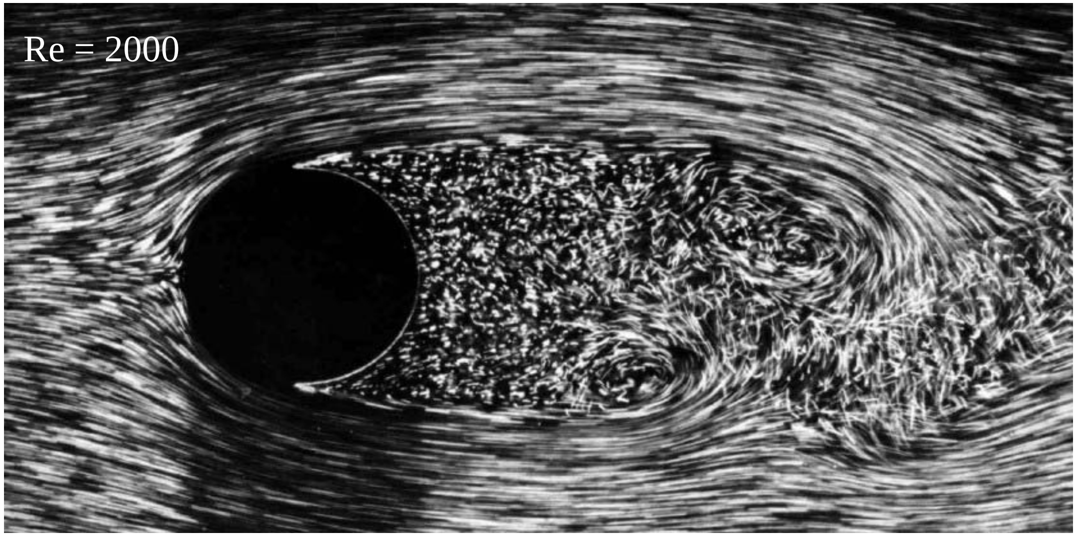
PNV5203 – Interação Fluido Estrutura I

VIV – Vibração Induzida por Vórtices

ESCOLA POLITÉCNICA DA UNIVERSIDADE DE SÃO PAULO
DEPARTAMENTO DE ENGENHARIA NAVAL E OCEÂNICA

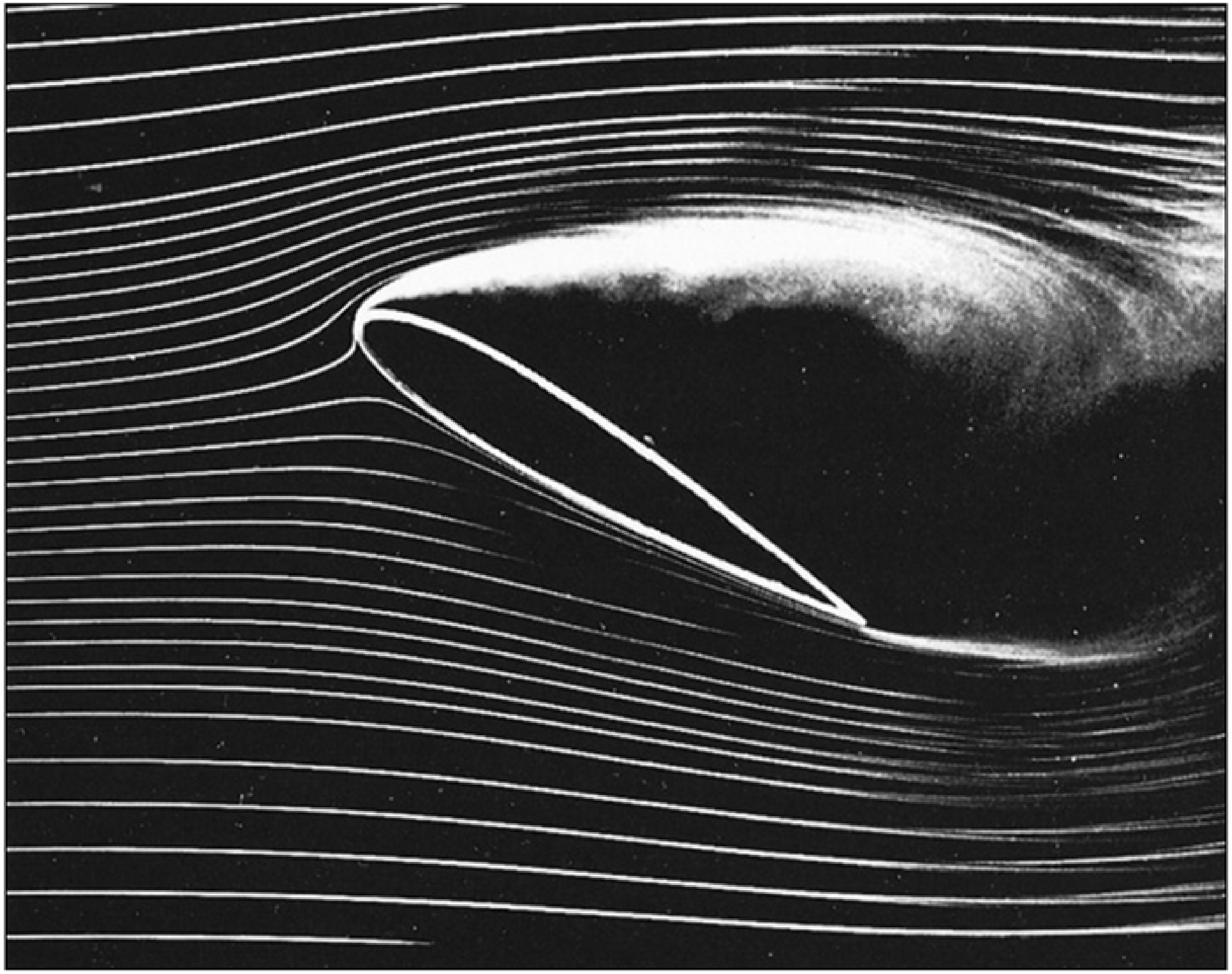
Separated flow



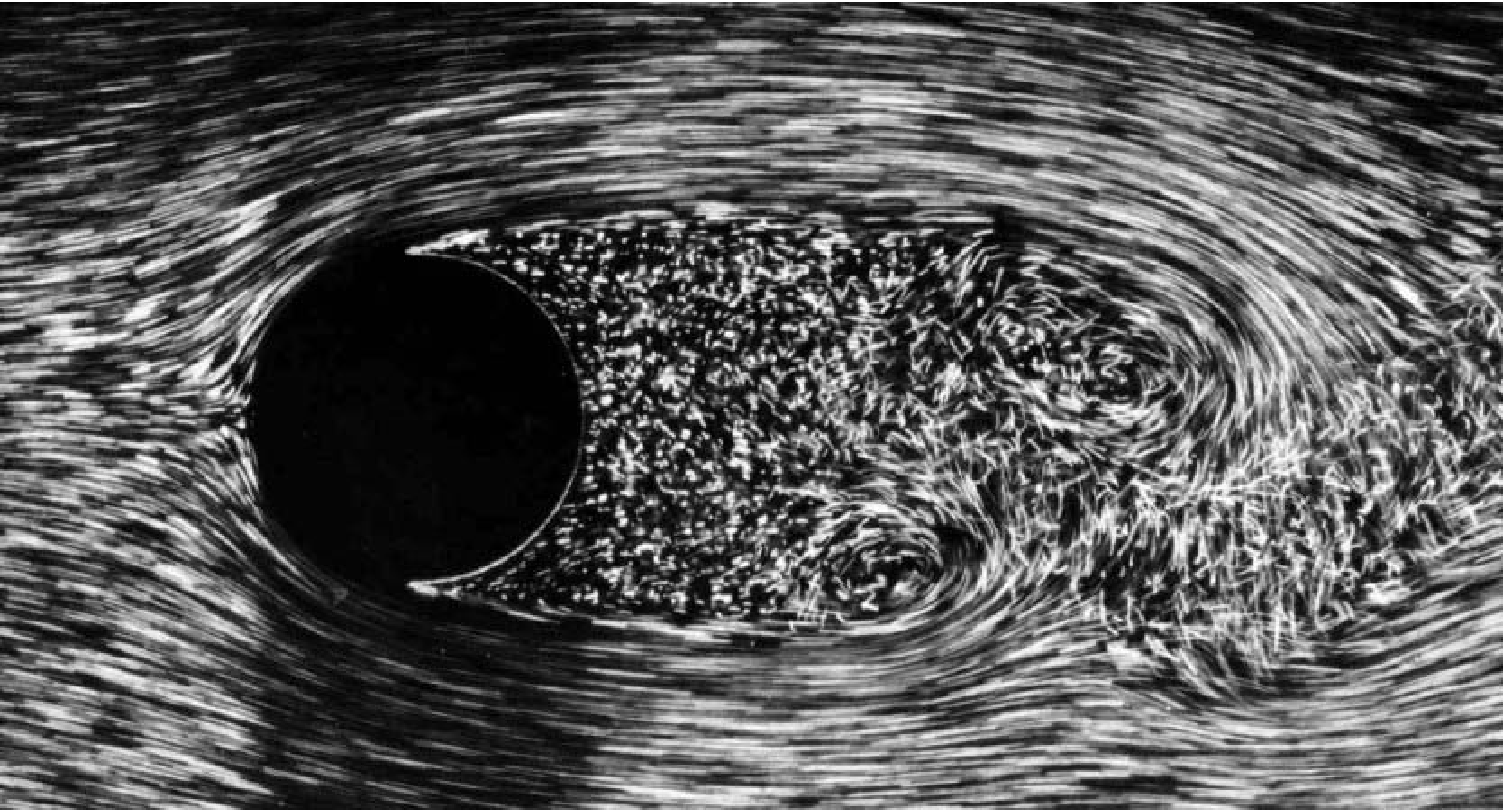


Van Dyke, An Album of Fluid Motion

Rombudo ou afilado?



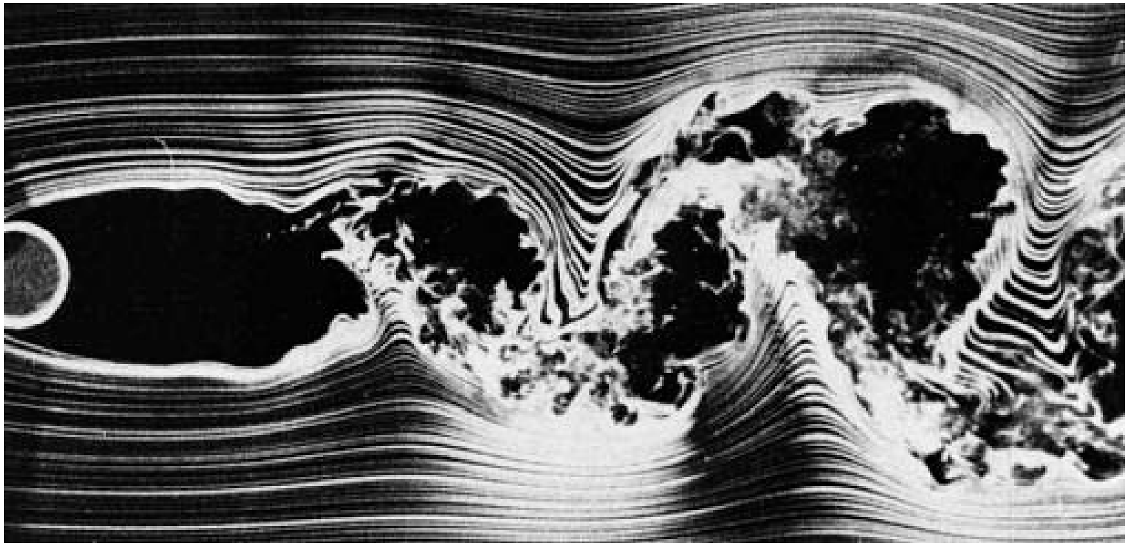
Separação



Esteira de vórtices

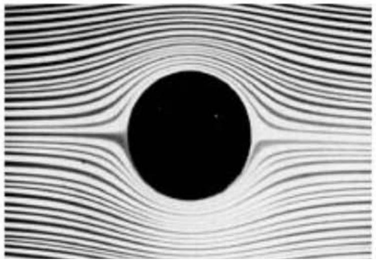
Laminar

Turbulento

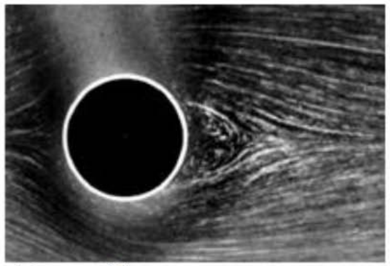


Formação e instabilidade da esteira

Forças inerciais desprezíveis
Forças viscosas dominam



Sem separação (creeping flow)



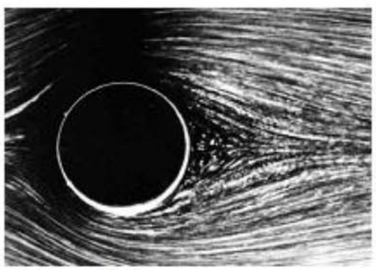
Re = 13

Re = 32

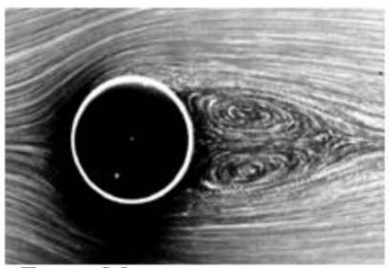
Re = 73

Re = 55

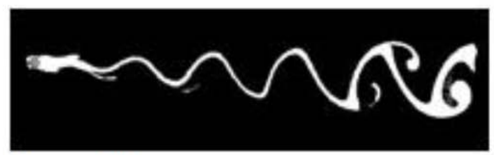
Re = 102



Re = 9,6



Re = 26

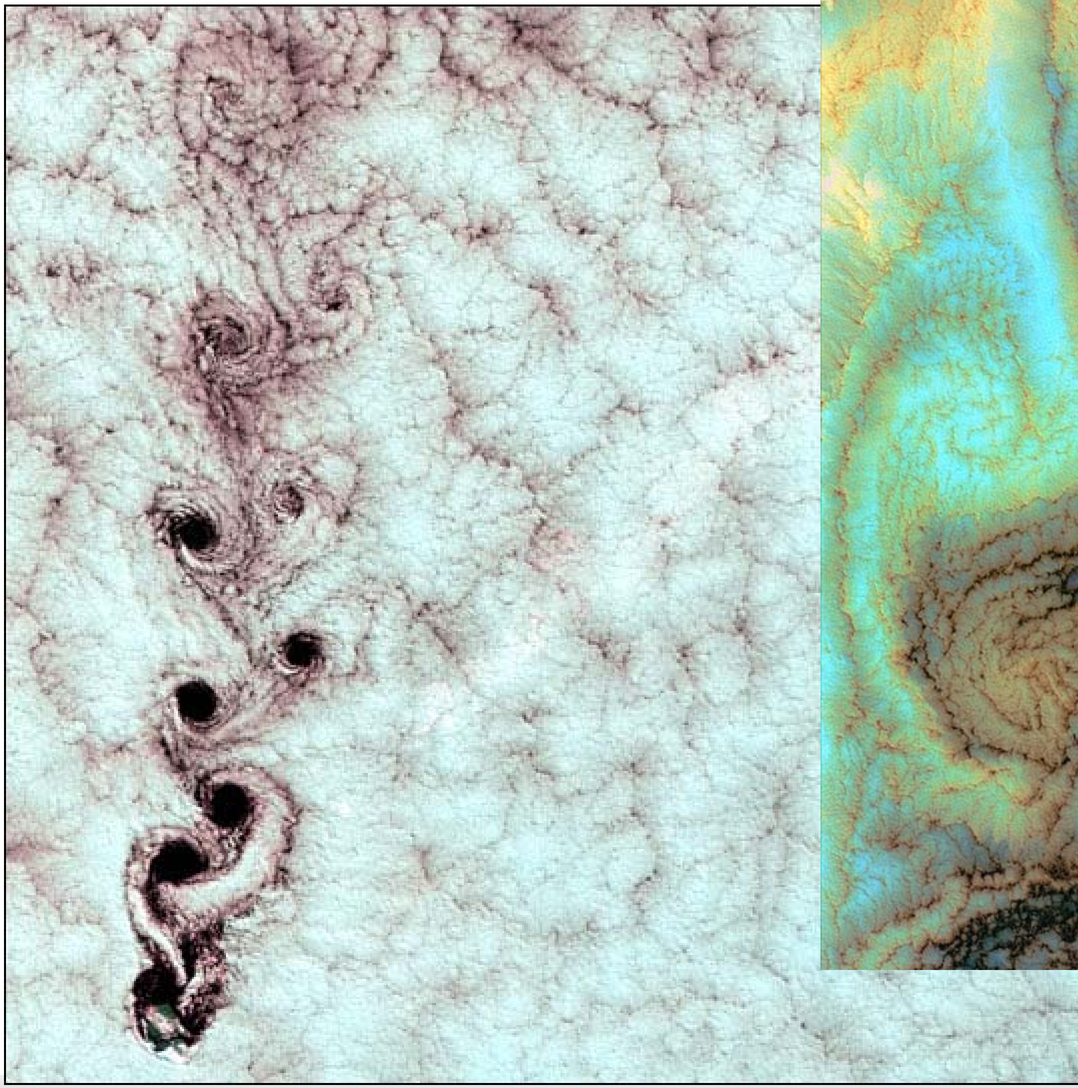


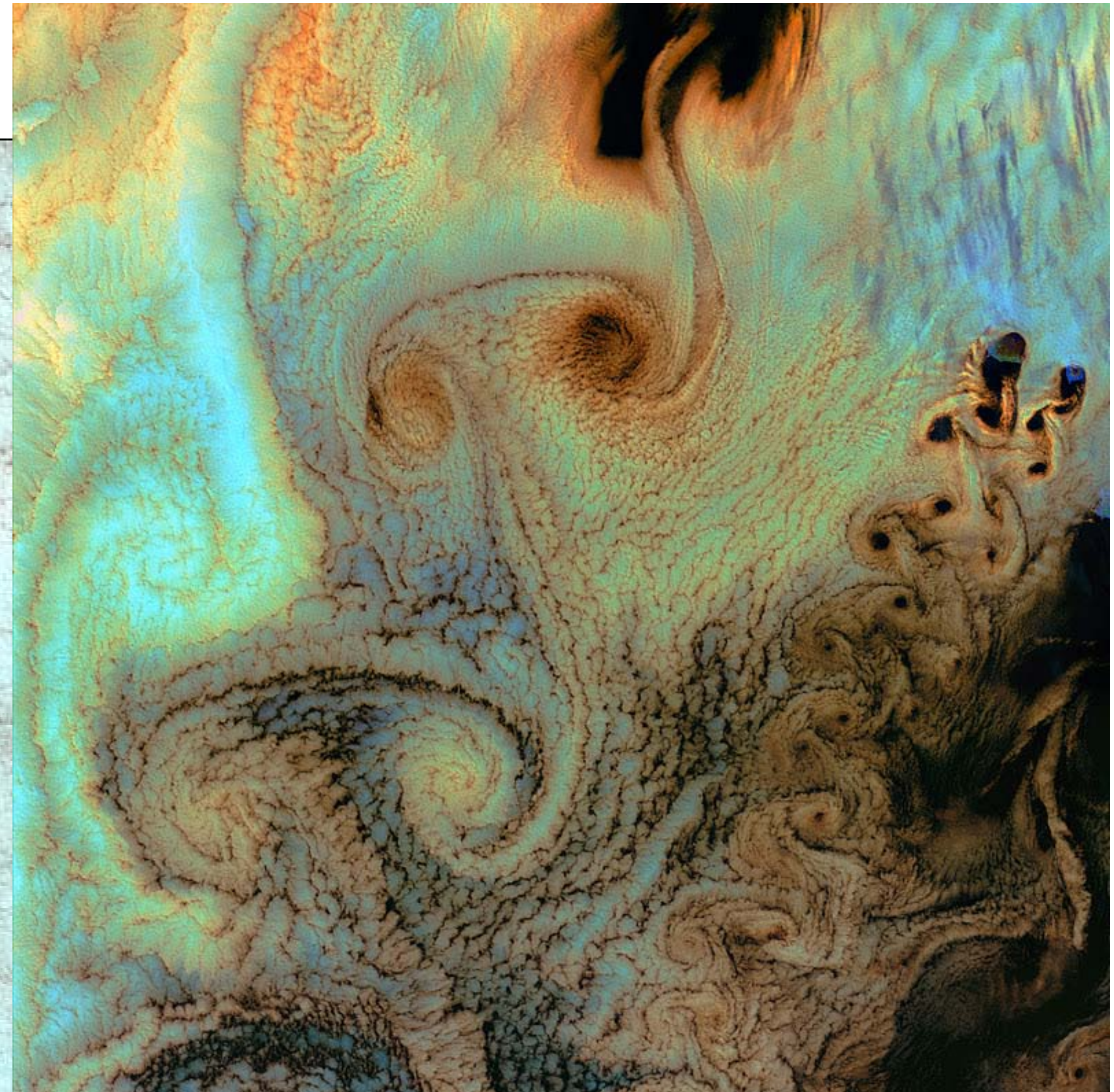
Re = 65

Re = 161

$$\mathrm{Re} = \frac{\rho U D}{\mu} = \frac{U D}{\nu}$$

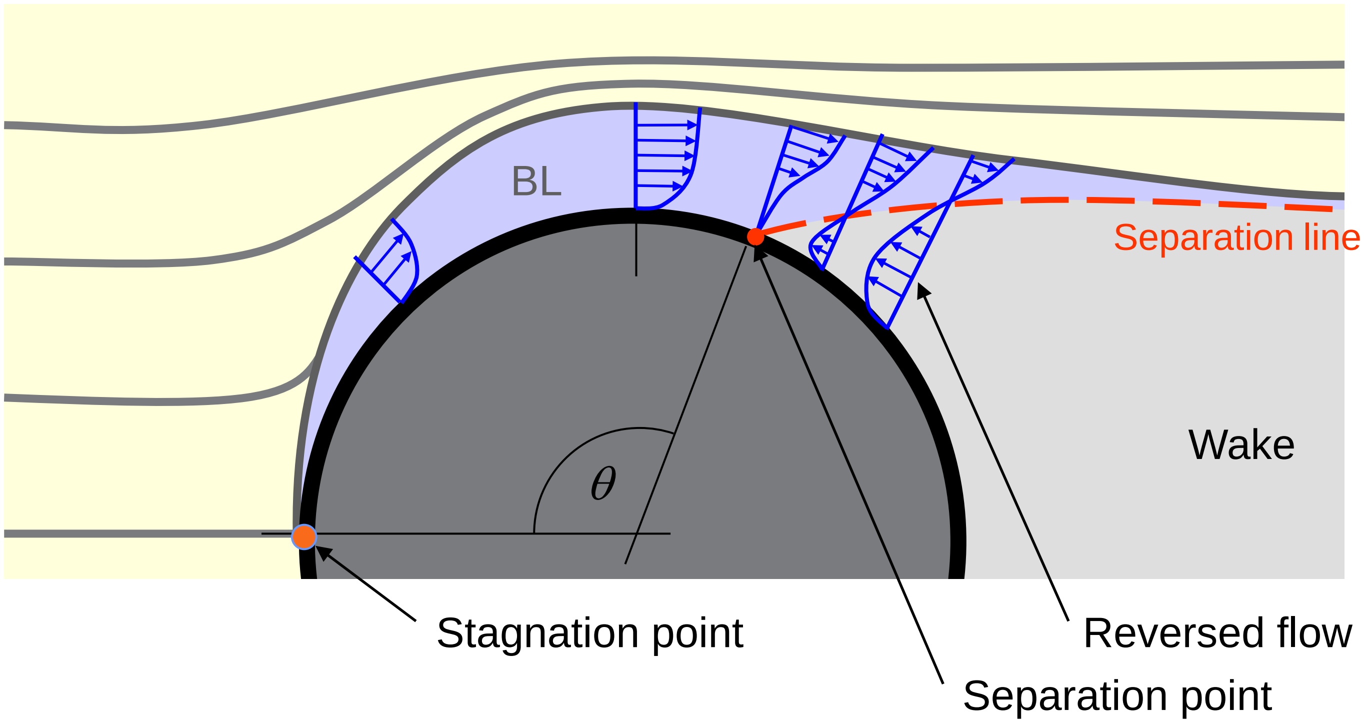
Esteira de vórtices

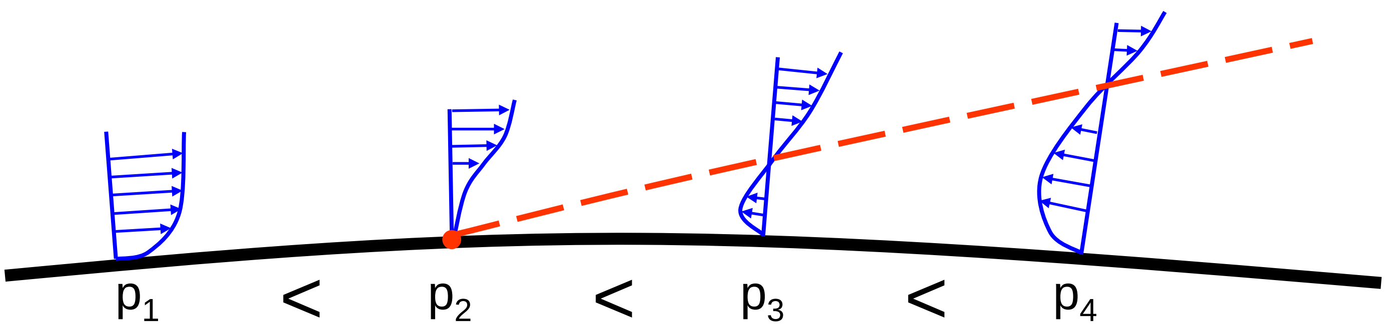




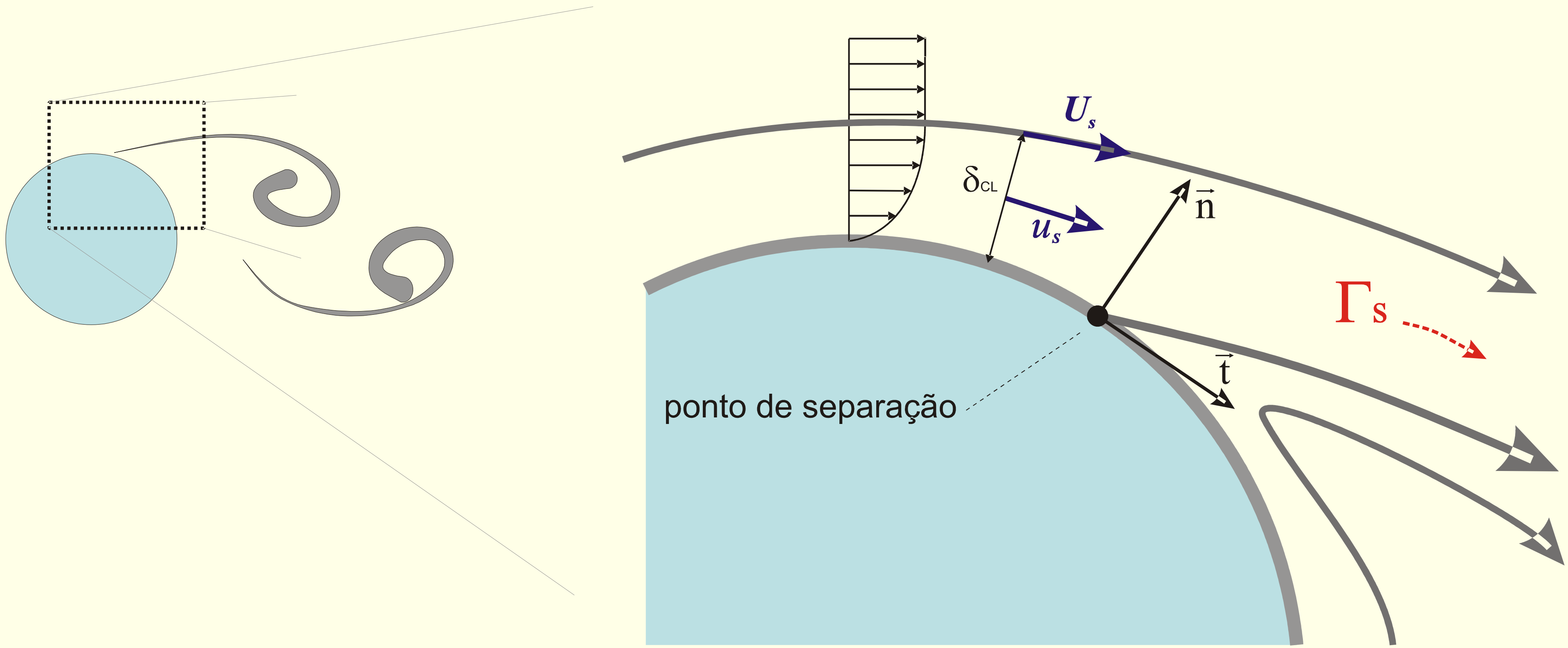
Aletian Islands. Credit: USGS

Separação do escoamento

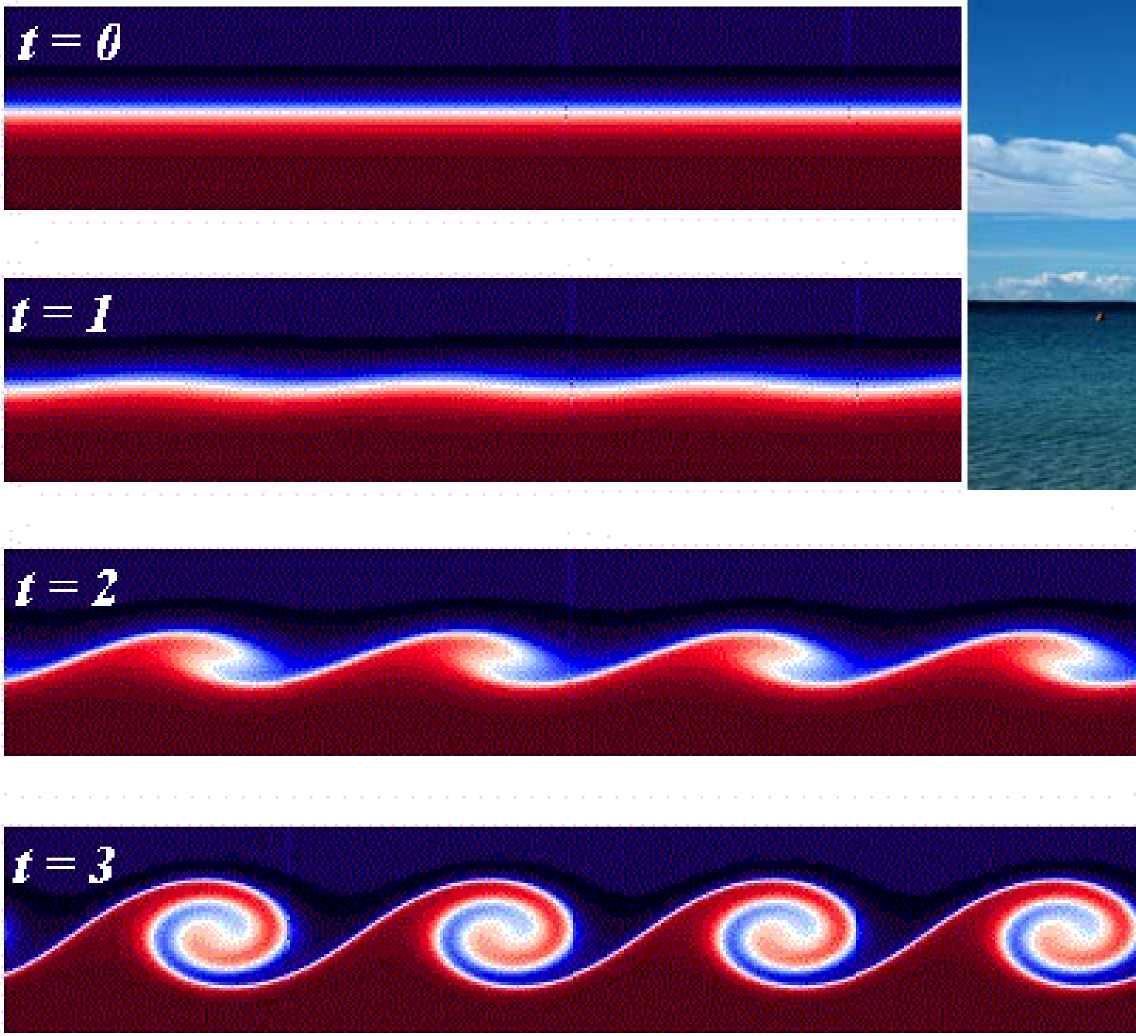




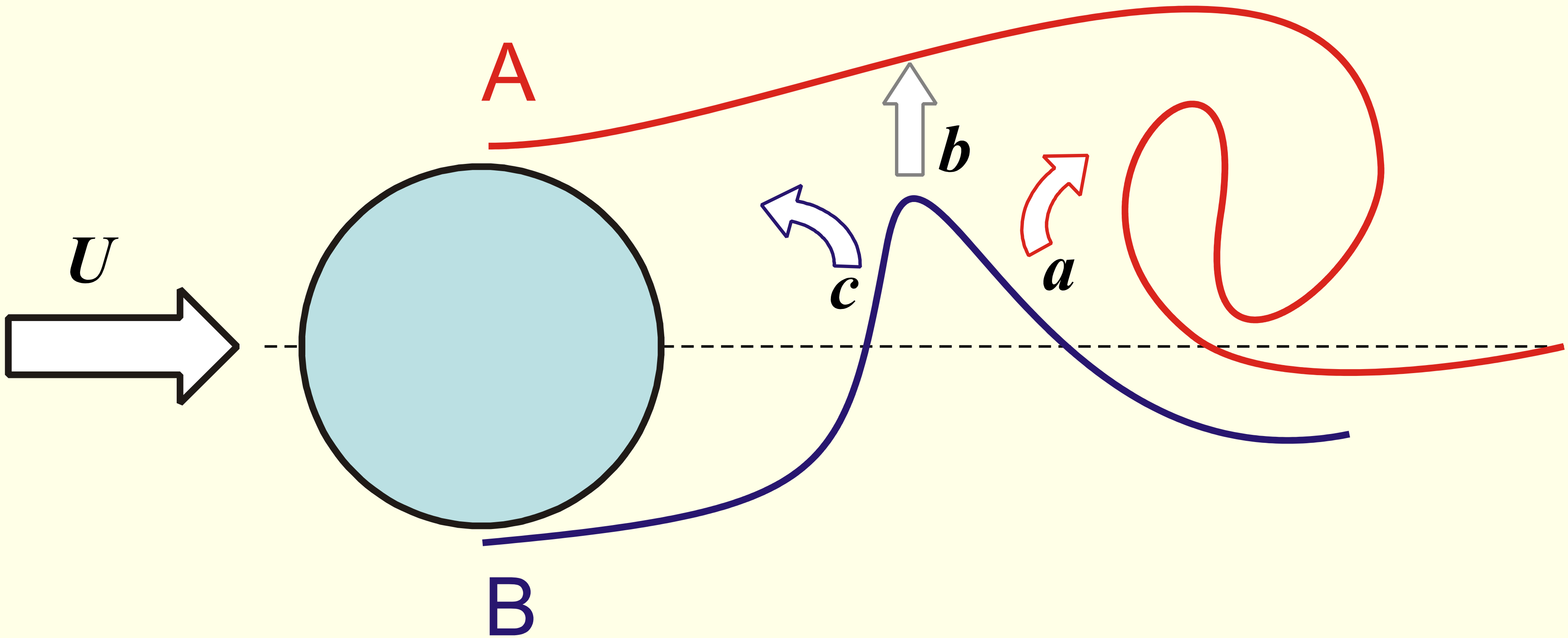
Separação do escoamento



Instabilidade de Kelvin–Helmholtz

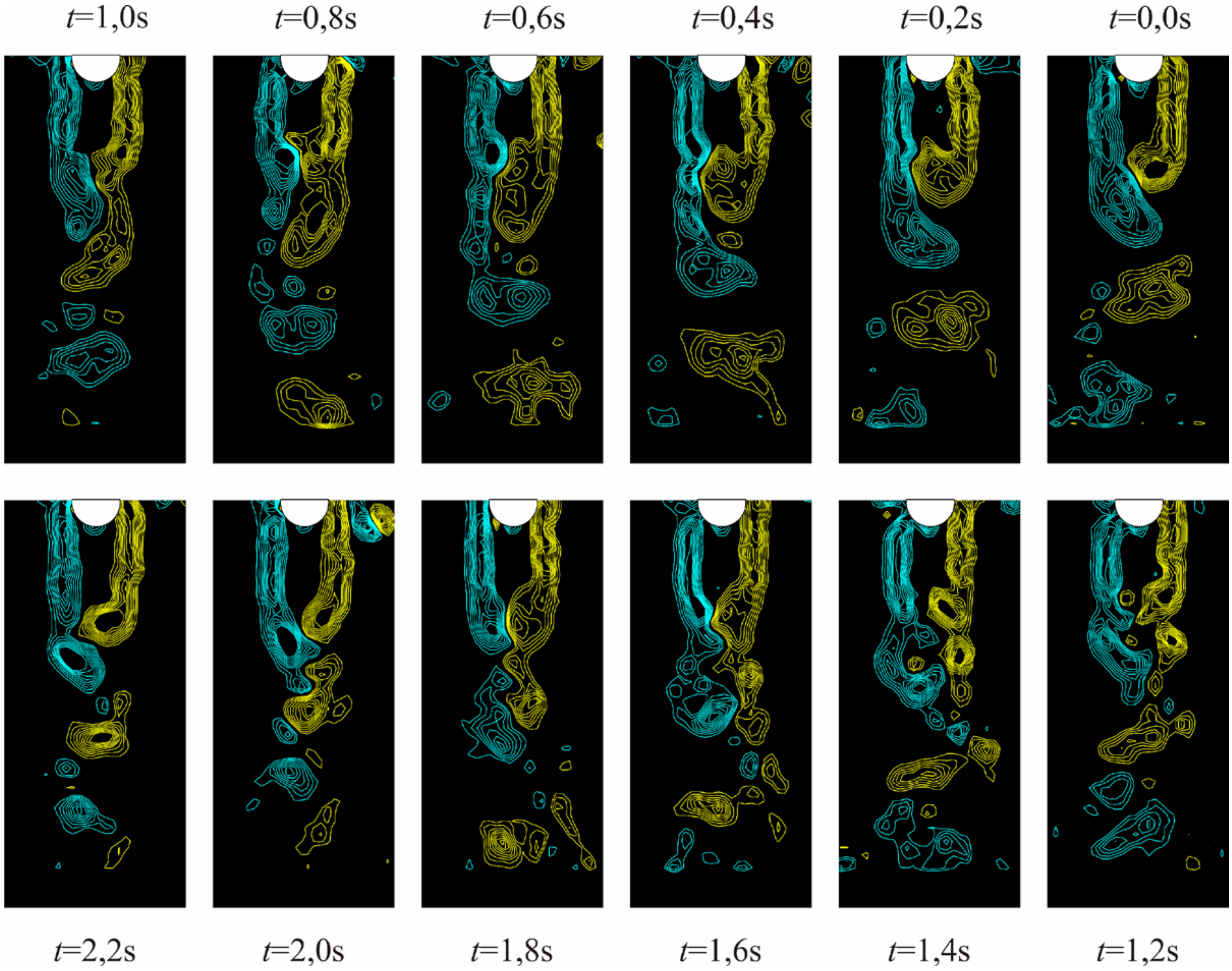


Interação das camadas cisalhantes

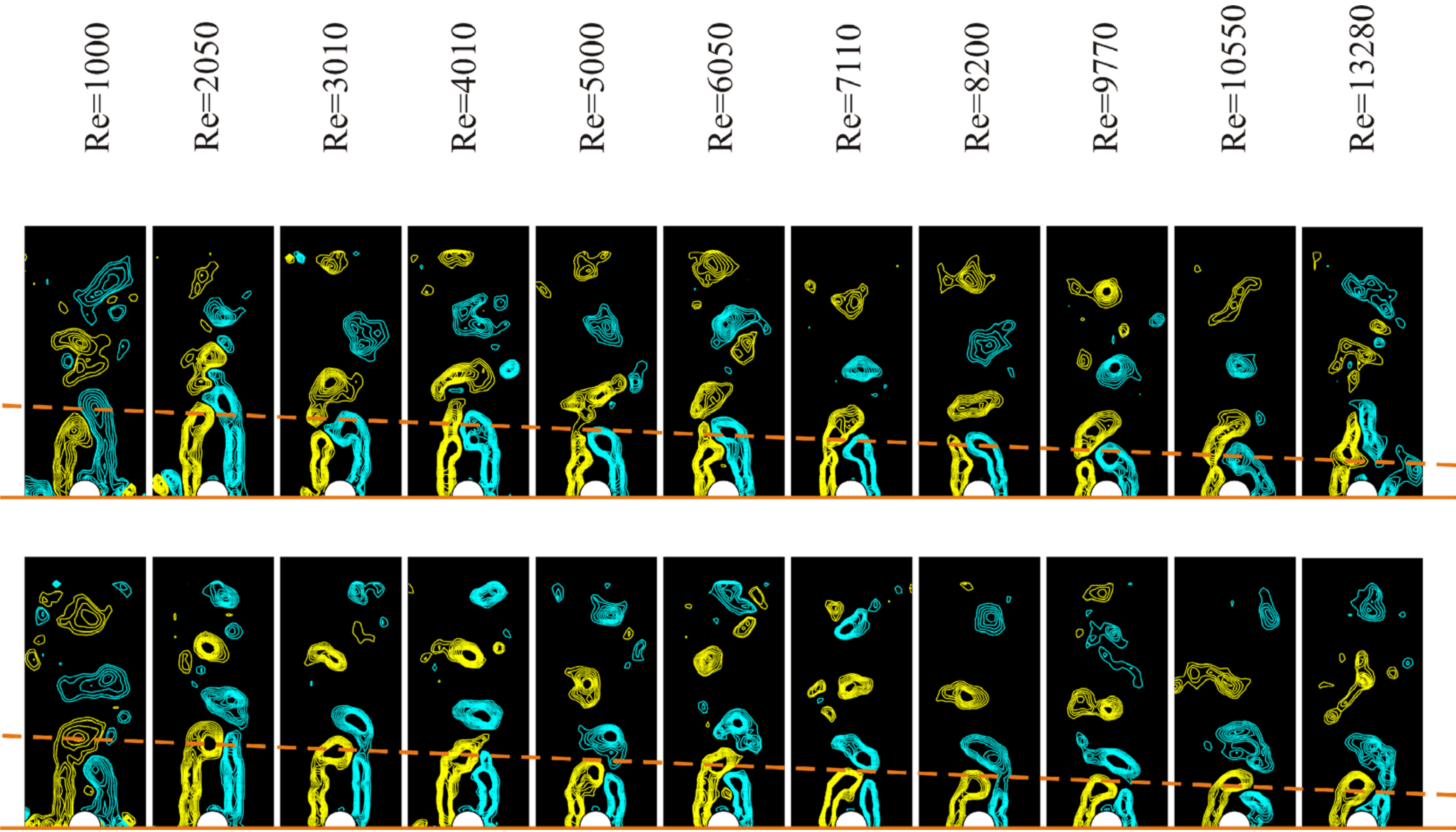


Gerrard (1966)

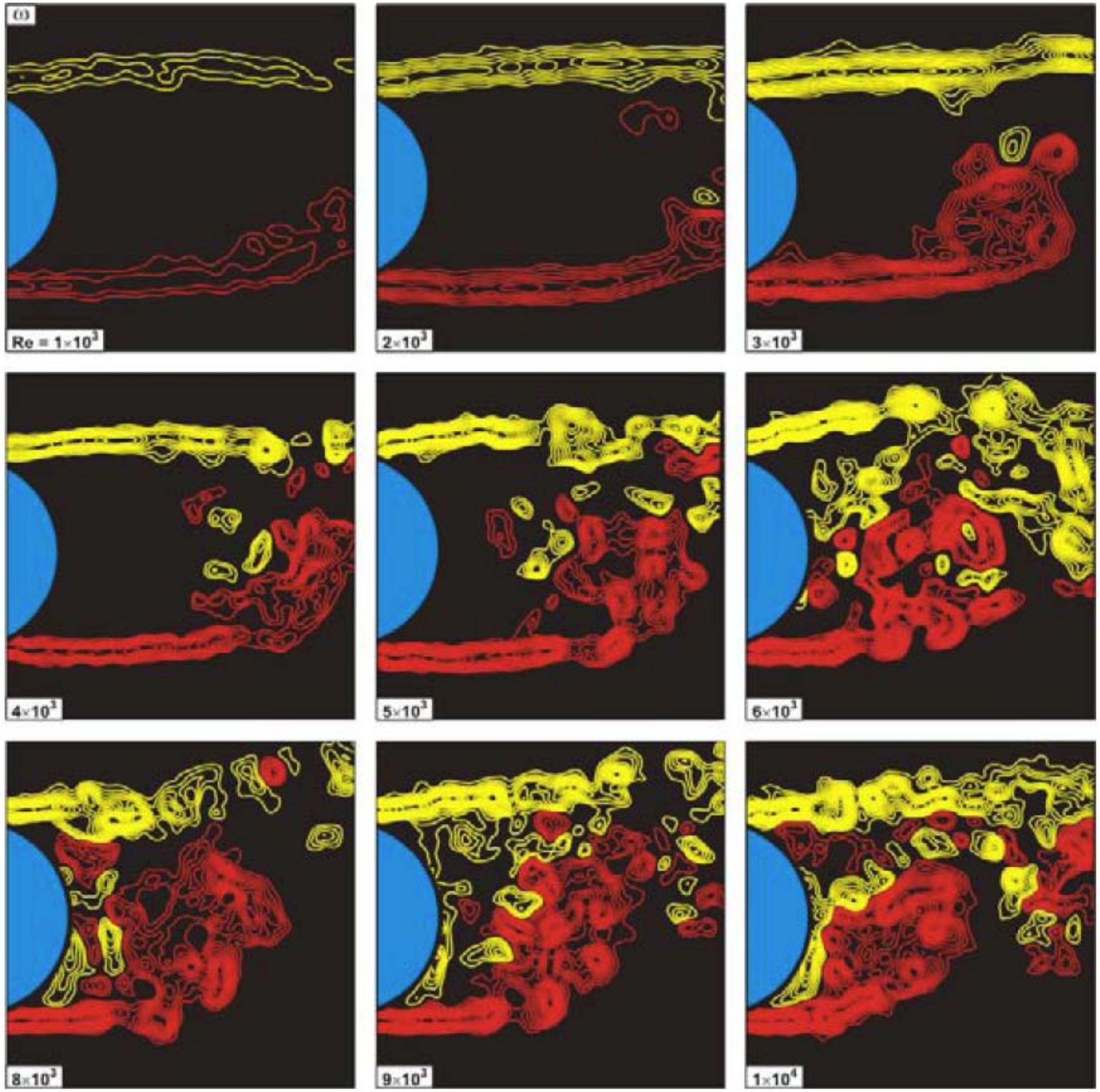
Emissão de vórtices



Comprimento de formação

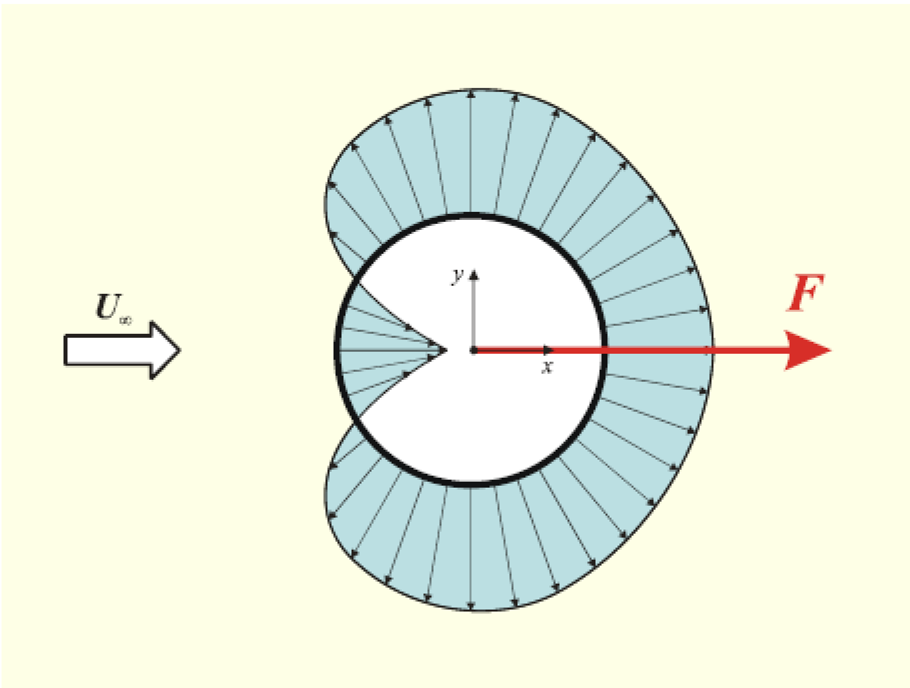


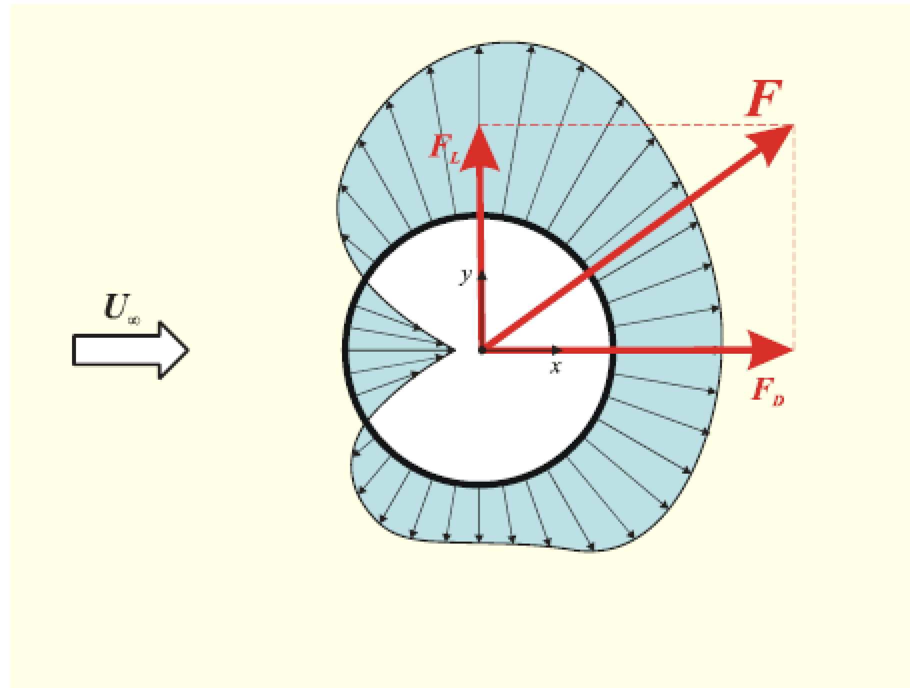
Comprimento de formação



D. Rockwell

Campo de pressão





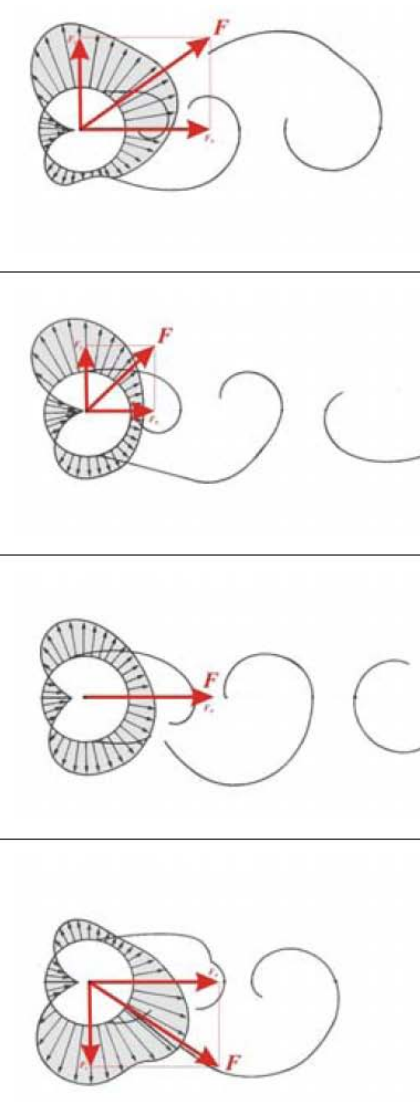
Força cíclica

$$t = \frac{1}{12} T_s$$

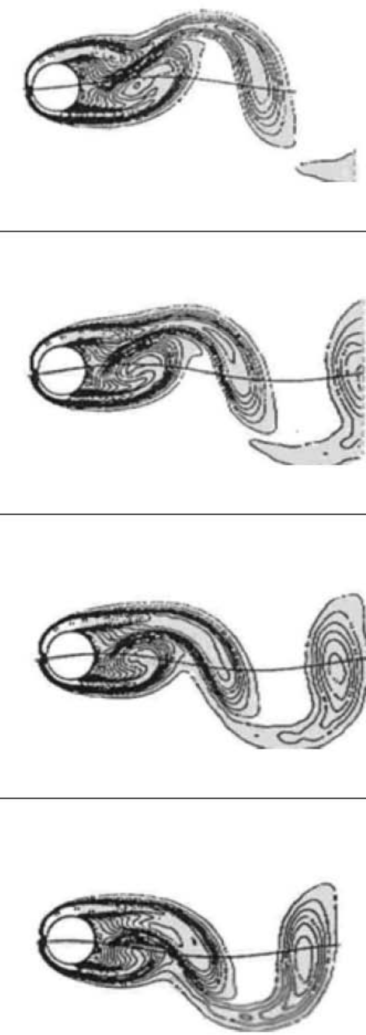
$$t = \frac{2}{12} T_s$$

$$t = \frac{3}{12} T_s$$

$$t = \frac{4}{12} T_s$$

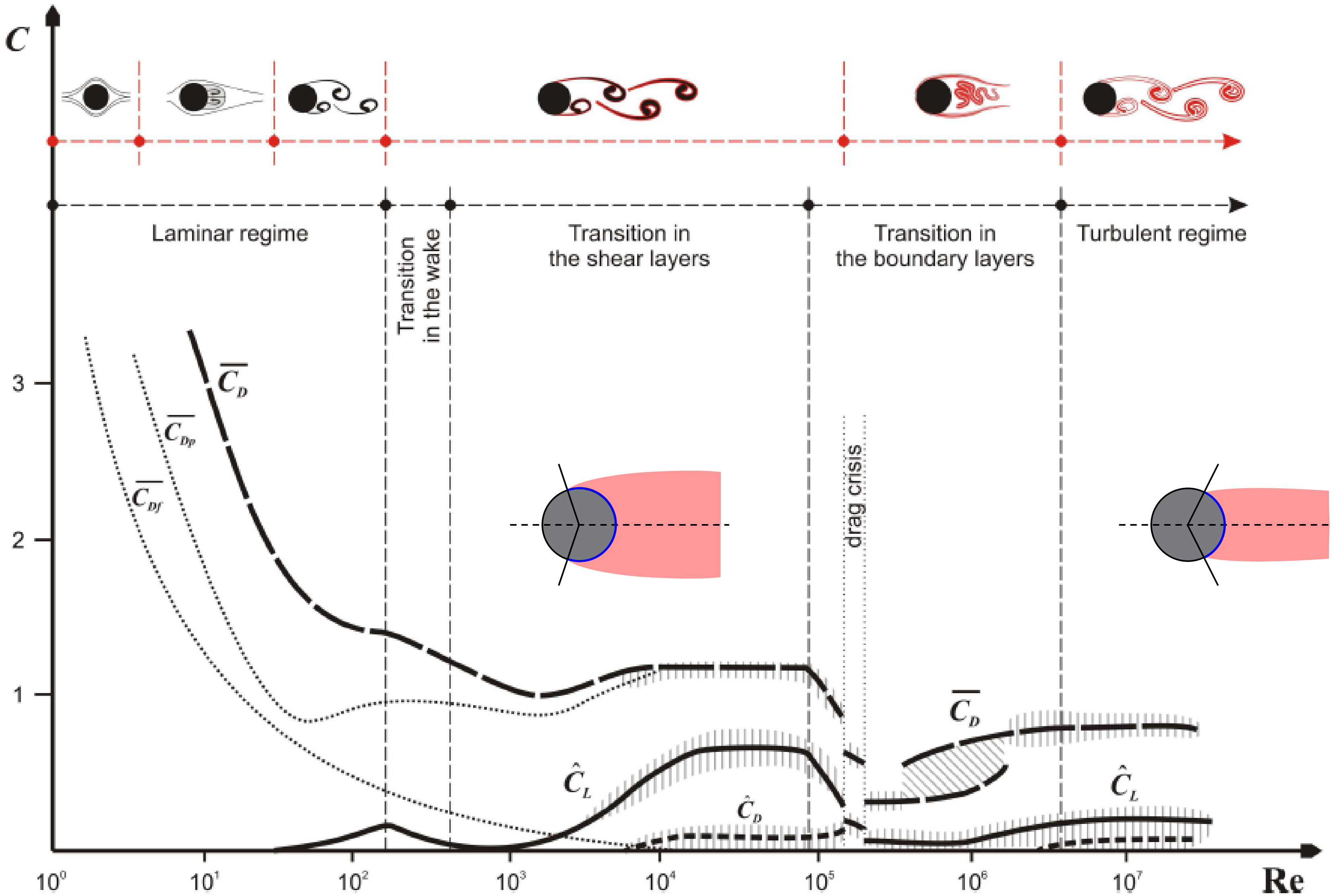


Drescher (1956)



Meneghini (1993)

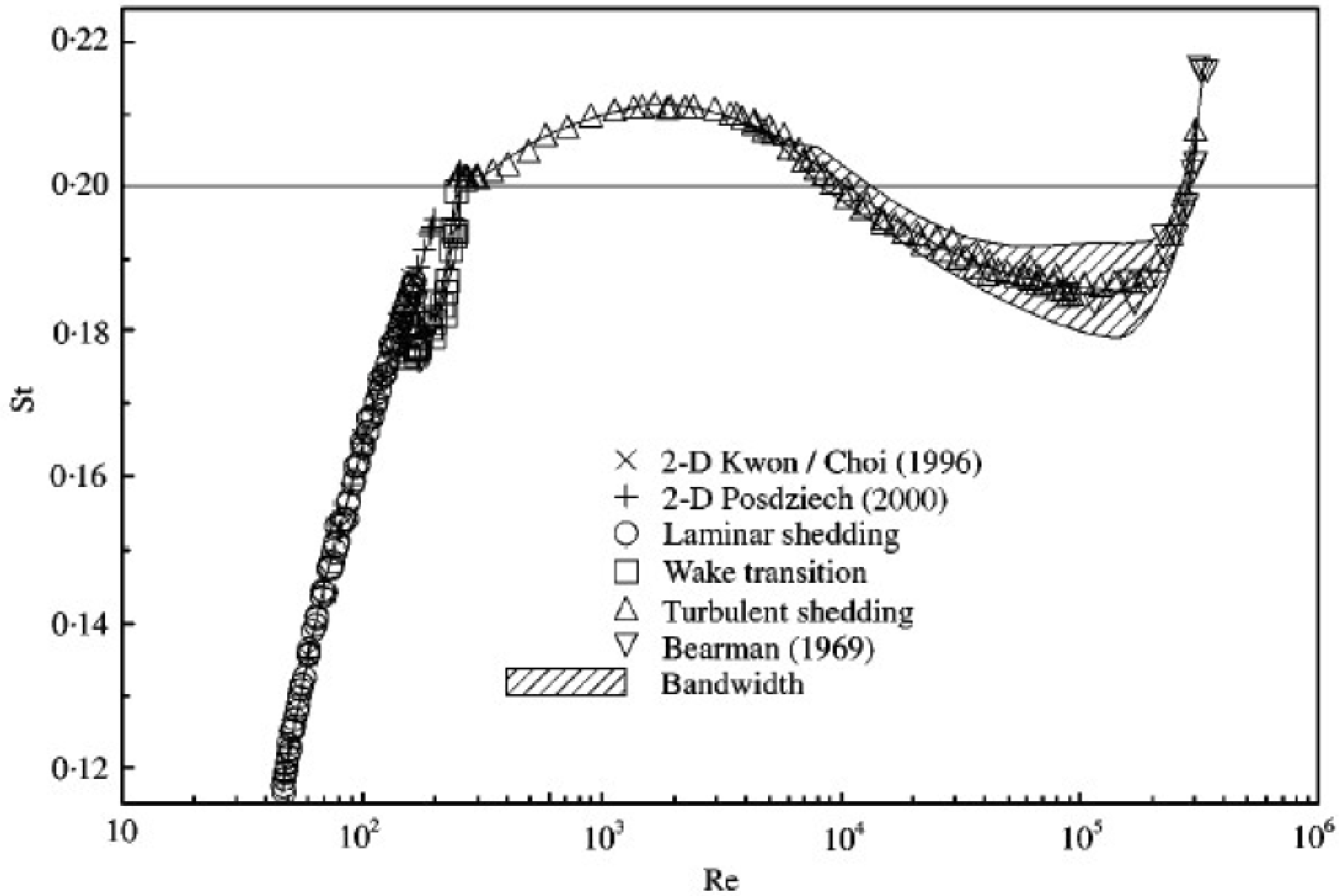
Forças hidrodinâmicas



Zdravkovich (1997)

Número de Strouhal

$$St = \frac{f_s D}{U}$$



Tridimensionalidade da esteira

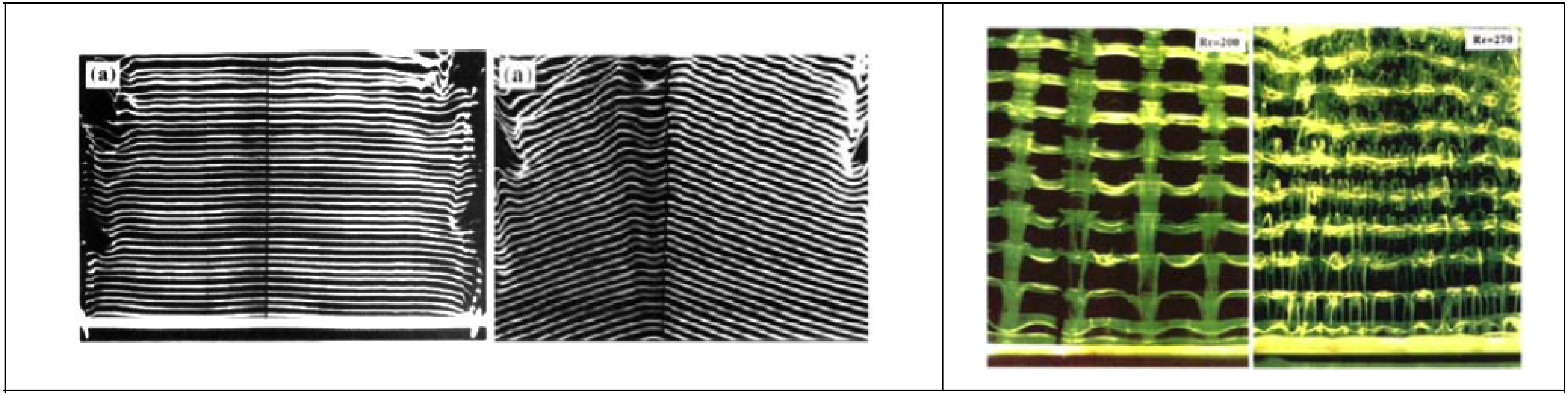


Figura 2.17: Efeitos tridimensionais na esteira. (esquerda) Transição entre os modos paralelo e oblíquo em Re=64. (direita) Formação de laços de vórtices (Modo A) e pares de vórtices (Modo B) na direção do escoamento para Re=200 e Re=270. Os cilindros estão na posição horizontal, na borda inferior das imagens. Reproduzido de Williamson (1996a)

Tridimensionalidade da esteira

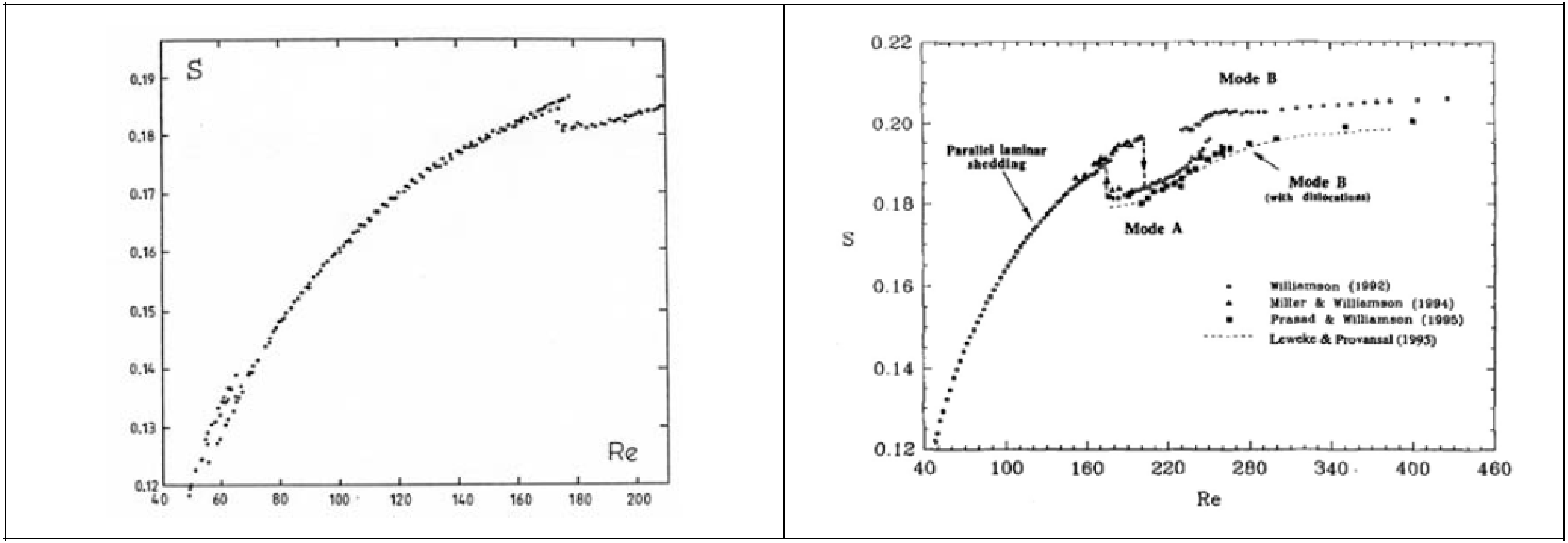


Figura 2.18: Variação do número de Strouhal por Reynolds na faixa onde se iniciam os fenômenos tridimensionais (esquerda); e com as transições de modos associadas às descontinuidades (direita). Reproduzido de Williamson (1996a)

Tridimensionalidade da esteira

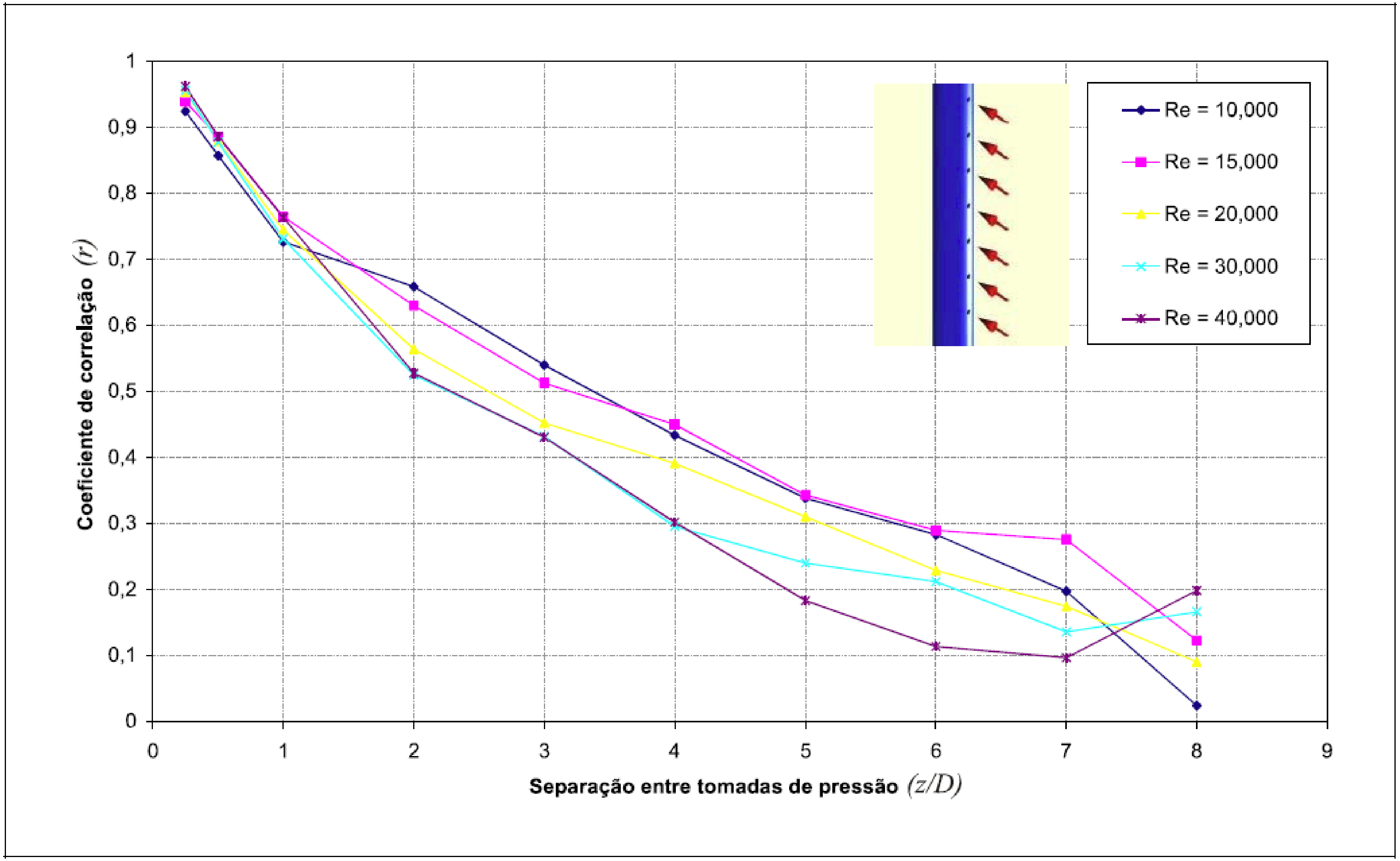


Figura 2.19: Coeficiente de correlação para pontos de tomada de pressão ao longo da geratriz de um cilindro para $10^4 < Re < 4 \times 10^4$. Adaptado de Ássi (2003a).

Fronteira de sincronização

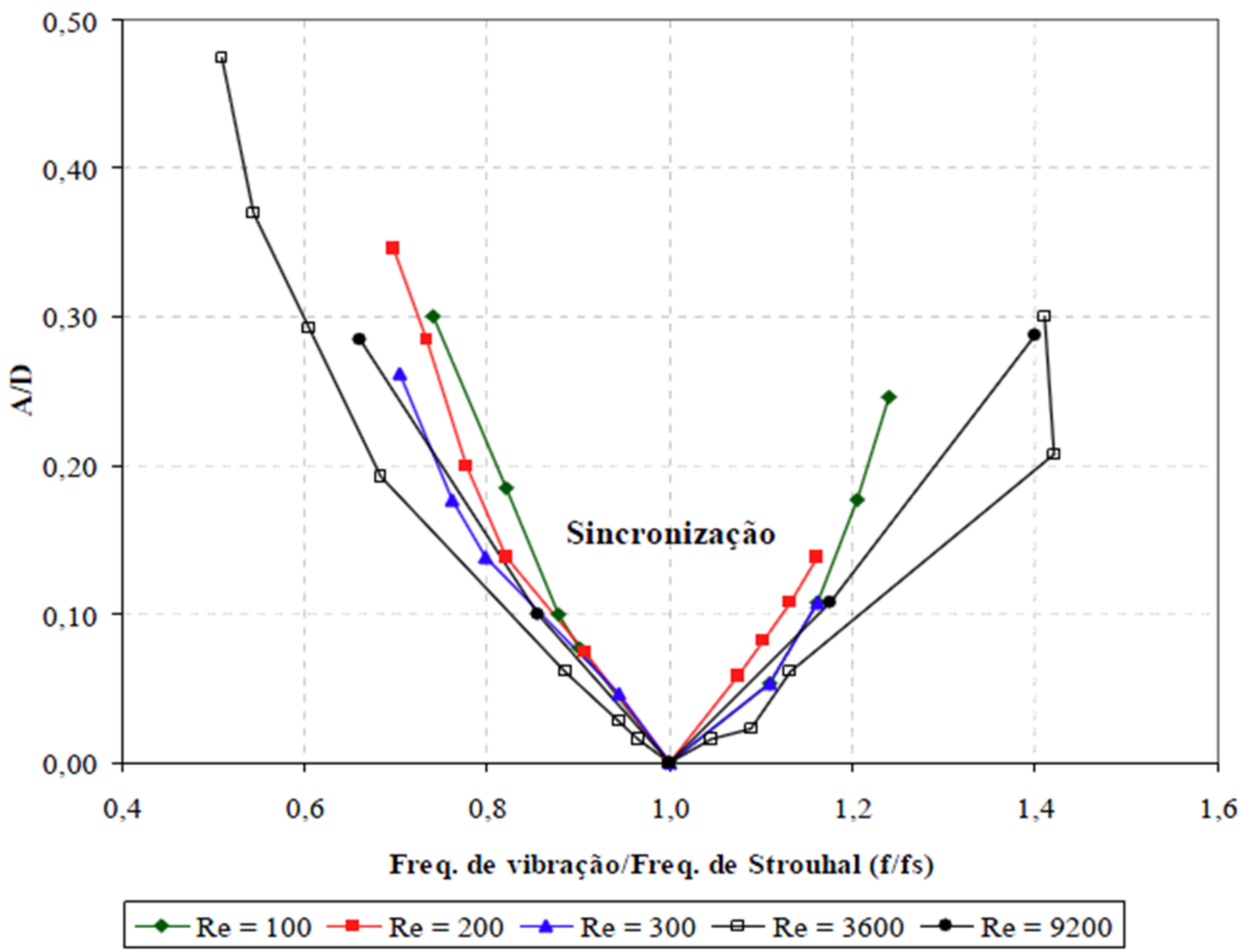


Fig. 3.18 – Faixa de sincronização para vibrações transversais, adaptado de Blevins (1990).

Modos da esteira: oscilação forçada

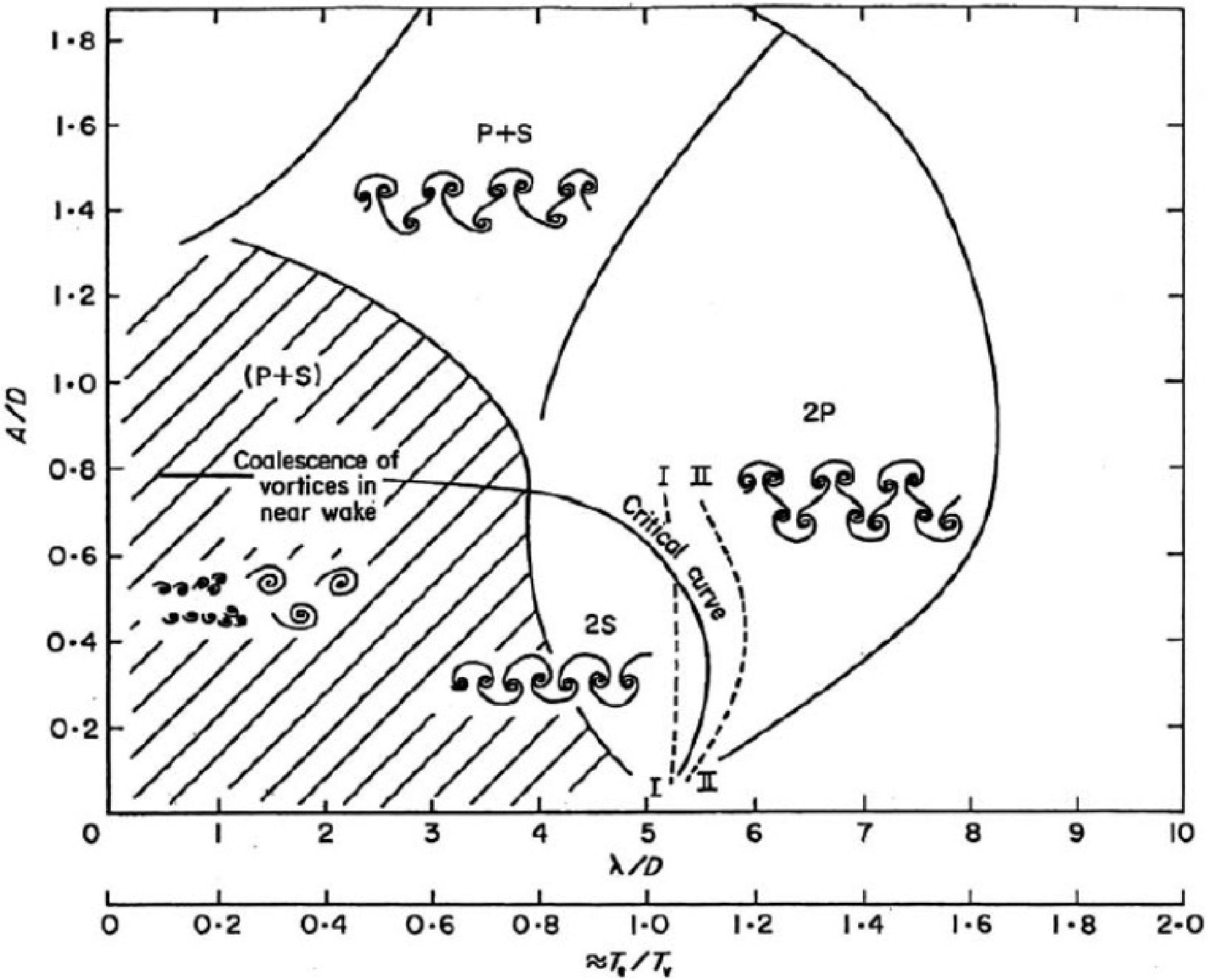


Figura 2.20: Mapa dos modos de emissão para um cilindro isolado sob oscilação forçada. Reproduzido de Williamson & Roshko (1988).

Modos de emissão de vórtices

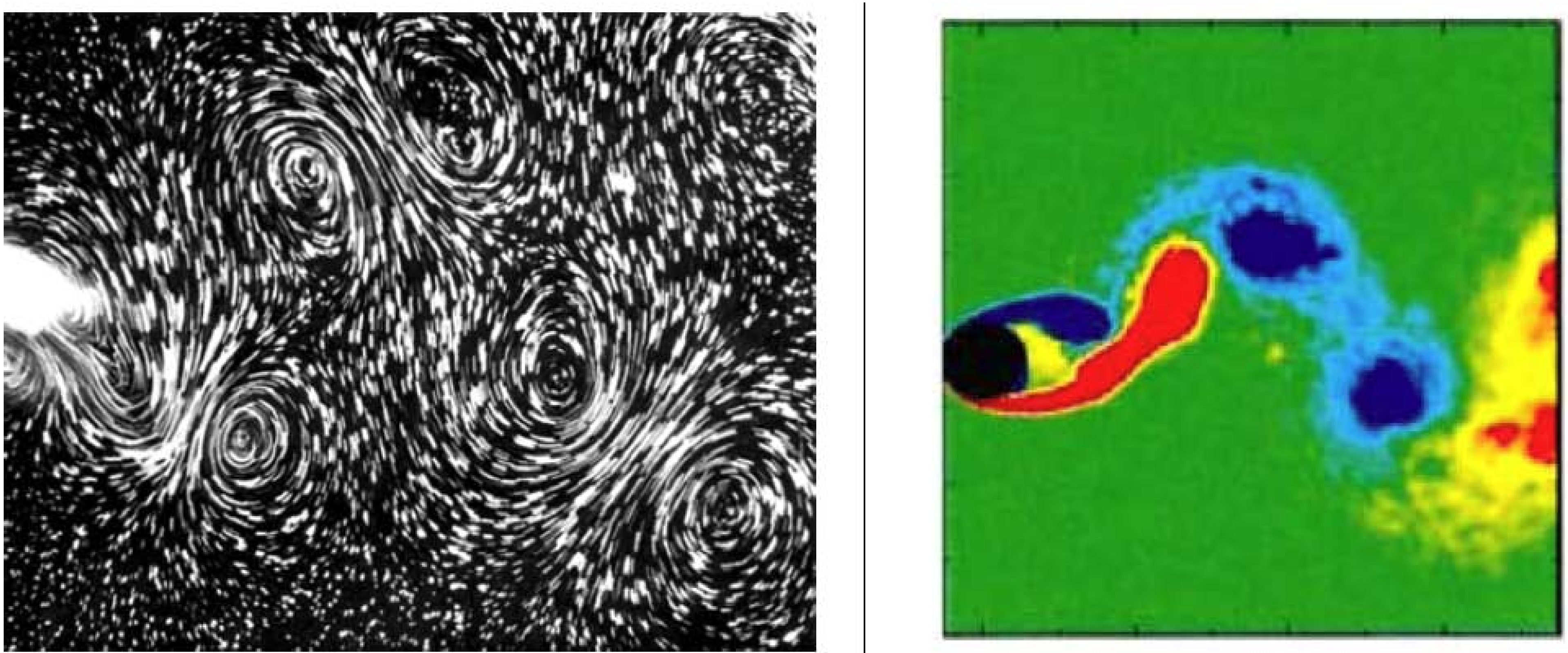


Figura 2.21: Modo de emissão 2P: (esquerda) visualização experimental de Williamson & Roshko (1988); e (direita) simulação numérica de Blackburn *et al.* (2000).

Modos de emissão de vórtices

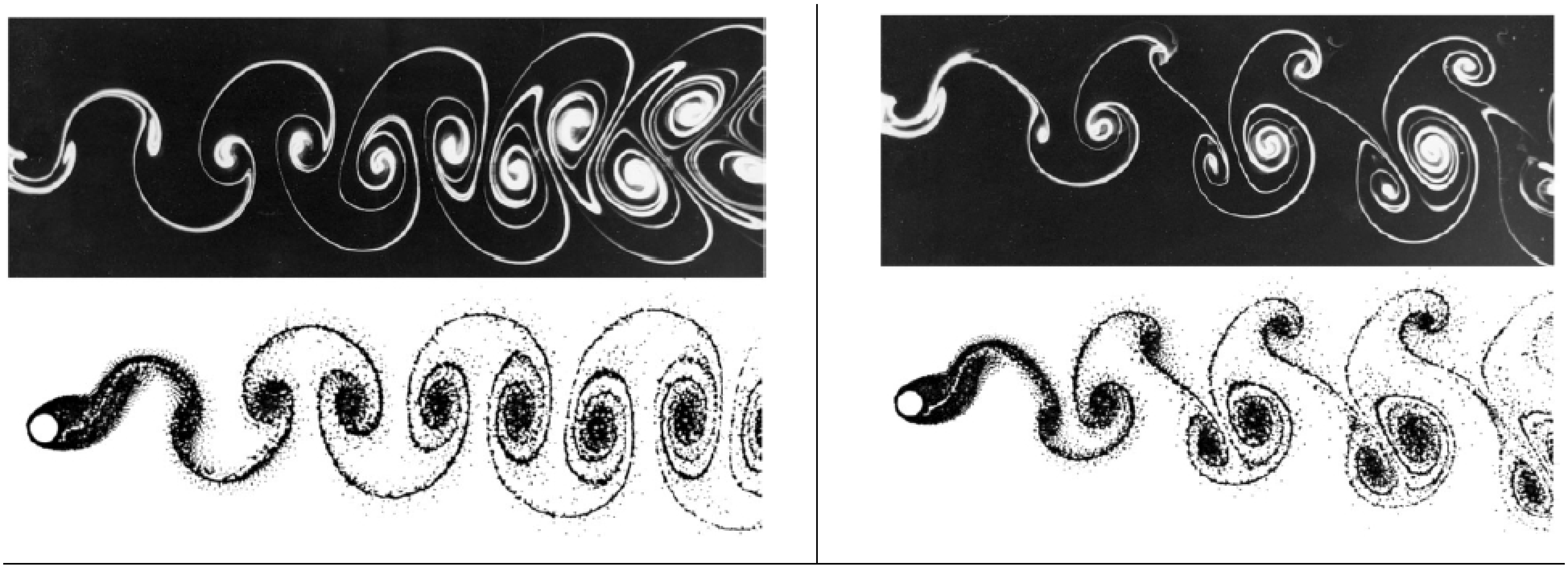


Figura 2.22: Modos de emissão: (esquerda) 2S; e (direita) P+S. Visualizações de Williamson & Govardhan (2004) e simulações numéricas de Meneghini & Bearman (1995).

Modos de emissão de vórtices

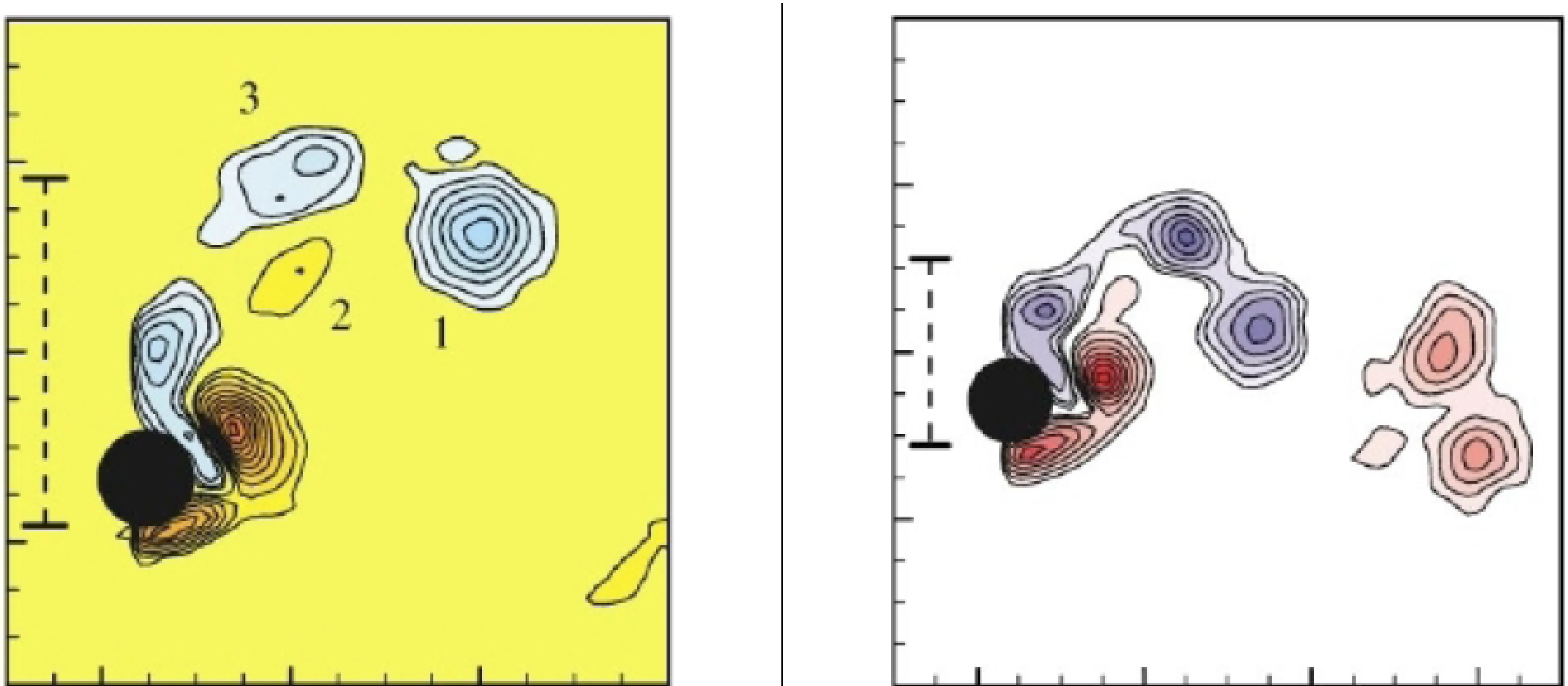
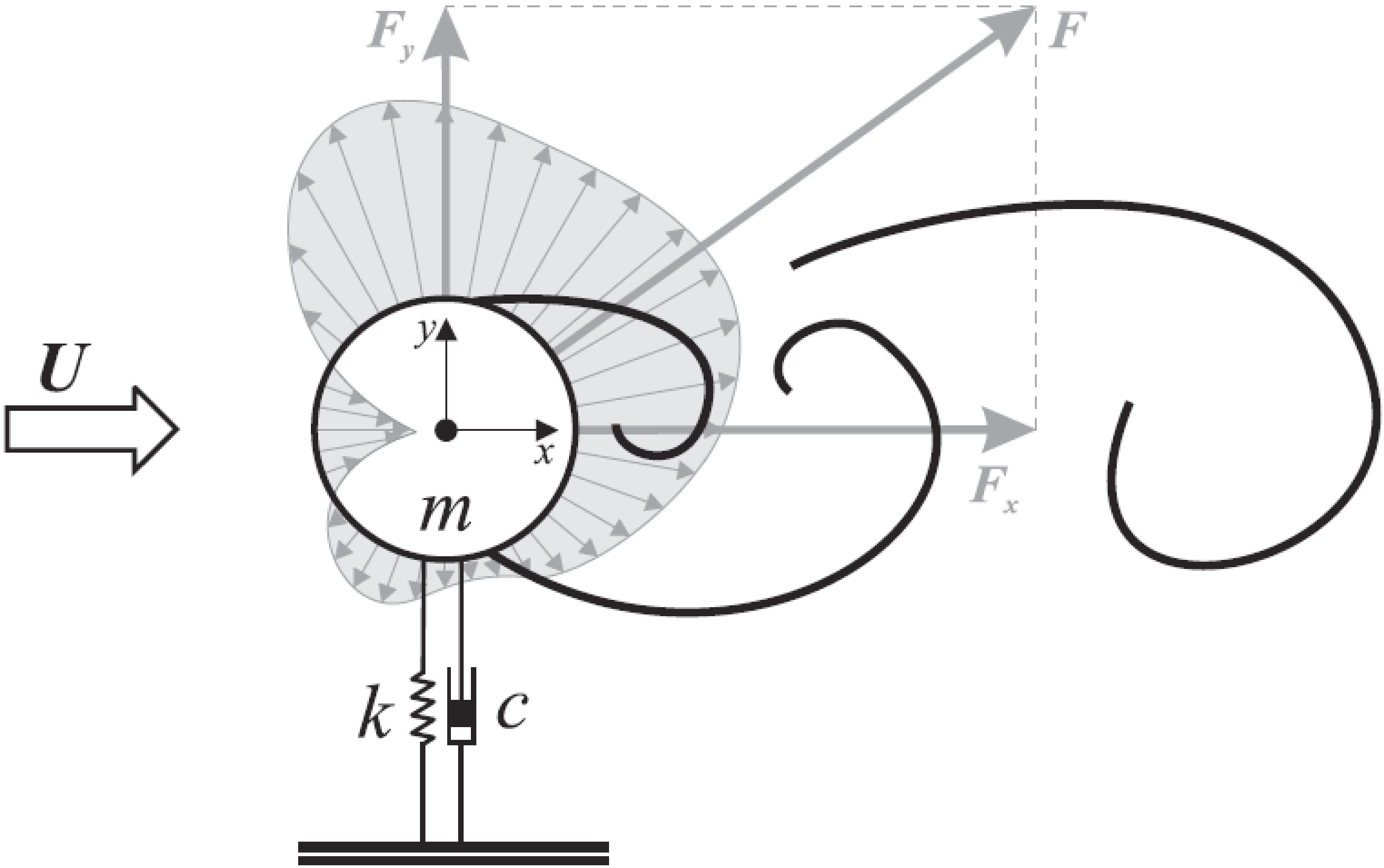
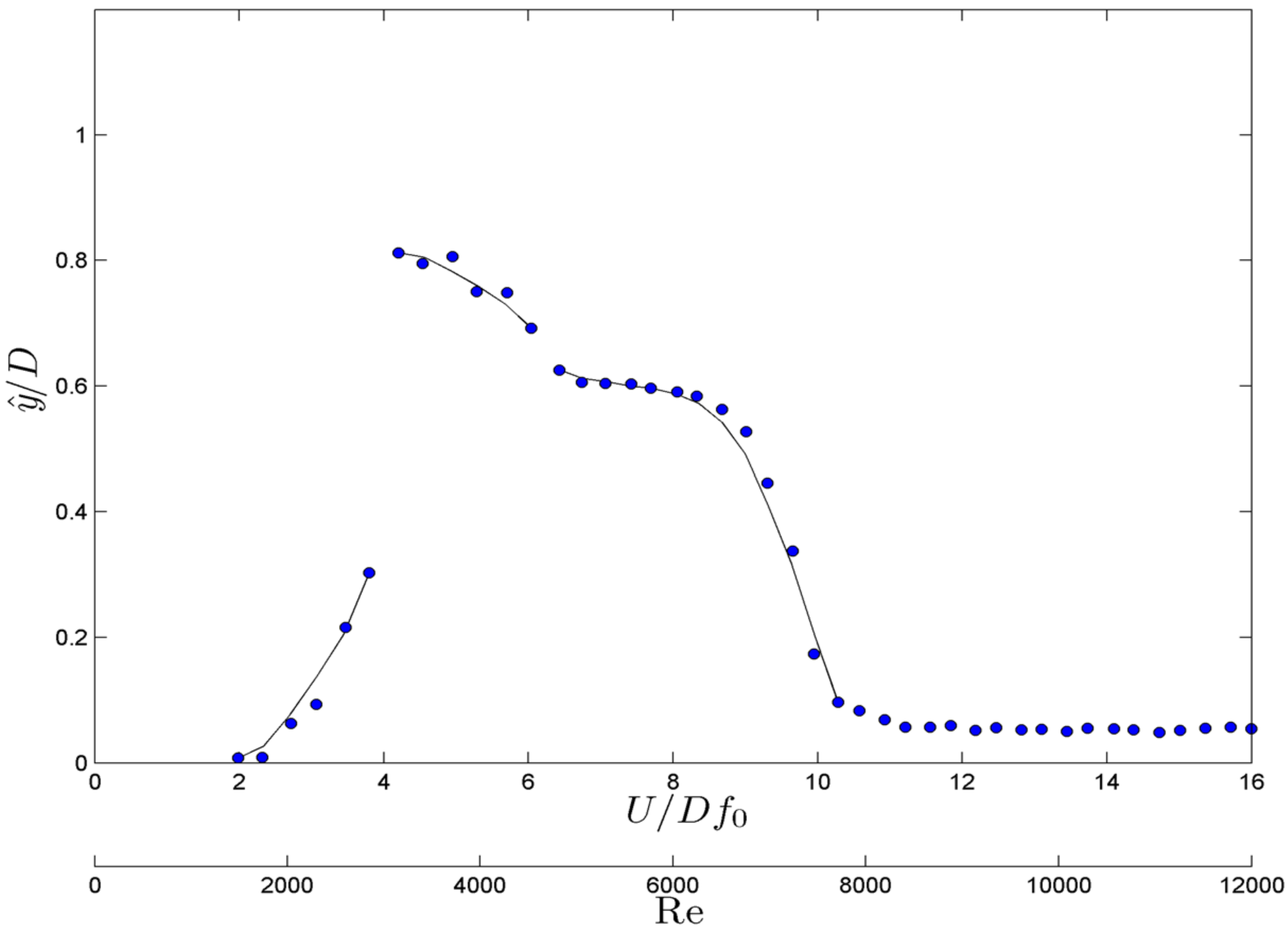


Figura 2.23: Modos de emissão: (esquerda) 2T; e (direita) 2C. Medições experimentais com PIV adaptadas de Williamson & Govardhan (2004).

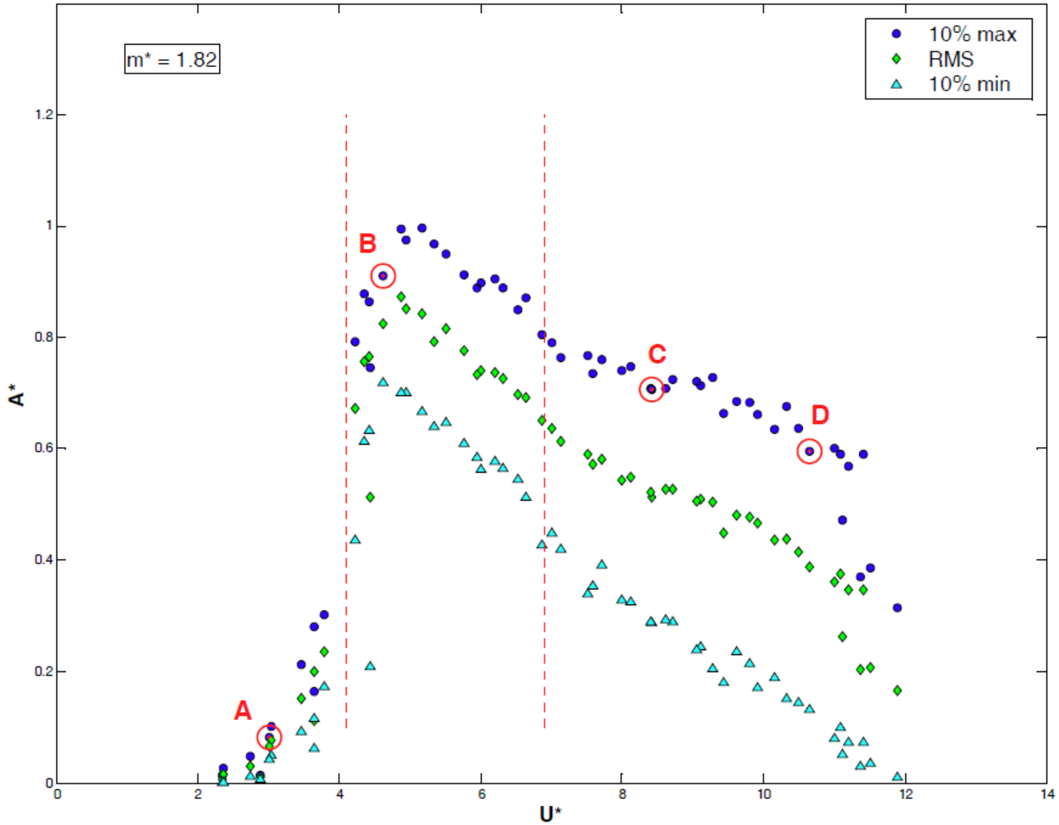
Interação Fluido Estrutura

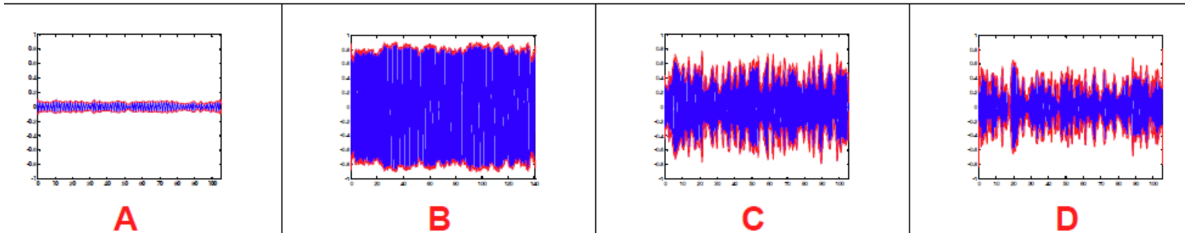


VIV: fenômeno ressonante



VIV: amplitude de vibração





Efeito da massa

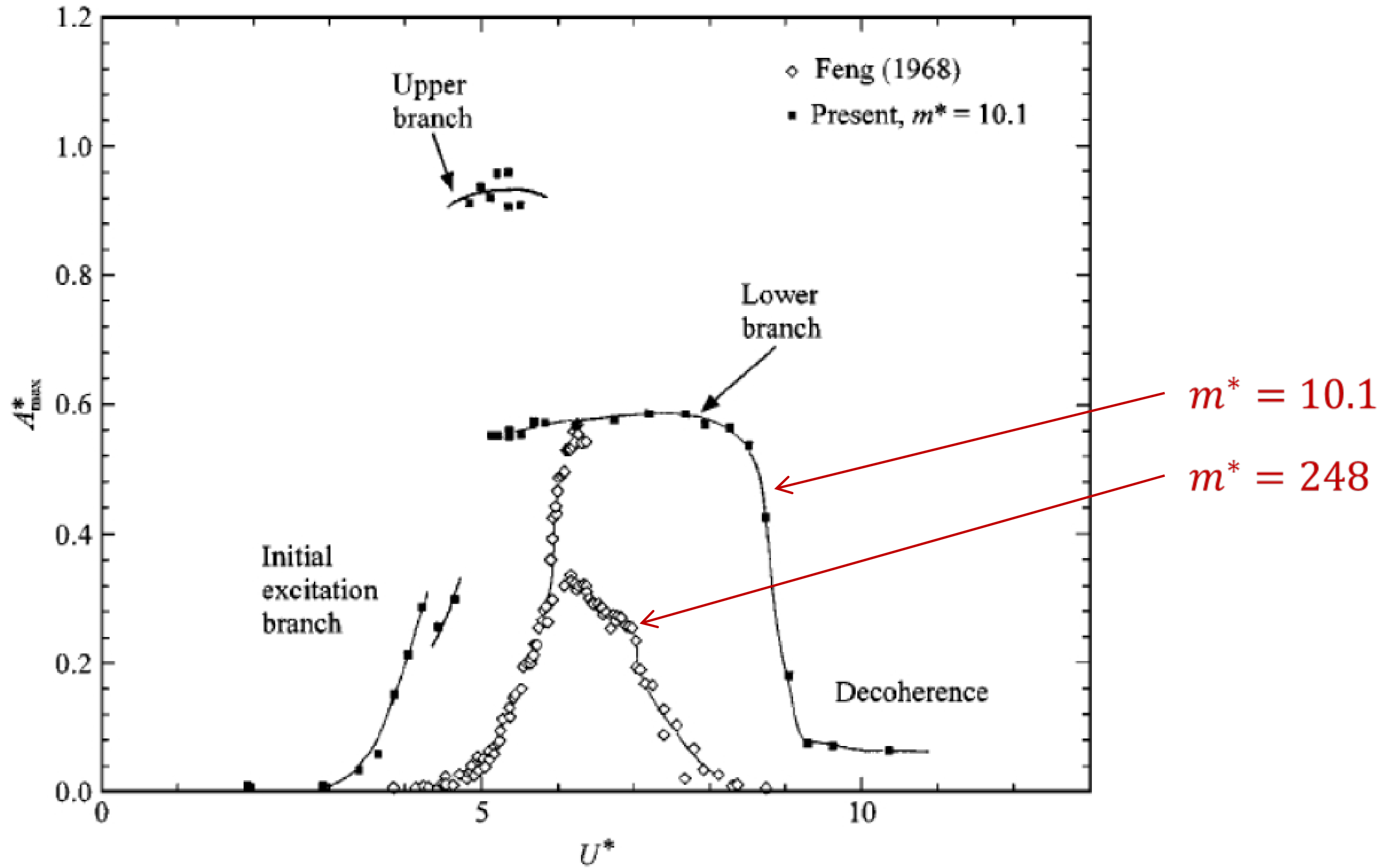
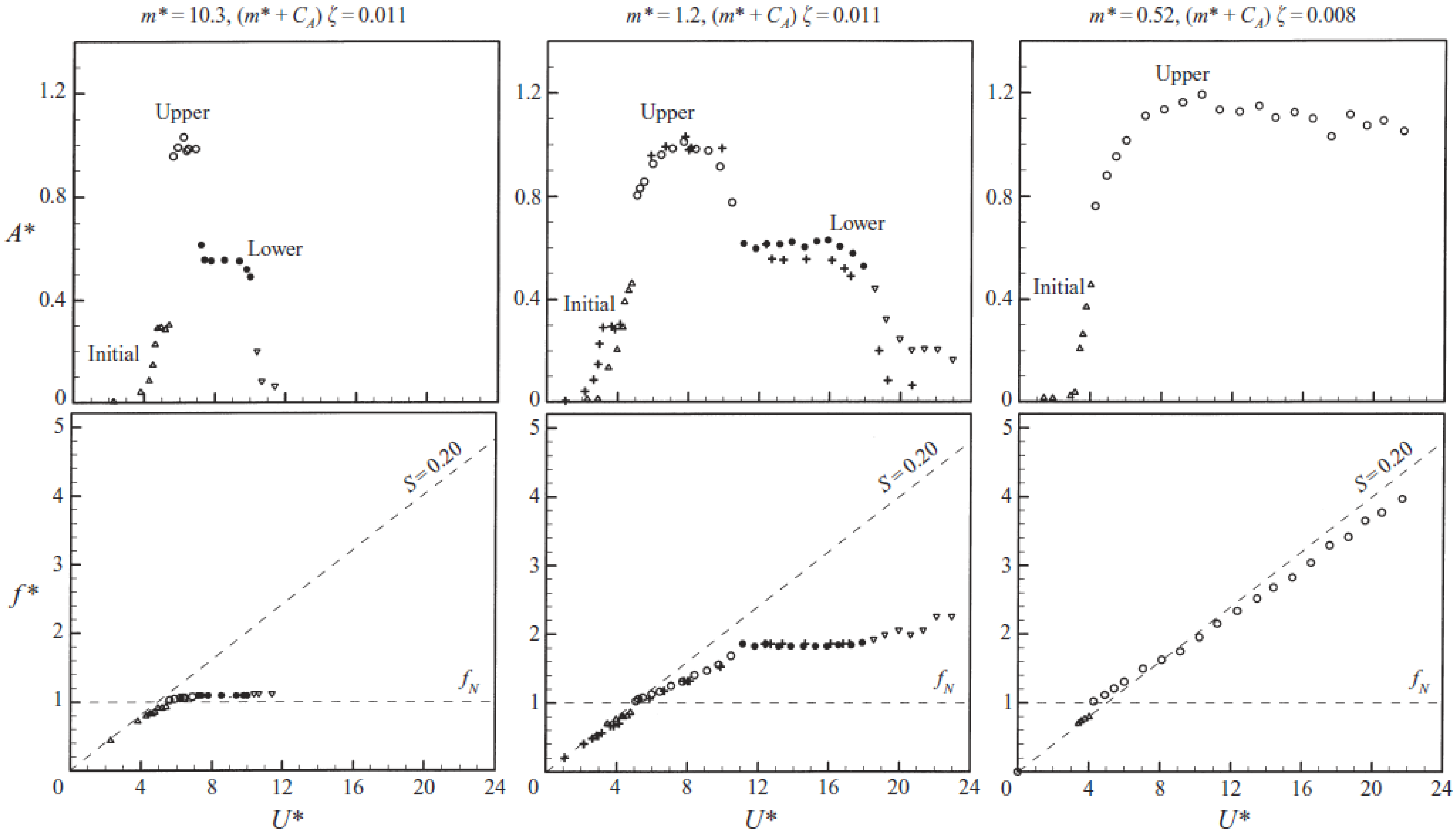
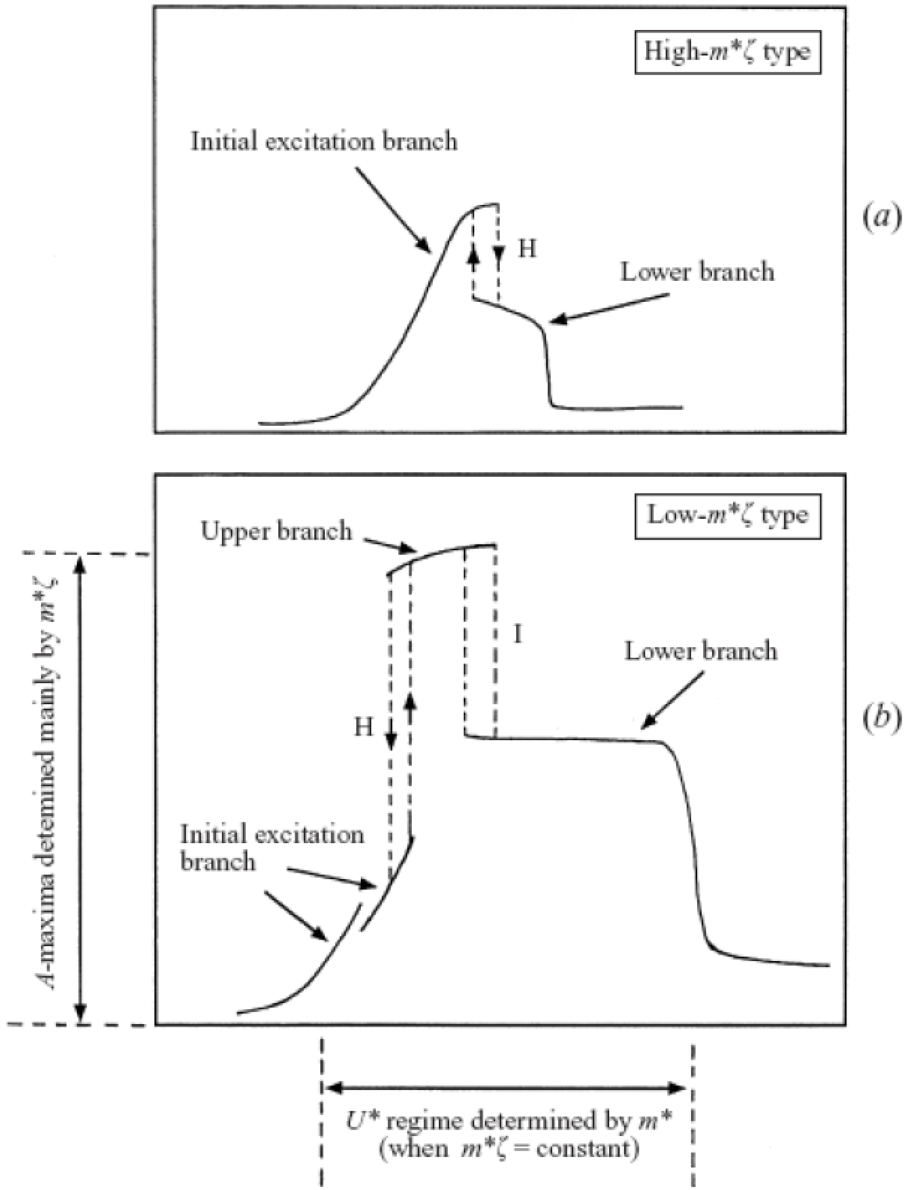


Figura 2.33: Amplitude de resposta para dois casos de cilindros rígidos oscilando transversalmente com $(m^*\zeta)$ distintos. Feng (1968): $m^* = 248$ e $(m^*\zeta) \cong 3{,}28$; Khalak & Williamson (1999): $m^*=10{,}1$ e $(m^*\zeta)=0{,}13$. Reproduzido de Khalak & Williamson (1999)



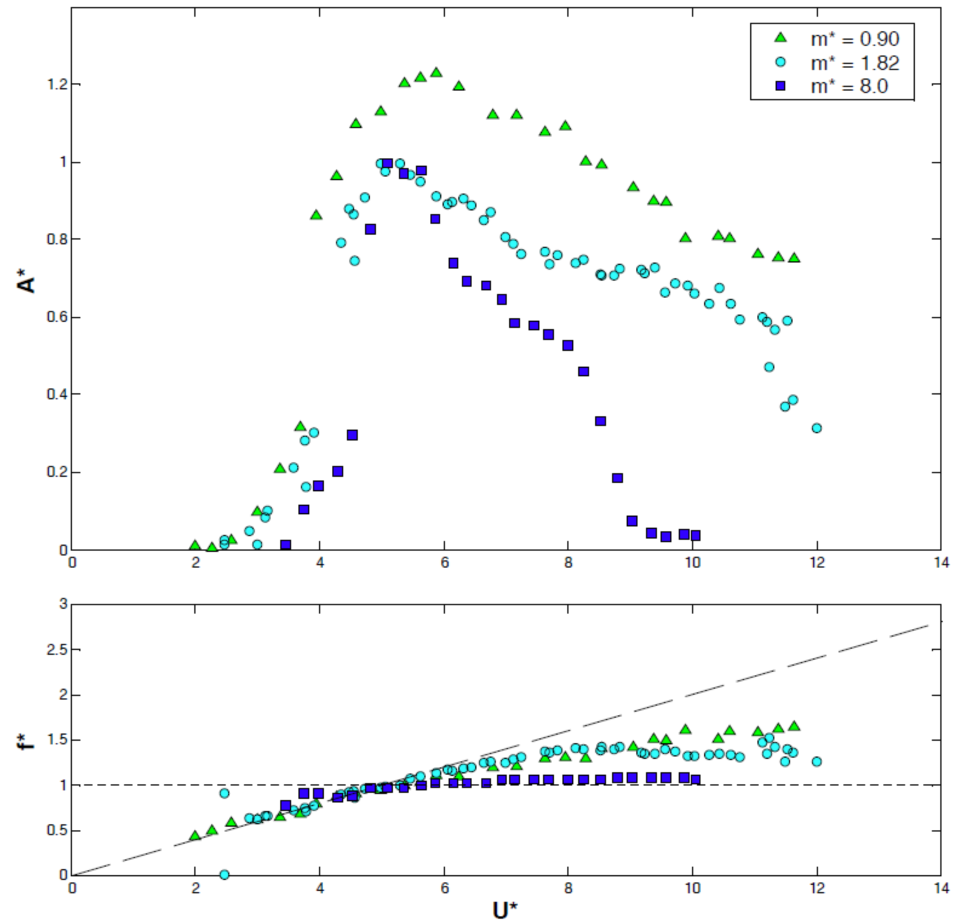
Govardhan & Williamson (2000)



Khalak & Williamson (1999)

$$A^* = \frac{\hat{y}}{D}$$

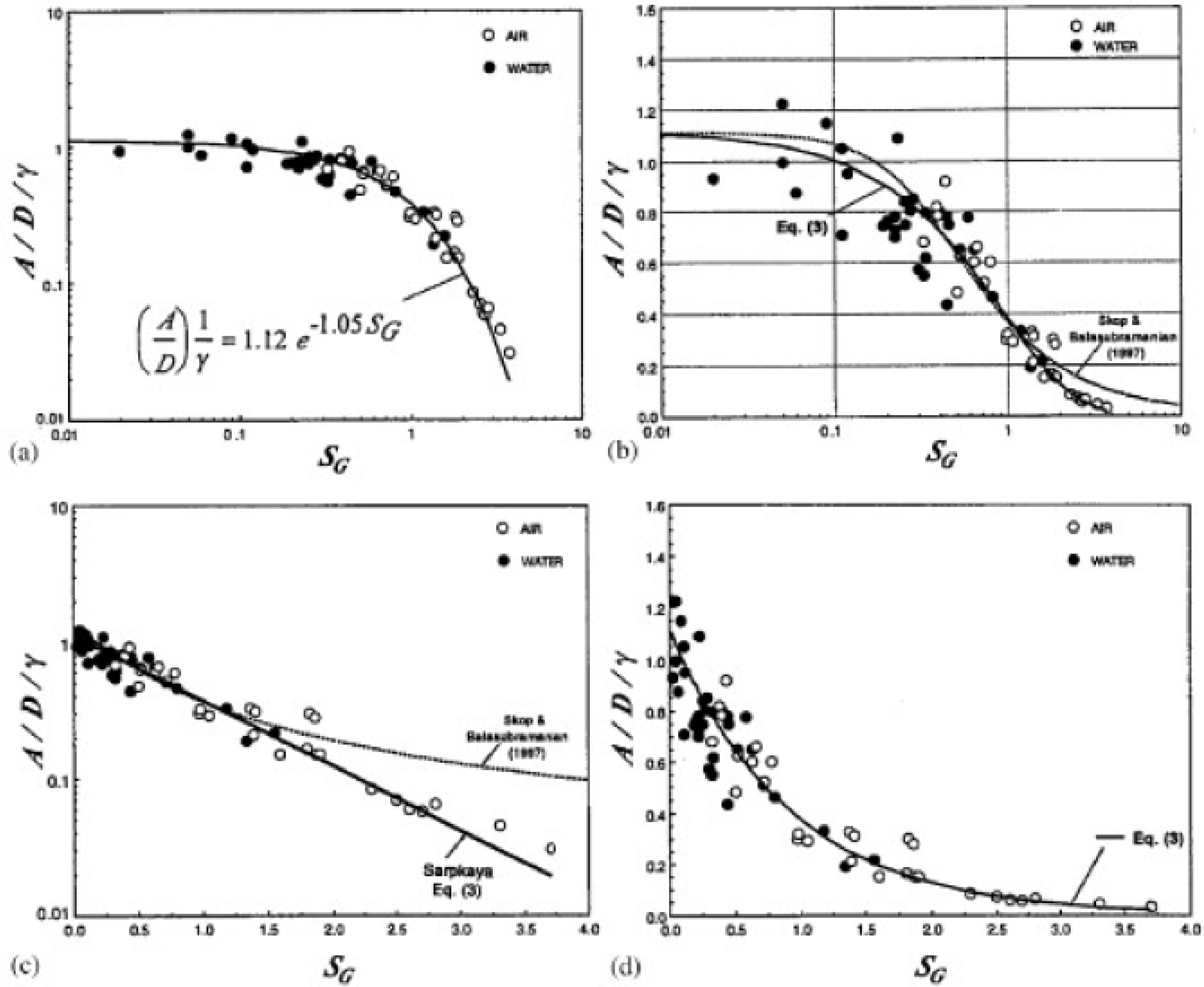
$$f^* = \frac{f}{f_0}$$



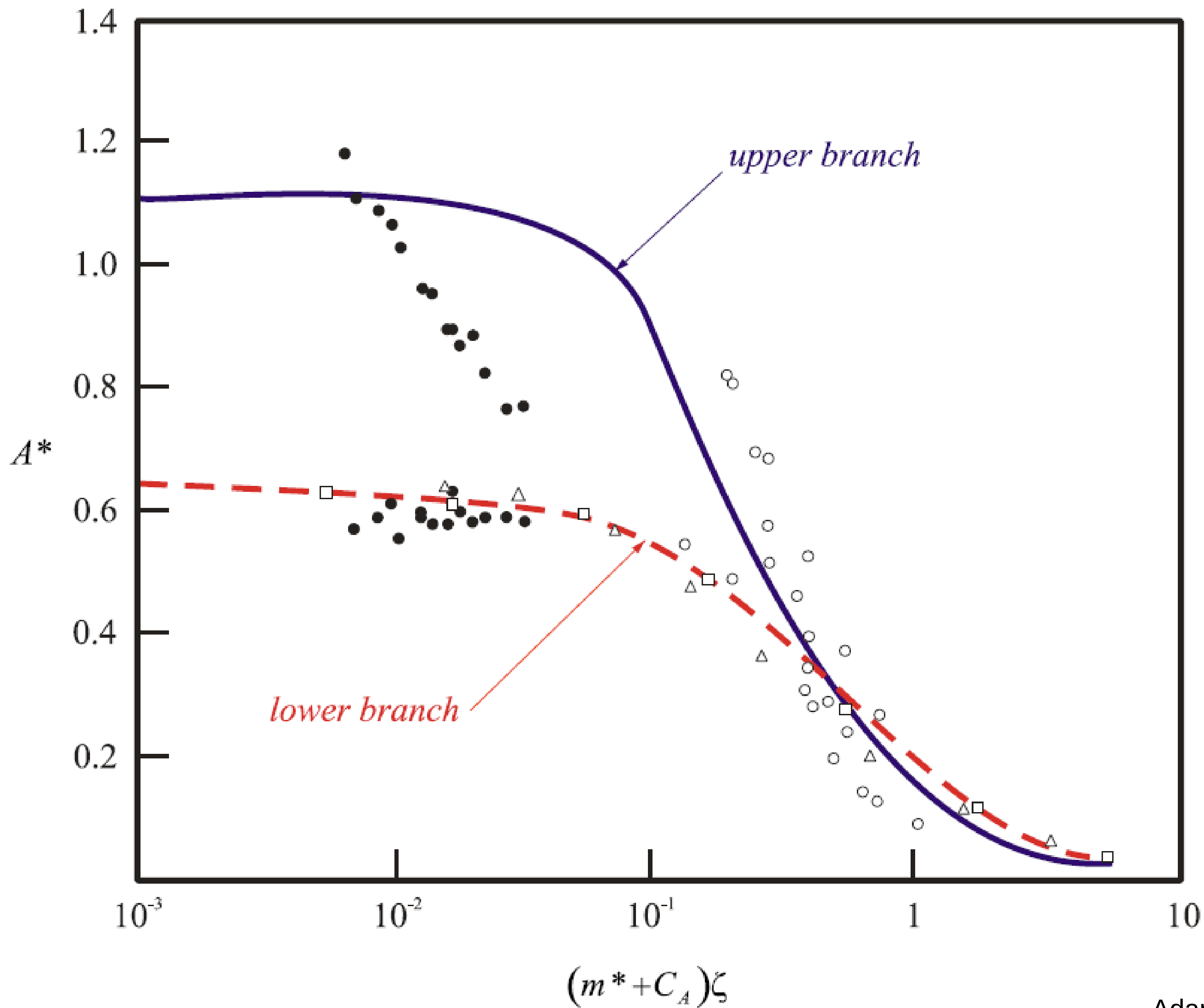
▲	$m^* = 0,90$	$\zeta = 0,0100$	$(m^*\zeta) = 0,009$
●	$m^* = 1,82$	$\zeta = 0,0079$	$(m^*\zeta) = 0,014$
■	$m^* = 8,0$	$\zeta = 0,0018$	$(m^*\zeta) = 0,014$

Tabela 2.5: Parâmetros adimensionais combinados de massa-amortecimento.

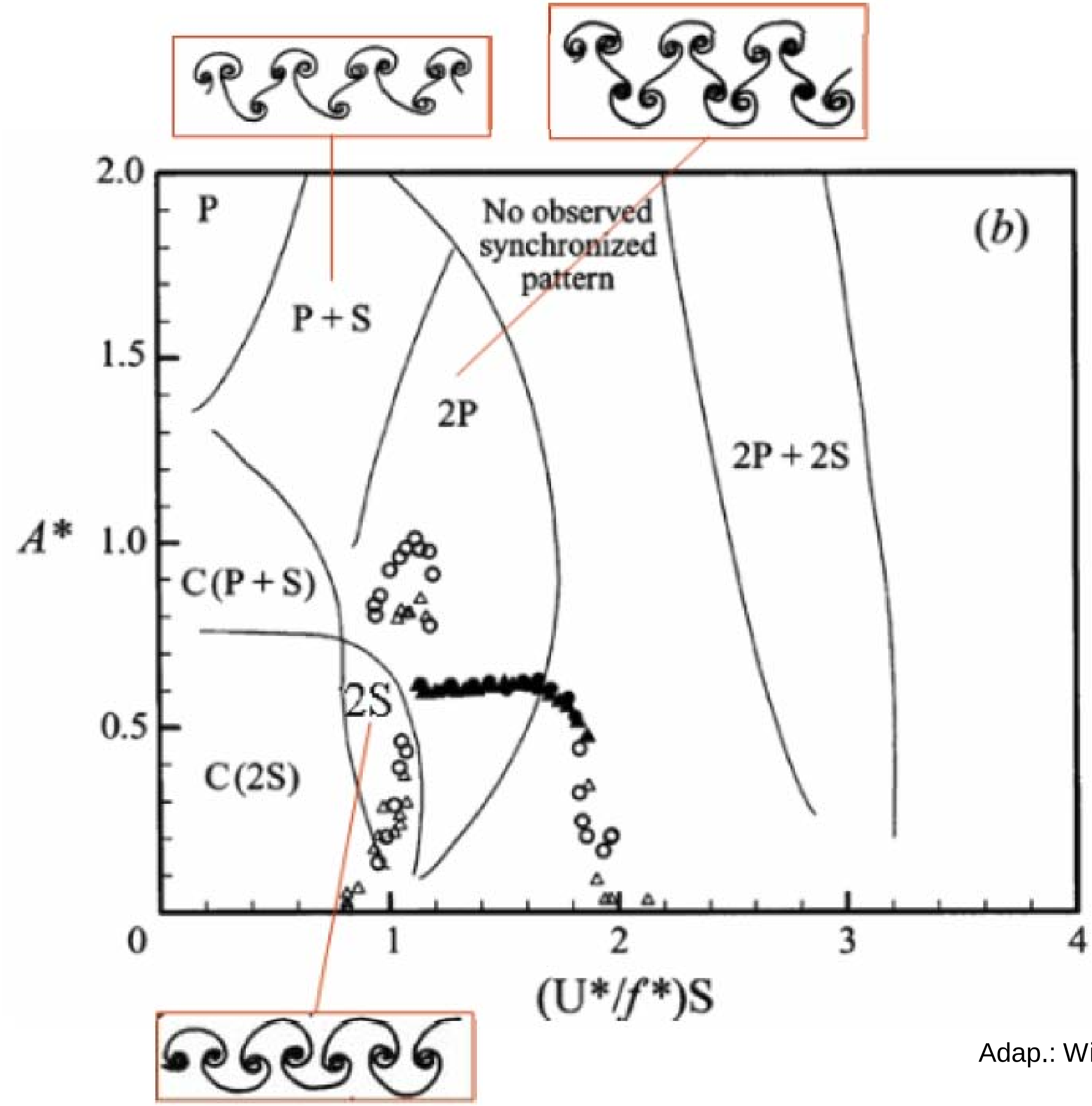
$(m^*\zeta)$	*Parâmetro de massa-amortecimento*
$S_G = 2\pi^3 St^2 (m^*\zeta)$	*Parâmetro de Skop-Griffin*
$Sc = \frac{\pi}{2}(m^*\zeta)$	*Número de Scruton*



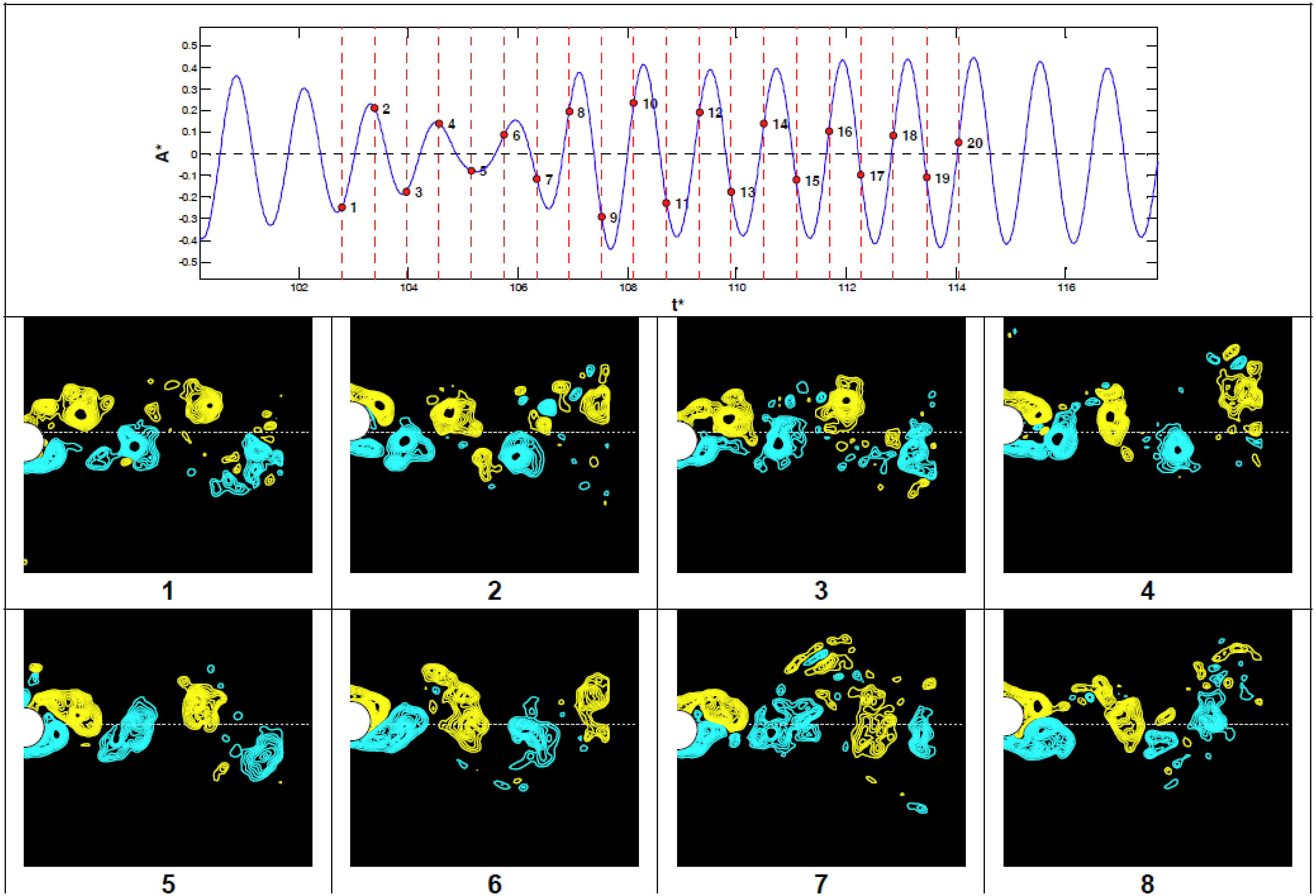
Sarpakaya (2004)



Adap.: Fujarra (2002)

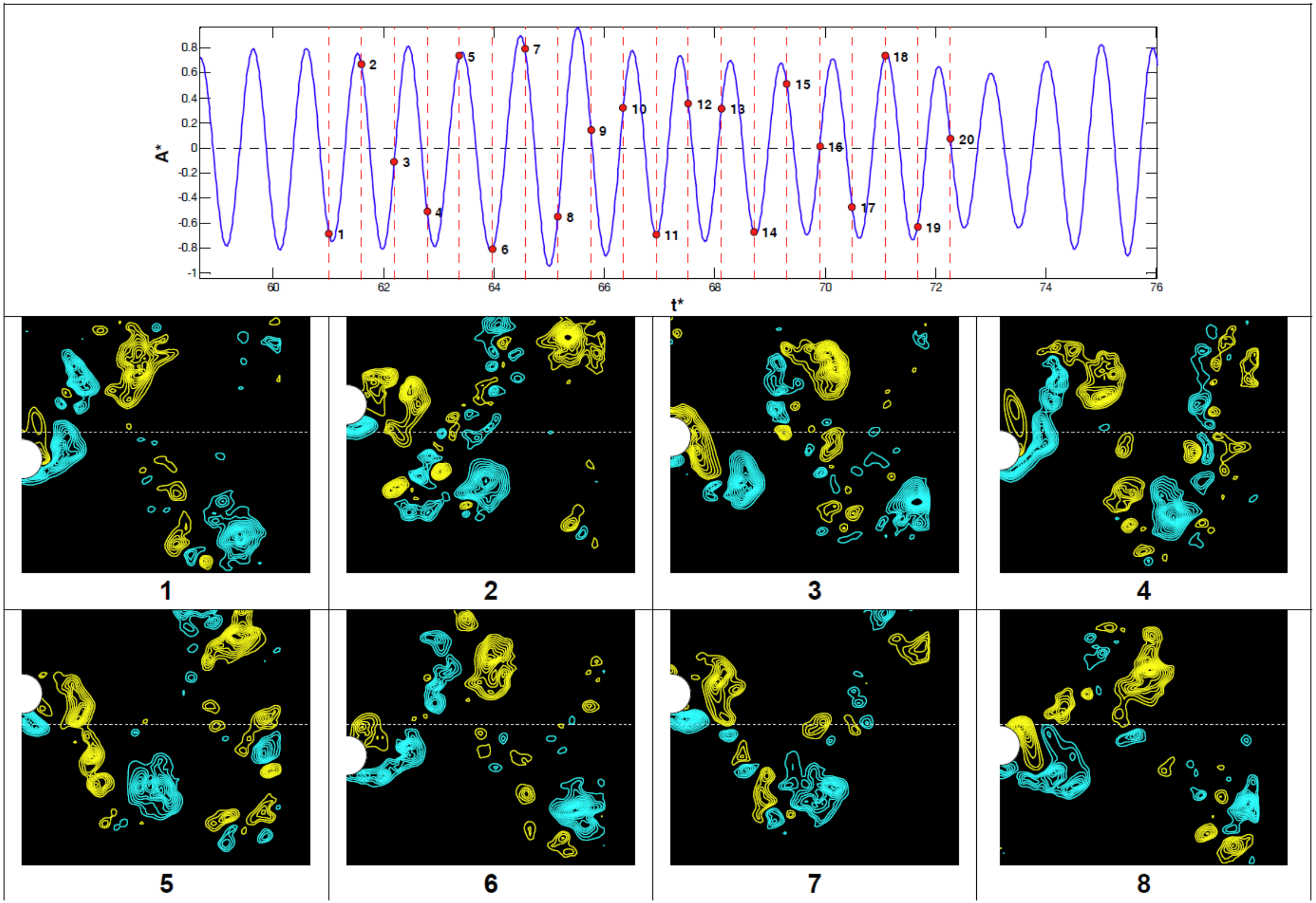


Adap.: Williamson & Gavardhan (2004)



$\mathrm{Re} = 5280$	$U^* = 4,4$	$A^* = 0,73$	$\Delta t = 0,5s$

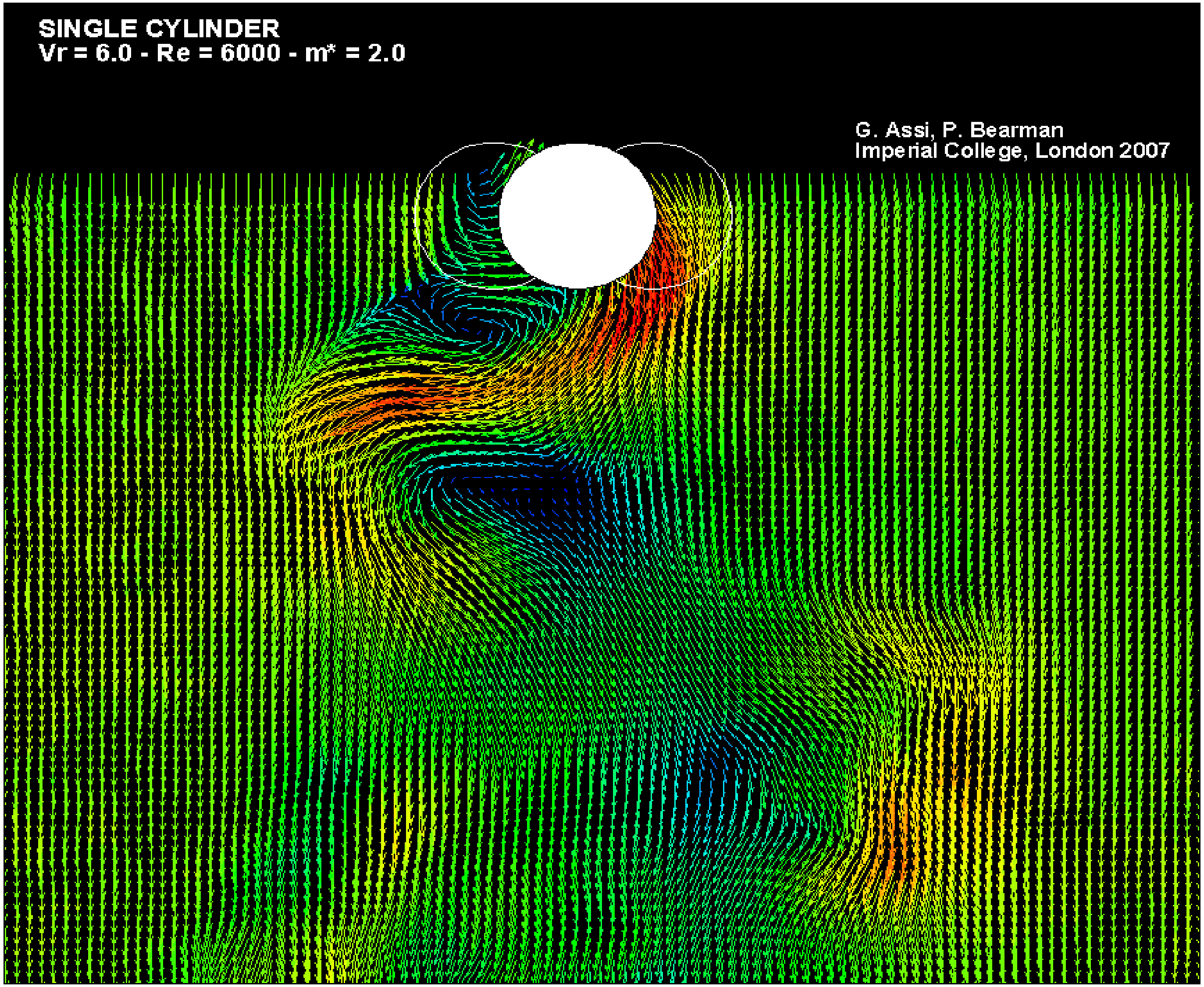
Figura 4.22: Dinâmica da esteira. Cilindro isolado oscilando transversalmente. U*=4,4



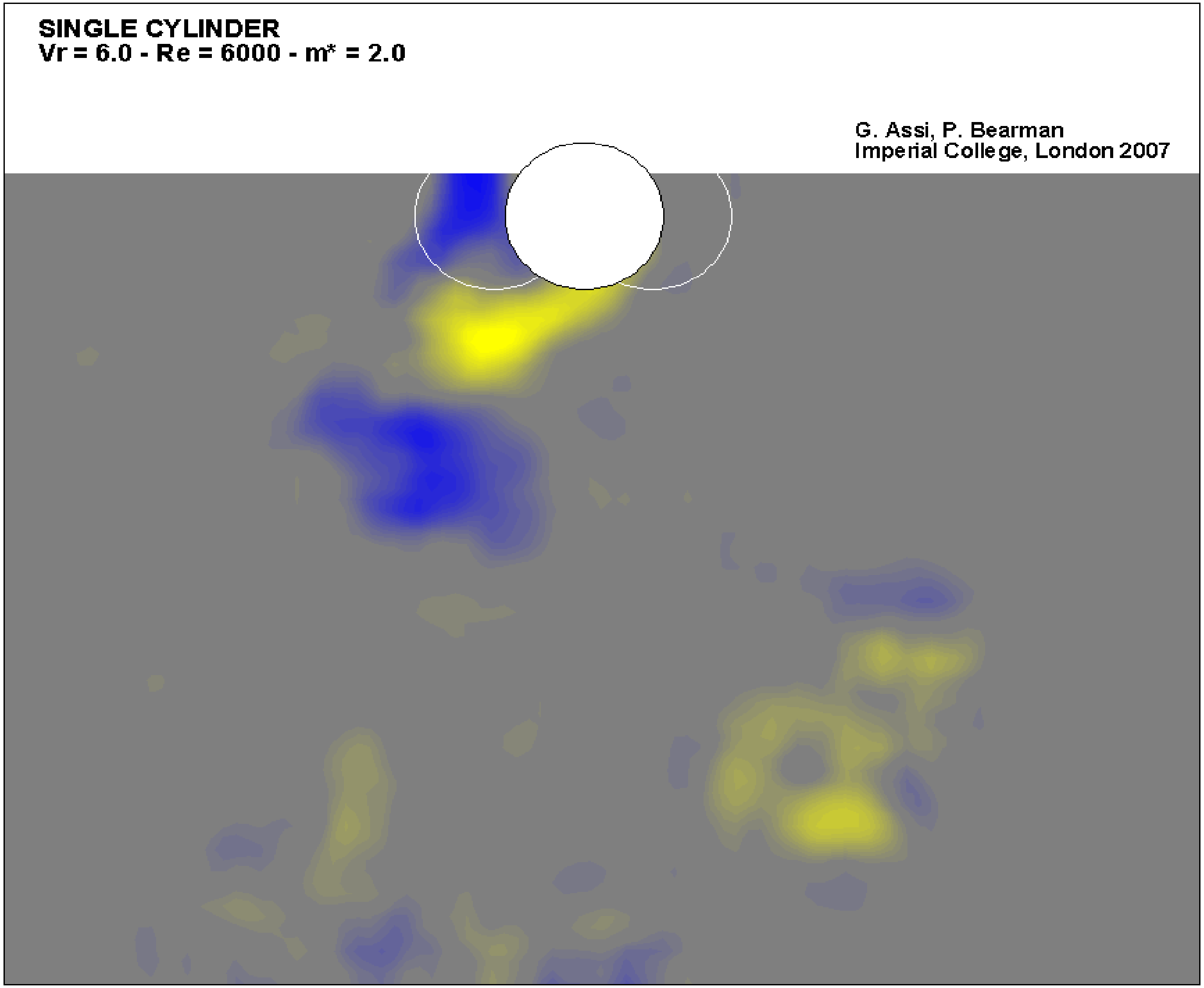
$\mathrm{Re} = 6288$	$U^* = 5,2$	$A^* = 0,95$	$\Delta t = 0,5s$

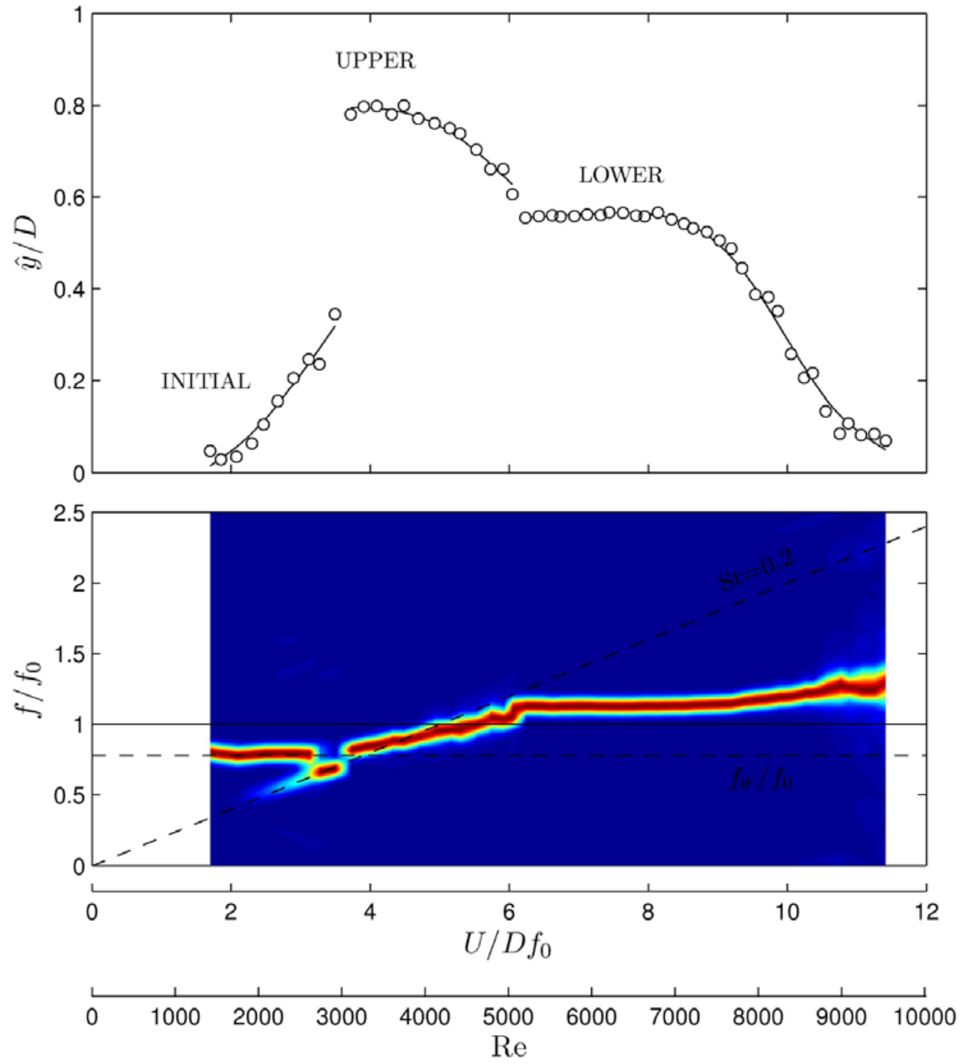
Figura 4.24: Dinâmica da esteira. Cilindro isolado oscilando transversalmente. U*=5,2

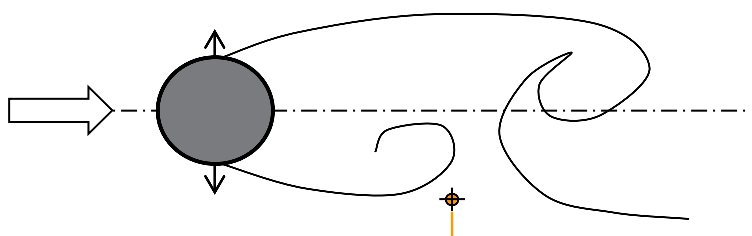
VIV of a cylinder: velocity field



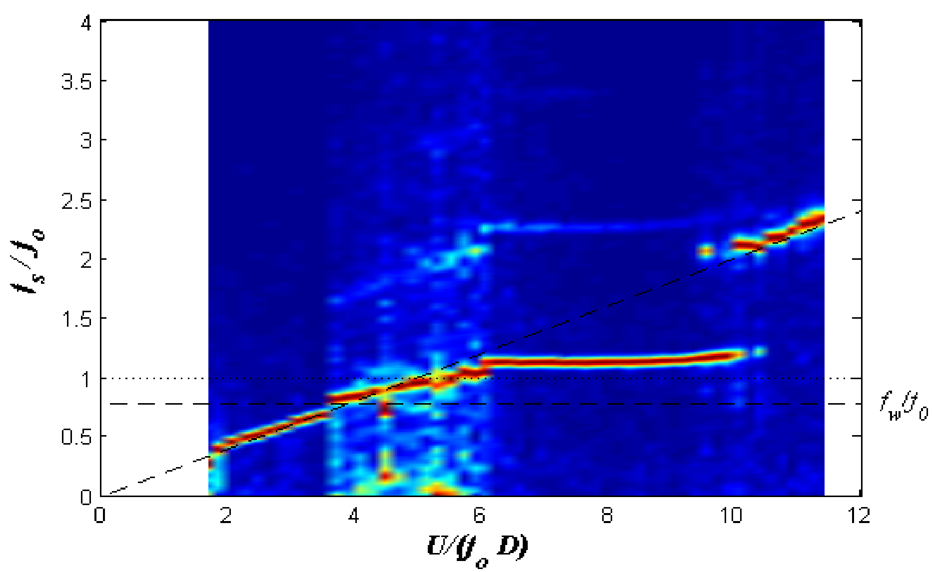
VIV of a cylinder: vorticity field







Velocity fluctuation in the wake



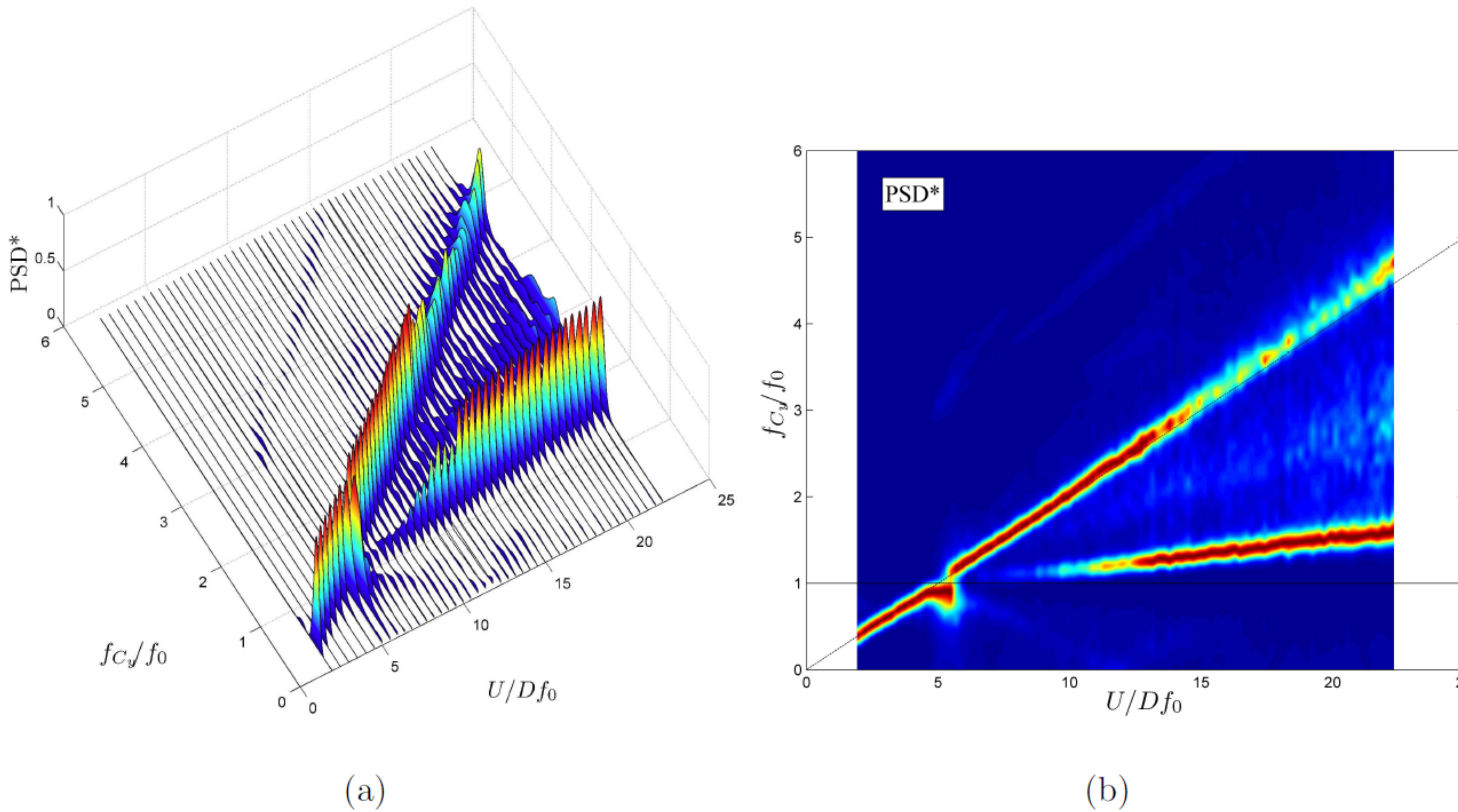


Fig. A.2: Examples of normalised PSD*. All similar plots in the present work have been generated like this one.

Modelo harmônico

- Oscilador harmônico linear

$$m\ddot{y} + c\dot{y} + ky = F_y(t)$$

$$y(t) = \hat{y}\sin(2\pi f t),$$

- Força hidrodinâmica

$$F_y(t) = \hat{F}_y \sin(2\pi f t + \phi),$$

$$C_y(t) = \frac{F_y(t)}{\frac{1}{2}\rho U^2 D L},$$

$$C_y(t) = \overline{C}_y + \hat{C}_y \sin(2\pi f t + \phi).$$

- Parâmetros

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$$

$$\zeta = \frac{c}{2\sqrt{km}},$$

$$f_{0_d} = f_0\sqrt{1-\zeta^2}$$

$$m^* = \frac{m}{\rho \frac{\pi D^2}{4} L}$$

Modelo harmônico

- A amplitude de resposta será...

$$\frac{\hat{y}}{D} = \frac{1}{4\pi^3}\hat{C}_y \sin\phi \left(\frac{U}{Df_0}\right)^2 \left(\frac{1}{m^*\zeta}\right) \left(\frac{f_0}{f}\right)$$

- Com frequência...

$$\frac{f}{f_0} = \left[1 - \frac{1}{2\pi^3}\hat{C}_y \cos\phi \left(\frac{U}{Df_0}\right)^2 \left(\frac{1}{m^*}\right) \left(\frac{D}{\hat{y}}\right)\right]^{\frac{1}{2}}$$

- onde

$$\phi = \arctan\frac{2\zeta(f/f_0)}{1-(f/f_0)^2}$$

Modelo harmônico

- Na ressonância a amplitude máxima é

$$\left.\frac{\hat{y}}{D}\right|_{f=f_0} = \frac{\rho U^2\,\hat{C}_y}{4k\zeta}$$

- Considerando

$$\hat{C}_y \sim o(1)$$

- A amplitude estimada seria muito maior que a observada para sistemas em água, por exemplo.

$$\frac{\hat{y}}{D} >> 1$$

Modelo harmônico

- Observa-se: amplitude

$$\frac{\hat{y}}{D} = \frac{1}{4\pi^3}\hat{C}_y \sin\phi \left(\frac{U}{Df_0}\right)^2 \left(\frac{1}{m^*\zeta}\right) \left(\frac{f_0}{f}\right)$$

- Ordens de magnitude $\hat{C}_y \sim o(1)$

$$\frac{U}{Df_0} \sim \frac{1}{\mathrm{St}} \sim o(1) \text{ na ressonância}$$

$$\frac{1}{m^*} \sim o(1) \text{ em água} \qquad \frac{1}{m^*} \sim o(10^{-2} \to 10^{-3}) \text{ em ar}$$

$$\frac{\hat{y}}{D} \sim o(1) \text{ em água} \qquad \frac{\hat{y}}{D} \sim o(10^{-1}) \text{ em ar}$$

Modelo harmônico

- A frequência...

$$\frac{f}{f_0} = \left[1 - \frac{1}{2\pi^3}\hat{C}_y \cos\phi \left(\frac{U}{Df_0}\right)^2 \left(\frac{1}{m^*}\right)\left(\frac{D}{\hat{y}}\right)\right]^{\frac{1}{2}}$$

- Ordens de magnitude $\hat{C}_y \sim o(1)$

$$\frac{U}{Df_0} \sim \frac{1}{\mathrm{St}} \sim o(1) \text{ na ressonância}$$

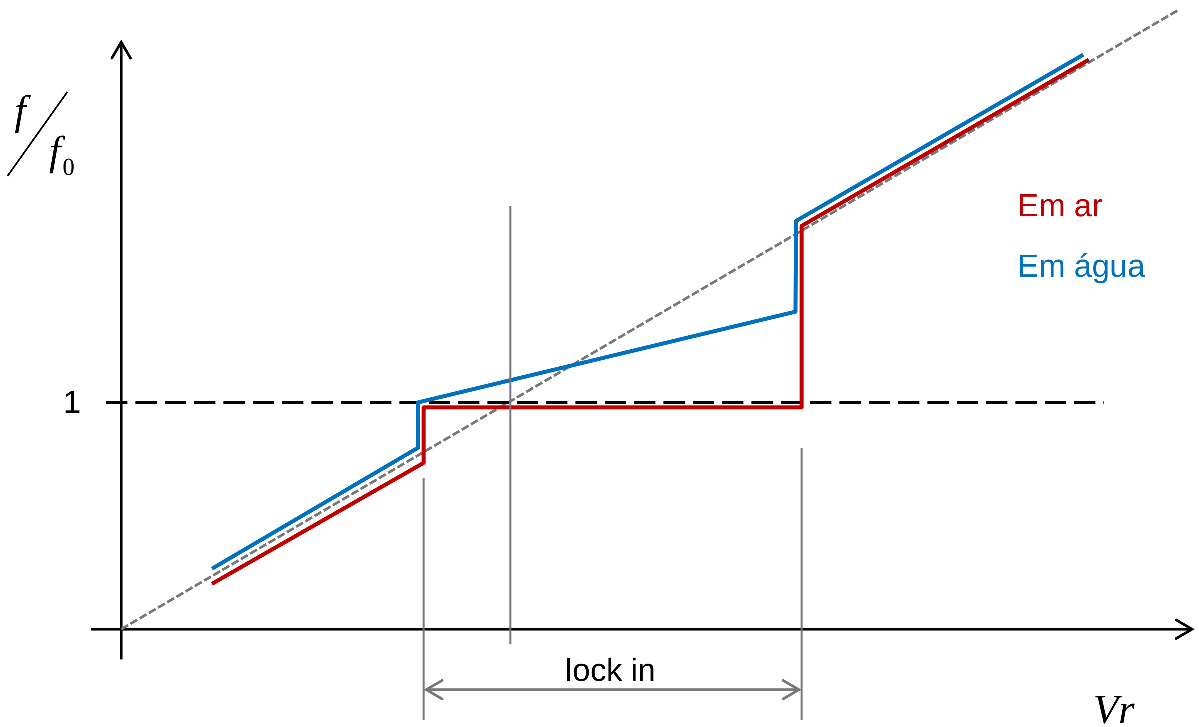
$$\frac{1}{m^*} \sim o(1) \text{ em água} \qquad \frac{1}{m^*} \sim o(10^{-2} \to 10^{-3}) \text{ em ar}$$

$$\frac{\hat{y}}{D} \sim o(1) \text{ em água} \qquad \frac{\hat{y}}{D} \sim o(10^{-1}) \text{ em ar}$$

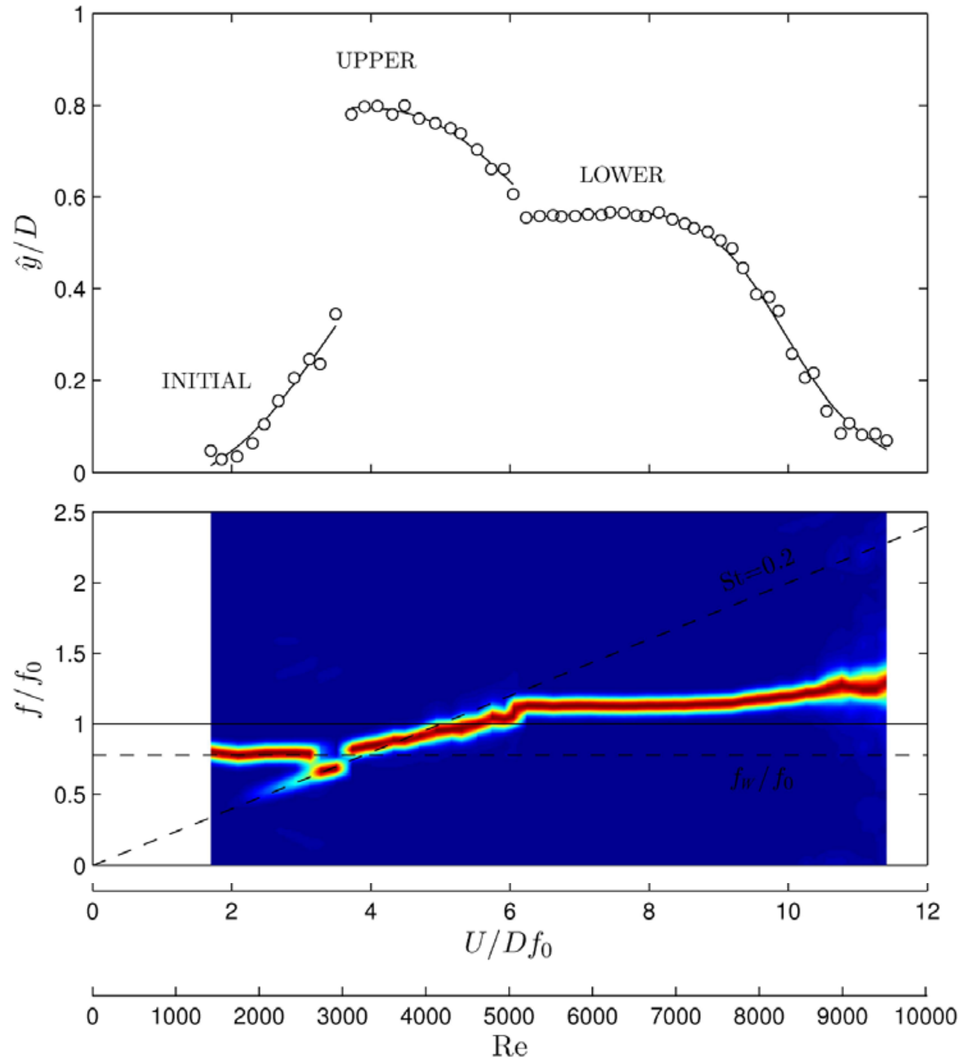
Modelo harmônico

- A frequência...

$$\frac{f}{f_0} = \left[1 - \frac{1}{2\pi^3}\hat{C}_y \cos\phi \left(\frac{U}{Df_0}\right)^2 \left(\frac{1}{m^*}\right)\left(\frac{D}{\hat{y}}\right)\right]^{\frac{1}{2}}$$

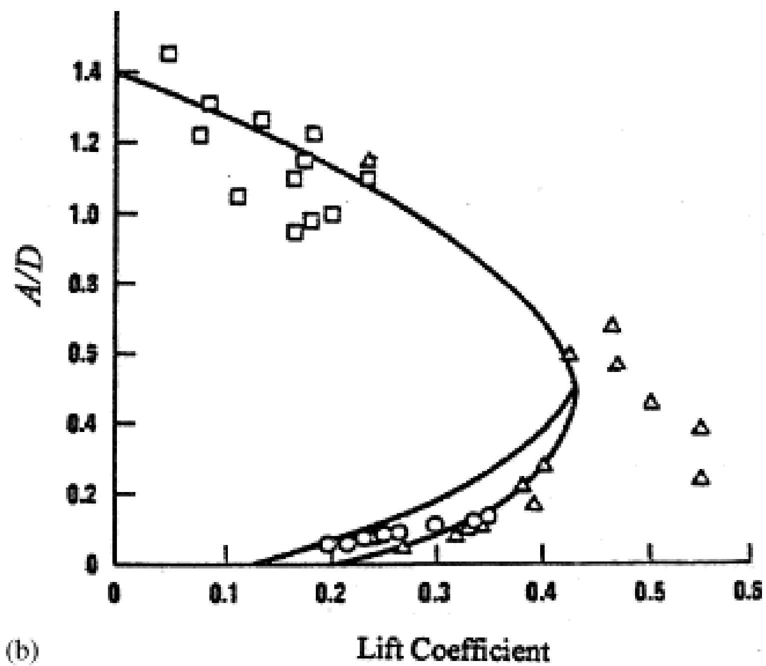


Modelo harmônico



Modelo harmônico

- Mas C_y depende da amplitude do movimento
  - C_y diminui para grandes amplitudes
  - Efeito autolimitante, independente do amortecimento



- Blevins & Burton (1976)
  - Polinômio de ordem 3
  - Resultado:

$$\frac{\hat{y}}{D} \rightarrow 1 \quad \text{quando} \quad \zeta \rightarrow 0$$

Blevins & Burton (1976)

Modelo harmônico

- Blevins & Burton (1976)
  - Polinômio de ordem 3
  - Resultado:

$$\frac{\hat{y}}{D} \rightarrow 1 \quad \text{quando} \quad \zeta \rightarrow 0$$

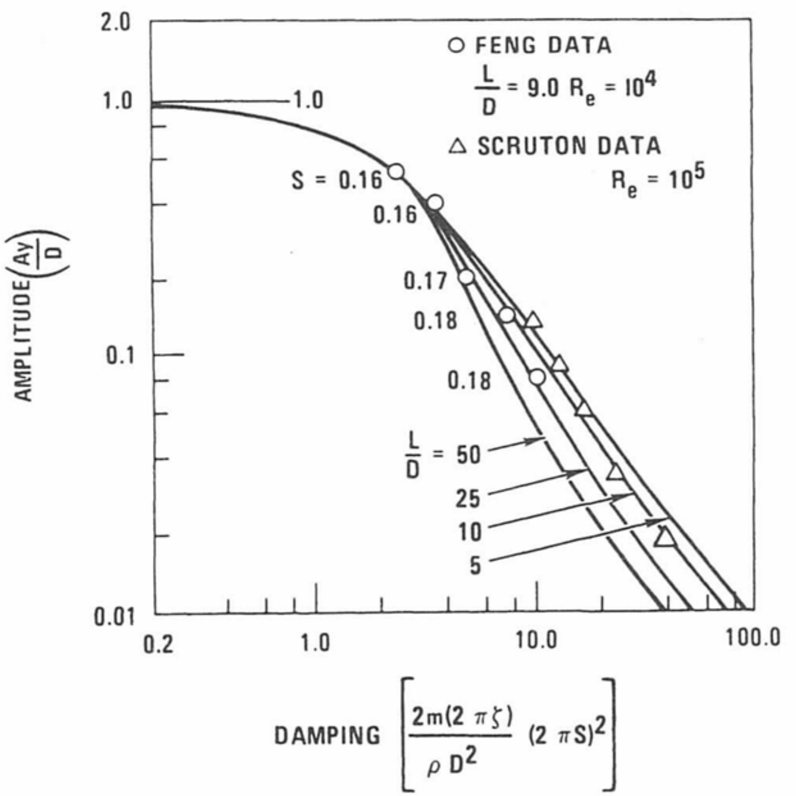


Fig. 3-19 Significant resonant amplitude for a spring-supported rigid cylinder ($\bar{y} = 1$) in comparison with experimental data of Feng (1968) and Scruton (1963).

Decomposição da força

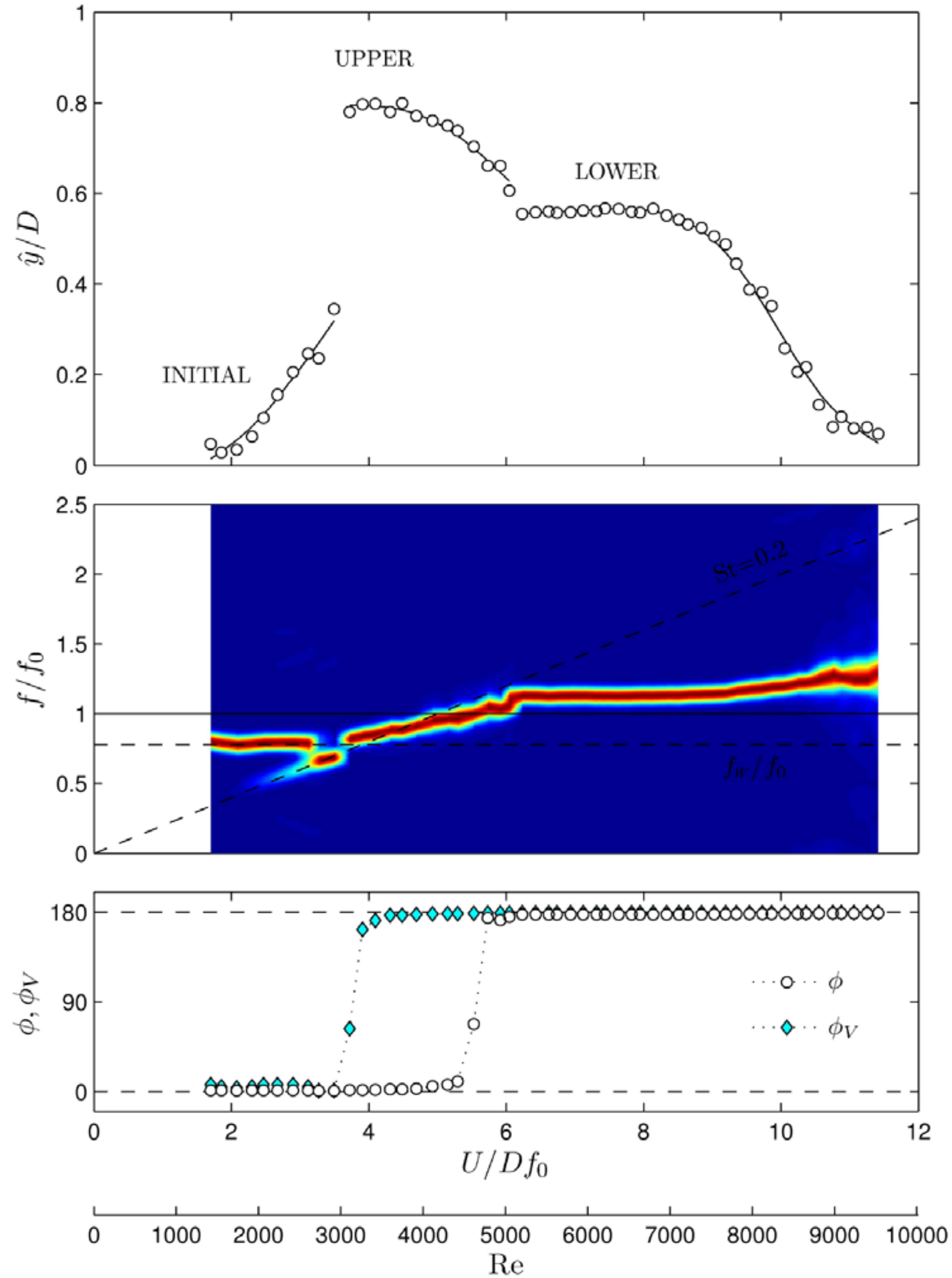
$$F_y = F_{y_P} + F_{y_V}.$$

$$\hat{C}_y \sin(2\pi f t + \phi) = \hat{C}_{y_P} \sin(2\pi f t + 180^\circ) + \hat{C}_{y_V} \sin(2\pi f t + \phi_V)$$

$$\phi_V = \arctan \frac{\hat{C}_y \sin\phi}{\hat{C}_y \cos\phi - 2\pi^3 \frac{\hat{y}}{D} \left(\frac{f}{f_0}\right)^2 \left(\frac{U}{D f_0}\right)^{-2}}$$

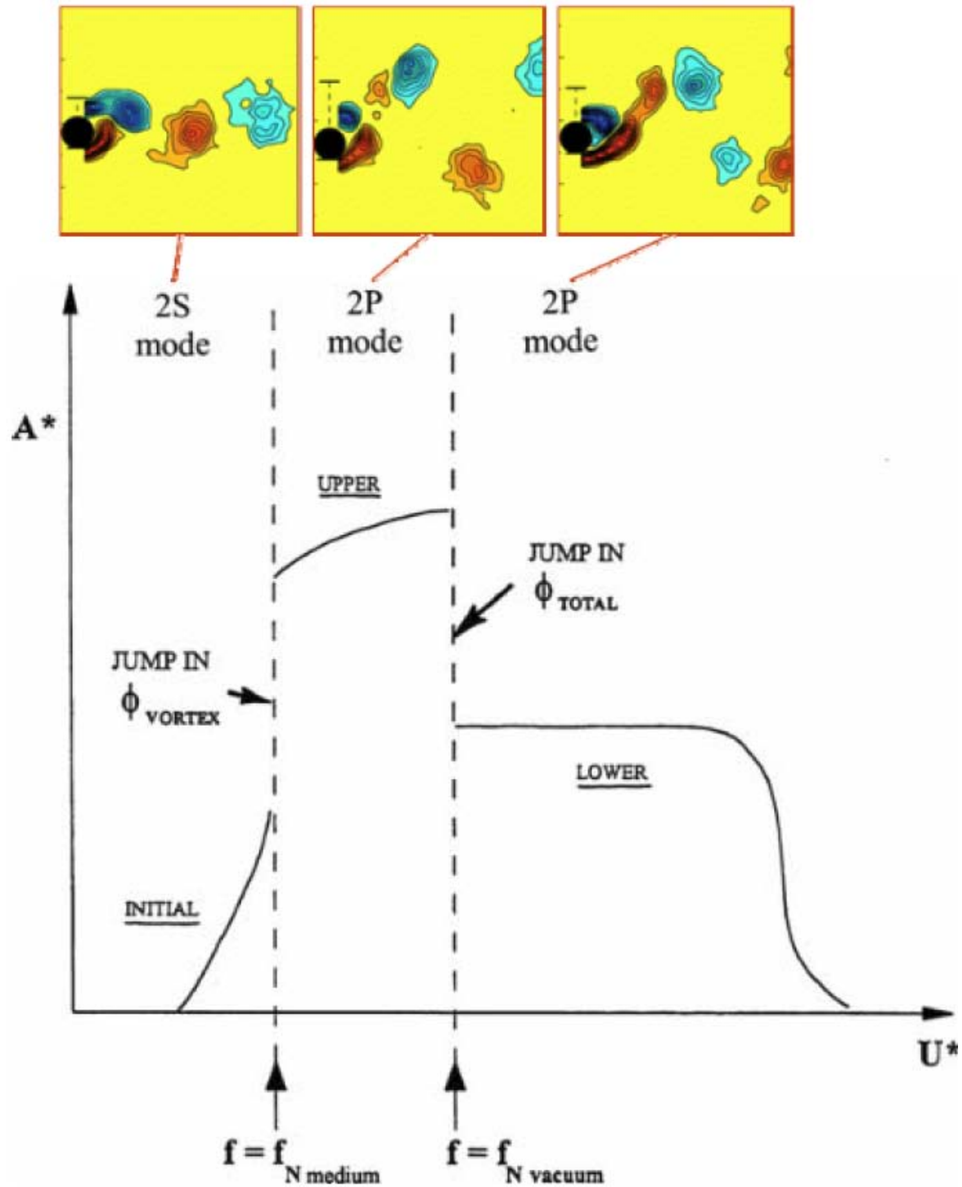
$$\hat{C}_{y_P} = 2\pi^3 \frac{\hat{y}}{D} \left(\frac{f}{f_0}\right)^2 \left(\frac{U}{D f_0}\right)^{-1}$$

$$\hat{C}_{y_V} = \left(\hat{C}_y{}^2 + \hat{C}_{y_P}^2 - 2\hat{C}_y \hat{C}_{y_P} \cos\phi\right)^{1/2}$$



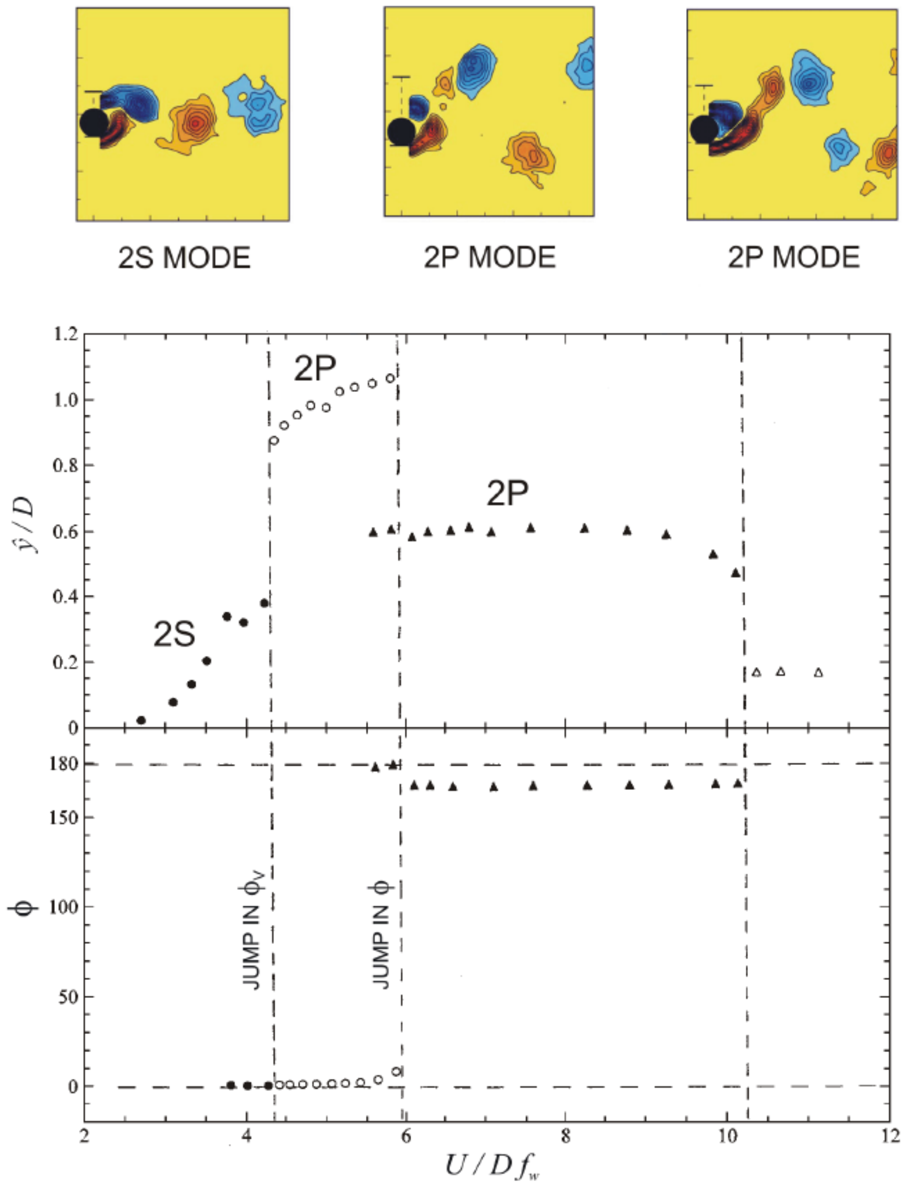
UPPER
LOWER
INITIAL
$\hat{y}/D$
St=0.2
f/f_0
f_w/f_0
ϕ, ϕ_V
ϕ
ϕ_V
U/Df_0
Re

Ramos de resposta

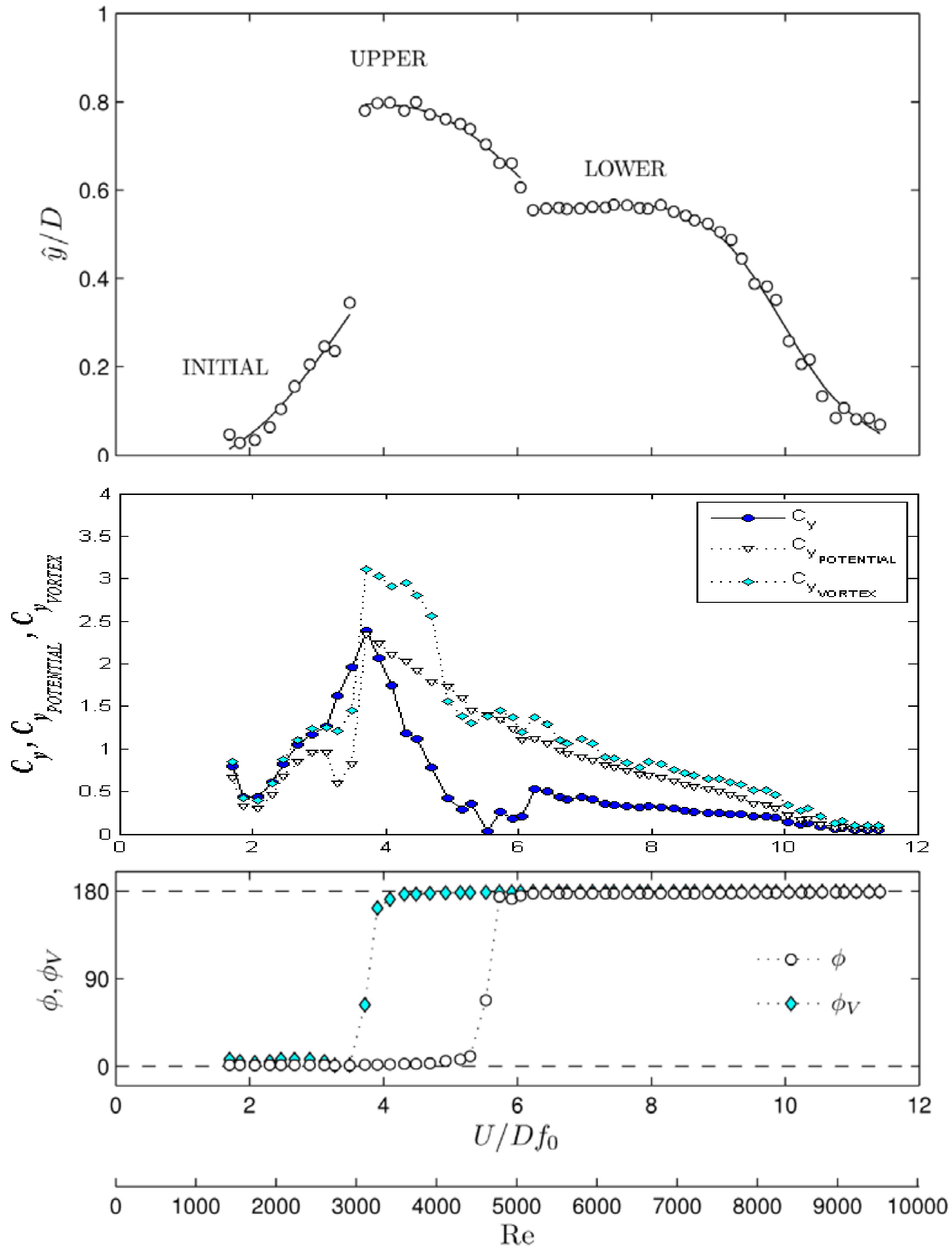


Williamson & Govardhan (2004)

Ramos de resposta



Resposta m* = 3.3 de Khalak & Williamson (1999)
PIV de Govardhan & Williamson (2000)


UPPER
LOWER
INITIAL
$\hat{y}/D$
$C_y, C_{y_{POTENTIAL}}, C_{y_{VORTEX}}$
C_y
$C_{y_{POTENTIAL}}$
$C_{y_{VORTEX}}$
ϕ, ϕ_V
ϕ
ϕ_V
U/Df_0
Re

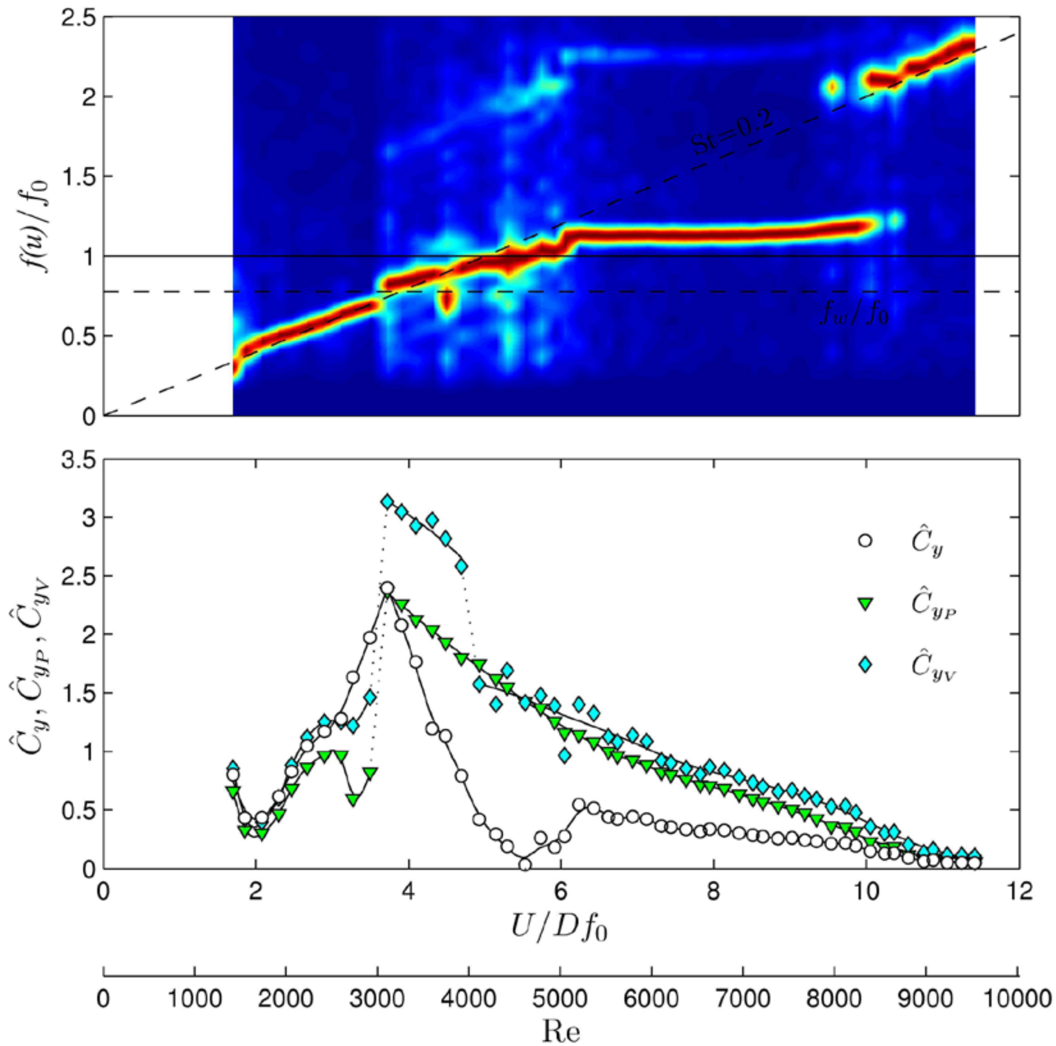


Fig. 5.4: Top: normalised PSD of velocity fluctuation (u) in the wake of a single cylinder. Please refer to Appendix A. Bottom: Decomposition of lift coefficient into potential and vortex components.

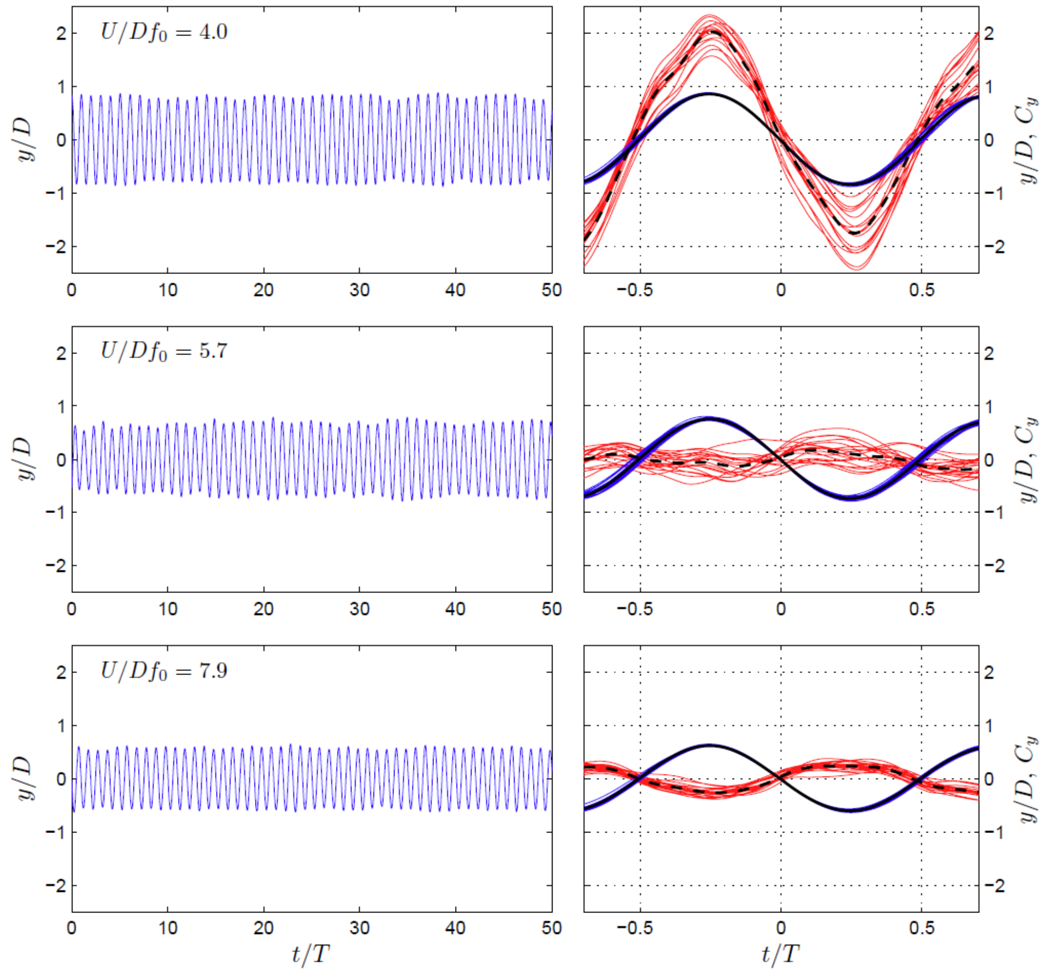


Fig. 5.2: Three examples of VIV time series. Left column: displacement signal for around 50 cycles of oscillation. Right column: superimposed plots of similar cycles. $\hat{y}$ in blue and C_y in red with average cycle in black. Top: upper branch; middle: transition between branches; bottom: lower branch.

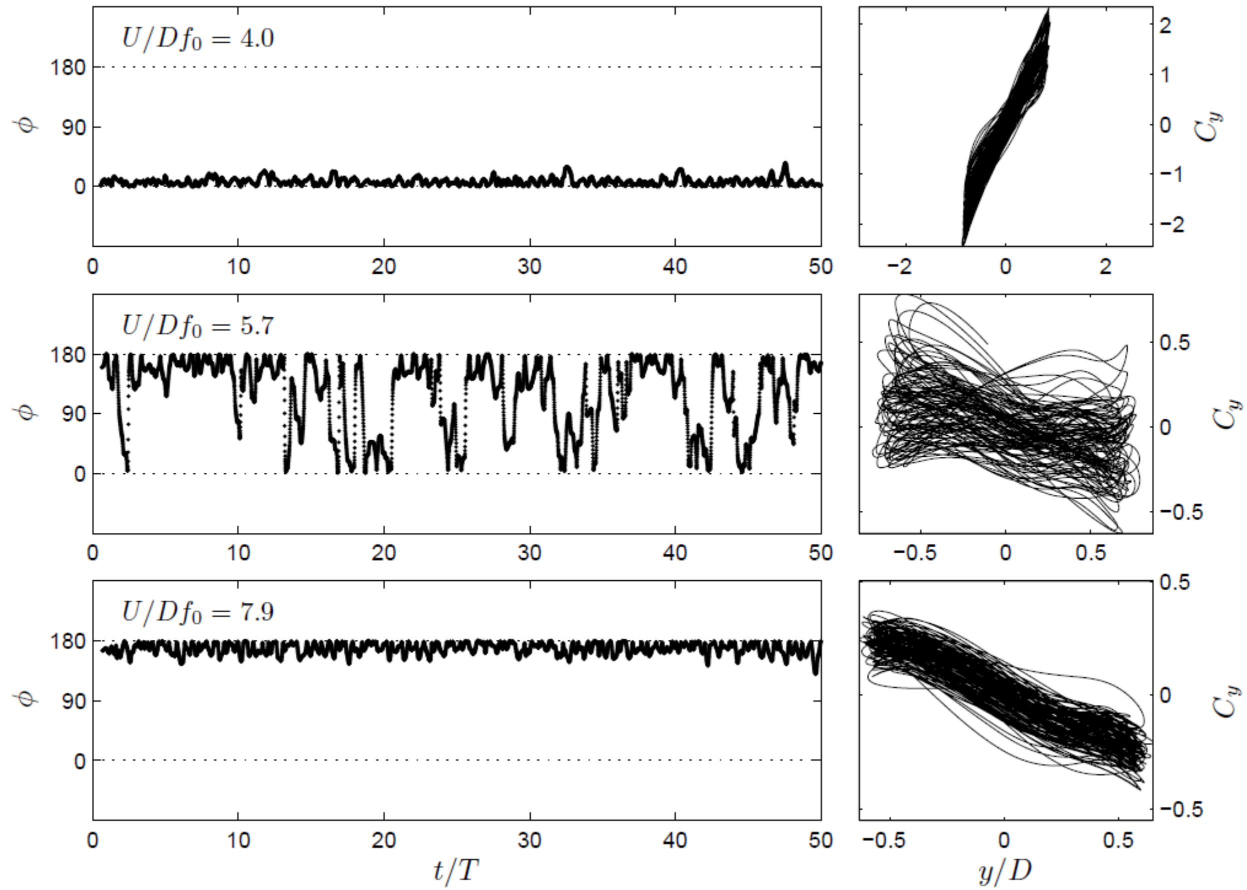


Fig. 5.3: Three examples of VIV phase angles. Left column: instantaneous phase angle ϕ for around 50 cycles of oscillation. Right column: Lissajous figures of C_y versus $\hat{y}$. Top: upper branch; middle: transition between branches; bottom: lower branch.

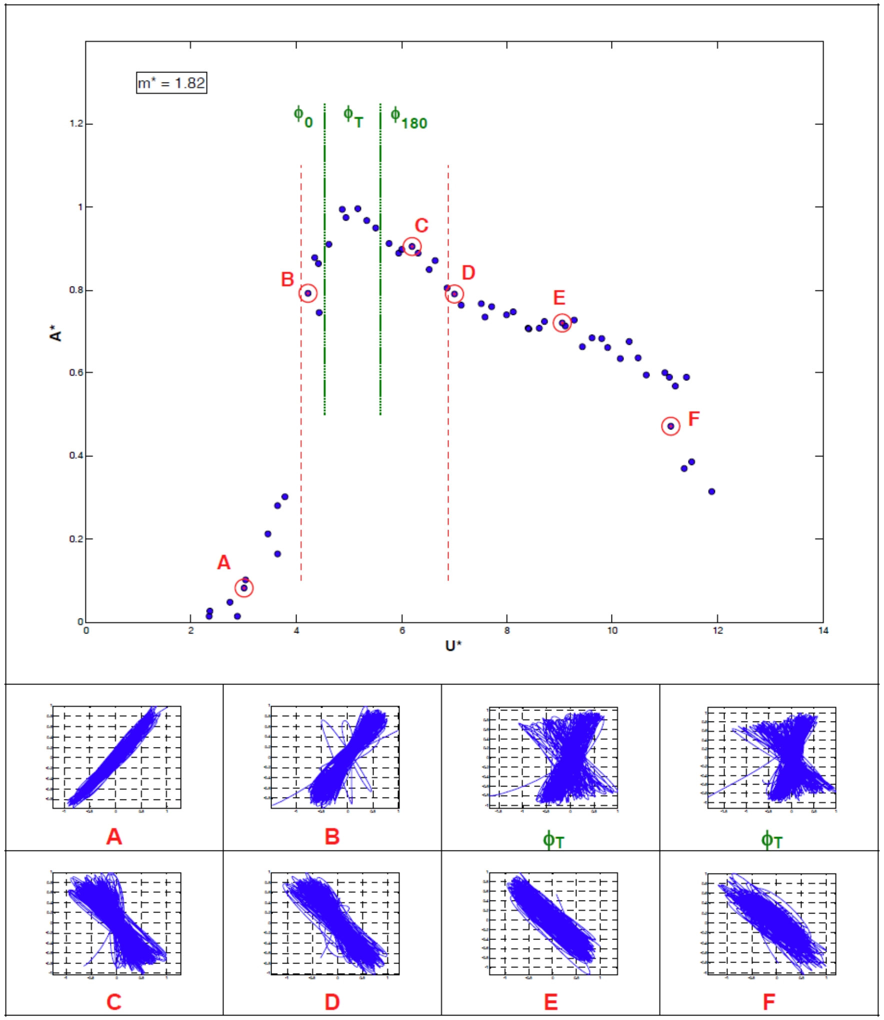
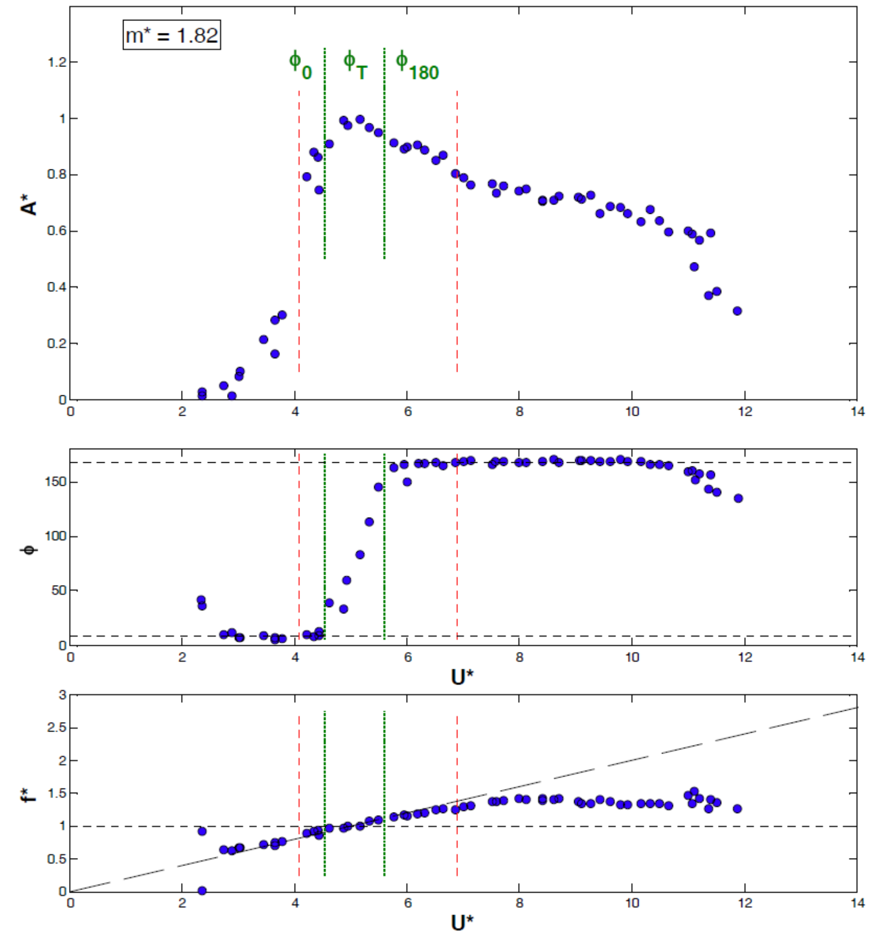
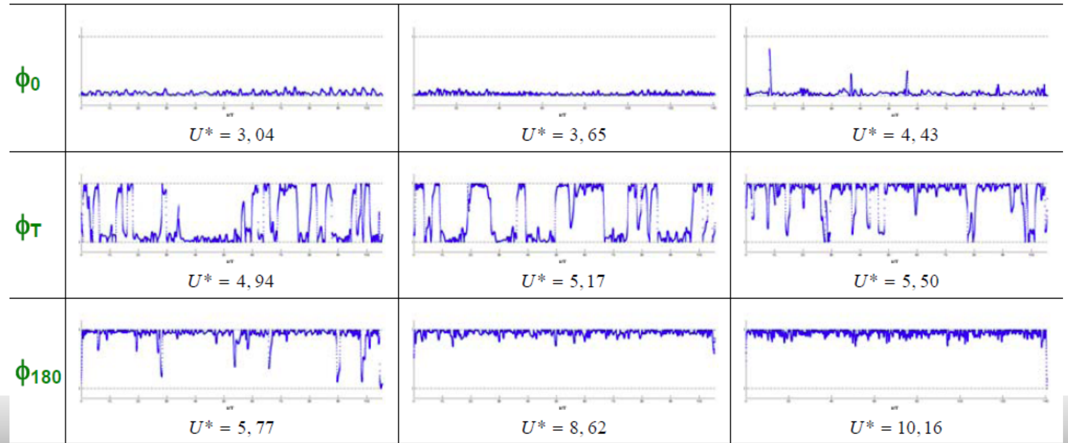
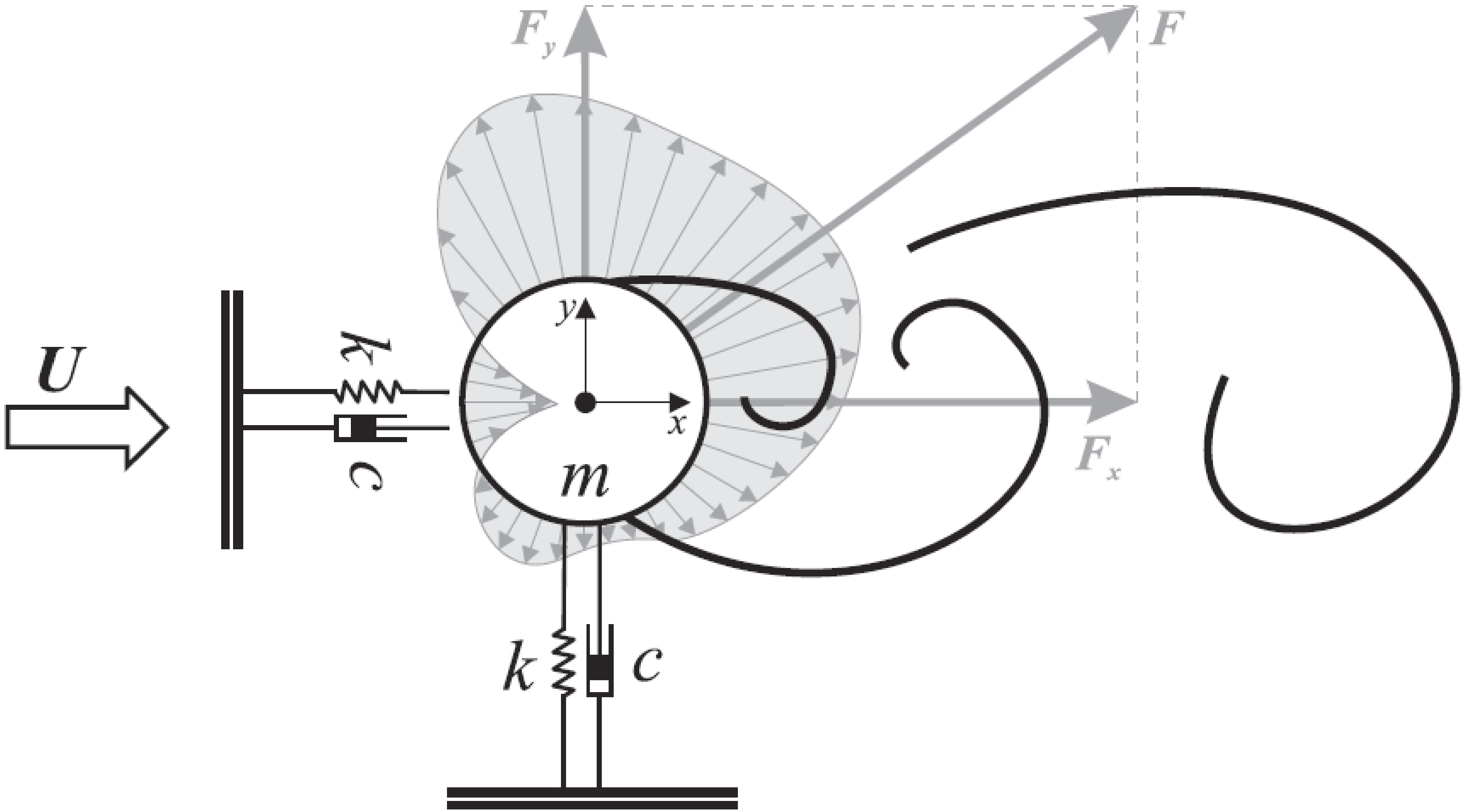


Figura 4.16: Transição entre o ângulo de fase. Verificação com figuras de Lissajous.

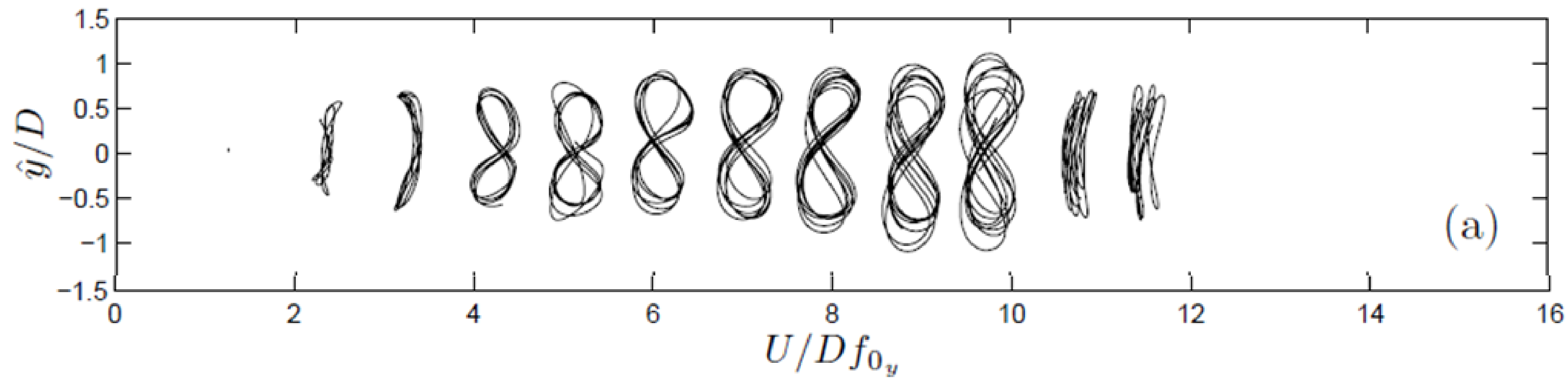




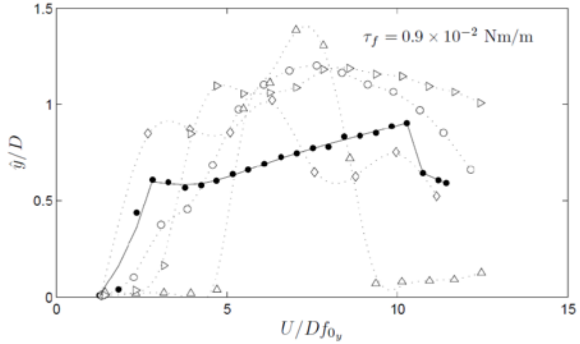
VIV com 2 graus de liberdade



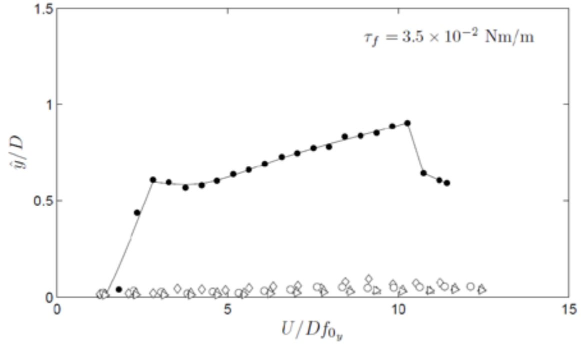
Trajetórias para sistemas com 2-dof



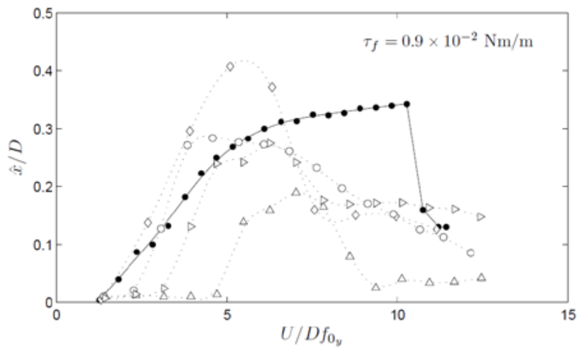
A few cycles of 2-dof trajectories versus reduced velocity: (a) plain cylinder,


$\tau_f = 0.9 \times 10^{-2}$ Nm/m
$\hat{y}/D$
U/Df_{0_y}

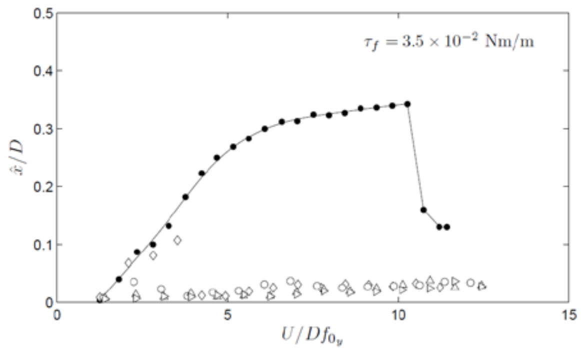
(a)


$\tau_f = 3.5 \times 10^{-2}$ Nm/m
$\hat{y}/D$
U/Df_{0_y}

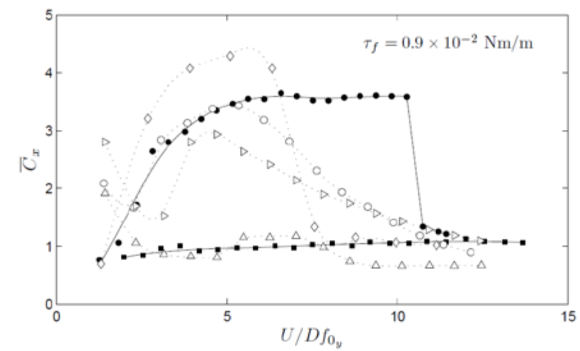
(b)


$\tau_f = 0.9 \times 10^{-2}$ Nm/m
$\hat{x}/D$
U/Df_{0_y}

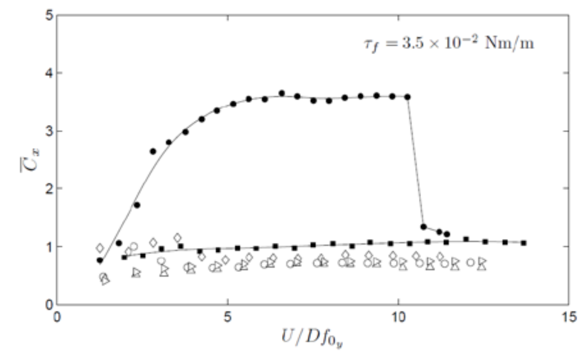
(c)


$\tau_f = 3.5 \times 10^{-2}$ Nm/m
$\hat{x}/D$
U/Df_{0_y}

(d)

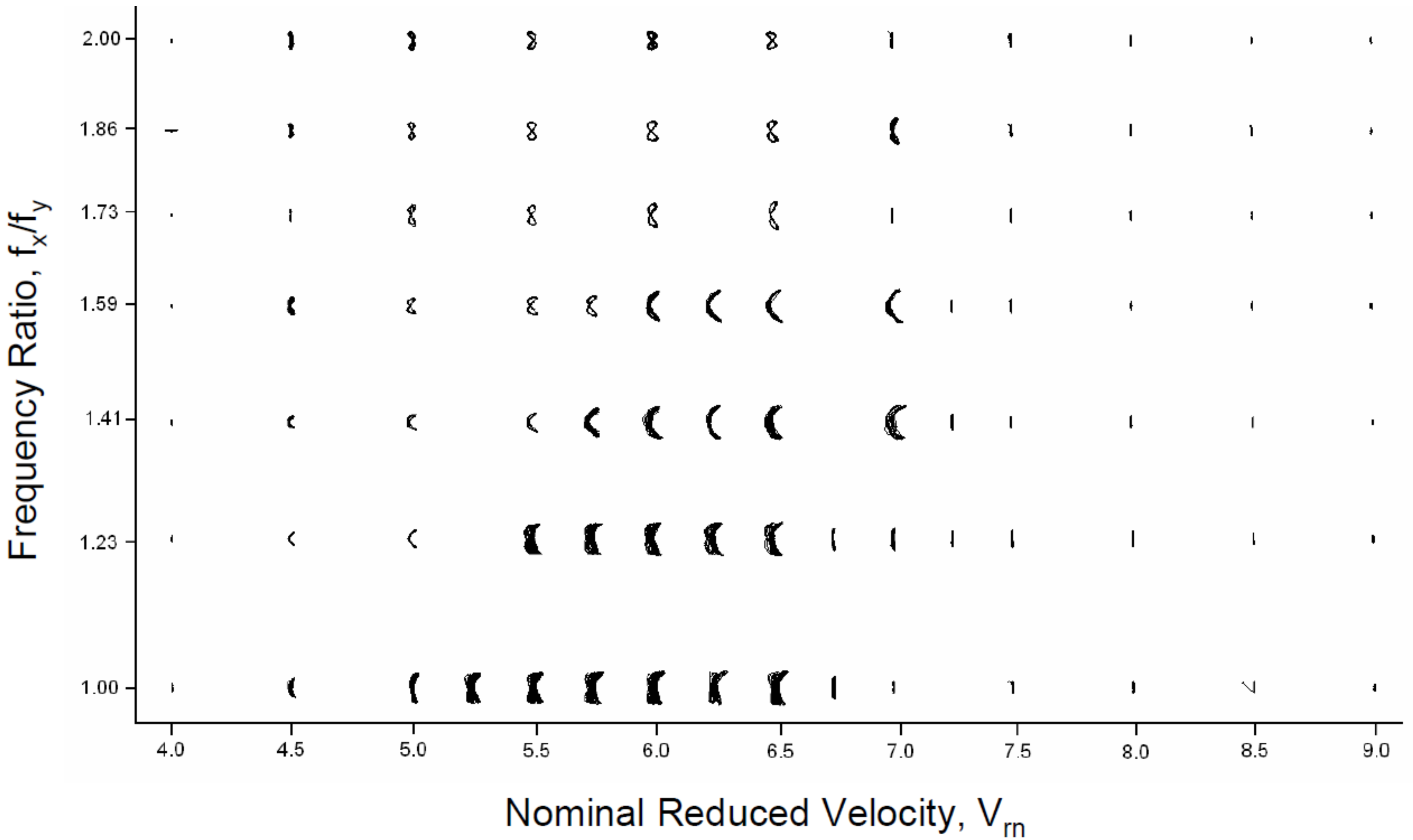

$\tau_f = 0.9 \times 10^{-2}$ Nm/m
$\overline{C}_x$
U/Df_{0_y}

(e)


$\tau_f = 3.5 \times 10^{-2}$ Nm/m
$\overline{C}_x$
U/Df_{0_y}

(f)

Trajetórias para sistemas com 2-dof



Rigid cylinder free to move in both transverse (y) and longitudinal (x) directions. High length:diameter ratio.

Techet (2005)

Added mass

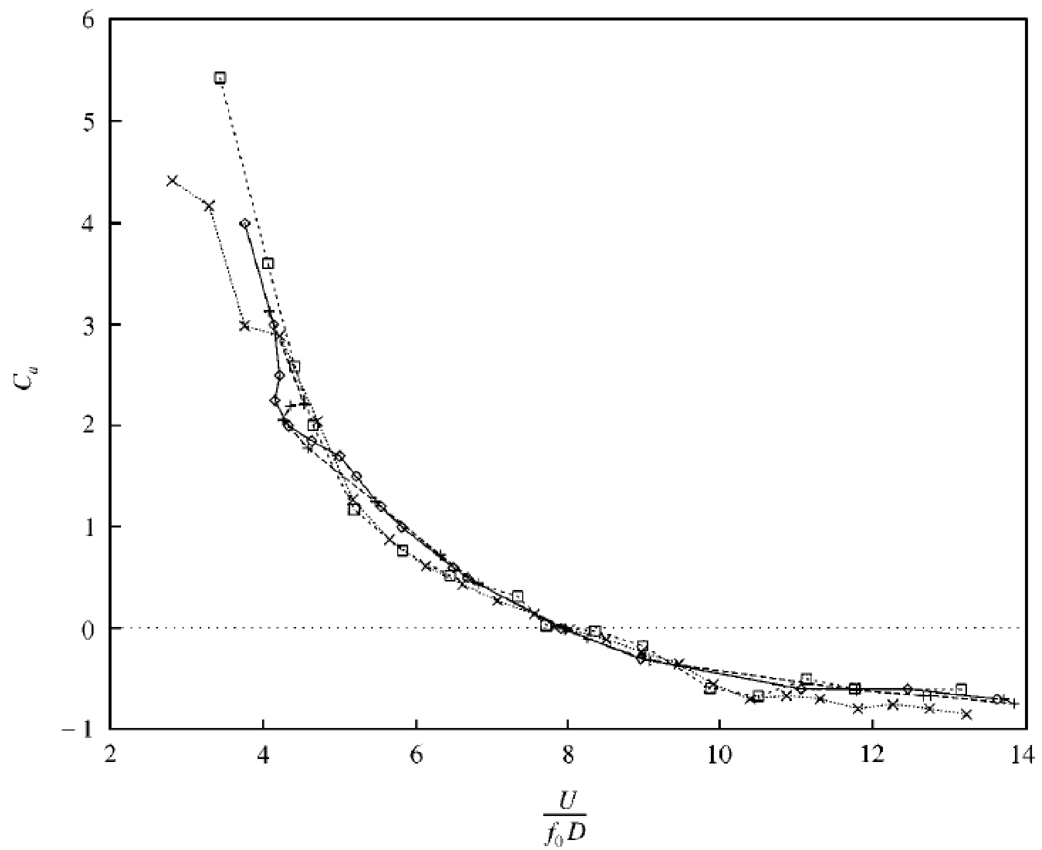


Figure 6. Comparison between added mass coefficients: —◇—, Gopalkrishnan, C_a; --- +---, Gopalkrishnan, C_{LA}; ---□---, Vikestad *et al.* (1997); ---- × ----, Present. The results of Gopalkrishnan for zero mean lift (mean power is zero) are found from the contour plots of the added mass coefficient and the lift coefficient in phase with acceleration.

Vikestad, Vandiver & Larsen (2000) JFS

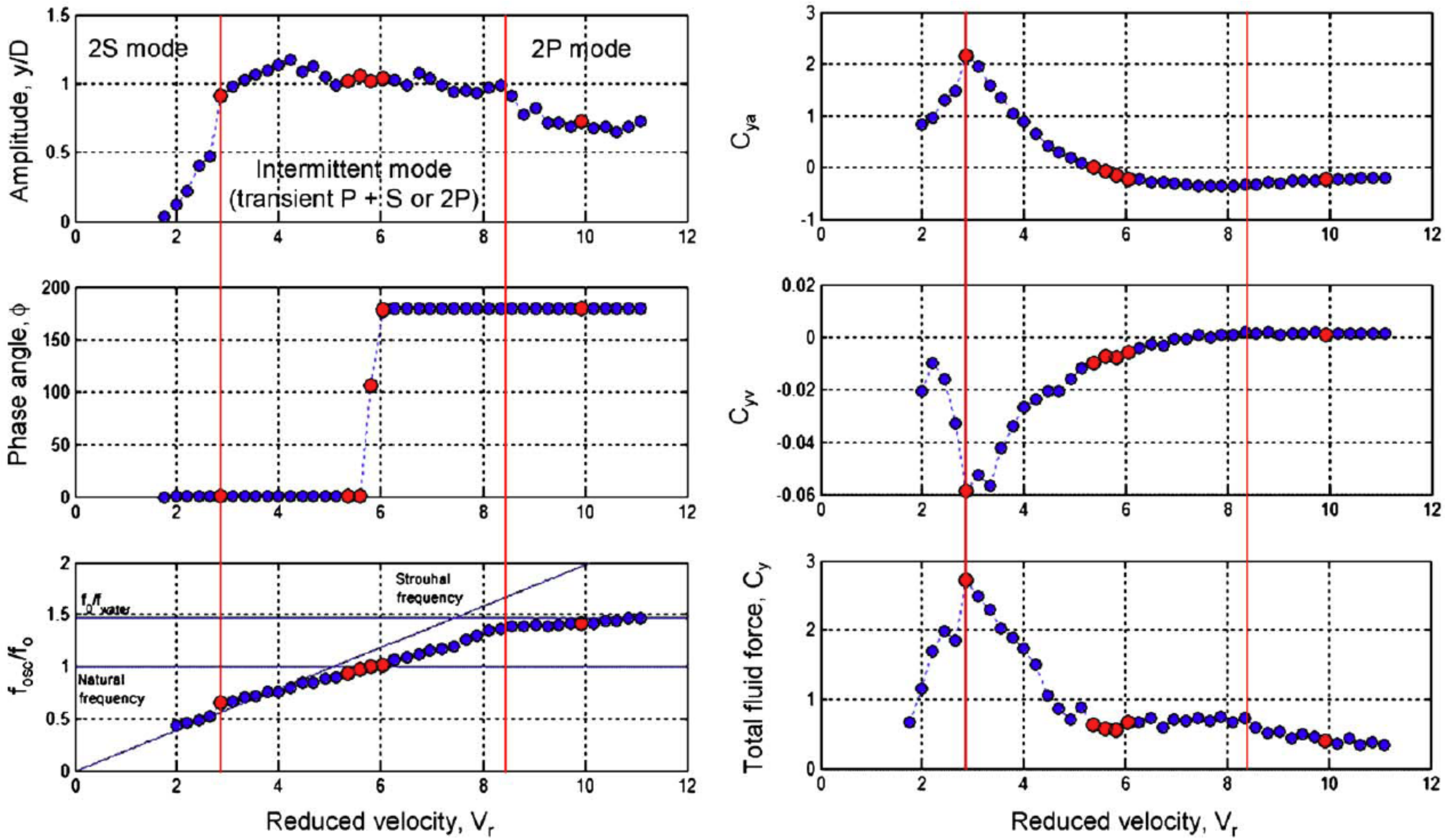


Fig. 2. Response and transverse force measurements for a plain cylinder with $m^* = 0.82$ and $\zeta_s = 1.5 \times 10^{-4}$.

Brankovic & Bearman (2006) JFS

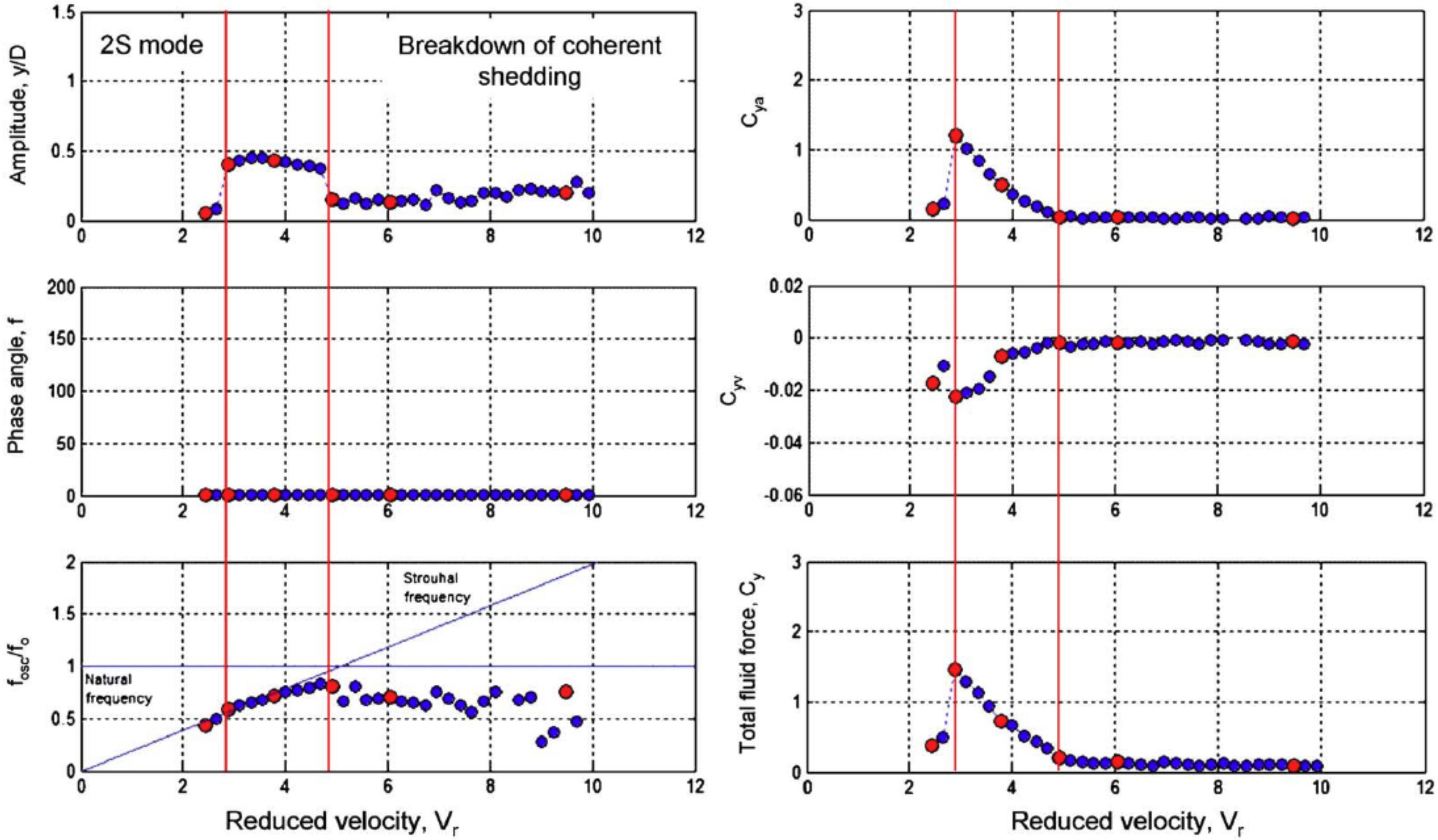


Fig. 4. Response and transverse force measurements for a straked cylinder with $m^* = 0.83$ and $\zeta_s = 2.5 \times 10^{-4}$.

Brankovic & Bearman (2006) JFS