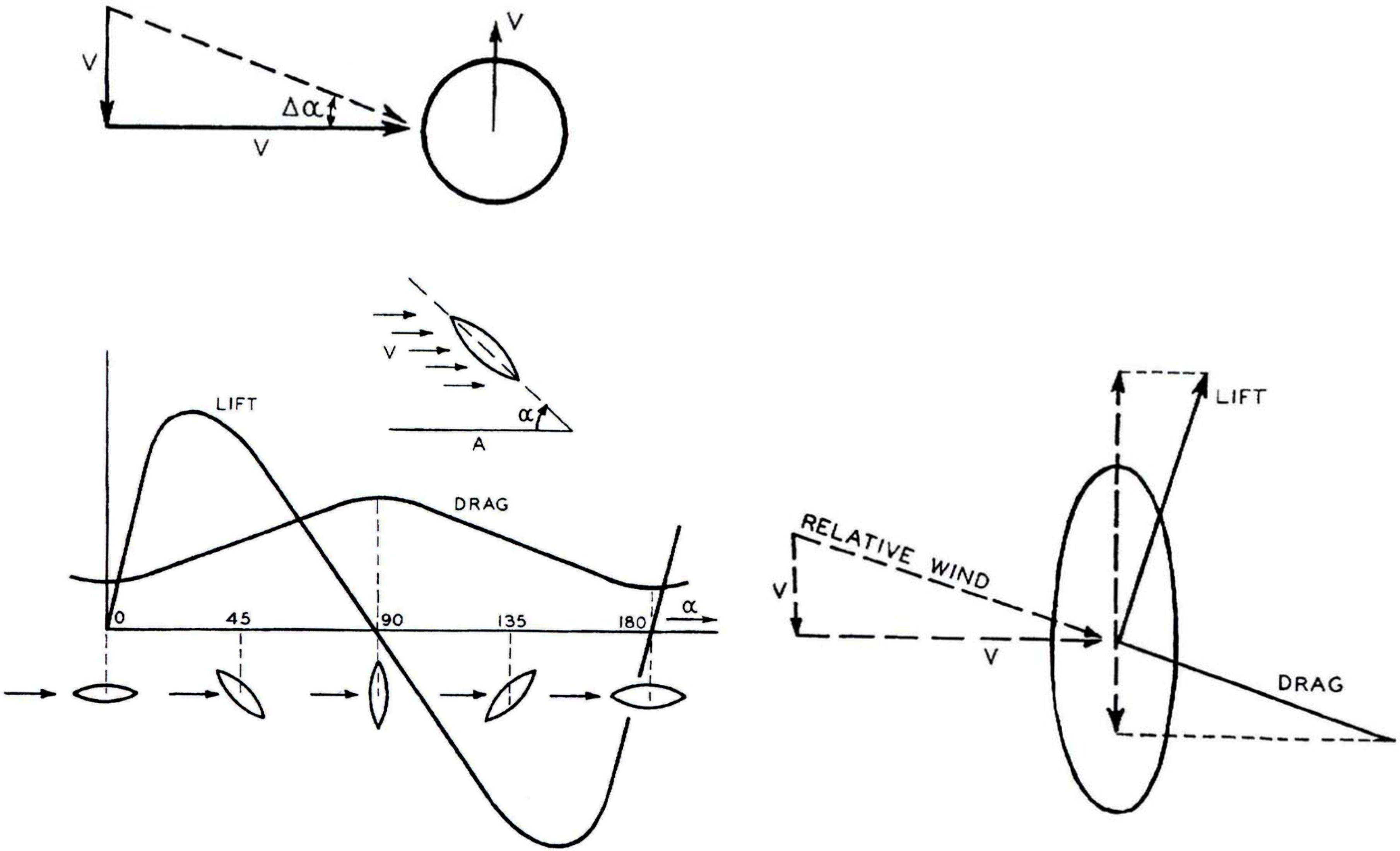
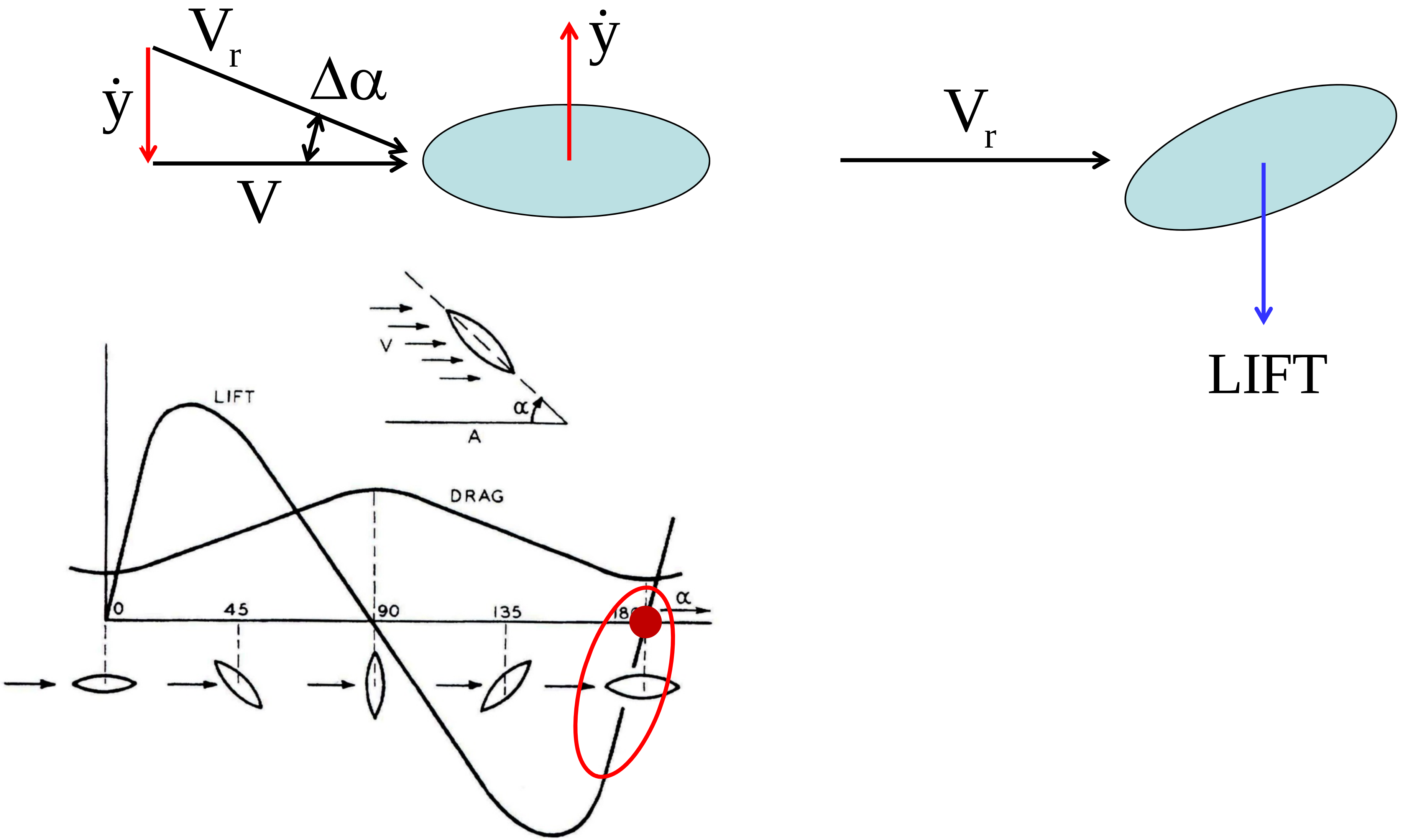
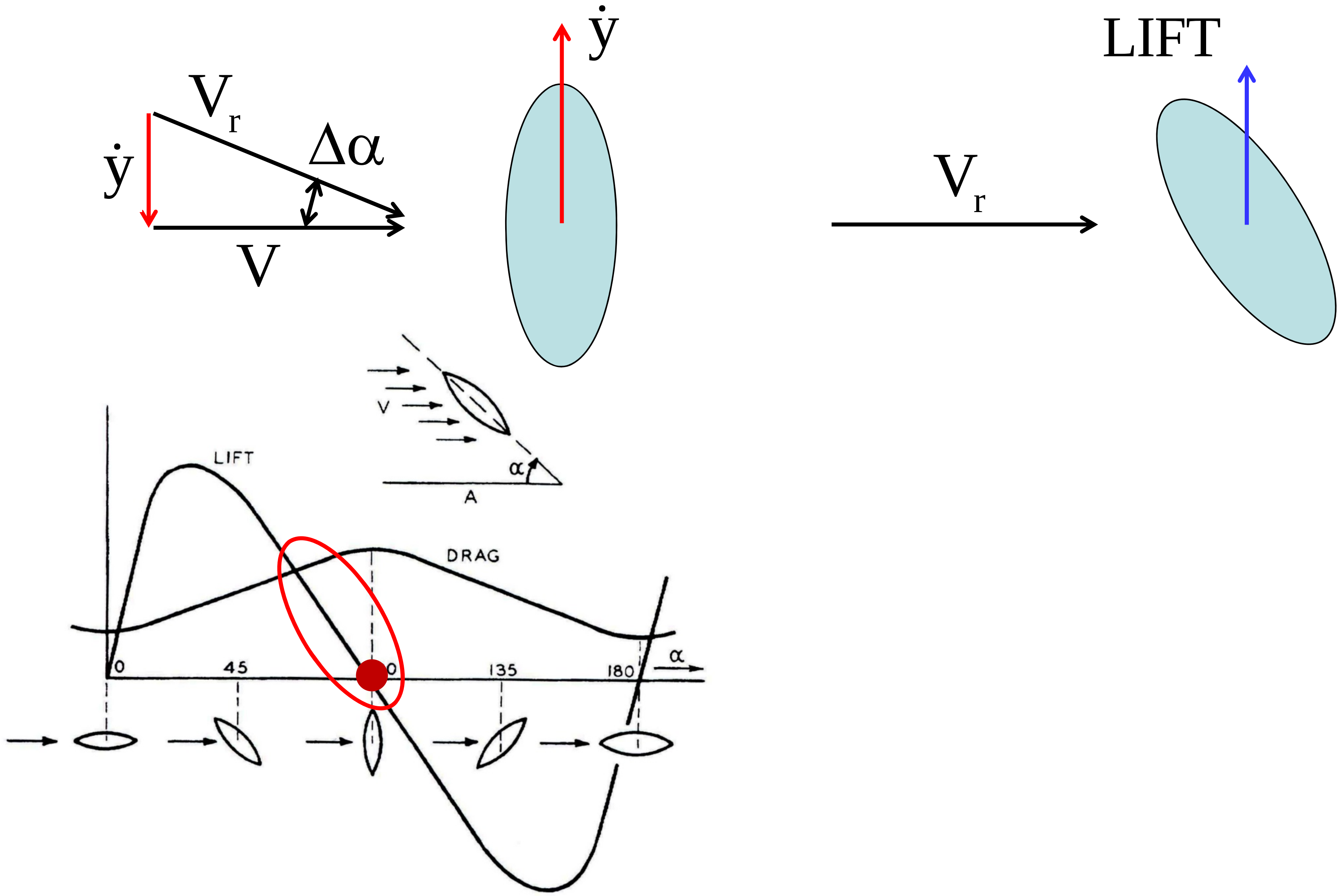


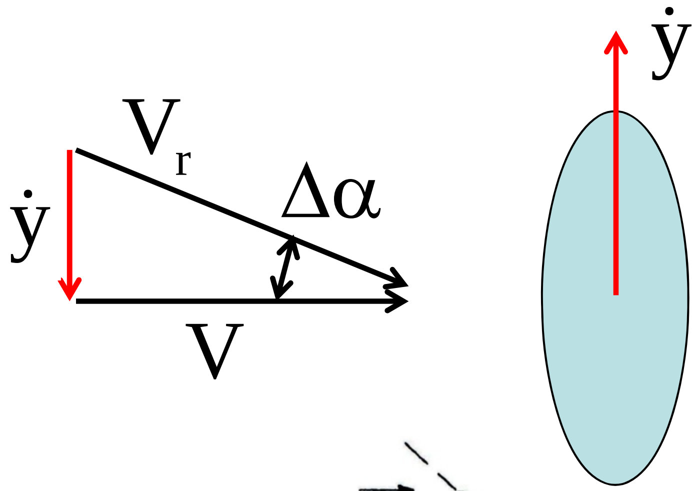
Crosswind galloping

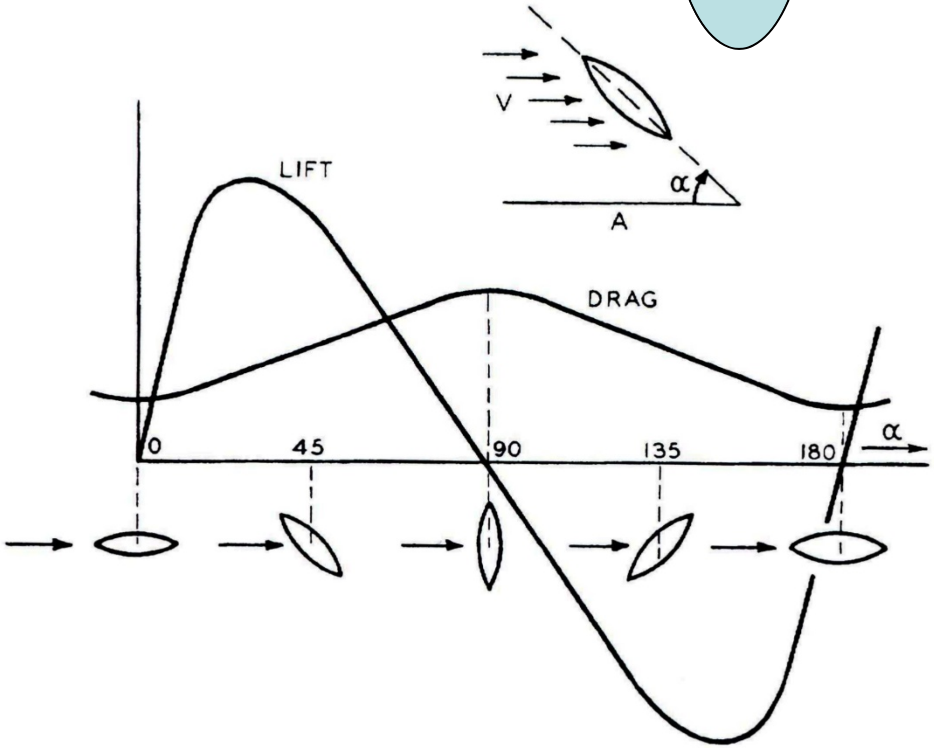


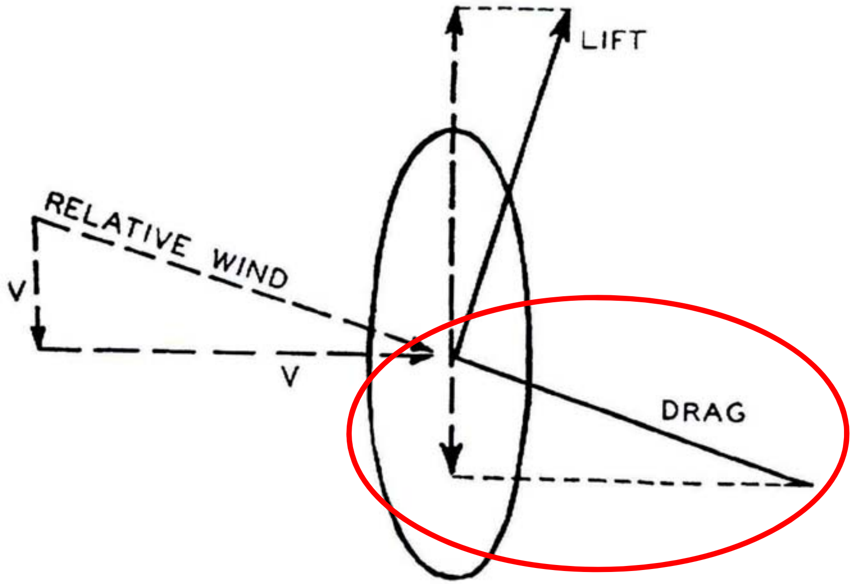
Crosswind galloping



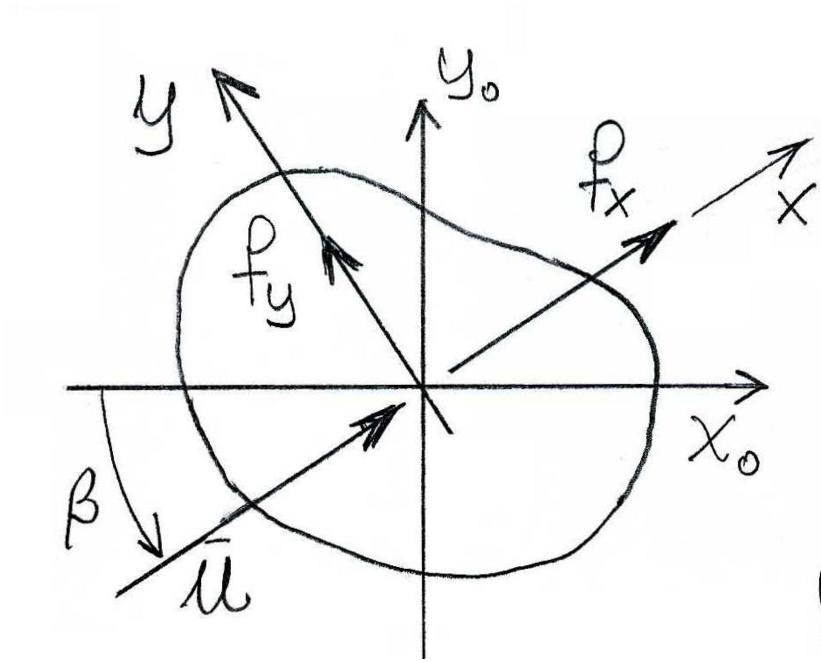
Crosswind galloping

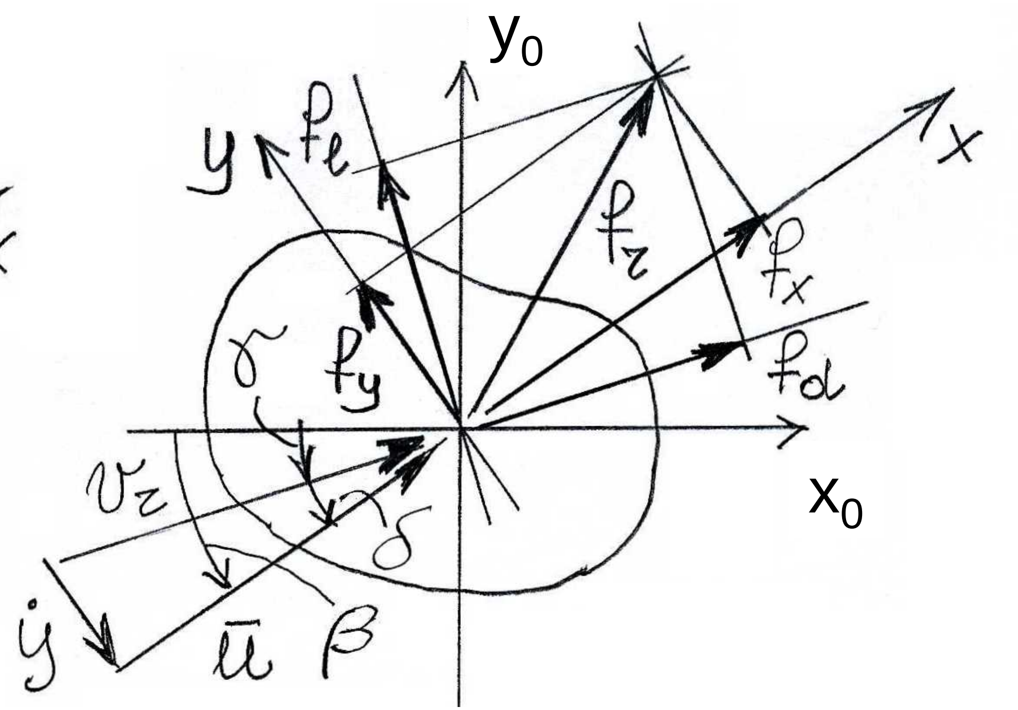






Crosswind galloping



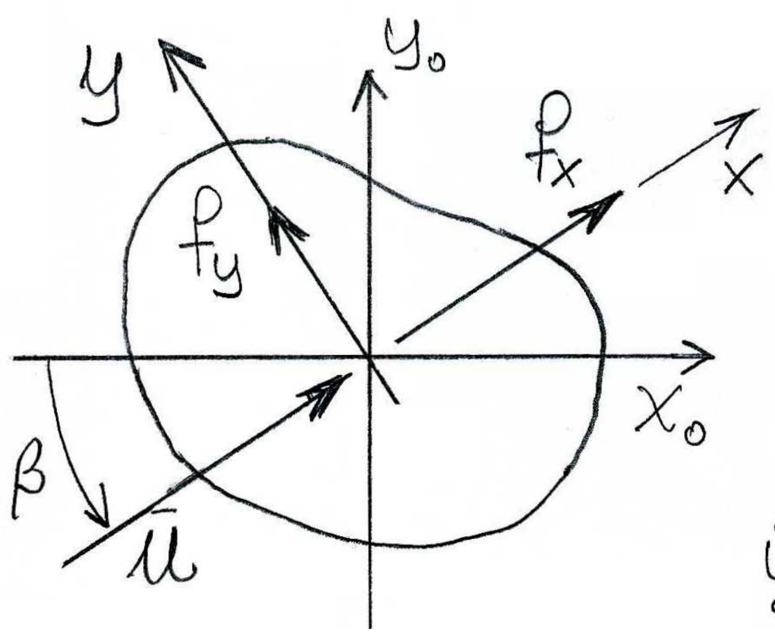


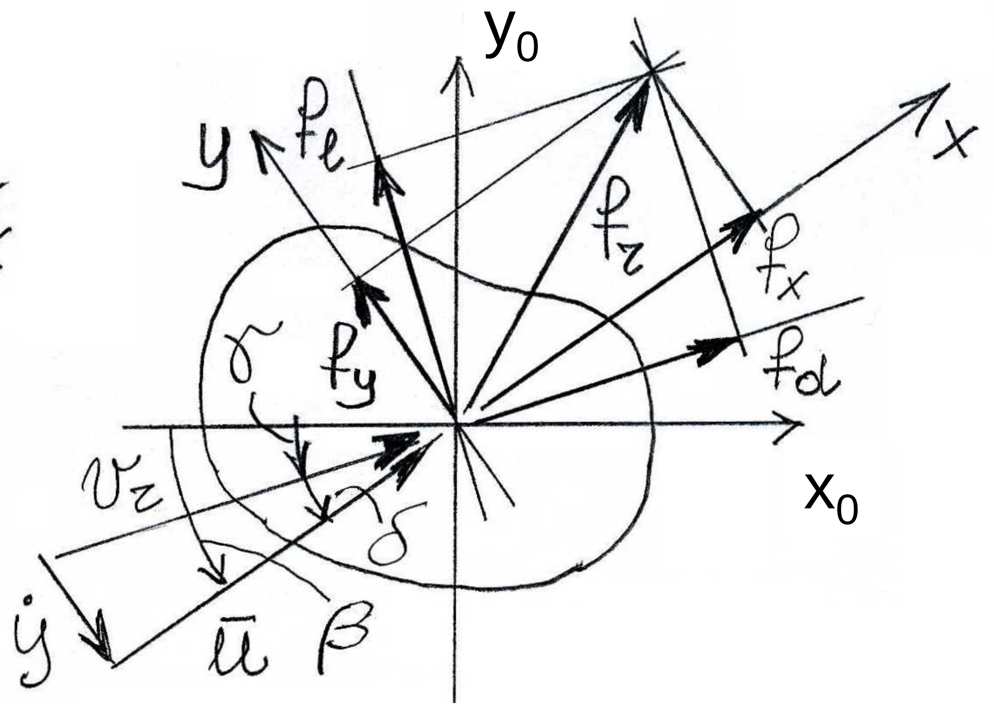
$$f_x = \frac{1}{2}\rho \bar{u}^2 b c_d(\beta); \quad f_y = \frac{1}{2}\rho \bar{u}^2 b c_l(\beta)$$

Quasi – steady theory

$$f_d = \frac{1}{2}\rho v_r^2 b c_d(\gamma); \quad f_l = \frac{1}{2}\rho v_r^2 b c_l(\gamma) \Rightarrow$$

$$f_y = -f_d \, sin\,\delta + f_l \, cos\,\delta = \frac{1}{2}\rho v_r^2 b\left[-c_d(\gamma) sin\,\delta + c_l(\gamma) cos\,\delta\right]$$

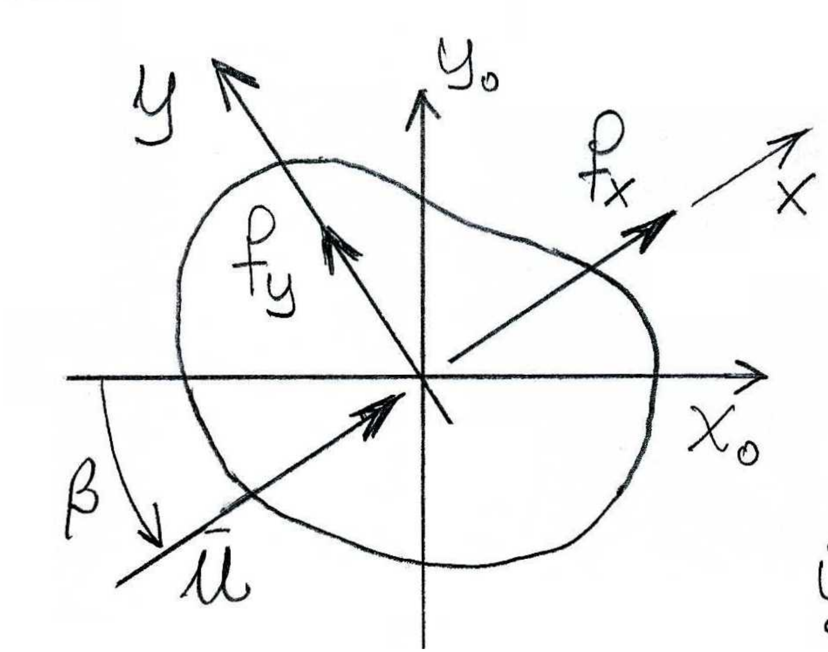


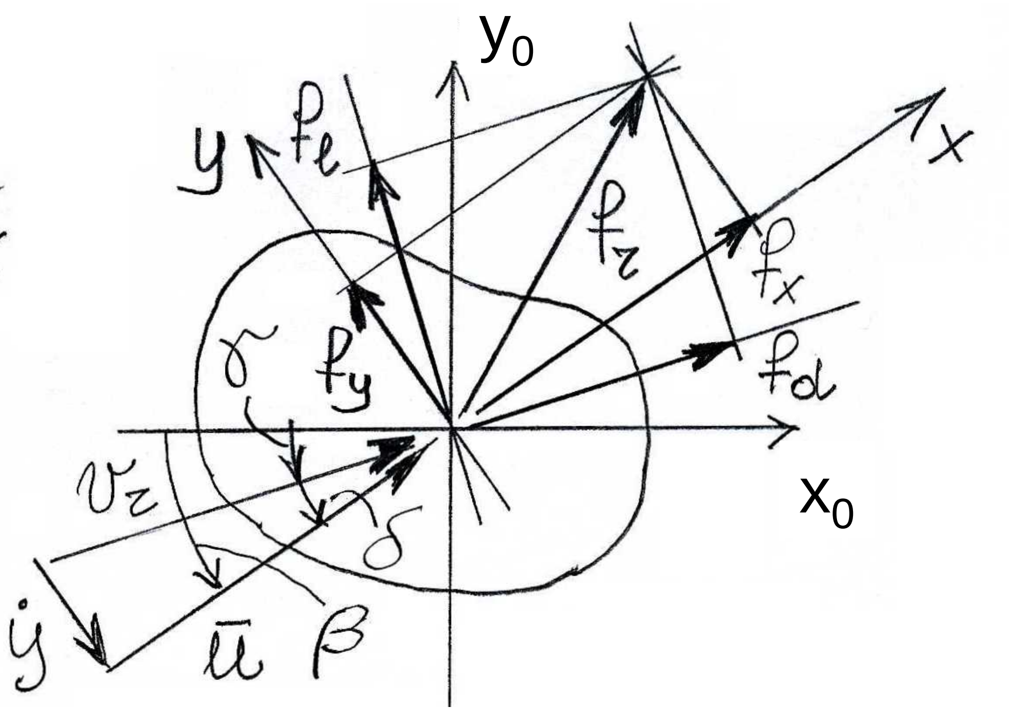


$$f_y = -f_d \, sin\delta + f_l \, cos\delta = \frac{1}{2}\rho v_r^2 b\left[-c_d(\gamma) sin\delta + c_l(\gamma) cos\delta\right]$$

$$\gamma = \beta - \delta\,; \quad \delta = arctg\frac{\dot{y}}{\bar{u}}\,; \quad v_r = \frac{\bar{u}}{cos\delta} \Rightarrow$$

$$f_y = \frac{1}{2}\rho\bar{u}^2 b\frac{1}{cos^2\delta}\left[-c_d(\beta-\delta) sin\delta + c_l(\beta-\delta) cos\delta\right]$$



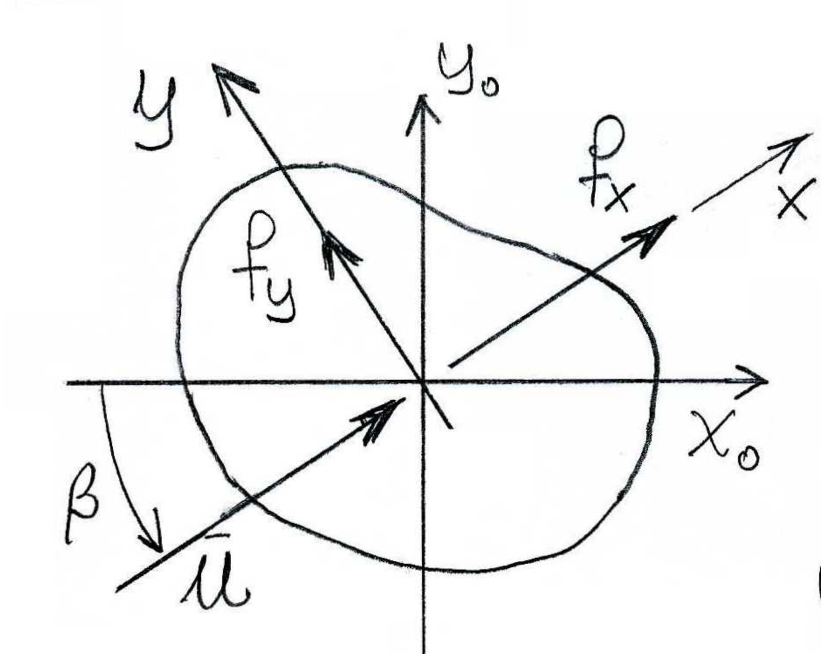


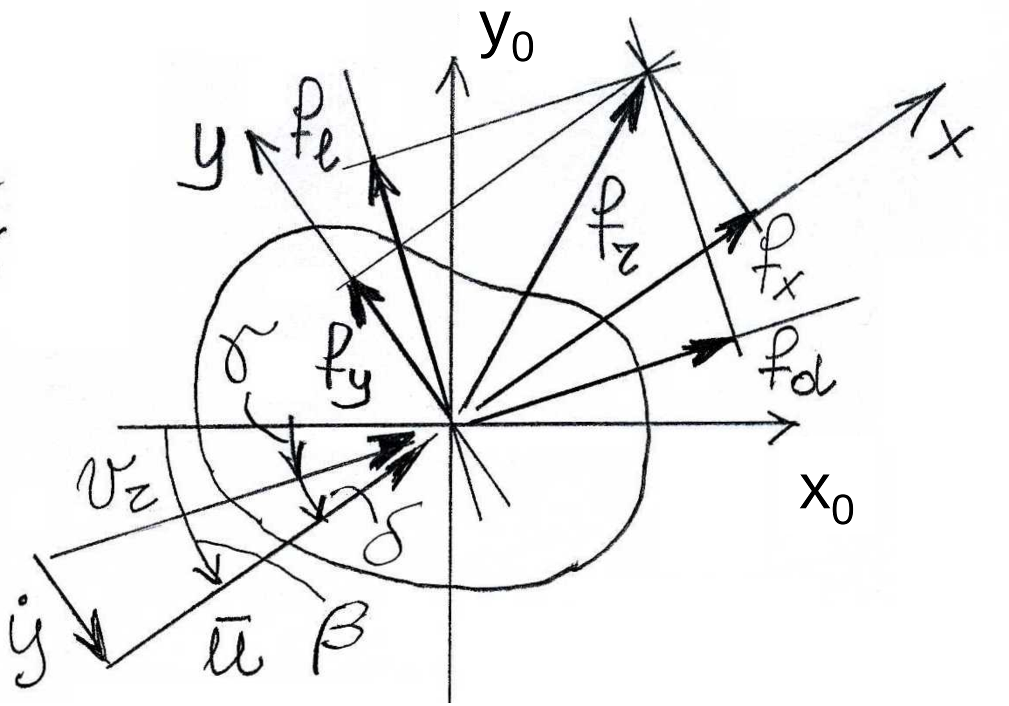
$$f_y = \frac{1}{2}\rho\bar{u}^2 b \frac{1}{\cos^2\delta}\left[-c_d(\beta-\delta)\sin\delta + c_l(\beta-\delta)\cos\delta\right]$$

Rotation of reference axis $: \beta = 0 \Rightarrow$

$$f_y = \frac{1}{2}\rho\bar{u}^2 b \frac{1}{\cos\delta}\left[-c_d(-\delta)\,\mathrm{tg}\delta + c_l(-\delta)\right] = \frac{1}{2}\delta\bar{u}^2 b c_{fy}$$

$$c_{fy} = \frac{1}{\cos\delta}\left[-c_d(-\delta)\,\mathrm{tg}\delta + c_l(-\delta)\right] = \sum_k \frac{1}{k!}\left.\frac{\partial^k c_{fy}(\delta)}{\partial\delta^k}\right|_{\delta=0}\cdot\delta^k$$





$$f_y = \frac{1}{2}\delta \bar{u}^2 b c_{fy}\ ; \quad c_{fy} = \sum_k \frac{1}{k!} \frac{\partial^k c_{fy}(\delta)}{\partial \delta^k}\bigg|_{\delta=0} \cdot \delta^k$$

Linearized analysis $(k = 0,1) \Rightarrow$ Incipient instability

$$c_{fy} = c_l - (c_d + c_l')\frac{\dot{y}}{\bar{u}} \quad \left(c_d = c_d\big|_{\delta=0}; c_l = c_l\big|_{\delta=0}\right)$$

Galloping coefficient

$$a_G = -(c_d + c_l') \Rightarrow c_{fy} = c_l + a_G \frac{\dot{y}}{\bar{u}}$$

$$f_y = \frac{1}{2}\delta \bar{u}^2 b c_{fy} \; ; \quad c_{fy} = c_l + a_G \frac{\dot{y}}{\bar{u}}$$

SDOF Equation of motion (per unit length)

$$\ddot{y} + 2\xi_s\omega_0\dot{y} + \omega_0^2 y = \frac{1}{m} f_y = \frac{1}{m}\frac{1}{2}\rho\bar{u}^2 b c_{fy} = \frac{1}{m}\frac{1}{2}\rho\bar{u}^2 b c_l + \frac{1}{m}\frac{1}{2}\rho\bar{u}^2 b a_G \frac{\dot{y}}{\bar{u}} \Rightarrow$$

$$\ddot{y} + \left(2\xi_s\omega_0 - \frac{1}{m}\frac{1}{2}\rho\bar{u}^2 b a_G \frac{1}{\bar{u}}\right)\dot{y} + \omega_0^2 y = \frac{1}{m}\frac{1}{2}\rho\bar{u}^2 b c_l \Rightarrow$$

$$\ddot{y} + 2\left(\xi_s + \xi_a\right)\omega_0\dot{y} + \omega_0^2 y = \frac{1}{m}\frac{1}{2}\rho\bar{u}^2 b c_l$$

Crosswind aerodynamic damping

$$\xi_a = -\frac{\rho\bar{u} b a_G}{4m\omega_0} = \frac{\rho\bar{u} b\left(c_d + c_l'\right)}{4m\omega_0}$$

Total crosswind damping

$$\xi_t = \xi_s + \xi_a = \xi_s - \frac{\rho\bar{u} b a_G}{4m\omega_0} = \xi_s + \frac{\rho\bar{u} b\left(c_d + c_l'\right)}{4m\omega_0}$$

$$\ddot{y} + 2\xi_t \omega_0 \dot{y} + \omega_0^2 y = \frac{1}{m}\frac{1}{2}\rho \bar{u}^2 b c_l$$

$$\xi_t = \xi_s + \xi_a = \xi_s - \frac{\rho \bar{u} b a_G}{4 m \omega_0} = \xi_s + \frac{\rho \bar{u} b \left(c_d + c_l'\right)}{4 m \omega_0}$$

GALLOPING necessary condition

Glauert – Den Hartog criterion

$$\xi_a < 0 \Rightarrow a_G > 0 \text{ or } \left(c_d + c_l'\right) < 0$$

GALLOPING necessary and sufficient condition

$$\xi_t \le 0 \Rightarrow \xi_s - \frac{\rho \bar{u} b a_G}{4 m \omega_0} = \xi_s + \frac{\rho \bar{u} b \left(c_d + c_l'\right)}{4 m \omega_0} \le 0$$

GALLOPING necessary and sufficient condition

$$\xi_t \le 0 \Rightarrow \xi_s - \frac{\rho \bar{u} b a_G}{4m\omega_0} = \xi_s + \frac{\rho \bar{u} b \left(c_d + c_l'\right)}{4m\omega_0} \le 0 \Rightarrow$$

$$\bar{u} \ge \frac{4m\omega_0 \xi_s}{\rho b a_G} = -\frac{4m\omega_0 \xi_s}{\rho b \left(c_d + c_l'\right)}$$

being $a_G > 0, \left(c_d + c_l'\right) < 0$

GALLOPING critical velocity

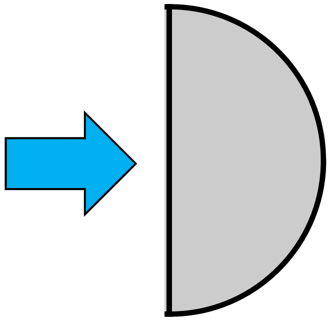
$$\bar{u}_{cr} = \frac{4m\omega_0 \xi_s}{\rho b a_G} = -\frac{4m\omega_0 \xi_s}{\rho b \left(c_d + c_l'\right)} \Rightarrow$$

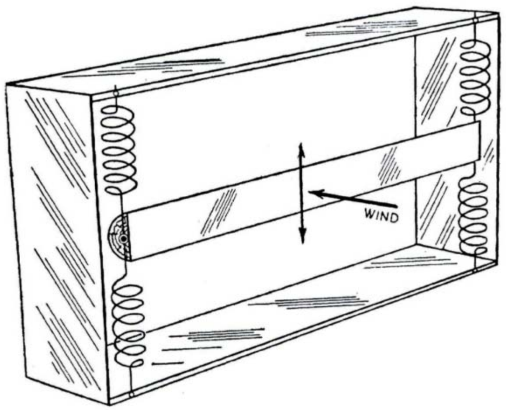
$$\bar{u}_{cr} = \frac{4m\omega_0 \xi_s}{\rho b a_G} \cdot \frac{\pi b}{\pi b} = \frac{\omega_0 b}{\pi a_G} \cdot \frac{4\pi m \xi_s}{\rho b^2} = \frac{\omega_0 b}{\pi a_G} \cdot Sc = \frac{2 n_0 b}{a_G} \cdot Sc$$

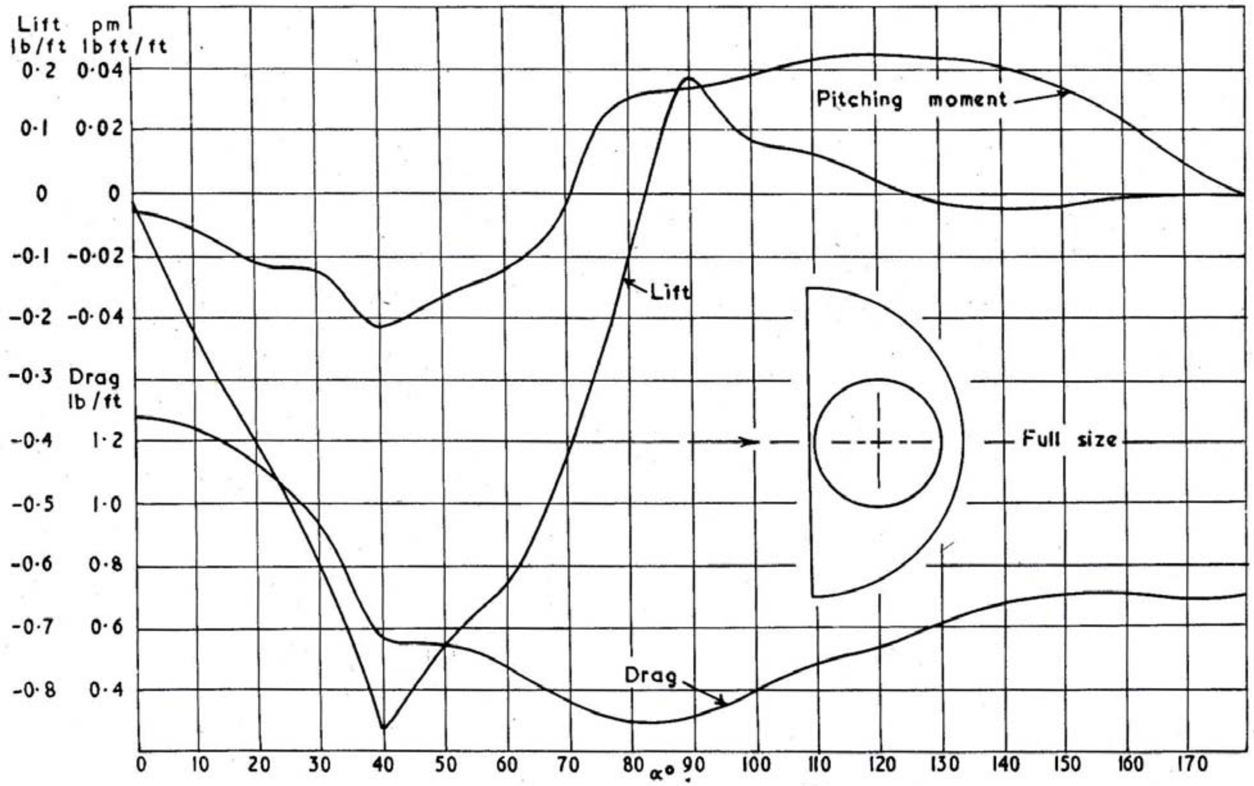
$$Sc = \frac{4\pi m \xi_s}{\rho b^2}$$

Necessary condition

$$c_d + c_l' < 0$$



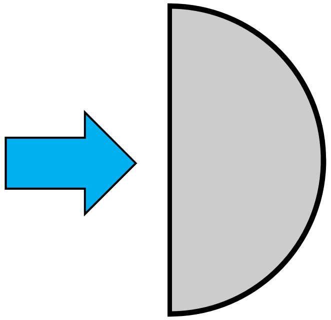


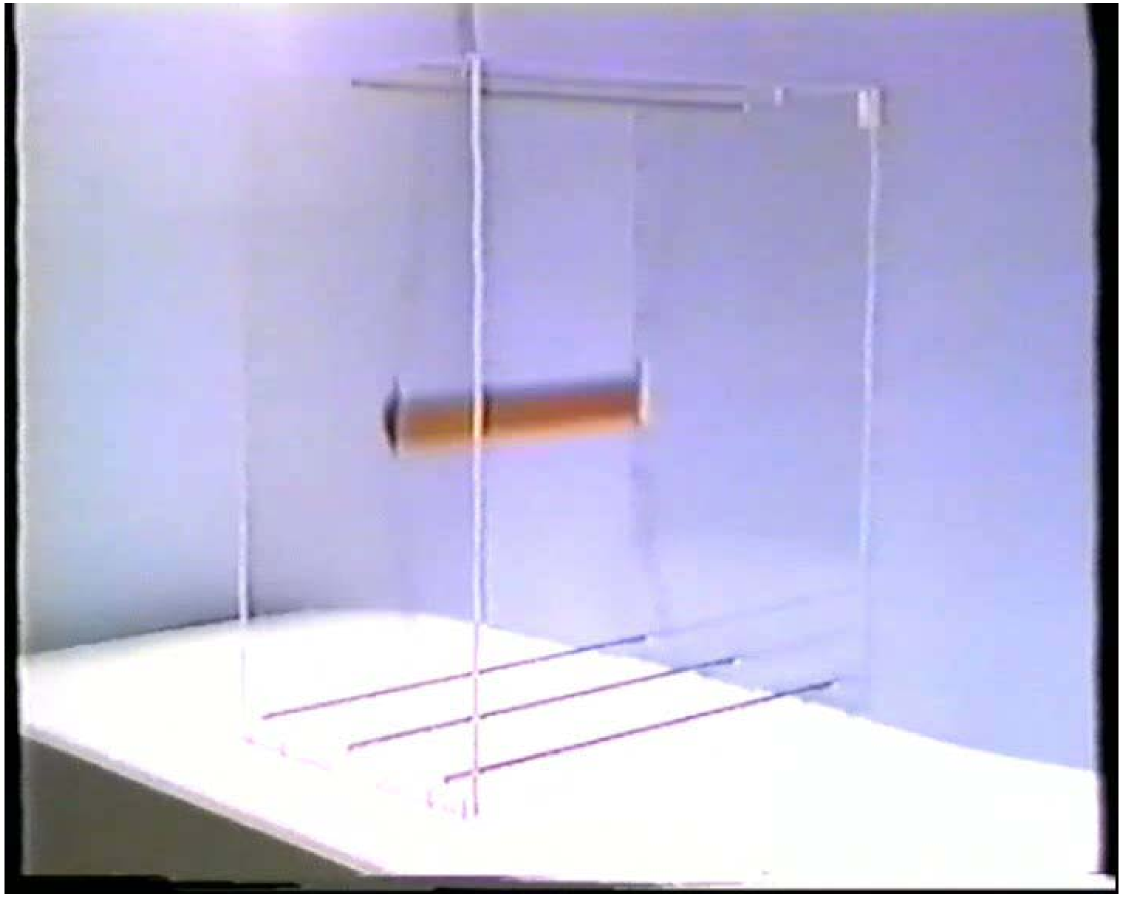


D-shaped section

Necessary condition

$$c_d + c_l' < 0$$

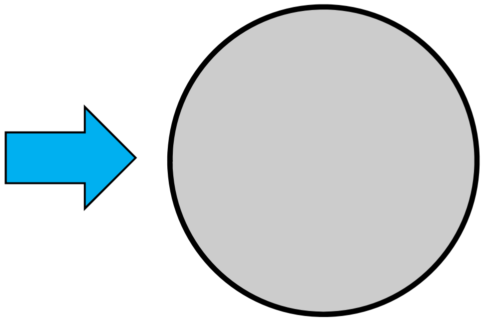


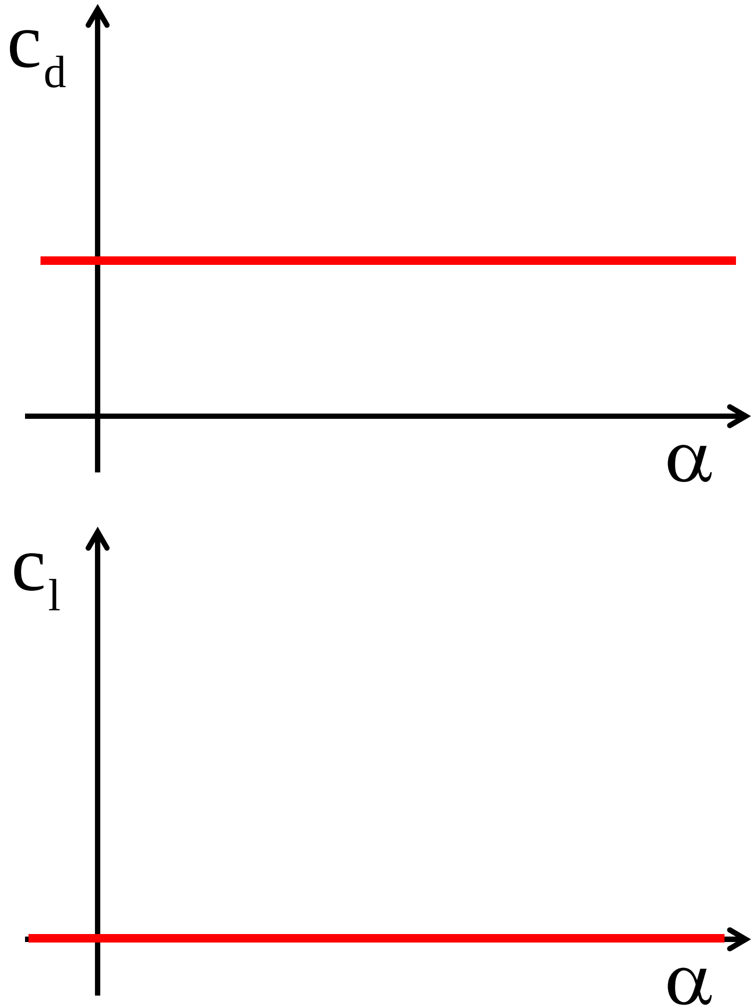


D-shaped section

Necessary condition

$$c_d + c_l' < 0$$

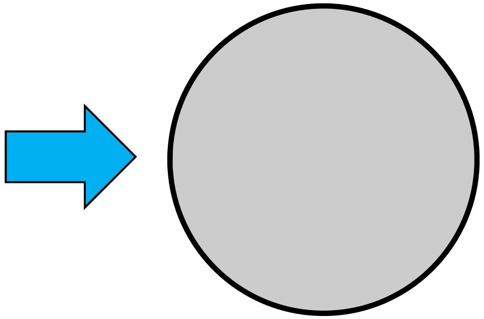


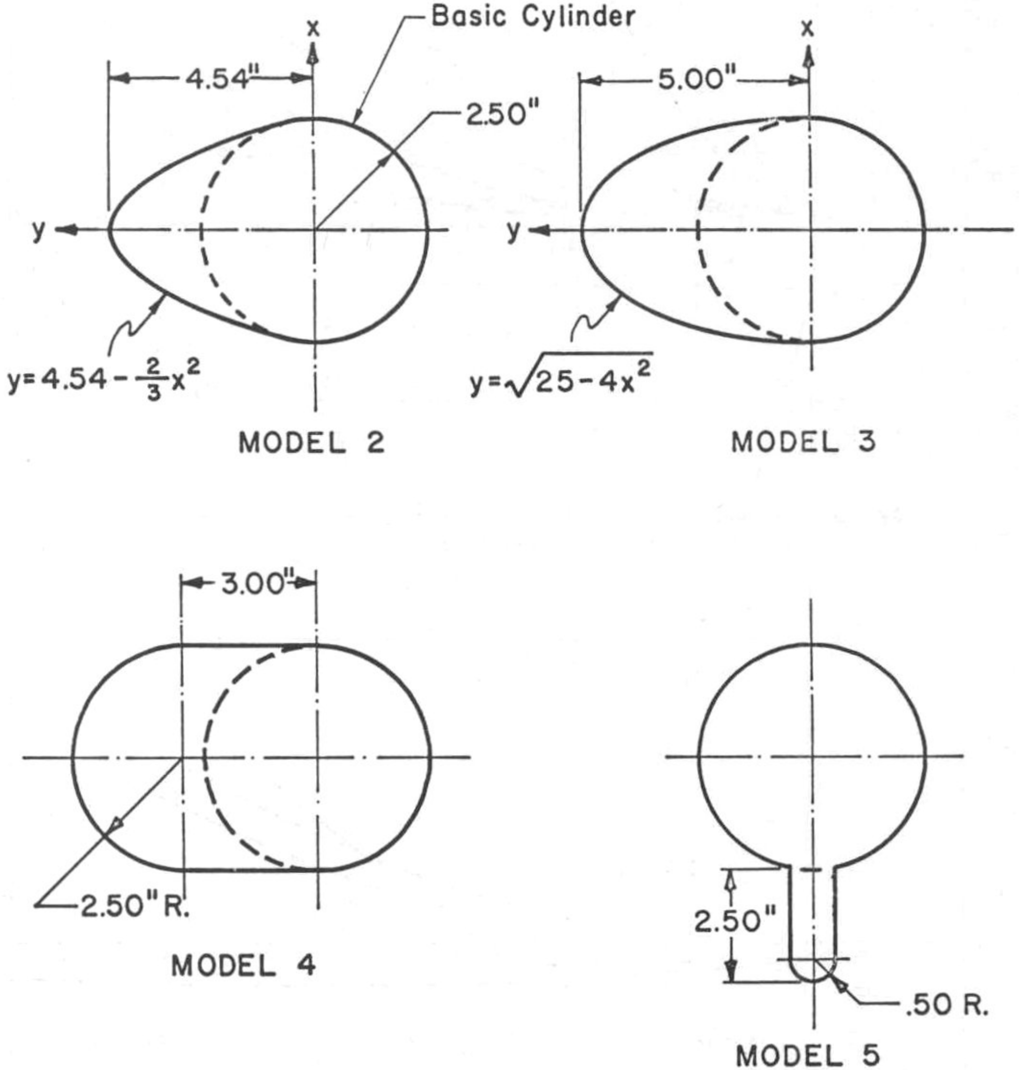


Circular section

Necessary condition

$$c_d + c_l' < 0$$

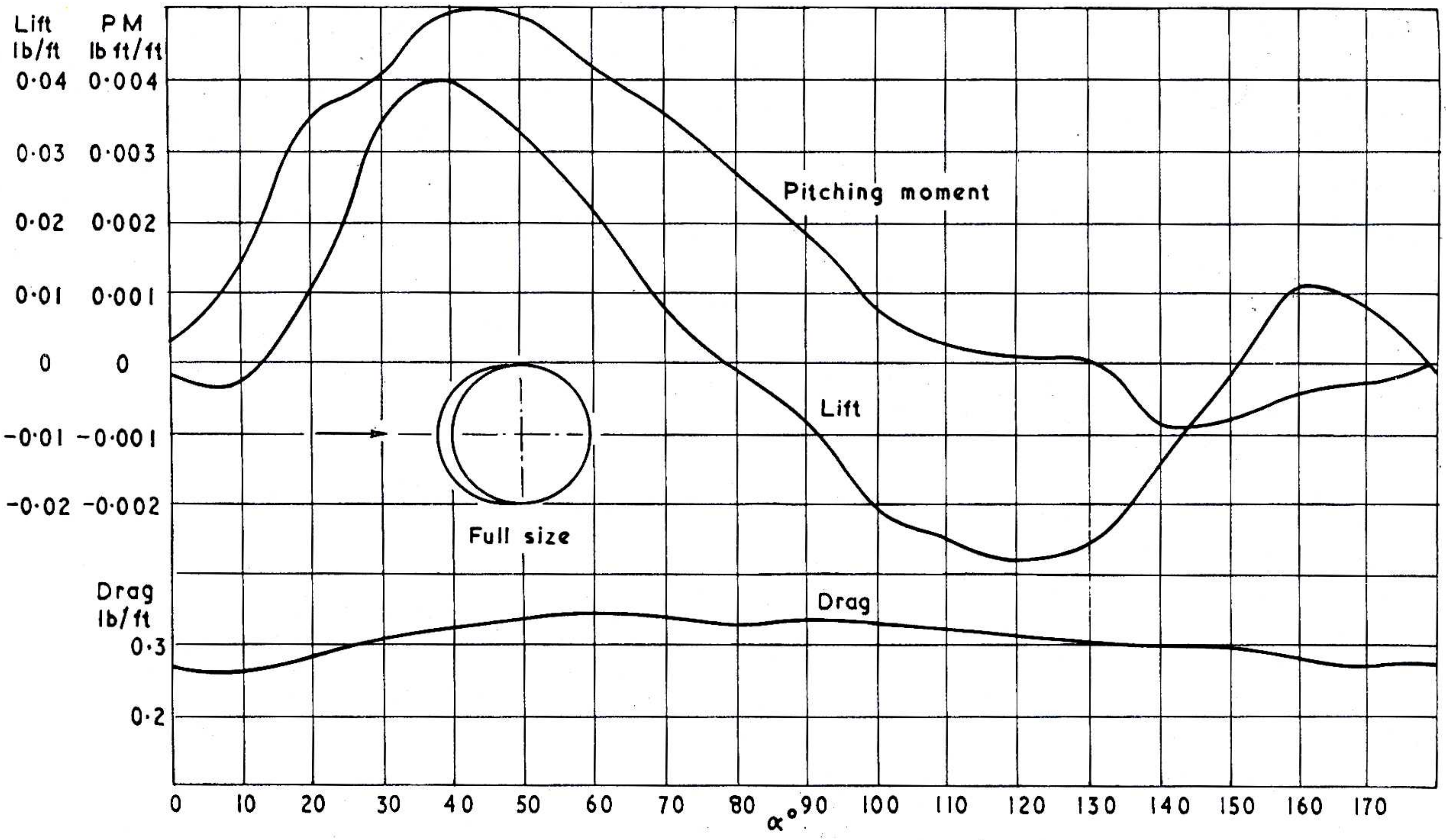




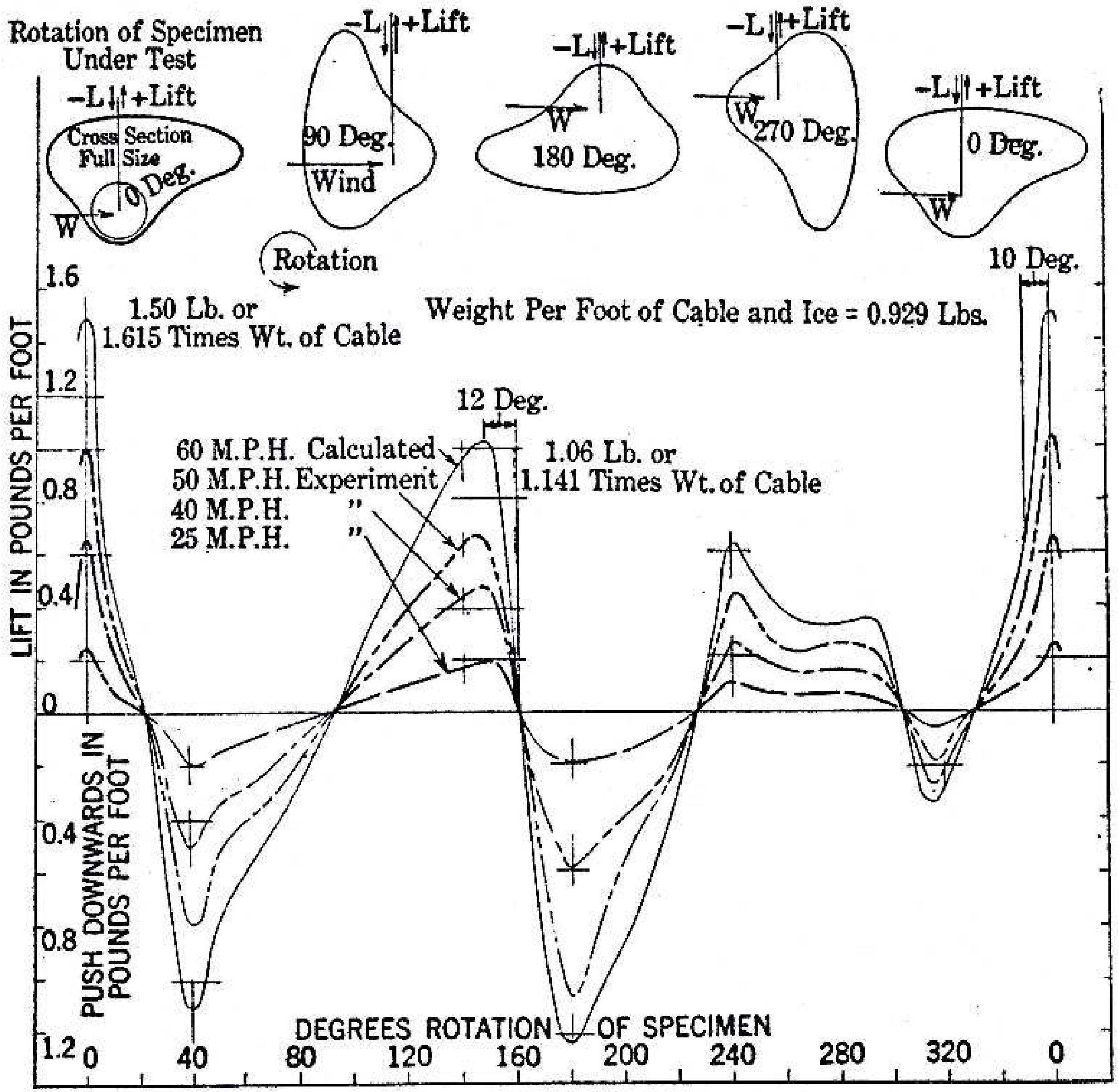
Iced cable section

Iced cables

Iced cables


Lift
lb/ft
PM
lb ft/ft
0·04 0·004
0·03 0·003
0·02 0·002
0·01 0·001
0 0
-0·01 -0·001
-0·02 -0·002
Pitching moment
Lift
Full size
Drag
lb/ft
0·3
0·2
Drag
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
α°

Iced cables

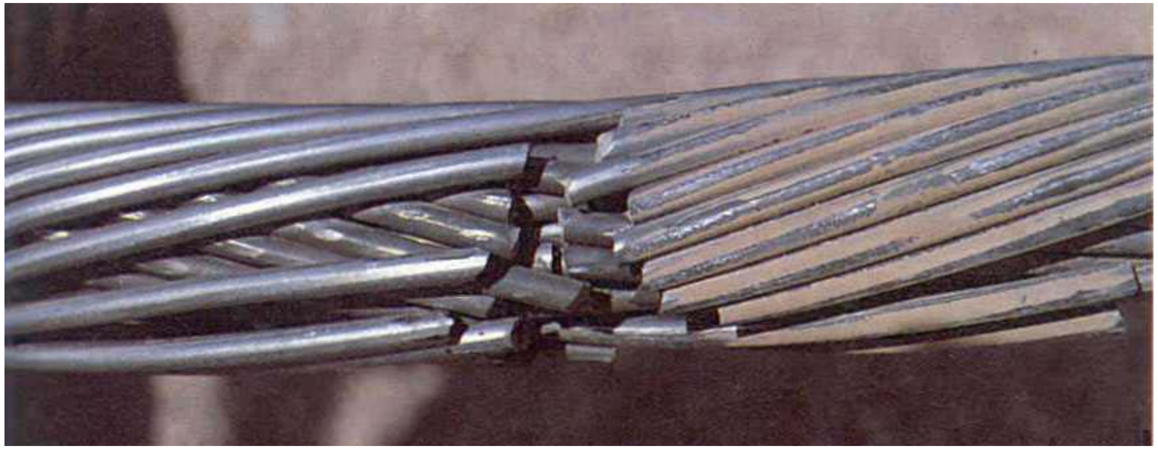


Rotation of Specimen Under Test
-L +Lift
Cross Section Full Size
0 Deg.
W
90 Deg.
Wind
180 Deg.
270 Deg.
0 Deg.
Rotation
10 Deg.
1.50 Lb. or 1.615 Times Wt. of Cable
Weight Per Foot of Cable and Ice = 0.929 Lbs.
12 Deg.
60 M.P.H. Calculated
50 M.P.H. Experiment
40 M.P.H. "
25 M.P.H. "
1.06 Lb. or 1.141 Times Wt. of Cable
LIFT IN POUNDS PER FOOT
PUSH DOWNWARDS IN POUNDS PER FOOT
DEGREES ROTATION OF SPECIMEN
1.6
1.2
0.8
0.4
0
0.4
0.8
1.2
0 40 80 120 160 200 240 280 320 0

Iced cables

Conductor galloping

Conductor galloping

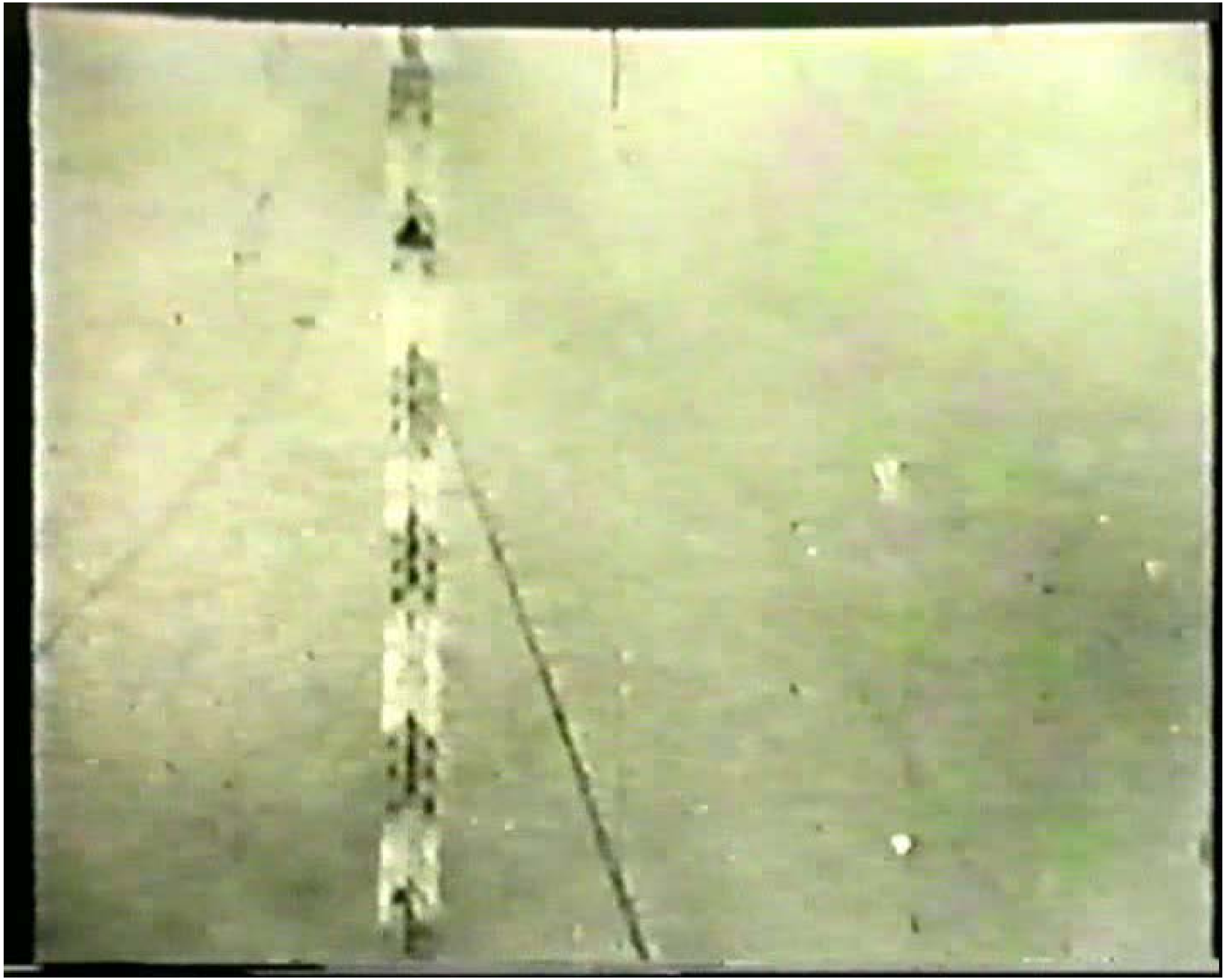


Fatigue collapse of conductors

Collapse of towers for transmission lines

Collapse of towers for transmission lines

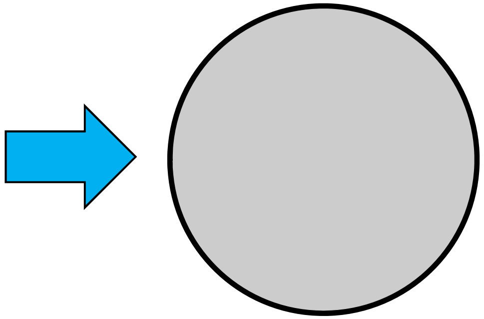
Devises to contrats galloping vibrations of transmission lines

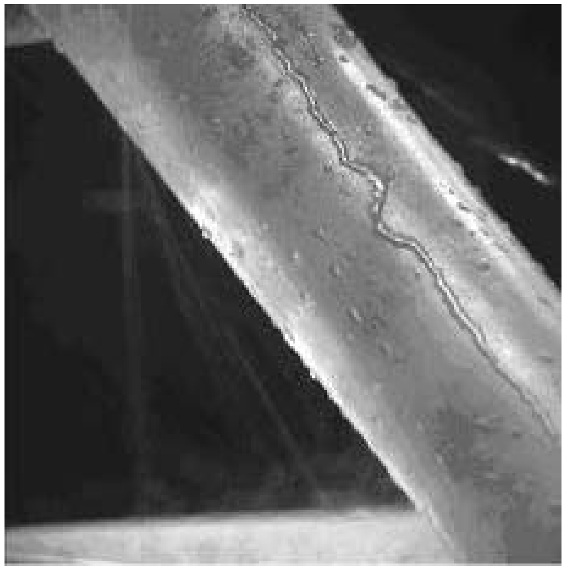


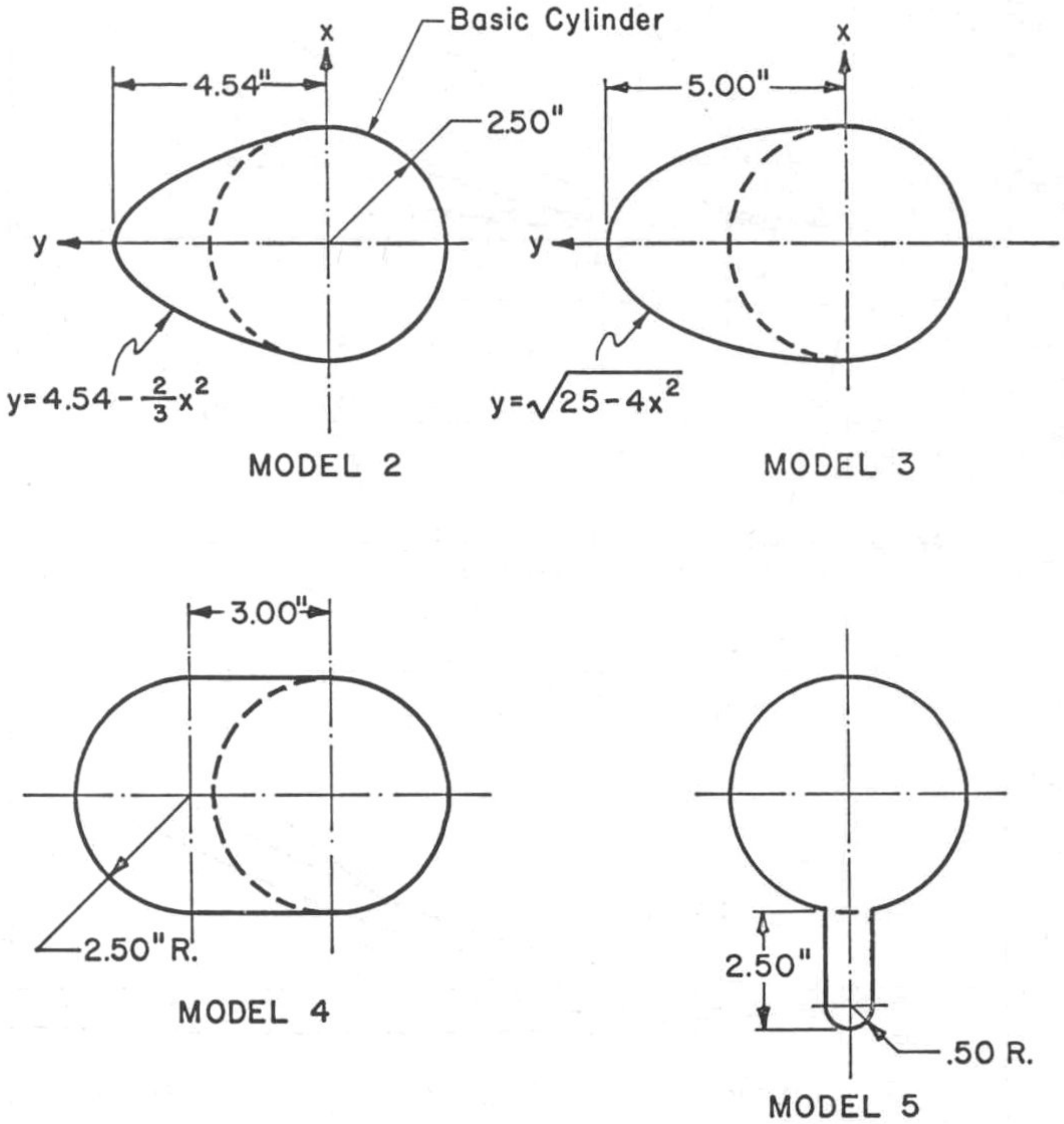
Cable galloping

Necessary condition

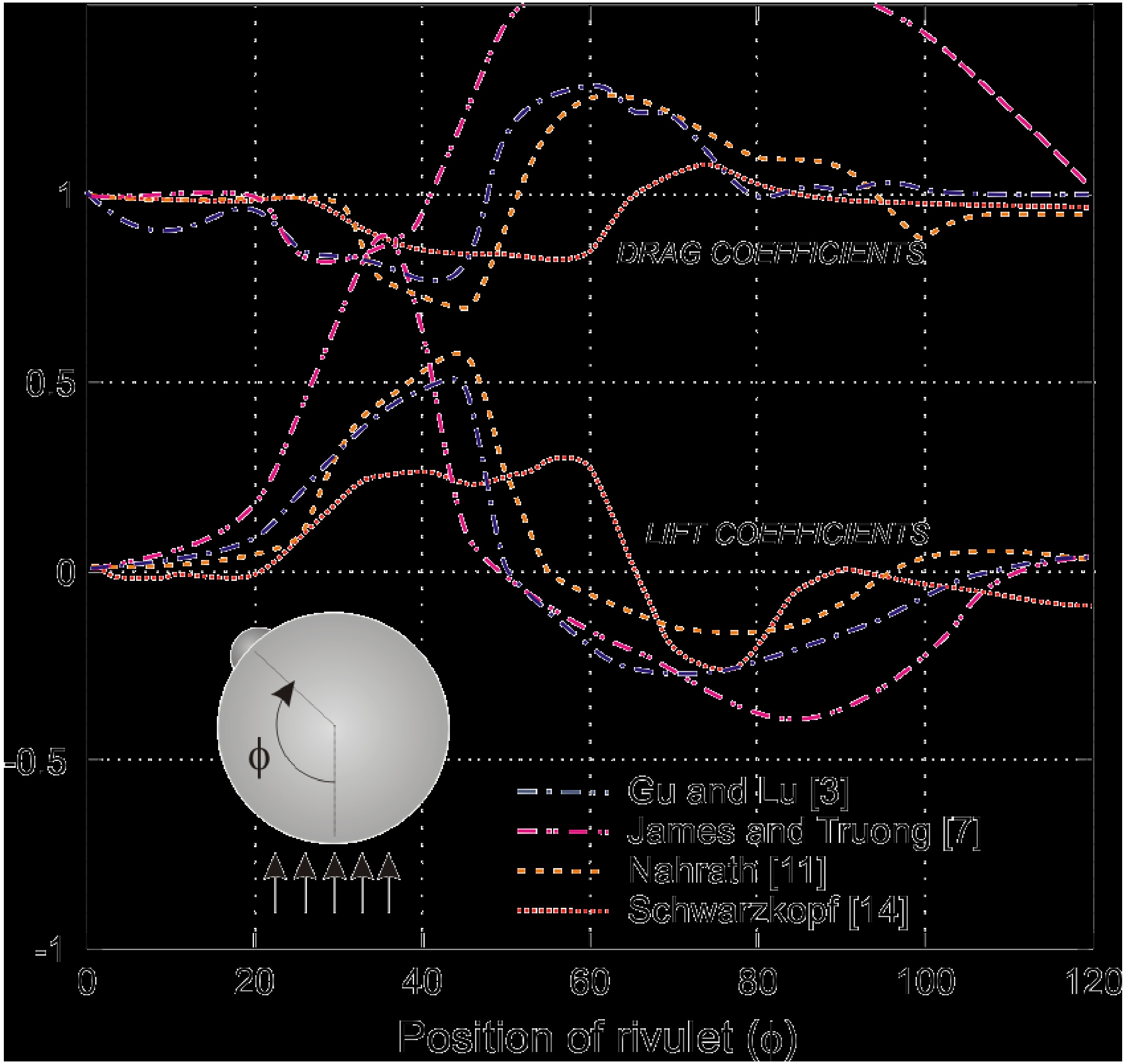
$$c_d + c_l' < 0$$







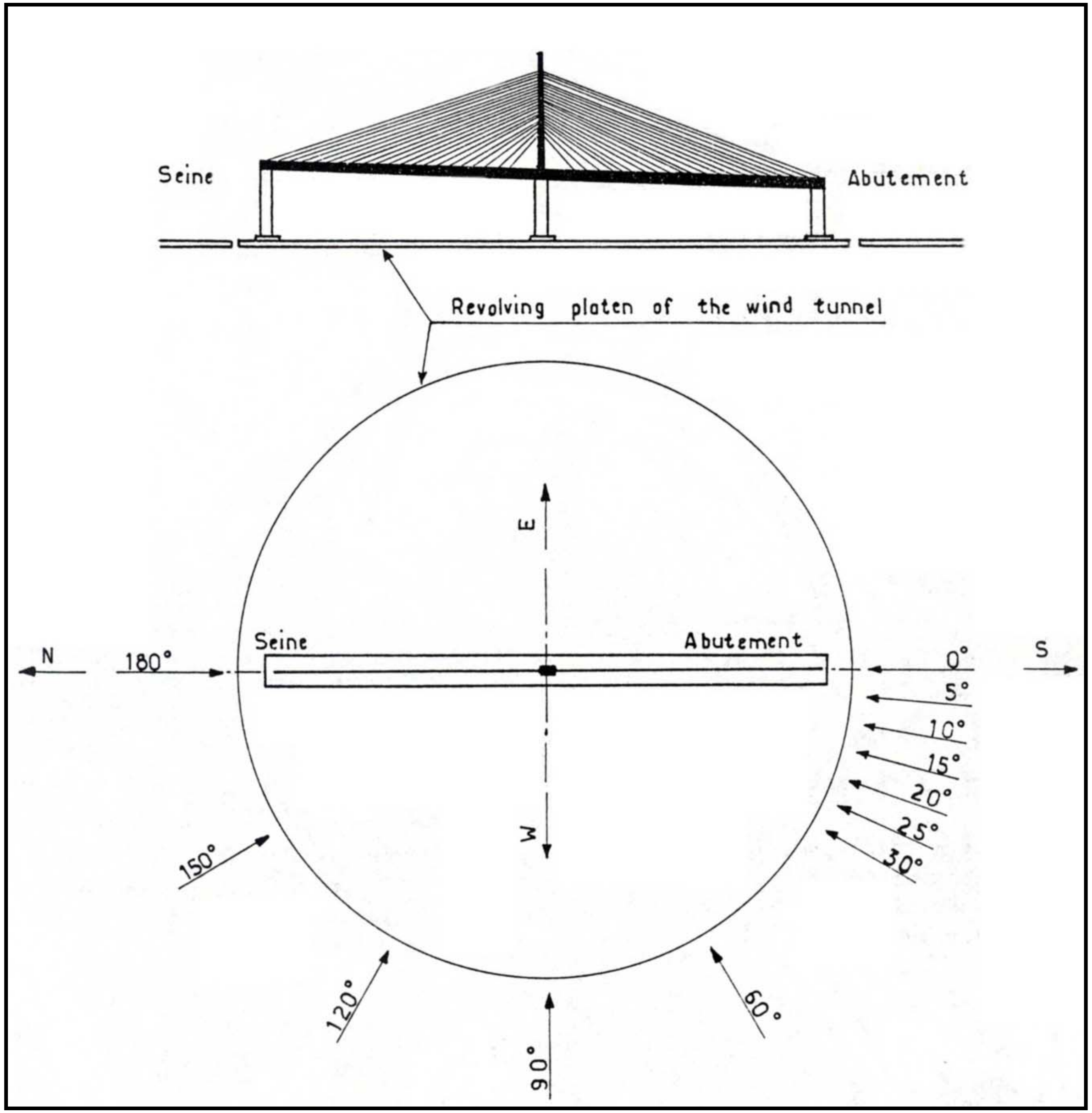
Water rivulet over cables

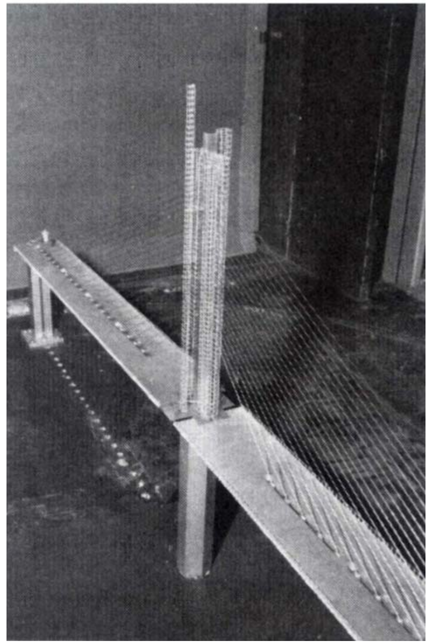


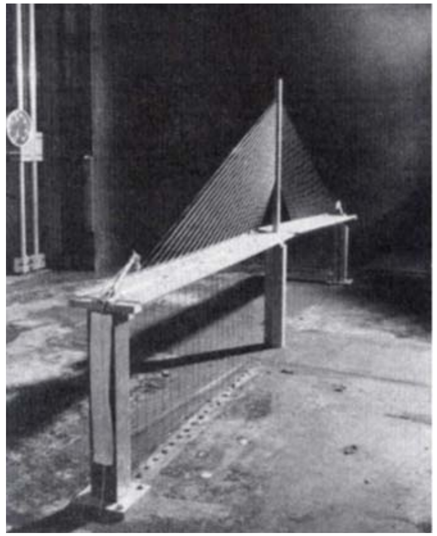
Water rivulet over cables

Brotonne Bridge, France, 1977

Brotonne Bridge, France, 1977

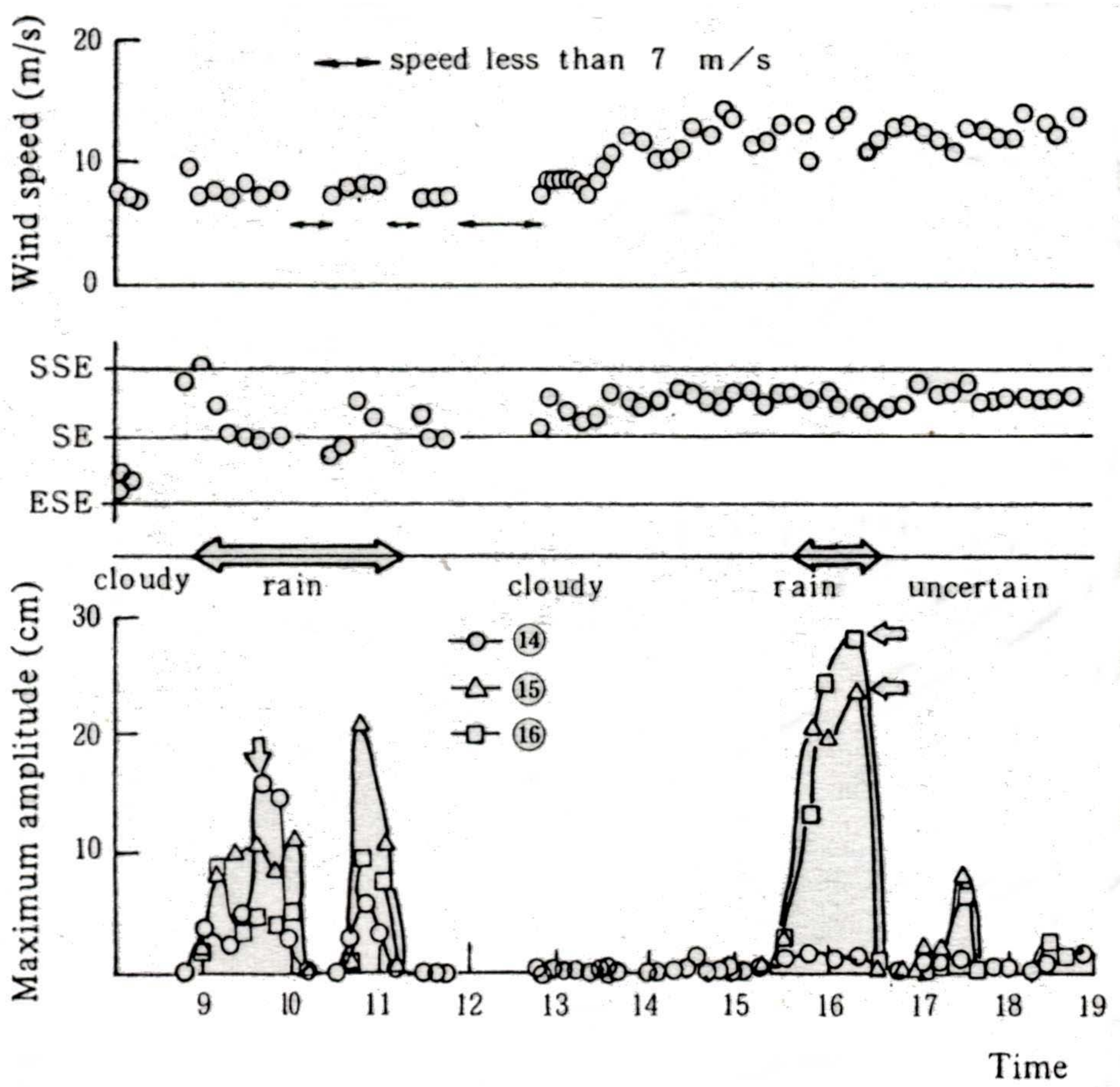




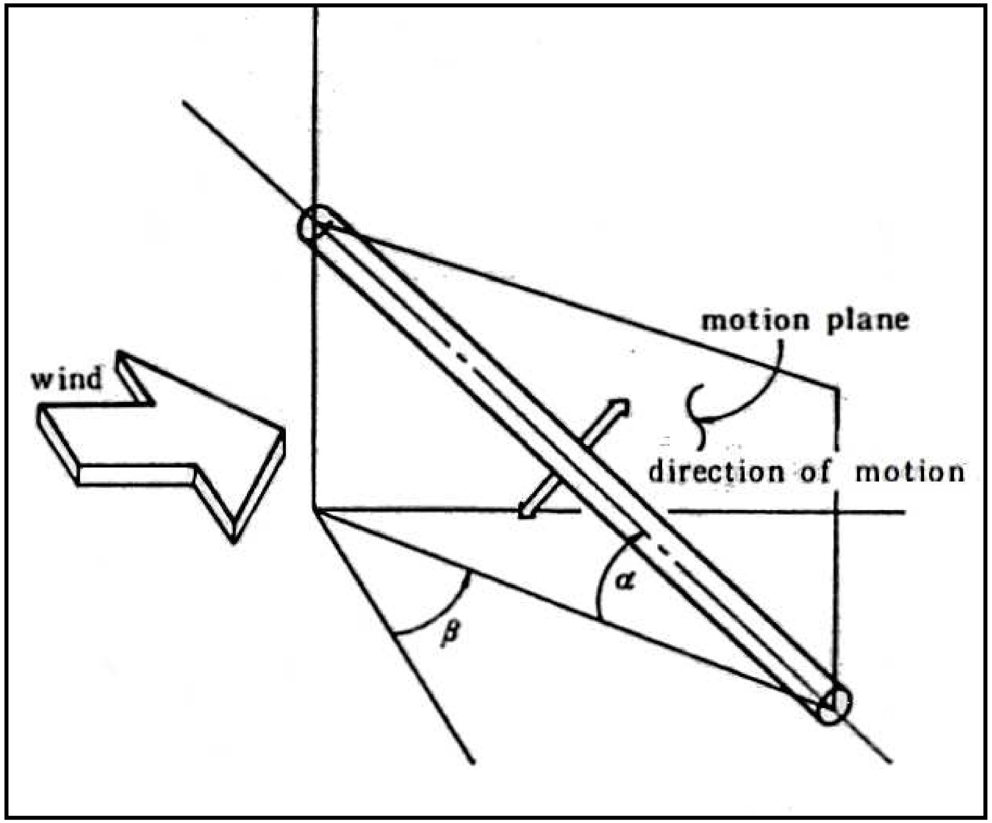


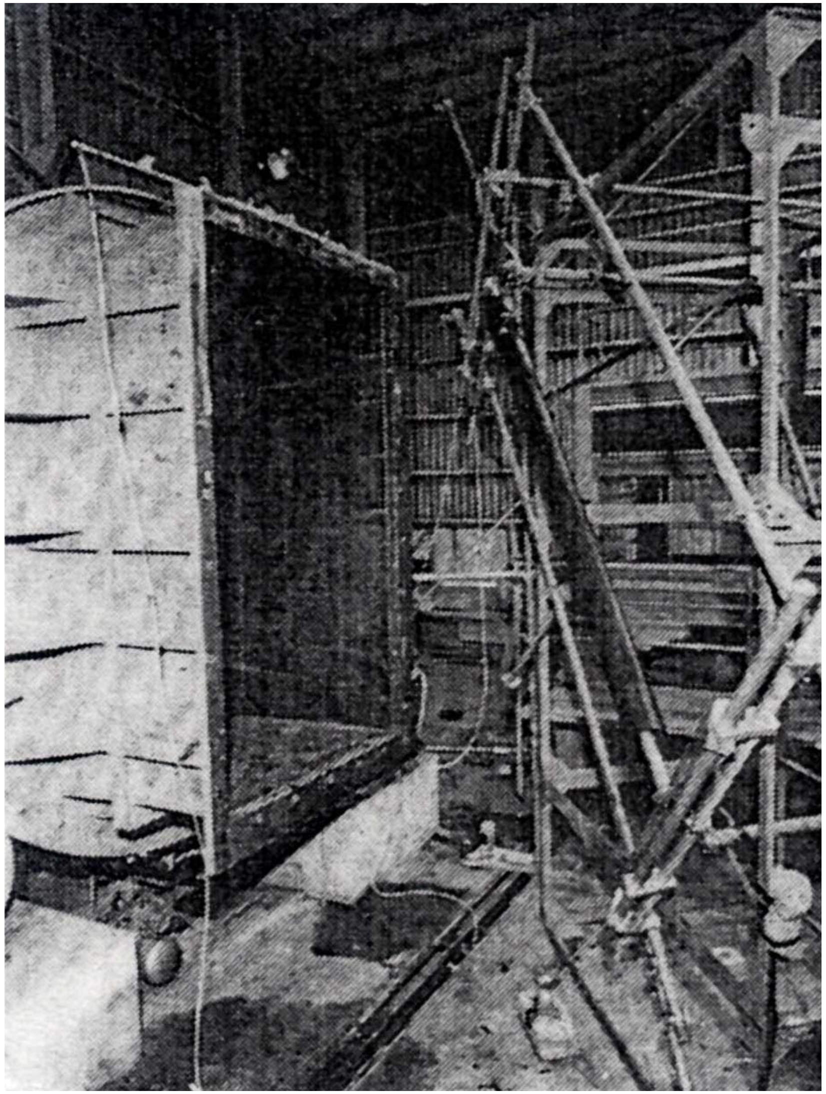
Brotonne Bridge, France, 1977

Meiko Nishi Bridge, Nagoya, Japan, 1985



Meiko Nishi Bridge, Nagoya, Japan, 1985

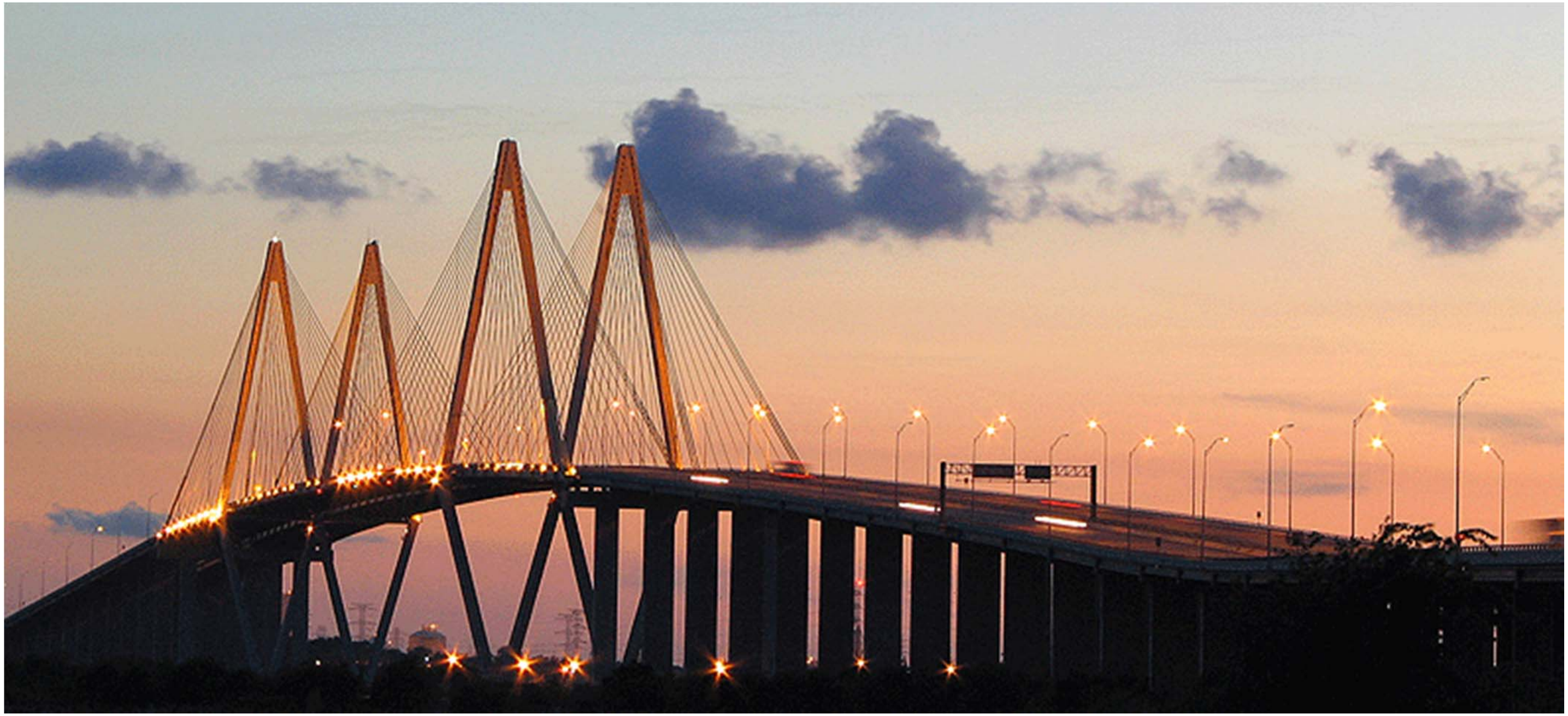




Meiko Nishi Bridge, Nagoya, Japan, 1985

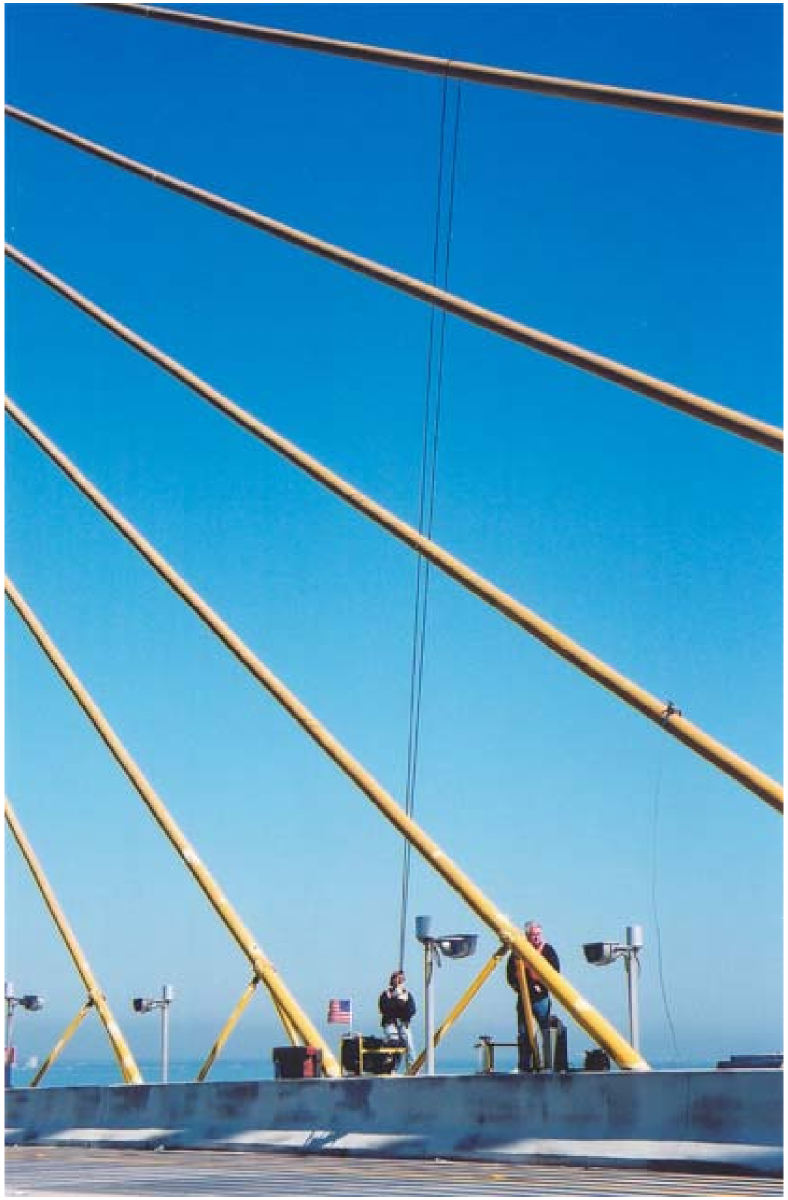
Higashi-Kobe Bridge, Japan, 1992

Tsurumi-Tsubasa Bridge, Yokohama, Japan, 1994



Fred Hatman Bridge, U.S.A., 1995

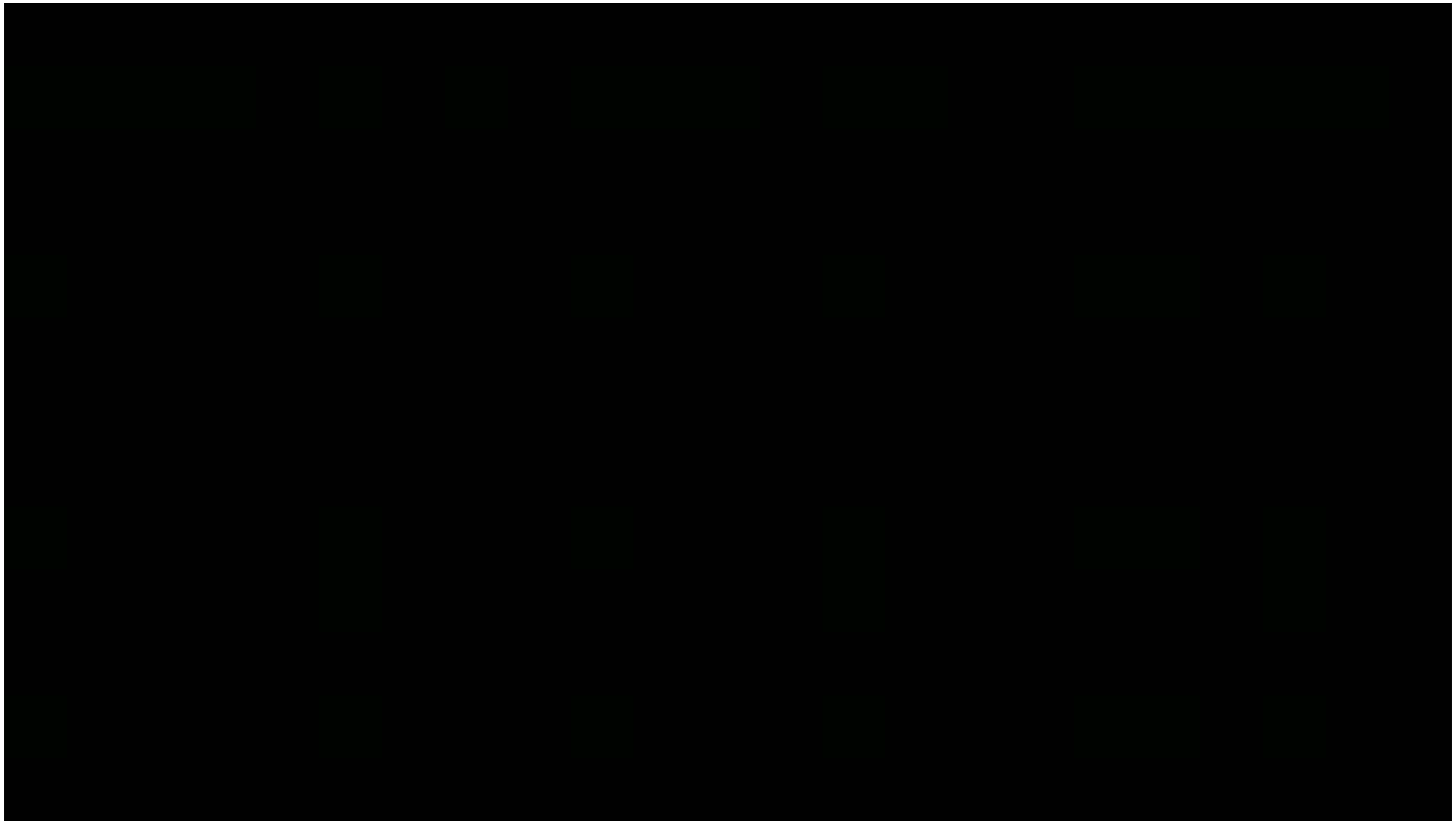
Fred Hatman Bridge, U.S.A., 1995



Fred Hatman Bridge, U.S.A., 1995

Fred Hatman Bridge, U.S.A., 1995

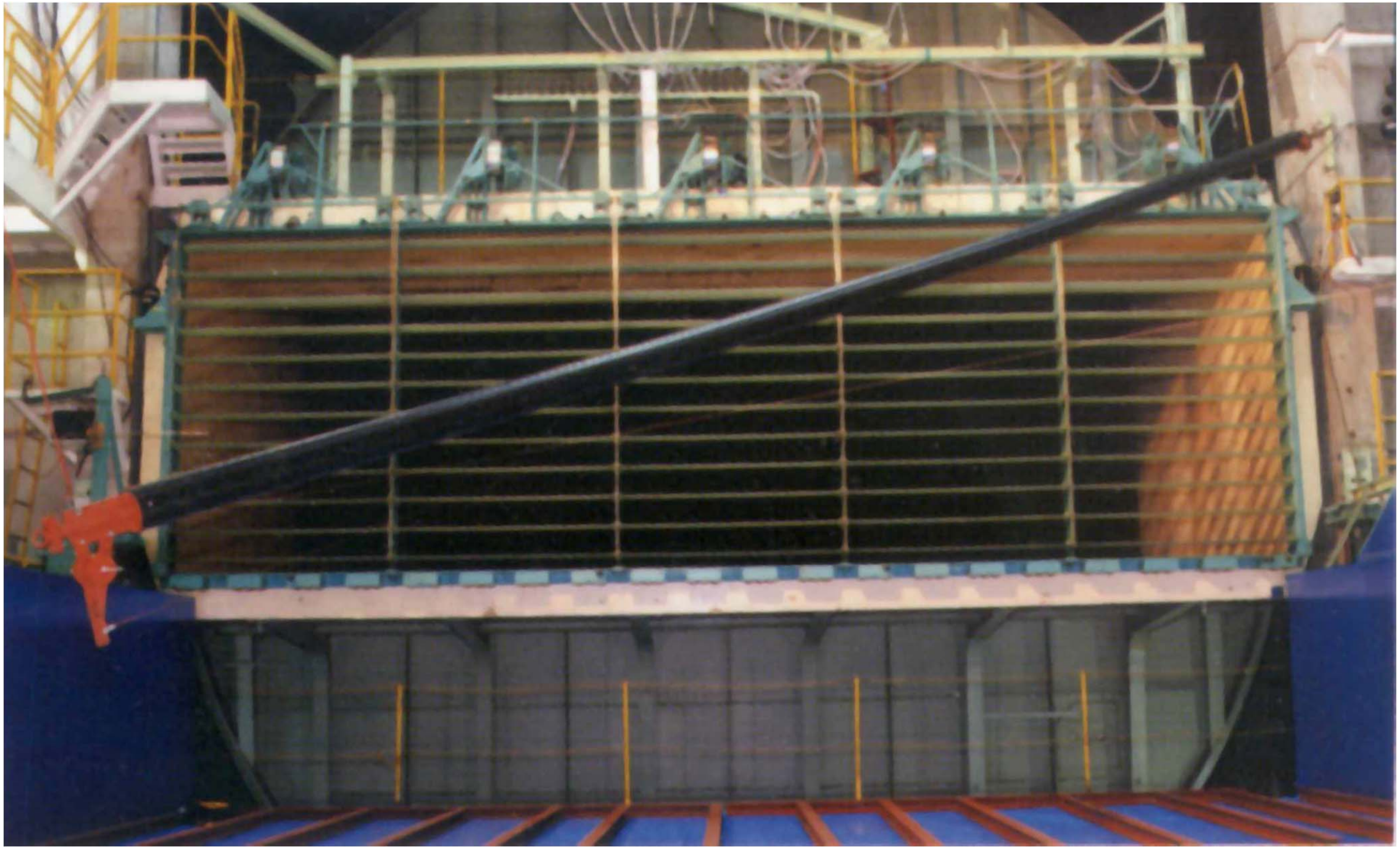
Øresund Cable Stayed Bridge, 1999



Øresund Cable Stayed Bridge, 1999

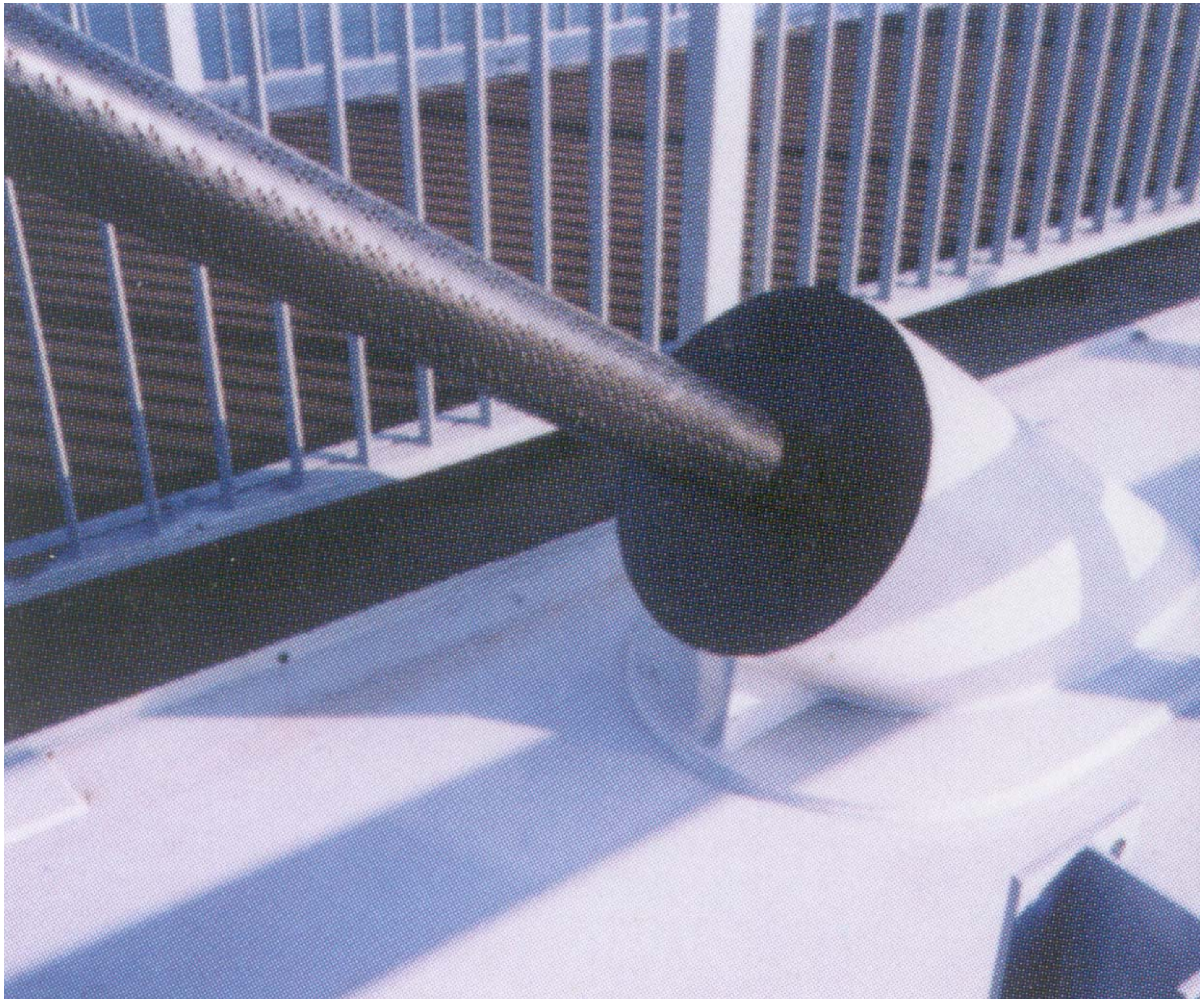
Dong Ting Bridge, China

Tatara Bridge, Japan, 1999



Tatara Bridge, Japan, 1999

Tatara Bridge, Japan, 1999



Tatara Bridge, Japan, 1999

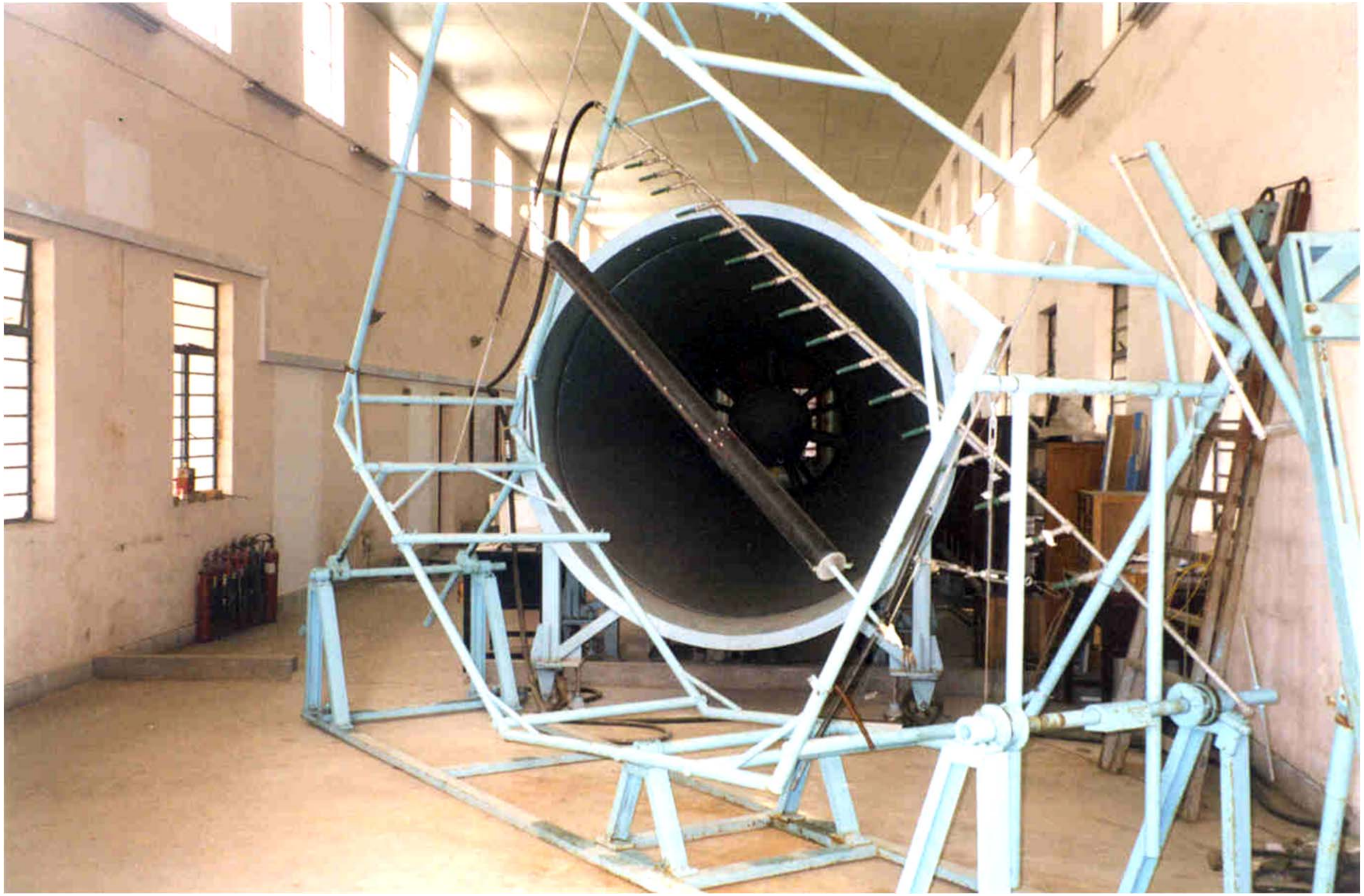
Sutong Bridge, Yangtze River, China, 2007

Sutong Bridge, Yangtze River, China, 2007

Russky Island Bridge, Vladivostok, Siberia, 2012

Russky Island Bridge, Vladivostok, Siberia, 2012

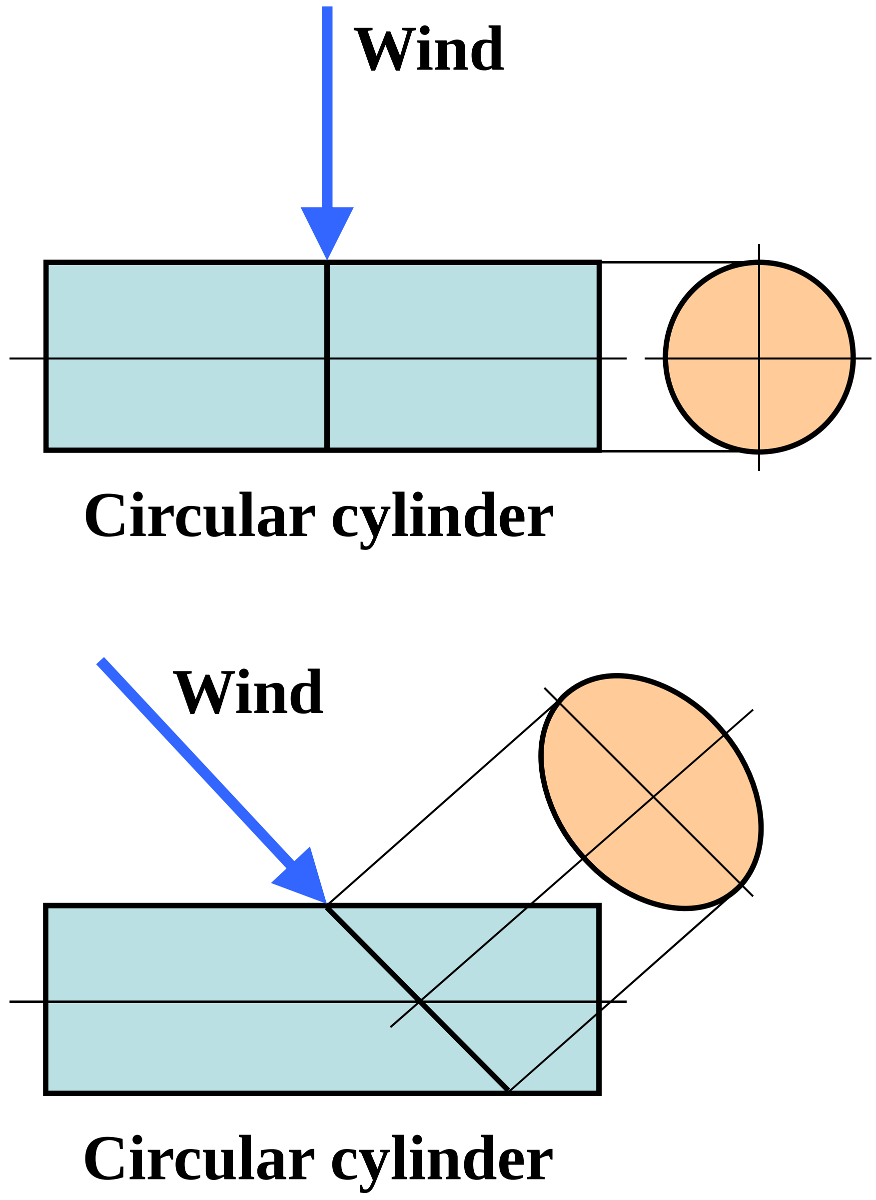
Russky Island Bridge, Vladivostok, Siberia, 2012



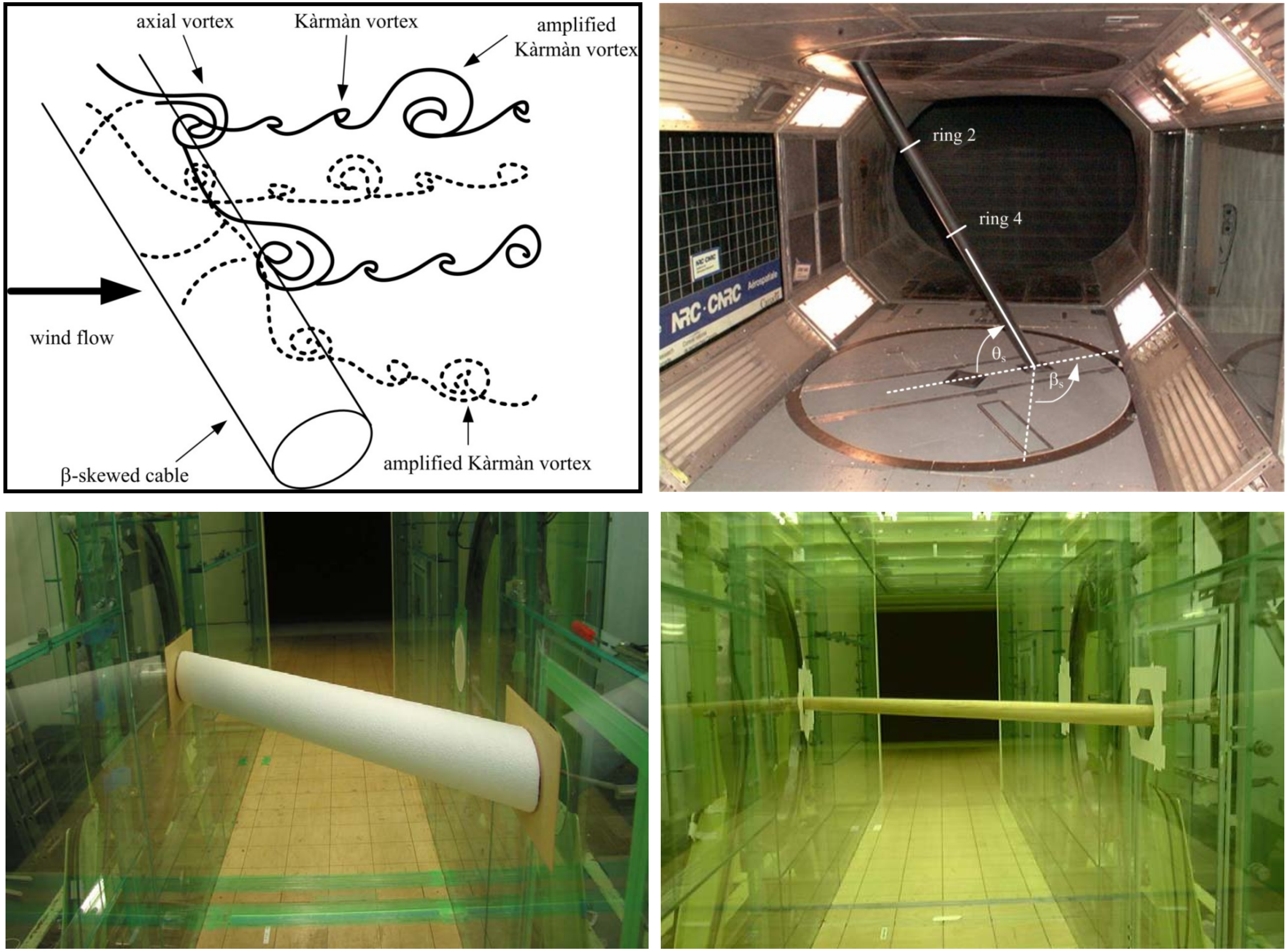
Rain-wind-induced vibrations

Rain-wind-induced vibrations

Rain-wind-induced vibrations



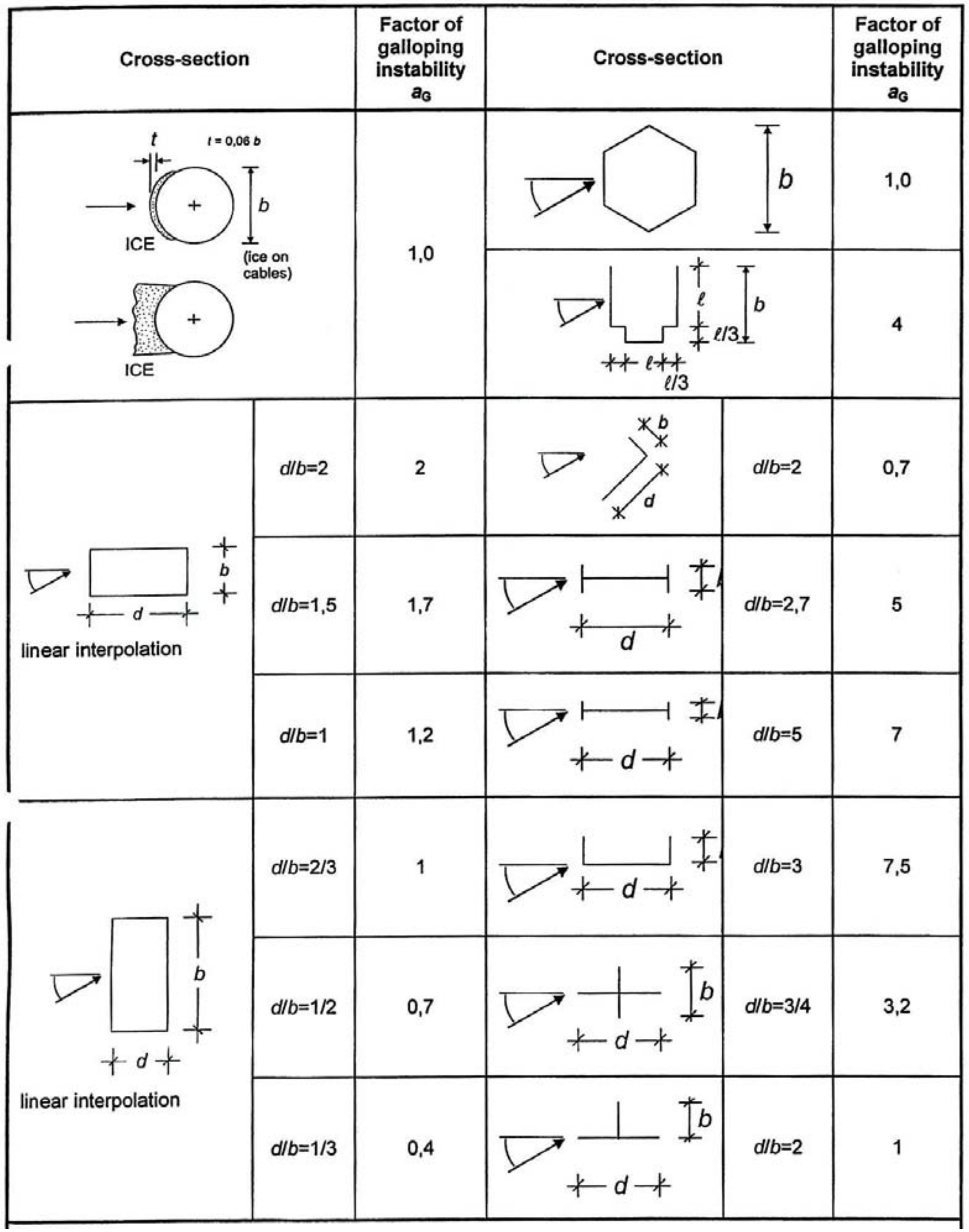
Aeroelastic instability of yawed dry circular cylinder



Aeroelastic instability of yawed dry circular cylinder

Galloping coefficient

$$a_G = -\left(c_d + c_l'\right)$$

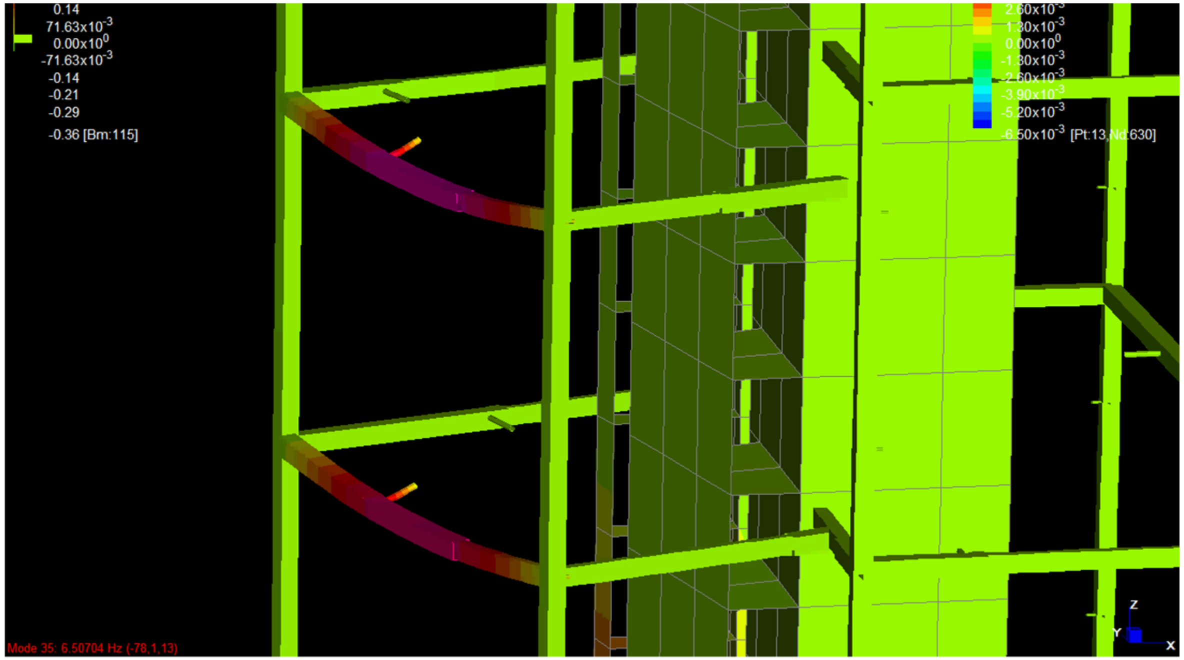


Cross-section		Factor of galloping instability a_G	Cross-section		Factor of galloping instability a_G
t, t = 0,06 b, b, ICE, (ice on cables), ICE		1,0	b		1,0
			ℓ, ℓ/3, b, ℓ, ℓ/3		4
b, d, linear interpolation	d/b=2	2	b, d	d/b=2	0,7
	d/b=1,5	1,7	d	d/b=2,7	5
	d/b=1	1,2	d	d/b=5	7
b, d, linear interpolation	d/b=2/3	1	d	d/b=3	7,5
	d/b=1/2	0,7	b, d	d/b=3/4	3,2
	d/b=1/3	0,4	b, d	d/b=2	1

Crosswind galloping

Megaframe beams

Length L = 11,2 m
Square side b = 600 mm
Mass per unit length m = 148,7 kg/m
Fundamental frequency n = 6,51 Hz
Damping coefficient ζ = 0,002



Megaframe beams

Length L = 11,2 m
Square side b = 600 mm
Mass per unit length m = 148,7 kg/m
Fundamental frequency n = 6,51 Hz
Damping coefficient ζ = 0,002

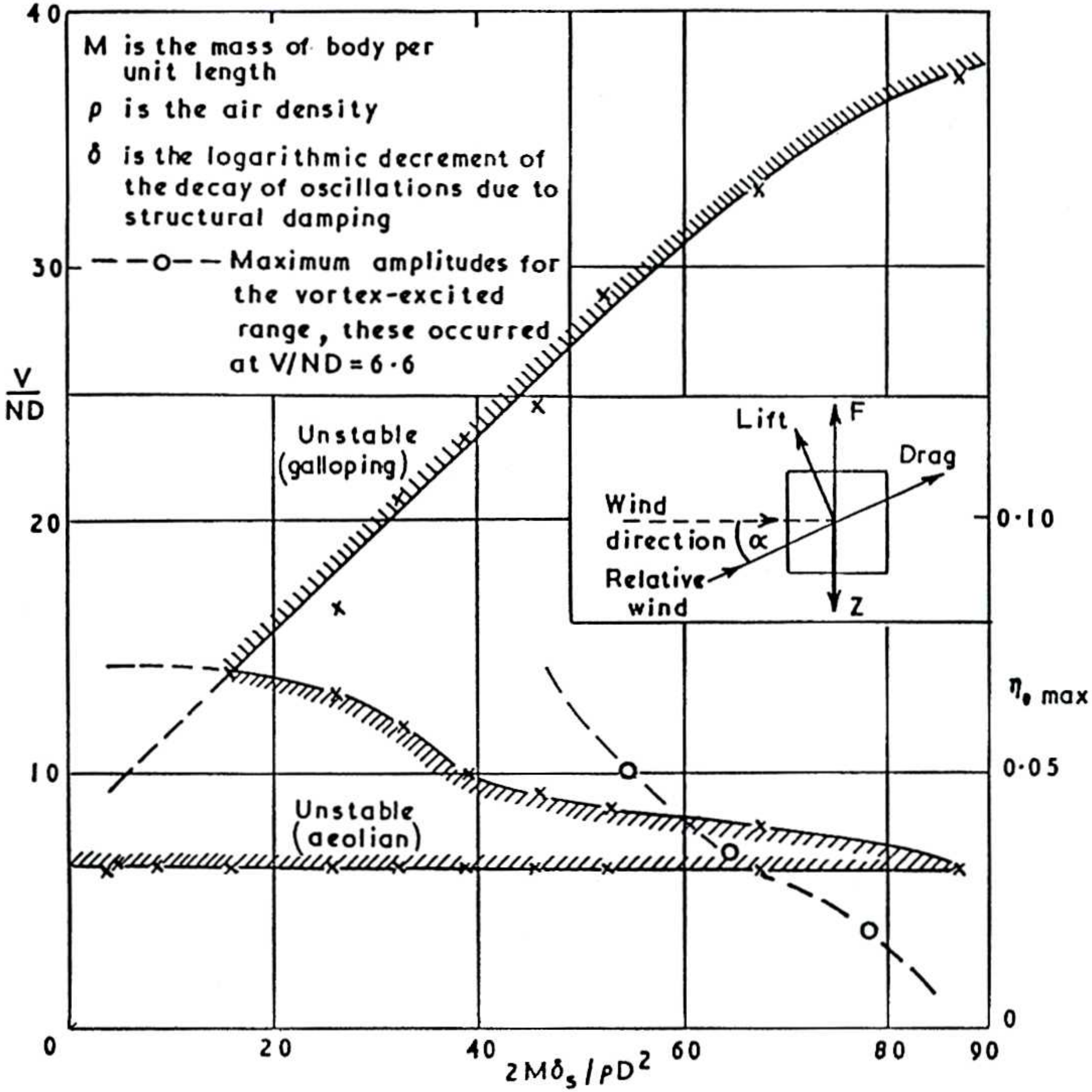
Scruton number

$$Sc = \frac{4\pi m \xi_s}{\rho b^2} = \frac{4\pi \times 148,7 \times 0,002}{1,25 \times 0,60^2} = 8,30$$

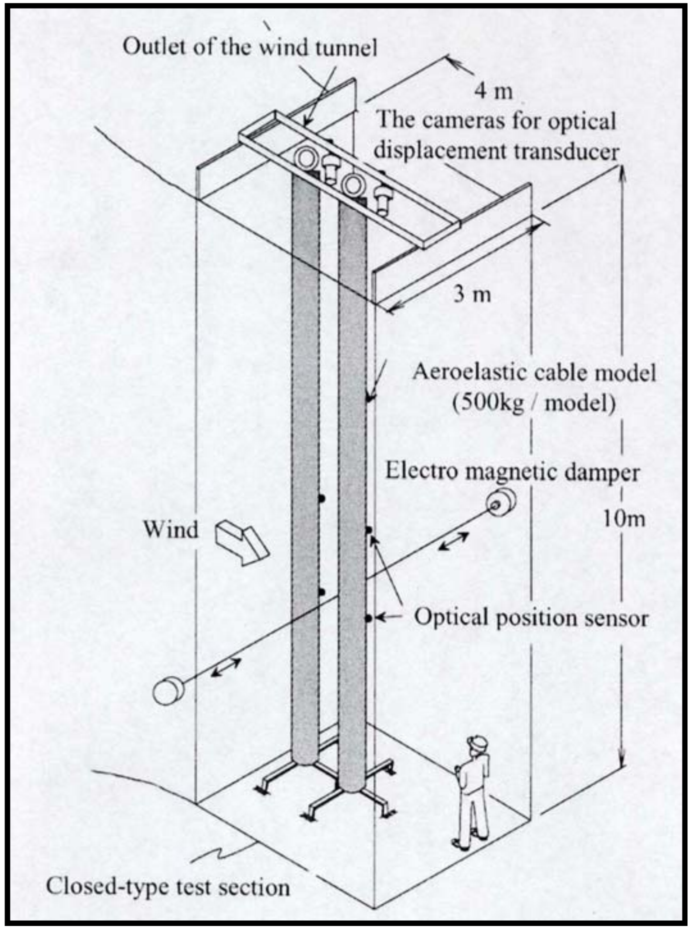
Galloping coefficient a_G = 1,2

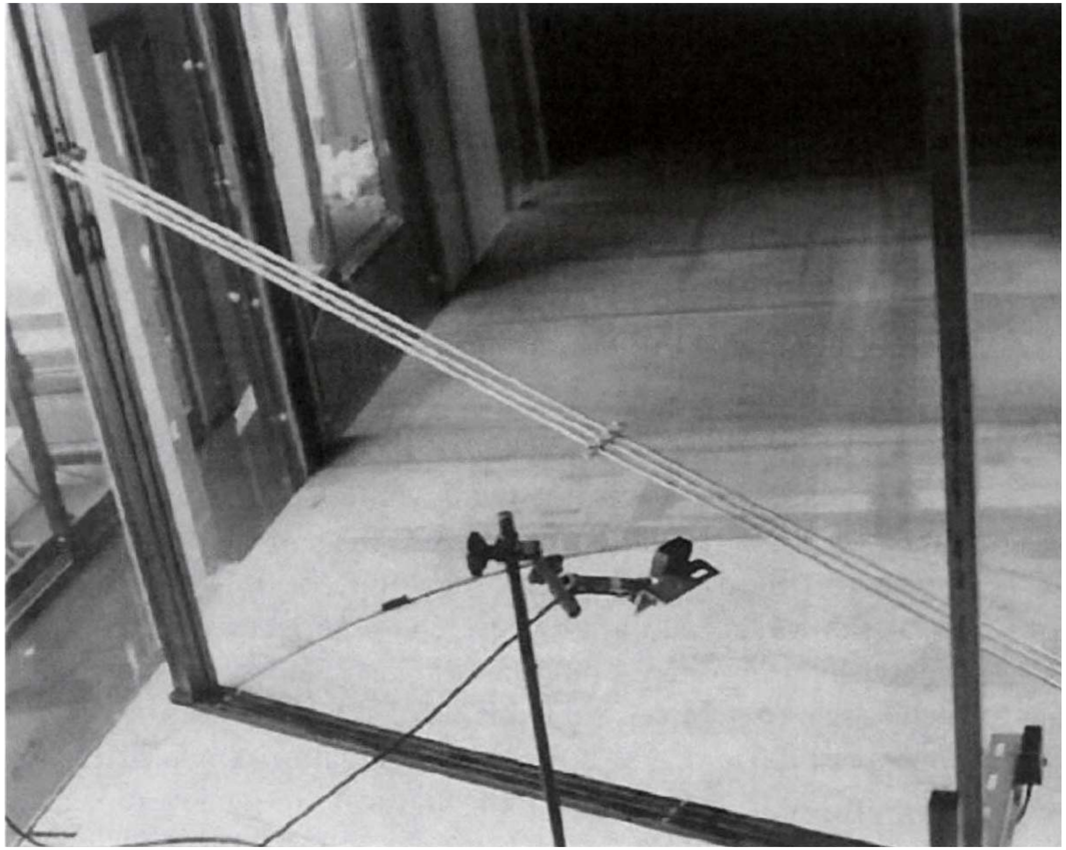
Galloping critical velocity

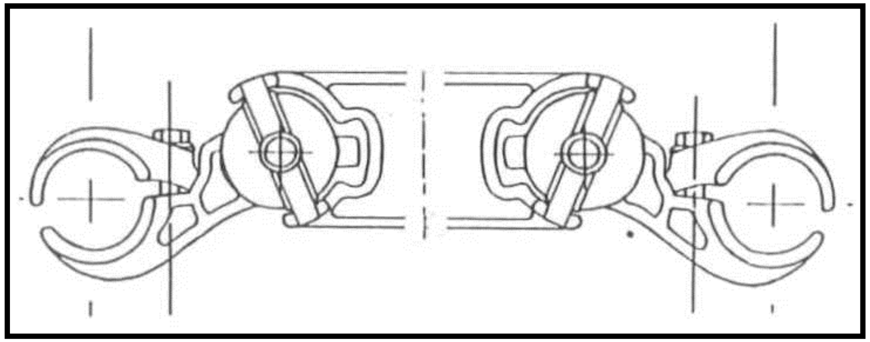
$$\bar{u}_{cr} = \frac{2nb}{a_G} \cdot Sc = \frac{2 \times 6,51 \times 0,60}{1,2} \cdot 8,30 = 54,0\ m/s$$



Galloping and vortex shedding critical interaction domains



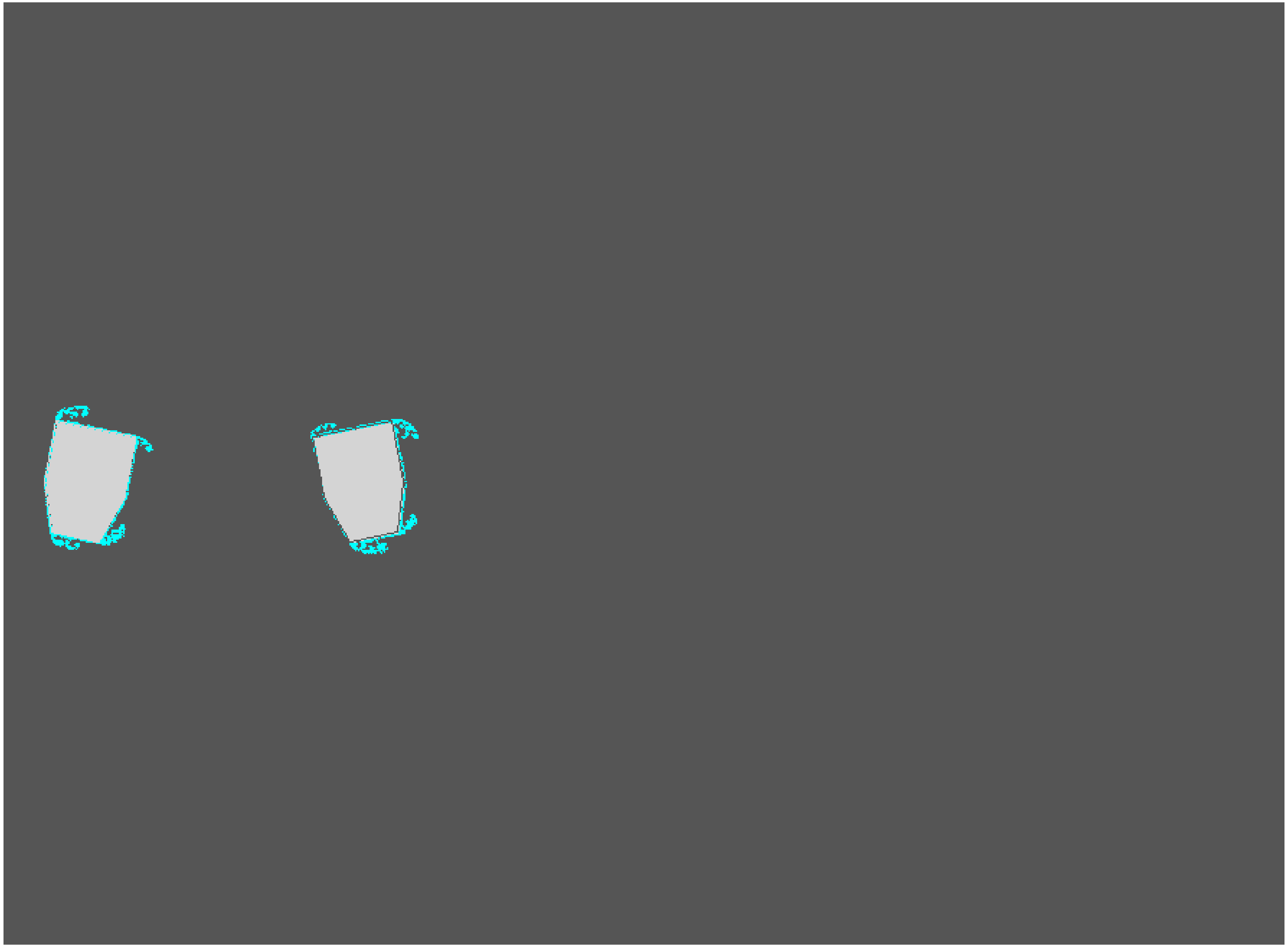




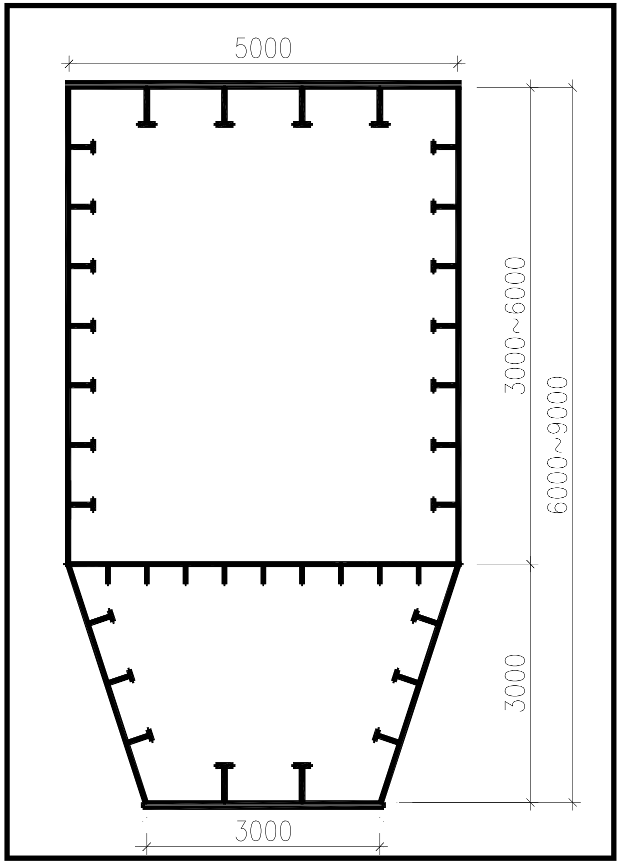
Wake galloping

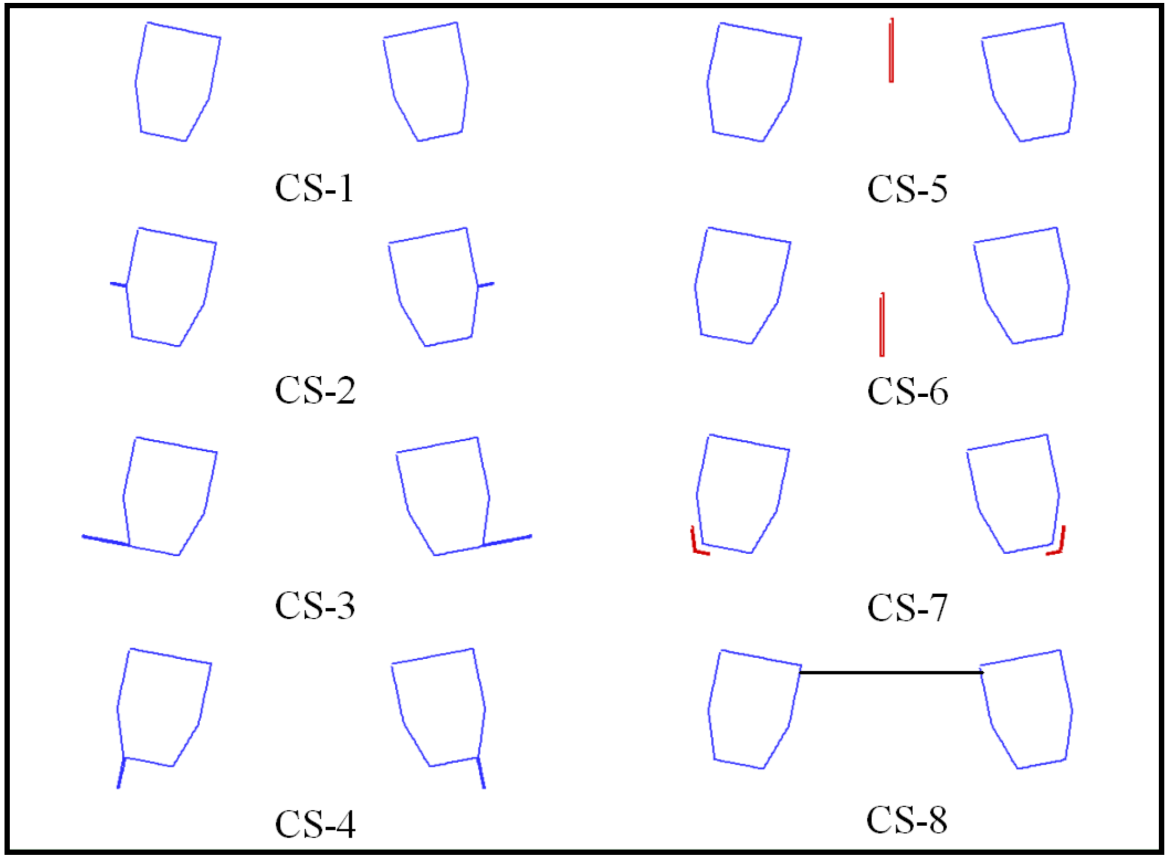
Dong Ping Bridge, China

Lupu Bridge, Shanghai, China, 2003



Lupu Bridge, Shanghai, China, 2003





Lupu Bridge, Shanghai, China, 2003

Lupu Bridge, Shanghai, China, 2003

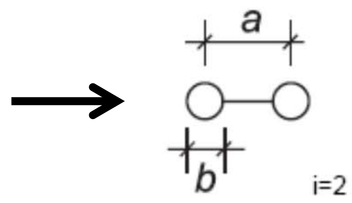
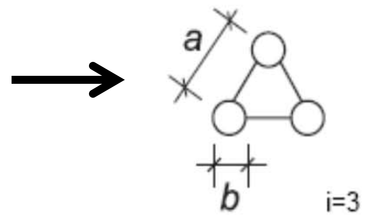
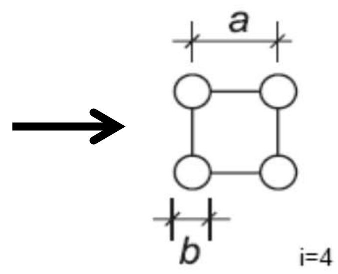
Lupu Bridge, Shanghai, China, 2003

Necessary condition

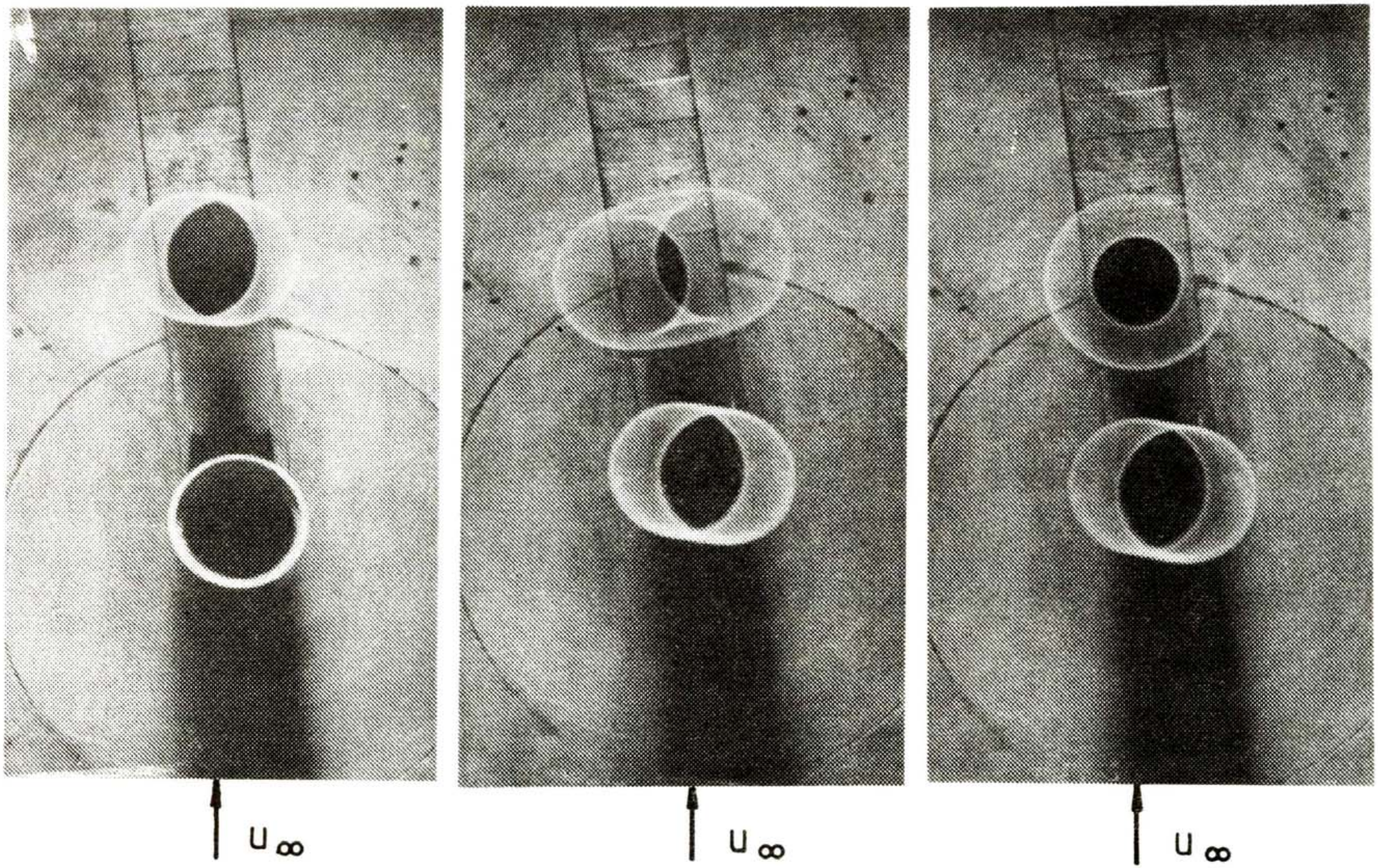
$$a_G > 0$$

Critical velocity

$$\bar{u}_{cr} = \frac{4m\omega_0\xi_s}{\rho b a_G} = \frac{2n_0 b}{a_G} \cdot Sc$$

Number of coupled cylinders	a_G	
	$a/b \leq 1{,}5$	$a/b \geq 2{,}5$
	1,5	3,0
	6,0	3,0
	1,0	2,0

Classical galloping for structurally connected circular cylinder



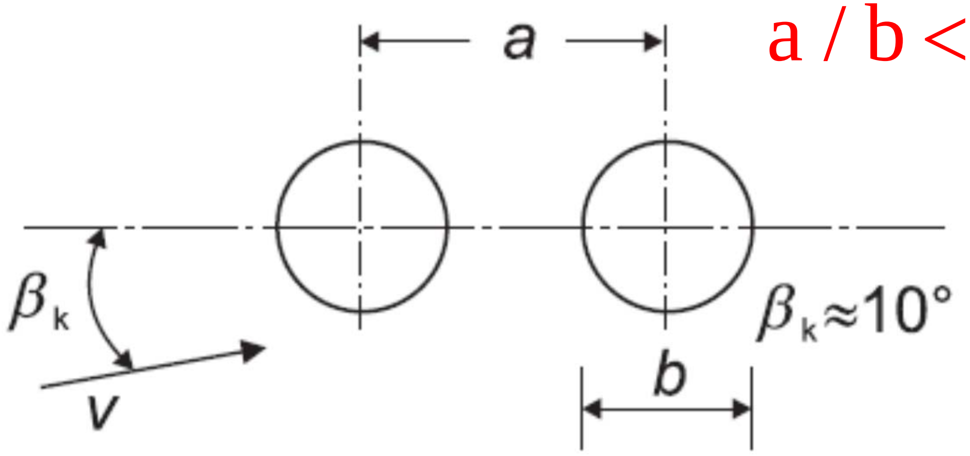
Interference galloping for non-structurally connected circular cylinder

Necessary condition

$$a_{IG} > 0$$

Critical velocity

$$v_{IG} = 3{,}5 \cdot n_1 \cdot \sqrt{\frac{a \cdot b}{a_{IG}} \cdot Sc}$$



$a / b < 3$

a_{IG} = Interference Galloping factor

In the lack of more accurate assessments,

a_{IG} can be taken as equal to 3

Interference galloping for non-structurally connected circular cylinder

Thermoelectric Power Plant, Priolo Gargallo, Siracusa

Coupled chimneys with Tuned Mass Damper (TMD)

$$h = 90\ \text{m};\ d = 6,4\ \text{m};\ a = 8,4\ \text{m} \Rightarrow a/d = 1,31$$

$$n_1 = 0,80\ \text{Hz};\ \xi = 0,08;\ m = 1.683\ \text{kg/m}$$

$$Sc = \frac{4\pi \cdot m \cdot \xi}{\rho \cdot d^2} = \frac{4\pi \cdot 1.683 \cdot 0,08}{1,25 \cdot 6,4^2} = 33,05$$

Classical galloping for structurally connected chimneys

$$a/d = 1,31 < 1,5 \Rightarrow a_G = 1,5$$

$$\overline{u}_{cr} = \frac{2n_1 b}{a_G} \cdot Sc = \frac{2 \times 0,80 \times 6,4}{1,5} \cdot 33,05 = 226\ \text{m/s}$$

Interference galloping for non – structurally connected chimneys

$$v_{IG} = 3,5 \cdot n_1 \cdot \sqrt{\frac{a \cdot b}{a_{IG}} \cdot Sc} = 3,5 \cdot 0,8 \cdot \sqrt{\frac{8,4 \cdot 6,4}{3} \cdot 33,05} = 68\ \text{m/s}$$

Thermoelectric Power Plant, Priolo Gargallo, Siracusa