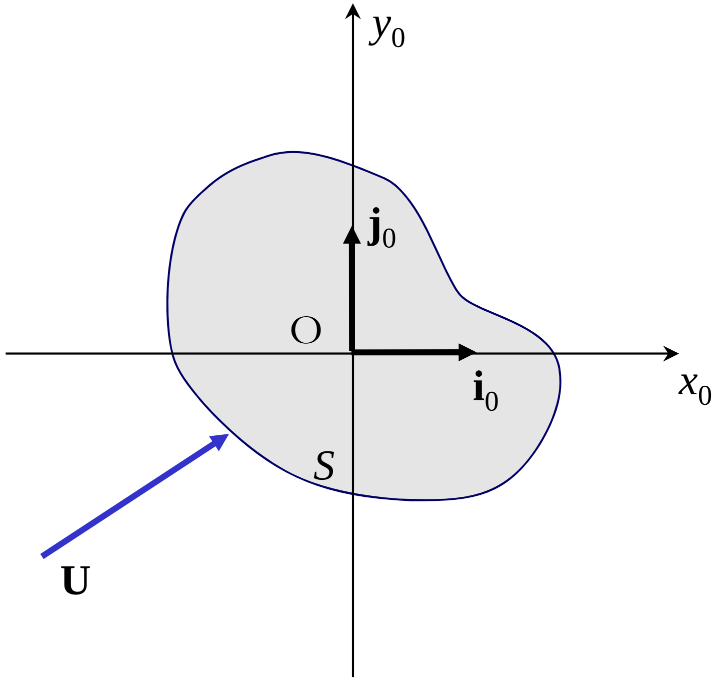
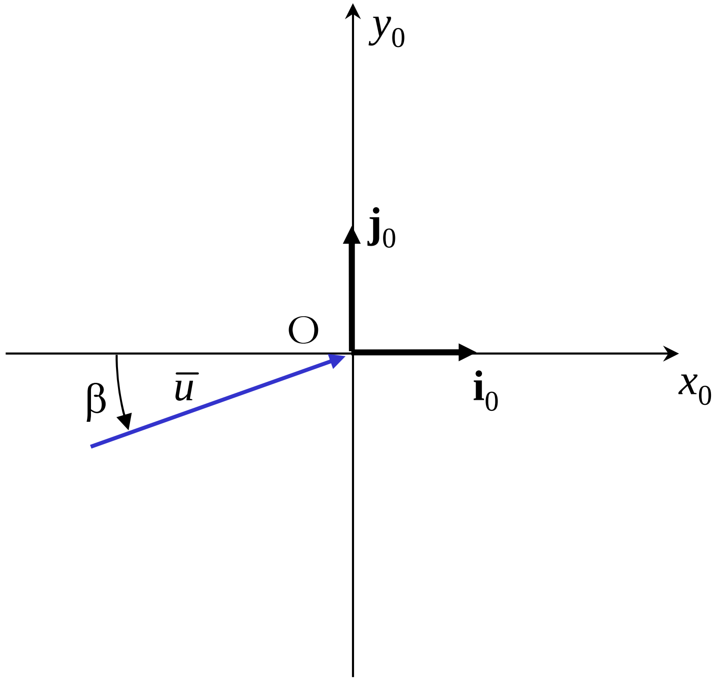
Slender cylinder in a turbulent wind field

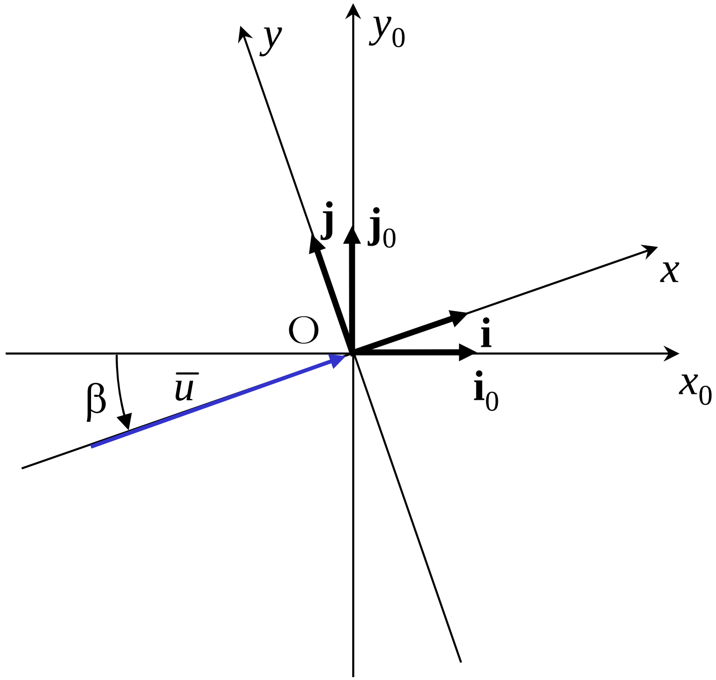


Turbulent wind field



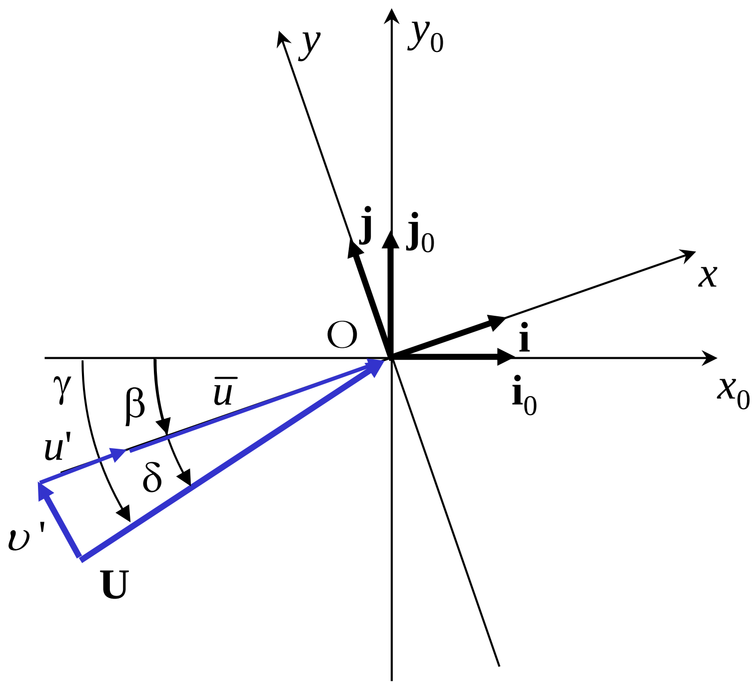
$\bar{u}$ = mean wind velocity

Turbulent wind field



$\overline{u}$ = mean wind velocity

Turbulent wind field



$$\mathbf{U}(t) = u(t)\,\mathbf{i} + \upsilon(t)\,\mathbf{j}$$

$$u(t) = \bar{u} + u'(t) \qquad \upsilon(t) = \upsilon'(t)$$

$$\delta(t) = \operatorname{arctg}\left\{\frac{\upsilon'(t)}{\bar{u} + u'(t)}\right\} \qquad \gamma(t) = \beta + \delta(t)$$

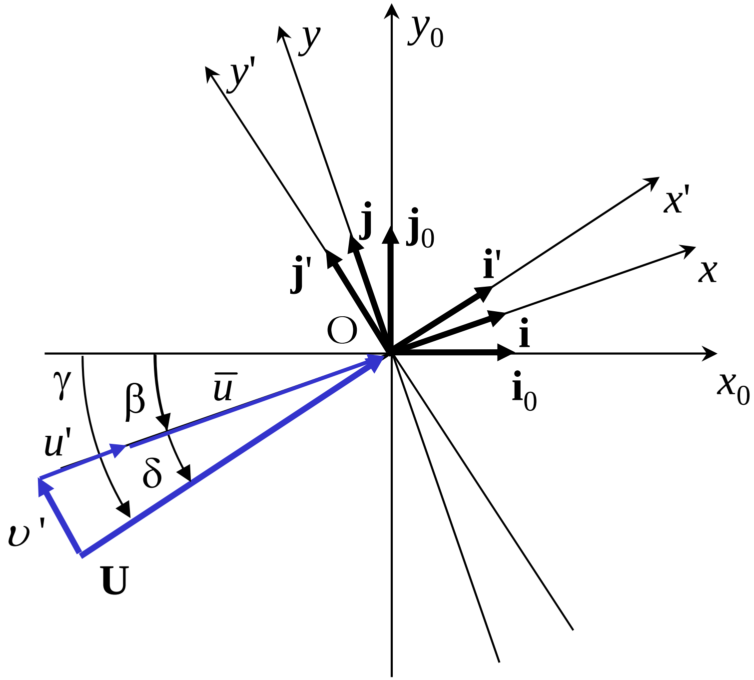
$$U(t) = \left\|\mathbf{U}(t)\right\| = \sqrt{\left[\bar{u} + u'(t)\right]^2 + \left[\upsilon'(t)\right]^2}$$

$\bar{u}$ = mean wind velocity

u' = longitudinal turbulence component (parallel to $\bar{u}$)

υ' = transversal turbulence component (orthogonal to $\bar{u}$)

Turbulent wind field



$$\mathbf{U}(t) = u(t)\,\mathbf{i} + \upsilon(t)\,\mathbf{j}$$

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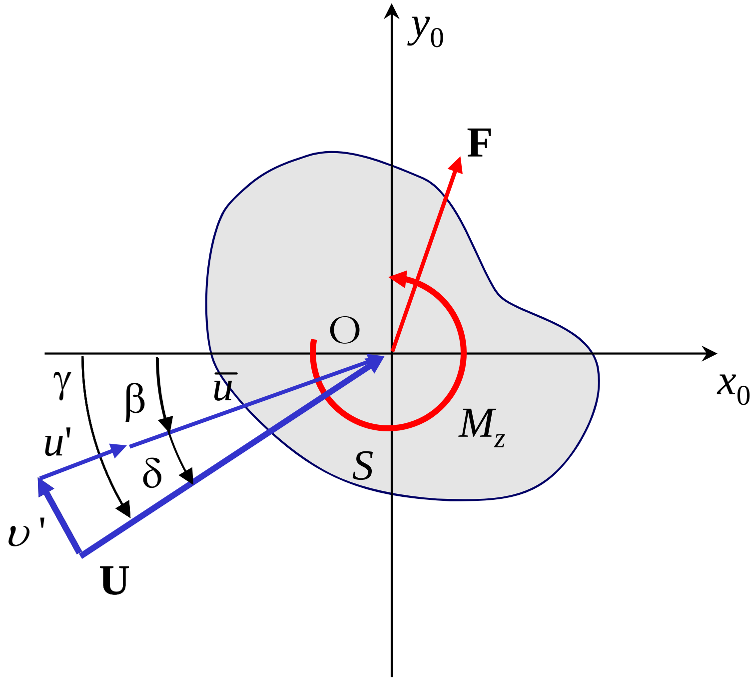
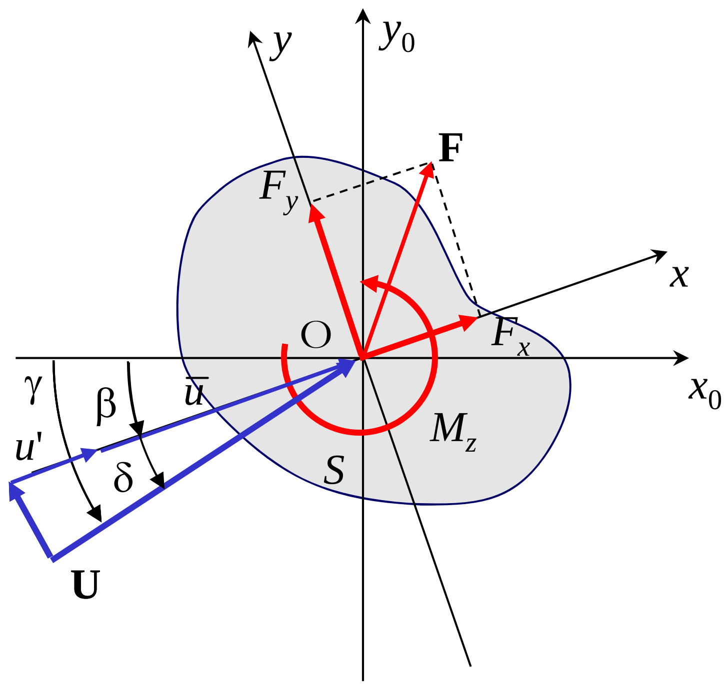
Wind induced actions on slender cylinders



$$\mathbf{F}(t) = \bar{\mathbf{F}} + \mathbf{F}'(t)$$

$$M_z(t) = \bar{M}_z + M_z'(t)$$

Wind induced actions on slender cylinders

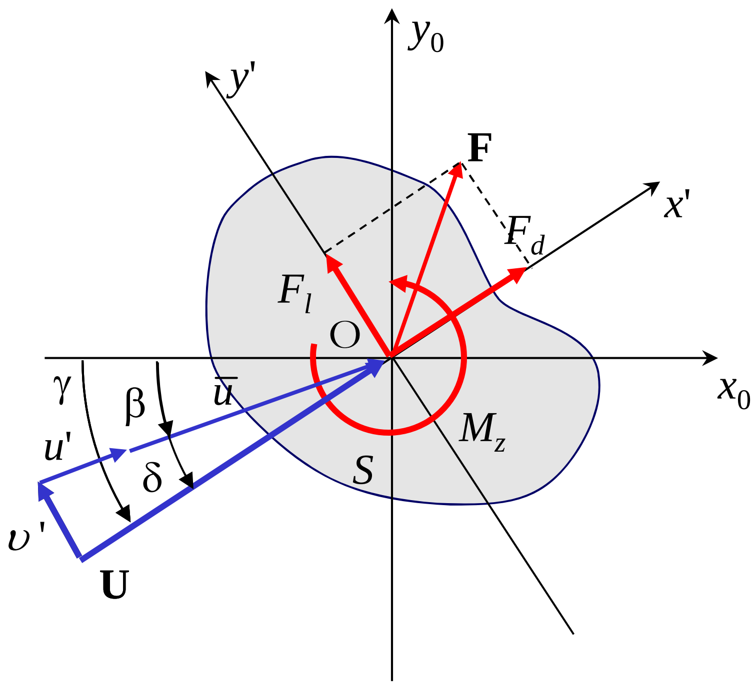


$$\mathbf{F}(t) = F_x(t)\,\mathbf{i} + F_y(t)\,\mathbf{j}$$

$$M_z(t) = \bar{M}_z + M_z'(t)$$

$$F_x(t) = \bar{F}_x + F_x'(t) \qquad F_y(t) = \bar{F}_y + F_y'(t)$$

Wind induced actions on slender cylinders



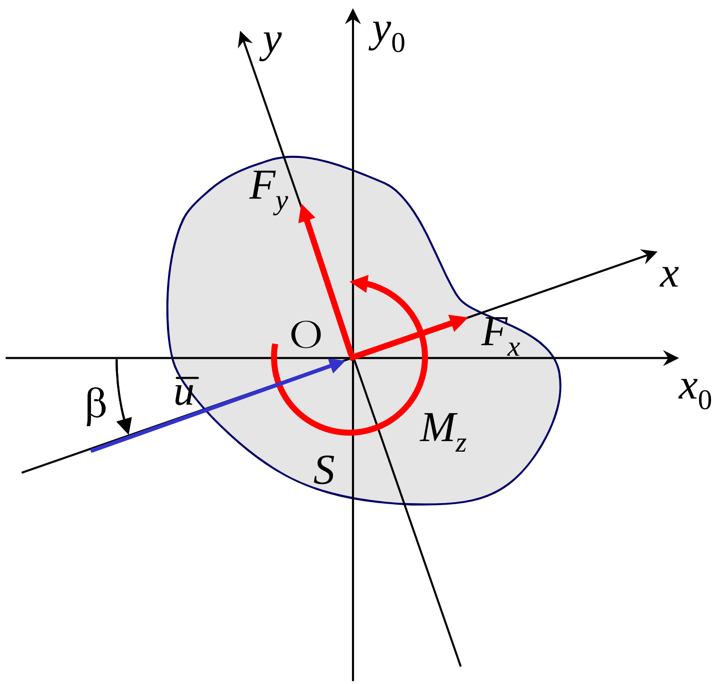
$$\mathbf{F}(t) = F_x(t)\,\mathbf{i} + F_y(t)\,\mathbf{j} = F_d(t)\,\mathbf{i}' + F_l(t)\,\mathbf{j}'$$

$$M_z(t) = \bar{M}_z + M_z'(t)$$

$$F_x(t) = \bar{F}_x + F_x'(t) \qquad F_y(t) = \bar{F}_y + F_y'(t)$$

$$F_d(t) = \bar{F}_d + F_d'(t) \qquad F_l(t) = \bar{F}_l + F_l'(t)$$

Wind induced actions on slender cylinders



Drag coefficient

$$c_d(\beta) = \frac{\bar{F}_x}{\frac{1}{2}\rho \bar{u}^2 b}$$

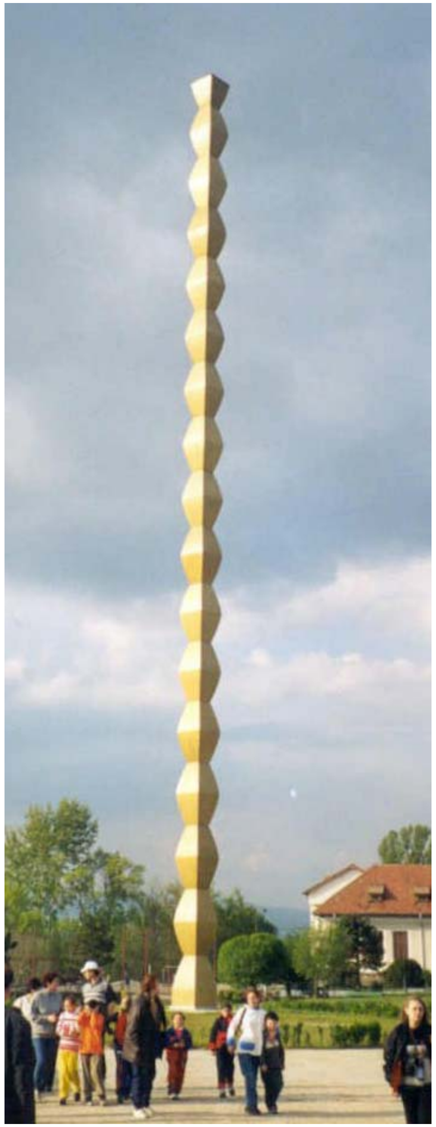
Lift coefficient

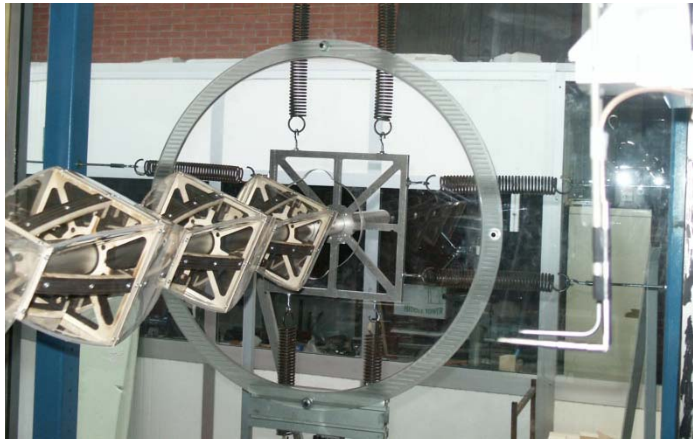
$$c_l(\beta) = \frac{\bar{F}_y}{\frac{1}{2}\rho \bar{u}^2 b}$$

Torque coefficient

$$c_m(\beta) = \frac{\bar{M}_z}{\frac{1}{2}\rho \bar{u}^2 b^2}$$

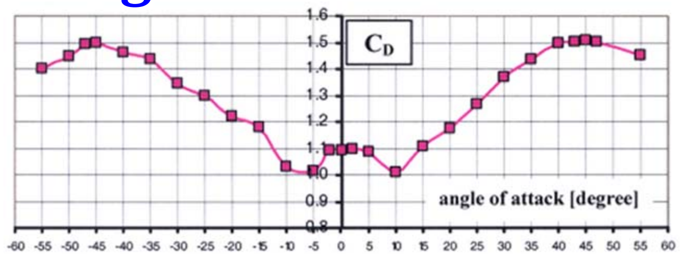
Brancusi Endless Column, Tîrgu Jiu, Rumania



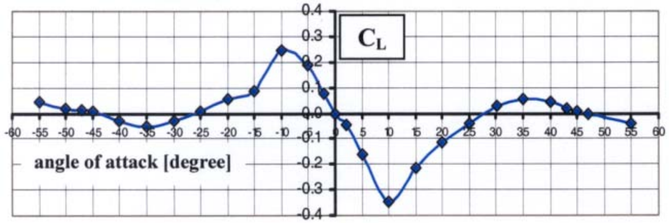


wind tunnel tests

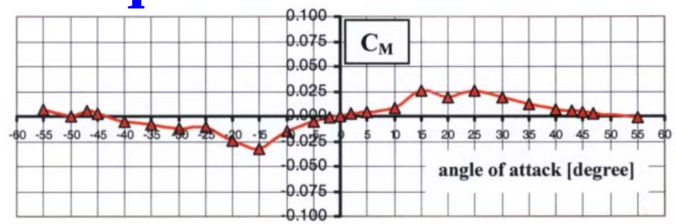
Drag coefficient



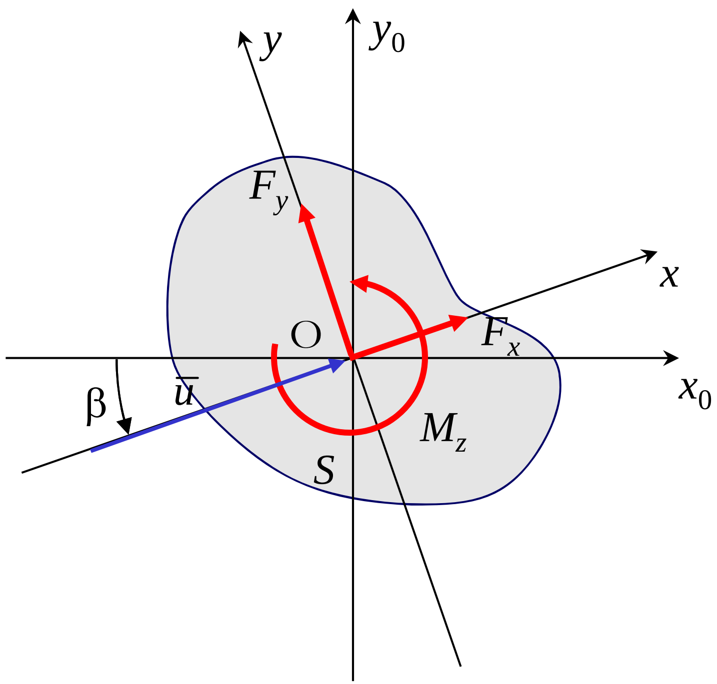
Lift coefficient



Torque coefficient



Wind induced actions on slender cylinders



Drag coefficient

$$c_d(\beta) = \frac{\bar{F}_x}{\frac{1}{2}\rho\bar{u}^2 b}$$

Lift coefficient

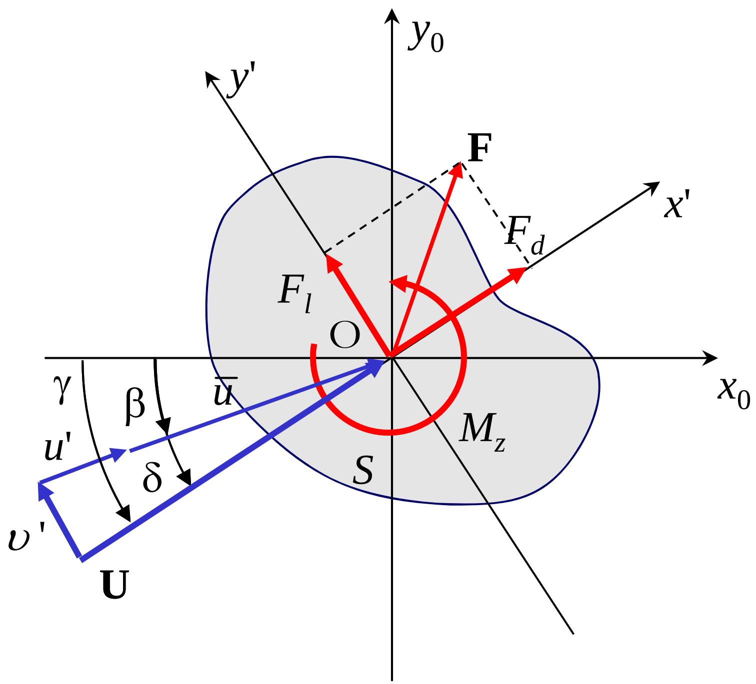
$$c_l(\beta) = \frac{\bar{F}_y}{\frac{1}{2}\rho\bar{u}^2 b}$$

Torque coefficient

$$c_m(\beta) = \frac{\bar{M}_z}{\frac{1}{2}\rho\bar{u}^2 b^2}$$

$$\bar{F}_x = \frac{1}{2}\rho\bar{u}^2 b c_d(\beta) \qquad \bar{F}_y = \frac{1}{2}\rho\bar{u}^2 b c_l(\beta) \qquad \bar{M}_z = \frac{1}{2}\rho\bar{u}^2 b^2 c_m(\beta)$$

Wind induced actions on slender cylinders



Drag coefficient $$c_d(\beta) = \frac{\bar{F}_x}{\frac{1}{2}\rho \bar{u}^2 b}$$

Lift coefficient $$c_l(\beta) = \frac{\bar{F}_y}{\frac{1}{2}\rho \bar{u}^2 b}$$

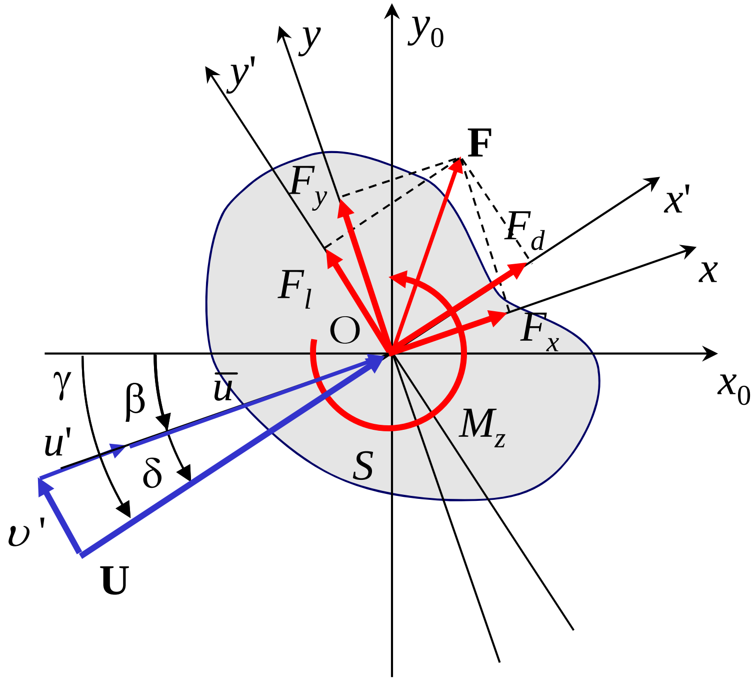
Torque coefficient $$c_m(\beta) = \frac{\bar{M}_z}{\frac{1}{2}\rho \bar{u}^2 b^2}$$

$$\bar{F}_x = \frac{1}{2}\rho \bar{u}^2 b c_d(\beta) \qquad \bar{F}_y = \frac{1}{2}\rho \bar{u}^2 b c_l(\beta) \qquad \bar{M}_z = \frac{1}{2}\rho \bar{u}^2 b^2 c_m(\beta)$$

Quasi-steady theory

$$F_d(t) = \frac{1}{2}\rho U^2(t) b c_d(\gamma(t)) \qquad F_l(t) = \frac{1}{2}\rho U^2(t) b c_l(\gamma(t)) \qquad M_z(t) = \frac{1}{2}\rho U^2(t) b^2 c_m(\gamma(t))$$

Wind induced actions on slender cylinders



Drag coefficient

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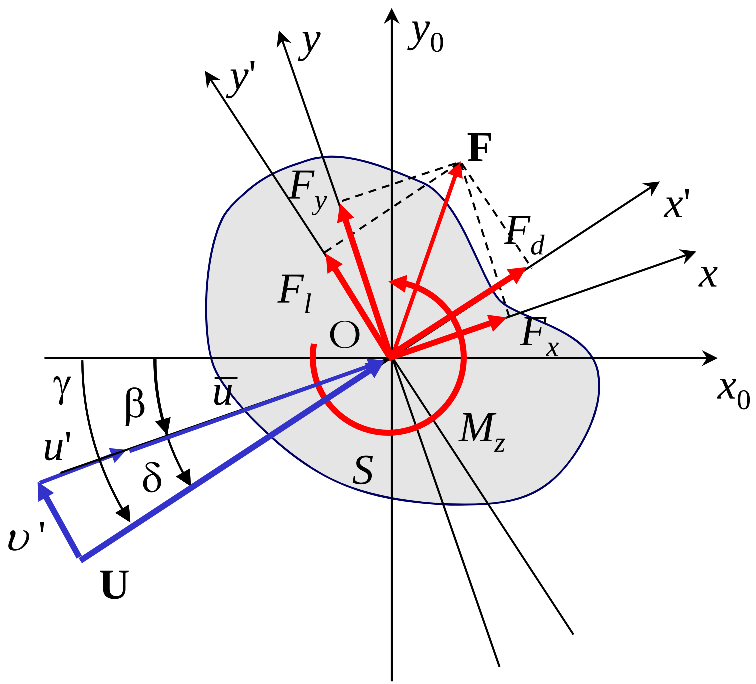
Quasi-steady theory

$$F_d(t) = \frac{1}{2}\rho U^2(t) b c_d(\gamma(t)) \qquad F_l(t) = \frac{1}{2}\rho U^2(t) b c_l(\gamma(t)) \qquad M_z(t) = \frac{1}{2}\rho U^2(t) b^2 c_m(\gamma(t))$$

Projection on x, y axes

$$F_x(t) = F_d(t)\cos\delta(t) - F_l(t)\sin\delta(t) \qquad F_y(t) = F_d(t)\sin\delta(t) + F_l(t)\cos\delta(t)$$

Wind induced actions on slender cylinders



$$F_x(t) = \frac{1}{2}\rho U^2(t) b c_x(\gamma)$$

$$F_y(t) = \frac{1}{2}\rho U^2(t) b c_y(\gamma)$$

$$M_\vartheta(t) = \frac{1}{2}\rho U^2(t) b^2 c_m(\gamma)$$

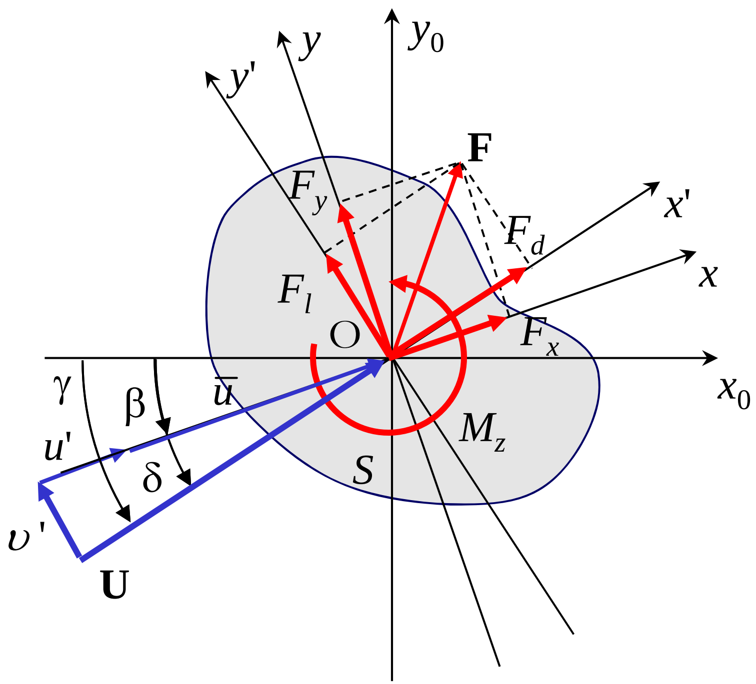
Quasi-steady theory

$$F_d(t) = \frac{1}{2}\rho U^2(t) b c_d(\gamma(t)) \qquad F_l(t) = \frac{1}{2}\rho U^2(t) b c_l(\gamma(t)) \qquad M_z(t) = \frac{1}{2}\rho U^2(t) b^2 c_m(\gamma(t))$$

Projection on x, y axes

$$F_x(t) = F_d(t)\cos\delta(t) - F_l(t)\sin\delta(t) \qquad F_y(t) = F_d(t)\sin\delta(t) + F_l(t)\cos\delta(t)$$

Wind induced actions on slender cylinders



$$F_x(t) = \frac{1}{2}\rho U^2(t) b c_x(\gamma)$$

$$F_y(t) = \frac{1}{2}\rho U^2(t) b c_y(\gamma)$$

$$M_\vartheta(t) = \frac{1}{2}\rho U^2(t) b^2 c_m(\gamma)$$

$$c_x(\gamma) = c_d(\gamma)\cos\delta - c_l(\gamma)\sin\delta$$

$$c_y(\gamma) = c_d(\gamma)\sin\delta + c_l(\gamma)\cos\delta$$

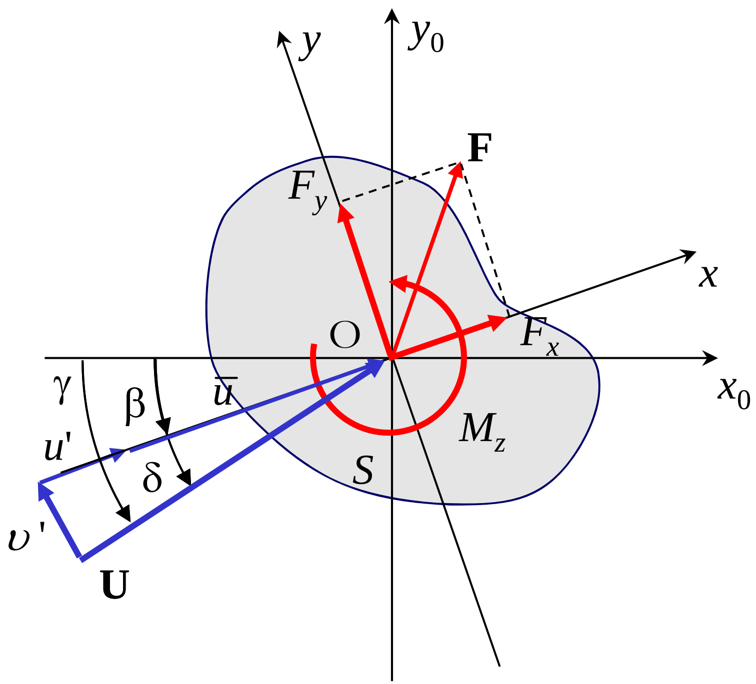
Quasi-steady theory

$$F_d(t) = \frac{1}{2}\rho U^2(t) b c_d\left(\gamma(t)\right) \quad F_l(t) = \frac{1}{2}\rho U^2(t) b c_l\left(\gamma(t)\right) \quad M_z(t) = \frac{1}{2}\rho U^2(t) b^2 c_m\left(\gamma(t)\right)$$

Projection on x, y axes

$$F_x(t) = F_d(t)\cos\delta(t) - F_l(t)\sin\delta(t) \qquad F_y(t) = F_d(t)\sin\delta(t) + F_l(t)\cos\delta(t)$$

Wind induced actions on slender cylinders



$$F_x(t) = \frac{1}{2}\rho U^2(t) b c_x(\gamma)$$

$$F_y(t) = \frac{1}{2}\rho U^2(t) b c_y(\gamma)$$

$$M_\vartheta(t) = \frac{1}{2}\rho U^2(t) b^2 c_m(\gamma)$$

$$c_x(\gamma) = c_d(\gamma)\cos\delta - c_l(\gamma)\sin\delta$$

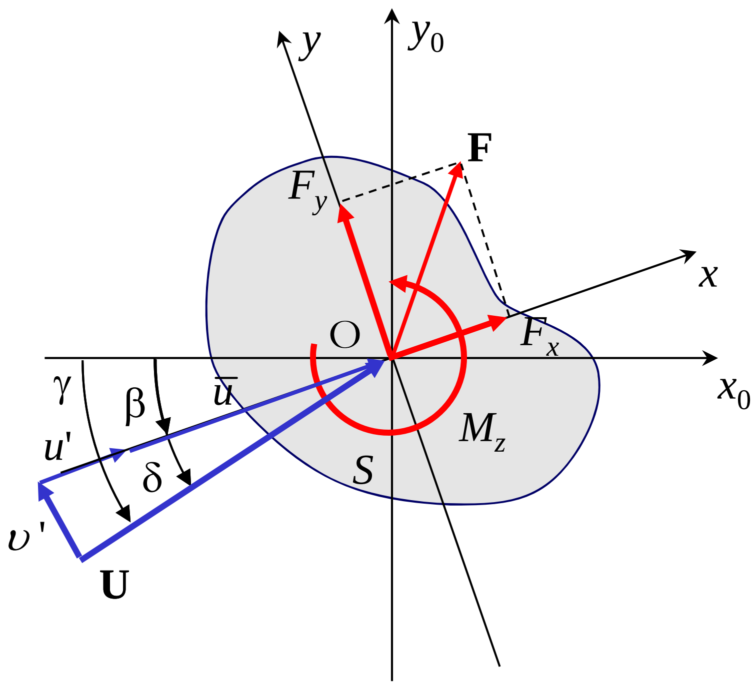
$$c_y(\gamma) = c_d(\gamma)\sin\delta + c_l(\gamma)\cos\delta$$

$$c_x(\gamma) = c_d + \delta(c_d' - c_l) + \frac{\delta^2}{2}(c_d'' - c_d - 2c_l') + \dots$$

$$c_y(\gamma) = c_l + \delta(c_d + c_l') + \frac{\delta^2}{2}(2c_d' + c_l'' - c_l) + \dots$$

$$c_m(\gamma) = c_m + \delta c_m' + \frac{\delta^2}{2}c_m'' + \dots$$

Wind induced actions on slender cylinders



$$F_x(t) = \frac{1}{2}\rho U^2(t) b c_x(\gamma)$$

$$F_y(t) = \frac{1}{2}\rho U^2(t) b c_y(\gamma)$$

$$M_\vartheta(t) = \frac{1}{2}\rho U^2(t) b^2 c_m(\gamma)$$

$$c_x(\gamma) = c_d(\gamma)\cos\delta - c_l(\gamma)\sin\delta$$

$$c_y(\gamma) = c_d(\gamma)\sin\delta + c_l(\gamma)\cos\delta$$

$$c_x(\gamma) = c_d + \delta(c_d' - c_l) + \frac{\delta^2}{2}(c_d'' - c_d - 2c_l') + \ldots$$

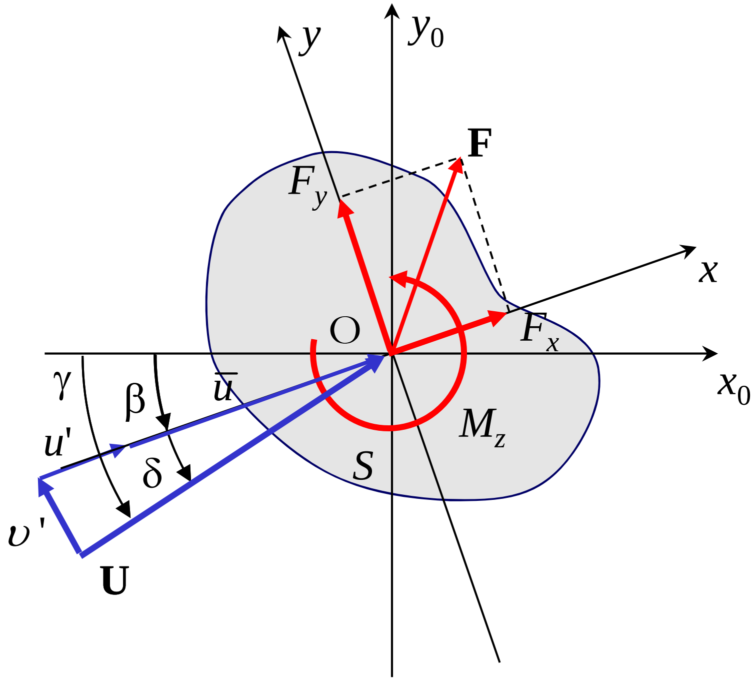
$$c_y(\gamma) = c_l + \delta(c_d + c_l') + \frac{\delta^2}{2}(2c_d' + c_l'' - c_l) + \ldots$$

$$c_m(\gamma) = c_m + \delta c_m' + \frac{\delta^2}{2} c_m'' + \ldots$$

$$\delta = \operatorname{arctg}\left\{\frac{\upsilon'(t)}{\bar{u} + u'(t)}\right\} = \frac{\upsilon'(t)}{\bar{u} + u'(t)} - \frac{[\upsilon'(t)]^3}{3[\bar{u} + u'(t)]^3} + \ldots$$

$$U^2(t) = [\bar{u} + u'(t)]^2 + \upsilon'^2(t)$$

Wind induced actions on slender cylinders

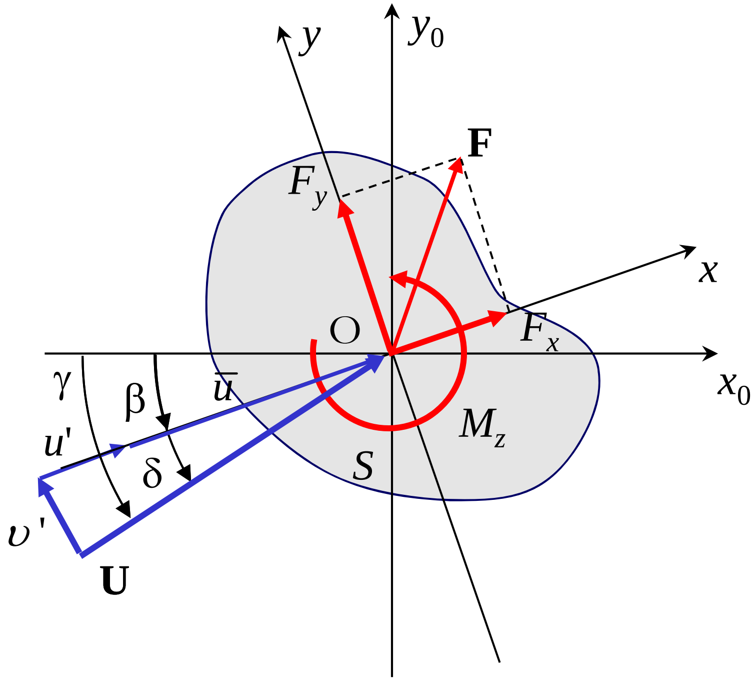


$$\bar{F}_x = \frac{1}{2}\rho\bar{u}^2 b c_d$$

$$\bar{F}_y = \frac{1}{2}\rho\bar{u}^2 b c_l$$

$$\bar{M}_z = \frac{1}{2}\rho\bar{u}^2 b^2 c_m$$

Wind induced actions on slender cylinders



$$\bar{F}_x = \frac{1}{2}\rho\bar{u}^2 b c_d$$

$$\bar{F}_y = \frac{1}{2}\rho\bar{u}^2 b c_l$$

$$\bar{M}_z = \frac{1}{2}\rho\bar{u}^2 b^2 c_m$$

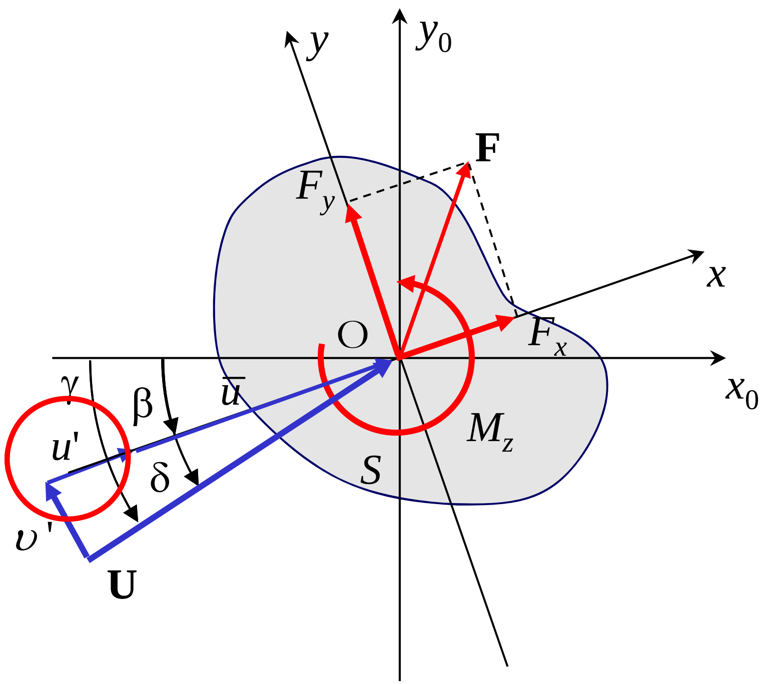
Small turbulence, i.e. $u'/\bar{u} << 1, \upsilon'/\bar{u} << 1$

$$F_x'(t) = \rho\bar{u}bc_d u'(t) + \frac{1}{2}\rho\bar{u}b\left(c_d' - c_l\right)\upsilon'(t)$$

$$F_y'(t) = \rho\bar{u}bc_l u'(t) + \frac{1}{2}\rho\bar{u}b\left(c_d + c_l'\right)\upsilon'(t)$$

$$M_z'(t) = \rho\bar{u}b^2 c_m u'(t) + \frac{1}{2}\rho\bar{u}b^2 c_m'\upsilon'(t)$$

Wind induced actions on slender cylinders



$$\bar{F}_x = \frac{1}{2}\rho\bar{u}^2 b c_d$$

$$\bar{F}_y = \frac{1}{2}\rho\bar{u}^2 b c_l$$

$$\bar{M}_z = \frac{1}{2}\rho\bar{u}^2 b^2 c_m$$

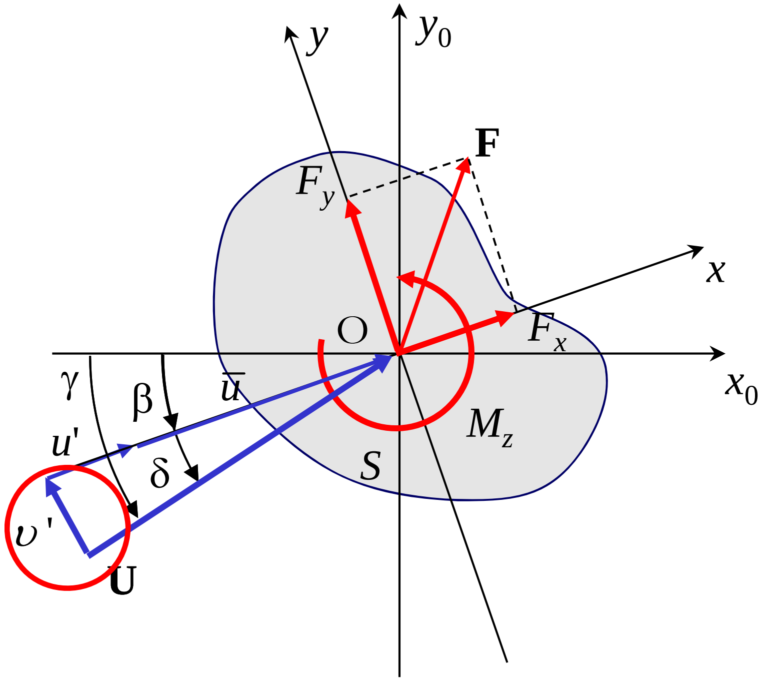
Small turbulence, i.e. $u'/\bar{u} << 1, \upsilon'/\bar{u} << 1$

$$F'_x(t) = \rho\bar{u}bc_d u'(t) + \frac{1}{2}\rho\bar{u}b(c'_d - c_l)\upsilon'(t)$$

$$F'_y(t) = \rho\bar{u}bc_l u'(t) + \frac{1}{2}\rho\bar{u}b(c_d + c'_l)\upsilon'(t)$$

$$M'_z(t) = \rho\bar{u}b^2 c_m u'(t) + \frac{1}{2}\rho\bar{u}b^2 c'_m \upsilon'(t)$$

Wind induced actions on slender cylinders



$$\bar{F}_x = \frac{1}{2}\rho\bar{u}^2 b c_d$$

$$\bar{F}_y = \frac{1}{2}\rho\bar{u}^2 b c_l$$

$$\bar{M}_z = \frac{1}{2}\rho\bar{u}^2 b^2 c_m$$

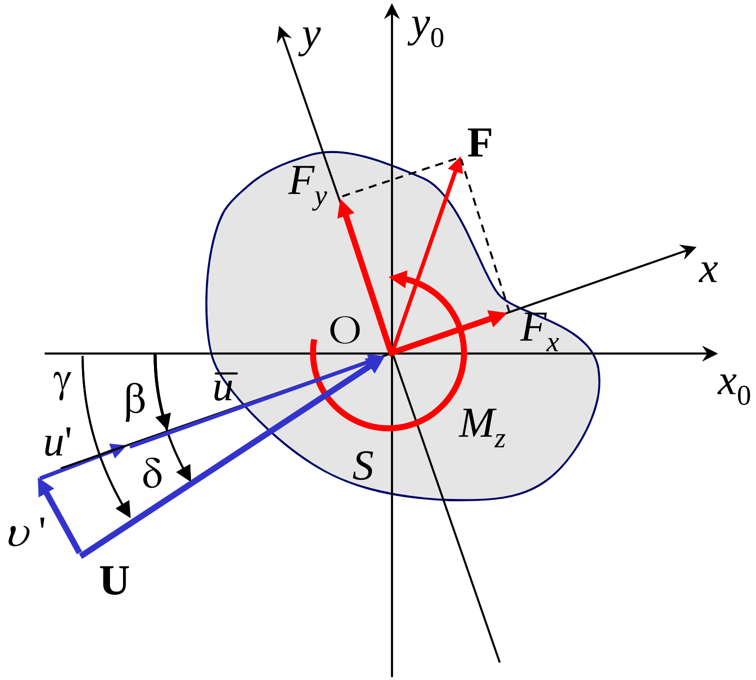
Small turbulence, i.e. $u'/\bar{u} << 1, \upsilon'/\bar{u} << 1$

$$F_x'(t) = \rho\bar{u}bc_d u'(t) + \frac{1}{2}\rho\bar{u}b\left(c_d' - c_l\right)\upsilon'(t)$$

$$F_y'(t) = \rho\bar{u}bc_l u'(t) + \frac{1}{2}\rho\bar{u}b\left(c_d + c_l'\right)\upsilon'(t)$$

$$M_z'(t) = \rho\bar{u}b^2 c_m u'(t) + \frac{1}{2}\rho\bar{u}b^2 c_m'\upsilon'(t)$$

Wind induced actions on slender cylinders



$$\bar{F}_x = \frac{1}{2}\rho\bar{u}^2 b c_d$$

$$\bar{F}_y = \frac{1}{2}\rho\bar{u}^2 b c_l$$

$$\bar{M}_z = \frac{1}{2}\rho\bar{u}^2 b^2 c_m$$

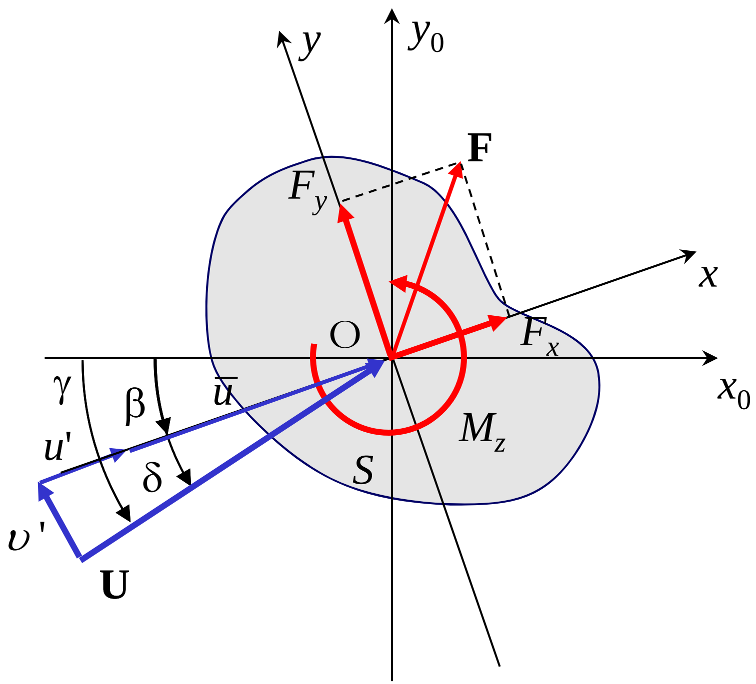
Small turbulence, i.e. $u'/\bar{u} \ll 1, \upsilon'/\bar{u} \ll 1$

$$\boxed{F'_x(t) = \rho\bar{u}bc_d u'(t)} + \frac{1}{2}\rho\bar{u}b\left(c'_d - c_l\right)\upsilon'(t)$$

$$F'_y(t) = \rho\bar{u}bc_l u'(t) + \frac{1}{2}\rho\bar{u}b\left(c_d + c'_l\right)\upsilon'(t)$$

$$M'_z(t) = \rho\bar{u}b^2 c_m u'(t) + \frac{1}{2}\rho\bar{u}b^2 c'_m \upsilon'(t)$$

Wind induced actions on slender cylinders



$$\bar{F}_x = \frac{1}{2}\rho\bar{u}^2 b c_d$$

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$$\bar{M}_z = \frac{1}{2}\rho\bar{u}^2 b^2 c_m$$

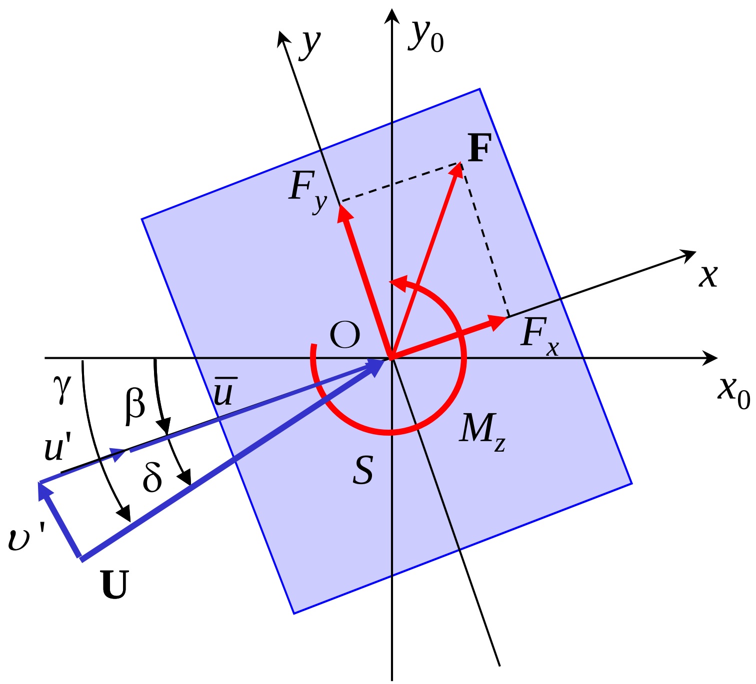
Small turbulence, i.e. $u'/\bar{u} \ll 1, \upsilon'/\bar{u} \ll 1$

$$\boxed{F_x'(t) = \rho\bar{u}bc_d u'(t)} + \boxed{\frac{1}{2}\rho\bar{u}b\left(c_d' - c_l\right)\upsilon'(t)}$$

$$F_y'(t) = \rho\bar{u}bc_l u'(t) + \frac{1}{2}\rho\bar{u}b\left(c_d + c_l'\right)\upsilon'(t)$$

$$M_z'(t) = \rho\bar{u}b^2 c_m u'(t) + \frac{1}{2}\rho\bar{u}b^2 c_m'\upsilon'(t)$$

Wind induced actions on slender cylinders



$$\bar{F}_x = \frac{1}{2}\rho\bar{u}^2 b c_d$$

$$\bar{F}_y = \frac{1}{2}\rho\bar{u}^2 b c_l$$

$$\bar{M}_z = \frac{1}{2}\rho\bar{u}^2 b^2 c_m$$

x = symmetry axis

$c_l = c_m = c_d' = 0$

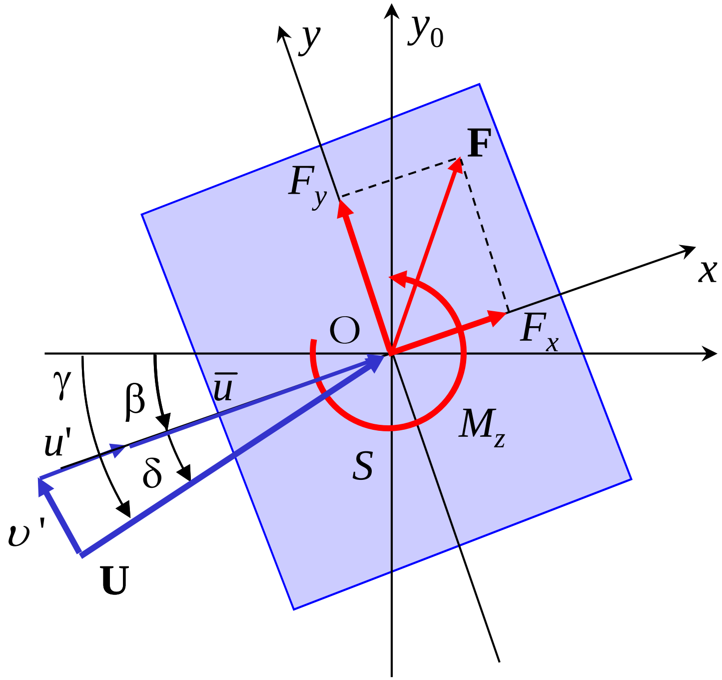
Small turbulence, i.e. $u'/\bar{u} << 1, \upsilon'/\bar{u} << 1$

$$F_x'(t) = \rho\bar{u}bc_d u'(t) + \frac{1}{2}\rho\bar{u}b\left(c_d' - c_l\right)\upsilon'(t)$$

$$F_y'(t) = \rho\bar{u}bc_l u'(t) + \frac{1}{2}\rho\bar{u}b\left(c_d + c_l'\right)\upsilon'(t)$$

$$M_z'(t) = \rho\bar{u}b^2 c_m u'(t) + \frac{1}{2}\rho\bar{u}b^2 c_m'\upsilon'(t)$$

Wind induced actions on slender cylinders



$$\bar{F}_x = \frac{1}{2}\rho\bar{u}^2 b c_d$$

$$\bar{F}_y = \frac{1}{2}\rho\bar{u}^2 b \cancel{c_l}$$

$$\bar{M}_z = \frac{1}{2}\rho\bar{u}^2 b^2 \cancel{c_m}$$

x = symmetry axis

$c_l = c_m = c'_d = 0$

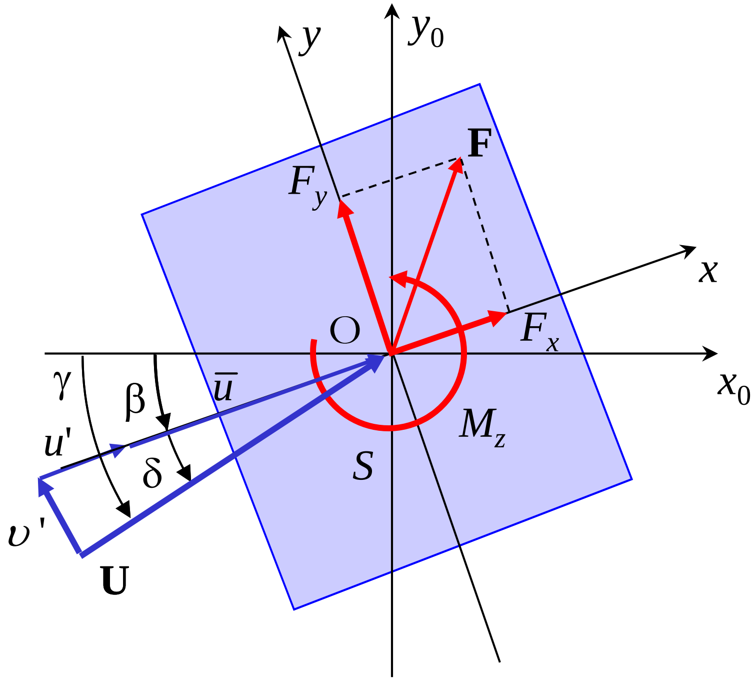
Small turbulence, i.e. $u'/\bar{u} << 1, \upsilon'/\bar{u} << 1$

$$F'_x(t) = \rho\bar{u}bc_d u'(t) + \frac{1}{2}\rho\bar{u}b\left(\cancel{c'_d} - \cancel{c_l}\right)\upsilon'(t)$$

$$F'_y(t) = \rho\bar{u}b\cancel{c_l}u'(t) + \frac{1}{2}\rho\bar{u}b\left(c_d + c'_l\right)\upsilon'(t)$$

$$M'_z(t) = \rho\bar{u}b^2\cancel{c_m}u'(t) + \frac{1}{2}\rho\bar{u}b^2 c'_m\upsilon'(t)$$

Wind induced actions on slender cylinders



$$\bar{F}_x = \frac{1}{2}\rho\bar{u}^2 b c_d$$

$$\bar{F}_y = 0$$

$$\bar{M}_z = 0$$

x = symmetry axis

$c_l = c_m = c_d' = 0$

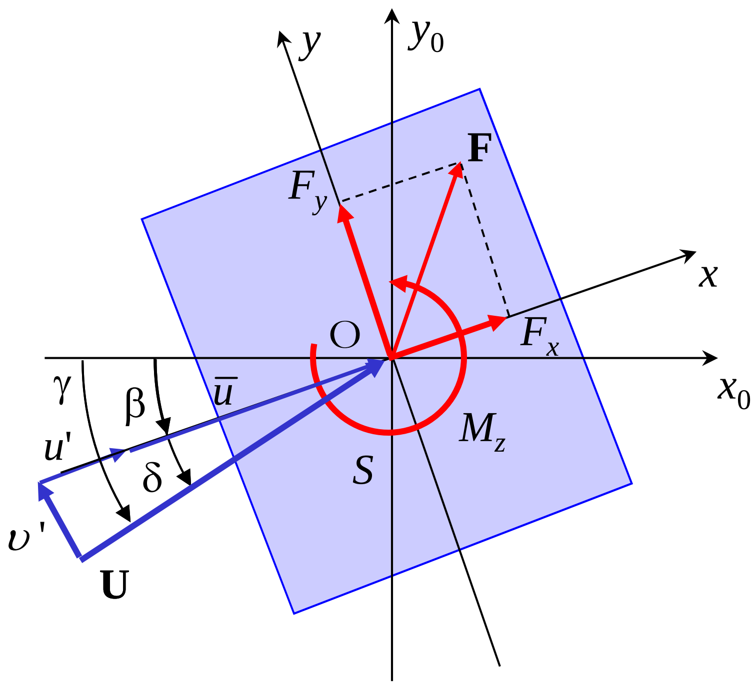
Small turbulence, i.e. $u'/\bar{u} << 1, \upsilon'/\bar{u} << 1$

$$F_x'(t) = \rho\bar{u}bc_d u'(t)$$

$$F_y'(t) = \frac{1}{2}\rho\bar{u}b\left(c_d + c_l'\right)\upsilon'(t)$$

$$M_z'(t) = \frac{1}{2}\rho\bar{u}b^2 c_m'\upsilon'(t)$$

Wind induced actions on slender cylinders



x = symmetry axis

$c_l = c_m = c_d' = 0$

$$\bar{F}_x = \frac{1}{2}\rho \bar{u}^2 b c_d$$

$$\bar{F}_y = 0$$

$$\bar{M}_z = 0$$

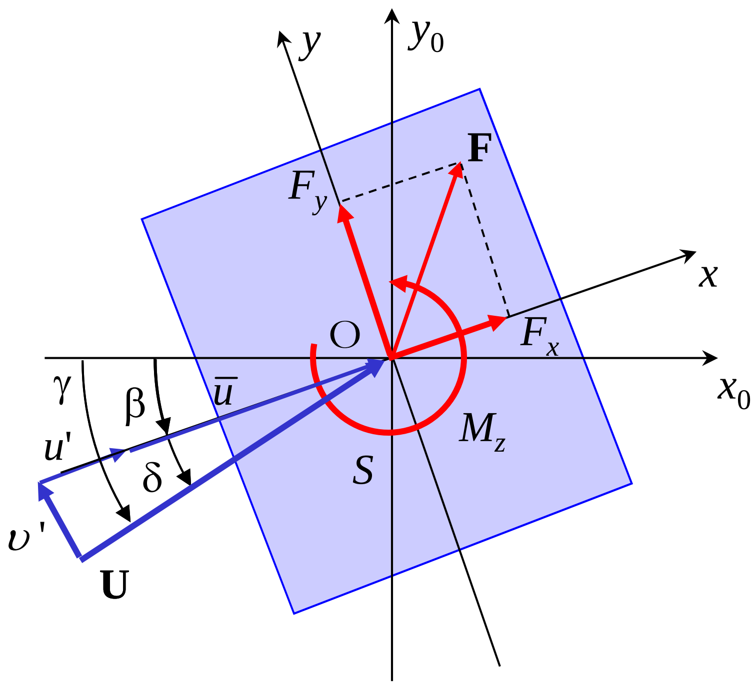
Small turbulence, i.e. $u'/\bar{u} << 1, \upsilon'/\bar{u} << 1$

$$\boxed{F_x'(t) = \rho \bar{u} b c_d u'(t)}$$

$$F_y'(t) = \frac{1}{2}\rho \bar{u} b \left(c_d + c_l'\right)\upsilon'(t)$$

$$M_z'(t) = \frac{1}{2}\rho \bar{u} b^2 c_m' \upsilon'(t)$$

Wind induced actions on slender cylinders



$$\bar{F}_x = \frac{1}{2}\rho\bar{u}^2 b c_d$$

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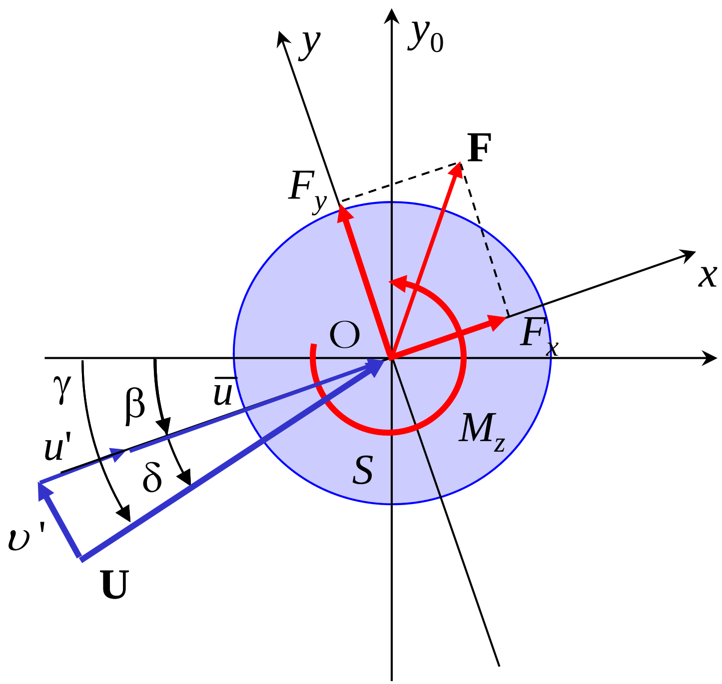
$$M'_z(t) = \frac{1}{2}\rho\bar{u}b^2 c'_m \upsilon'(t)$$

Wind induced actions on slender cylinders



$$\bar{F}_x = \frac{1}{2}\rho\bar{u}^2 b c_d$$

$$\bar{F}_y = 0$$

$$\bar{M}_z = 0$$

Small turbulence, i.e. $u'/\bar{u} << 1, \upsilon'/\bar{u} << 1$

polar symmetry

$$c_l = c_m = c_d' = 0$$

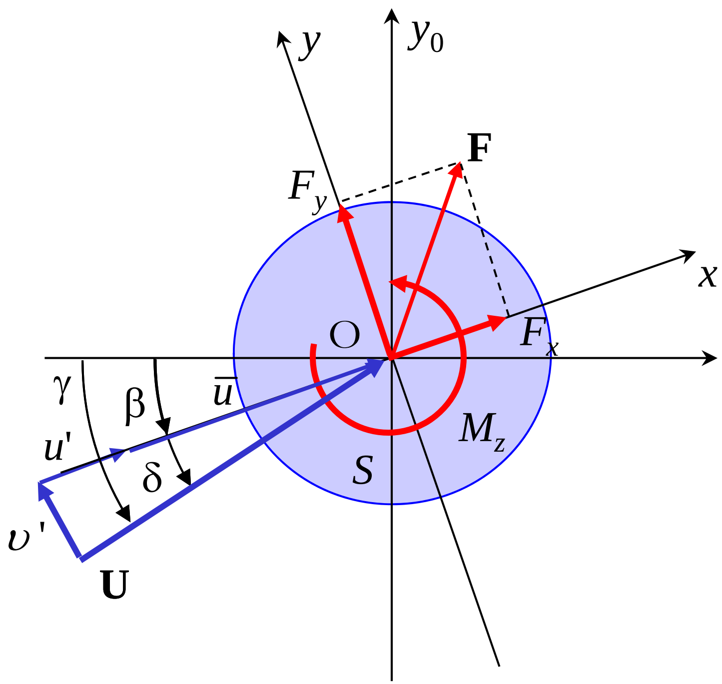
$$c_l' = c_m' = 0$$

$$F_x'(t) = \rho\bar{u}bc_d u'(t)$$

$$F_y'(t) = \frac{1}{2}\rho\bar{u}b\left(c_d + c_l'\right)\upsilon'(t)$$

$$M_z'(t) = \frac{1}{2}\rho\bar{u}b^2 c_m'\upsilon'(t)$$

Wind induced actions on slender cylinders



$$\bar{F}_x = \frac{1}{2}\rho\bar{u}^2 b c_d$$

$$\bar{F}_y = 0$$

$$\bar{M}_z = 0$$

Small turbulence, i.e. $u'/\bar{u} \ll 1, \upsilon'/\bar{u} \ll 1$

$$F'_x(t) = \rho\bar{u}bc_d u'(t)$$

$$F'_y(t) = \frac{1}{2}\rho\bar{u}b\left(c_d + \cancel{c'_l}\right)\upsilon'(t)$$

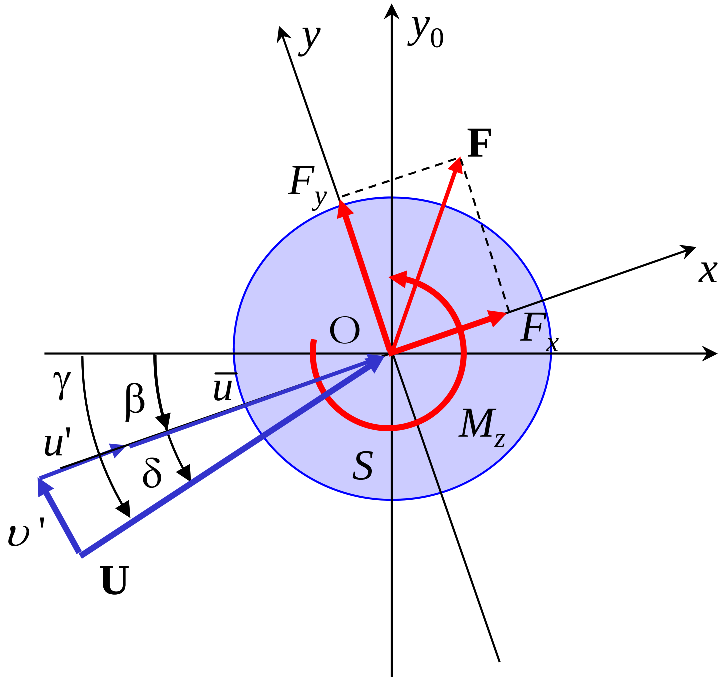
$$M'_z(t) = \frac{1}{2}\rho\bar{u}b^2\cancel{c'_m}\upsilon'(t)$$

polar symmetry

$$c_l = c_m = c'_d = 0$$

$$c'_l = c'_m = 0$$

Wind induced actions on slender cylinders



$$\bar{F}_x = \frac{1}{2}\rho\bar{u}^2 b c_d$$

$$\bar{F}_y = 0$$

$$\bar{M}_z = 0$$

Small turbulence, i.e. $u'/\bar{u} << 1, \upsilon'/\bar{u} << 1$

polar symmetry

$$c_l = c_m = c_d' = 0$$

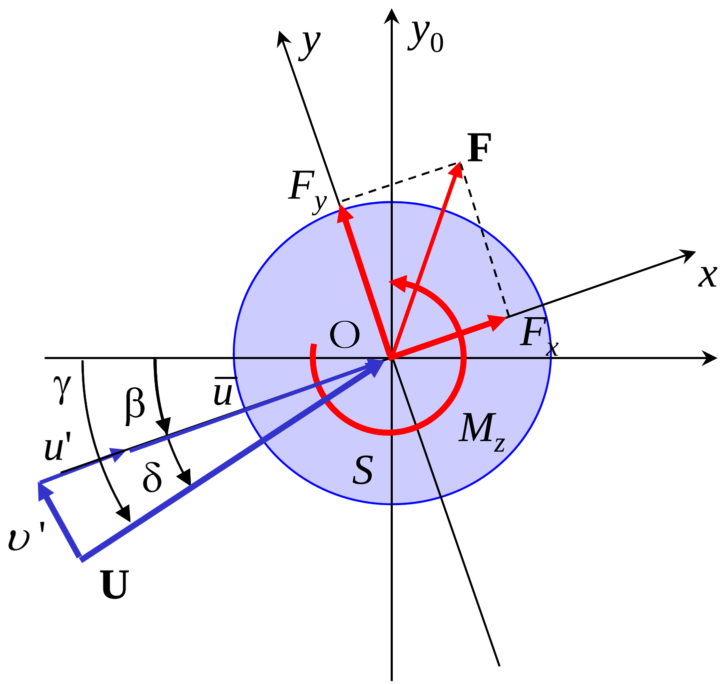
$$c_l' = c_m' = 0$$

$$F_x'(t) = \rho\bar{u}bc_d u'(t)$$

$$F_y'(t) = \frac{1}{2}\rho\bar{u}bc_d\upsilon'(t)$$

$$M_z'(t) = 0$$

Wind induced actions on slender cylinders



$$\bar{F}_x = \frac{1}{2}\rho\bar{u}^2 b c_d$$

$$\bar{F}_y = 0$$

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Small turbulence, i.e. $u'/\bar{u} \ll 1, \upsilon'/\bar{u} \ll 1$

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$$c_l = c_m = c_d' = 0$$

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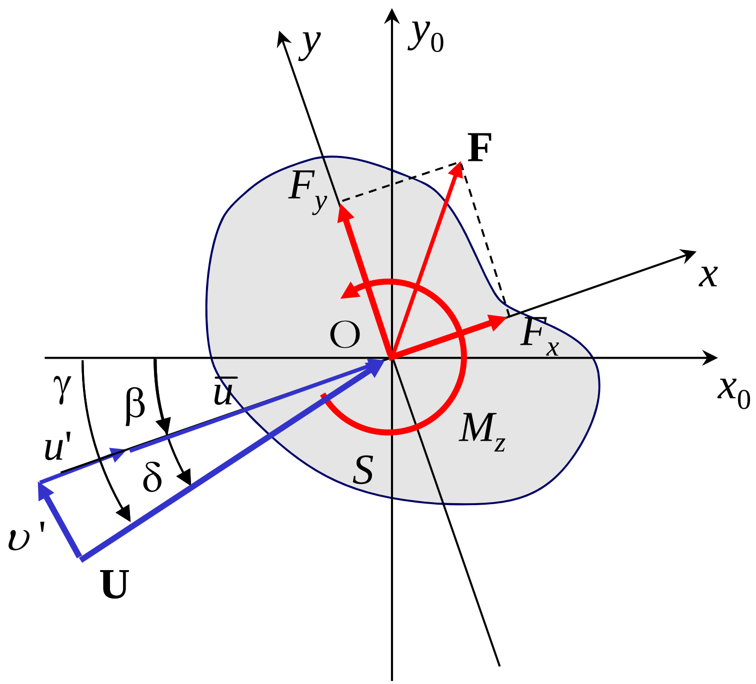
$$F_x'(t) = \rho\bar{u}bc_d u'(t)$$

$$F_y'(t) = \frac{1}{2}\rho\bar{u}bc_d \upsilon'(t)$$

$$M_z'(t) = 0$$

Wind induced actions on slender cylinders



$$\bar{F}_x = \frac{1}{2}\rho\bar{u}^2 b c_d$$

$$\bar{F}_y = \frac{1}{2}\rho\bar{u}^2 b c_l$$

$$\bar{M}_z = \frac{1}{2}\rho\bar{u}^2 b^2 c_m$$

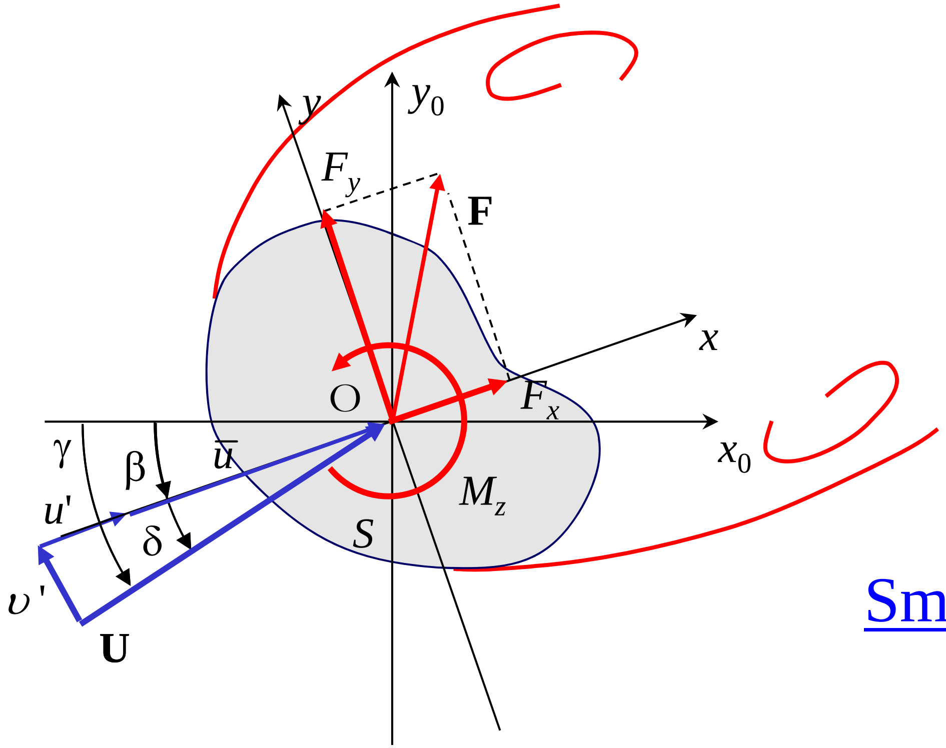
Small turbulence: $u'/\bar{u} << 1, \upsilon'/\bar{u} << 1$

$$F'_x(t) = \rho\bar{u}bc_d u'(t) + \frac{1}{2}\rho\bar{u}b\left(c'_d - c_l\right)\upsilon'(t)$$

$$F'_y(t) = \rho\bar{u}bc_l u'(t) + \frac{1}{2}\rho\bar{u}b\left(c_d + c'_l\right)\upsilon'(t)$$

$$M'_z(t) = \rho\bar{u}b^2 c_m u'(t) + \frac{1}{2}\rho\bar{u}b^2 c'_m \upsilon'(t)$$

Wind induced actions on slender cylinders



$$\bar{F}_x = \frac{1}{2}\rho\bar{u}^2 b c_d$$

$$\bar{F}_y = \frac{1}{2}\rho\bar{u}^2 b c_l$$

$$\bar{M}_z = \frac{1}{2}\rho\bar{u}^2 b^2 c_m$$

Small turbulence: $u'/\bar{u} << 1, \upsilon'/\bar{u} << 1$

$$F'_x(t) = \rho\bar{u}bc_d u'(t) + \frac{1}{2}\rho\bar{u}b\left(c'_d - c_l\right)\upsilon'(t)$$

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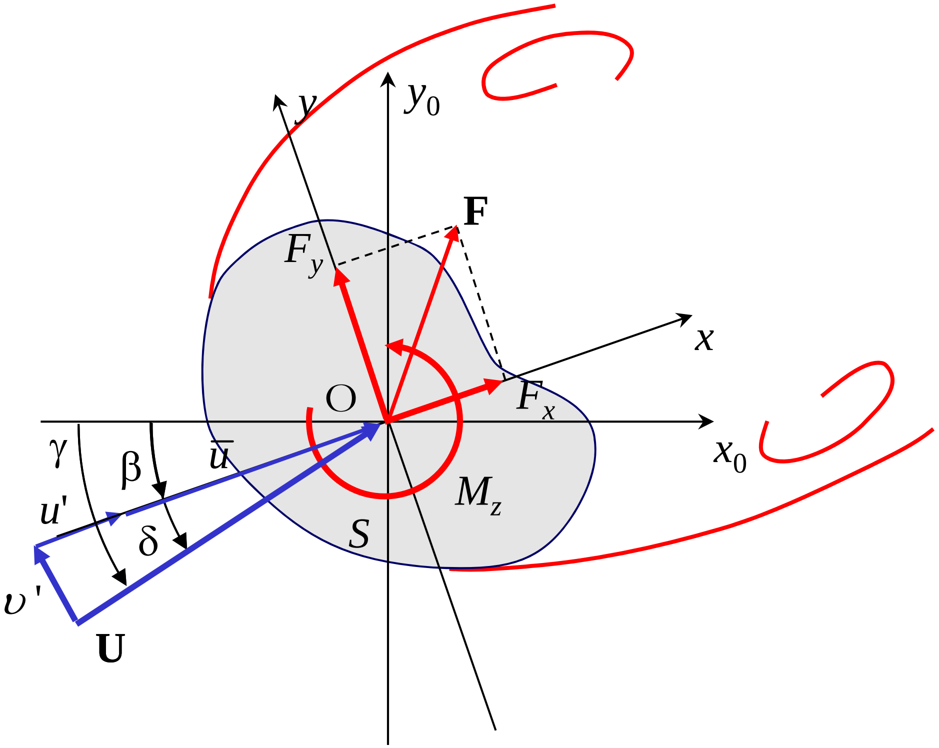
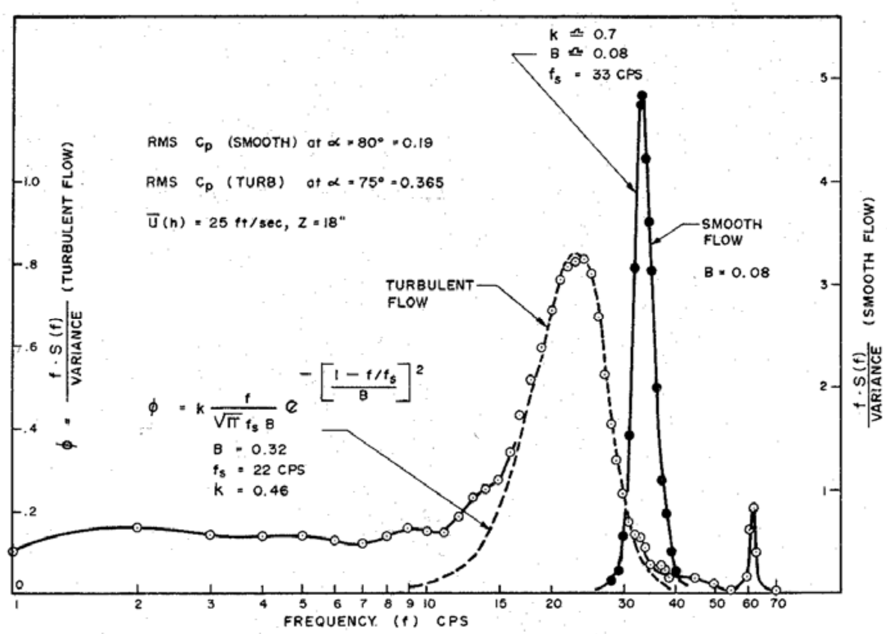
$$M'_z(t) = \rho\bar{u}b^2 c_m u'(t) + \frac{1}{2}\rho\bar{u}b^2 c'_m \upsilon'(t)$$

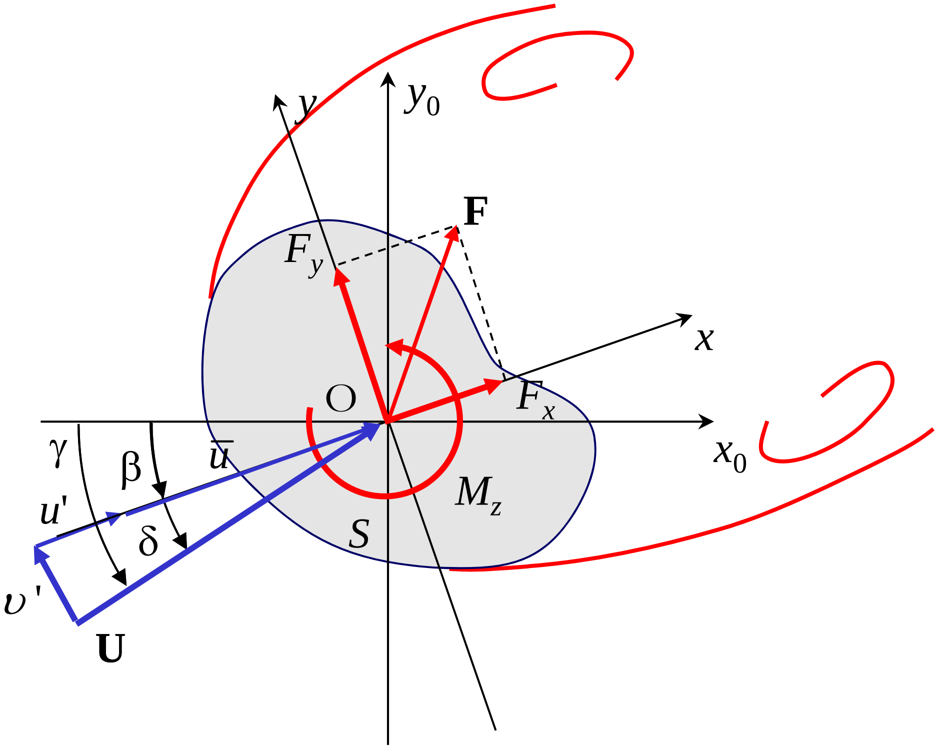
Wind induced actions on slender cylinders



Vickery & Clark (1972)

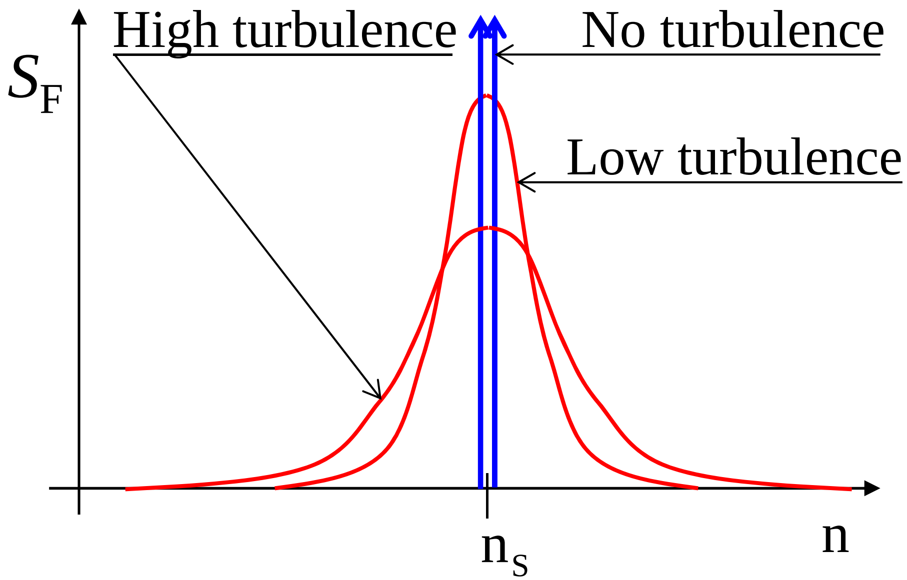


Wind induced actions on slender cylinders



Vickery & Clark (1972)

$$\boxed{\frac{nS(n)}{\tilde{C}_L^2} = \frac{n}{\sqrt{\pi}\beta n_S} \exp\left\{-\left[\frac{1-\frac{n}{n_s}}{\beta}\right]^2\right\}}$$

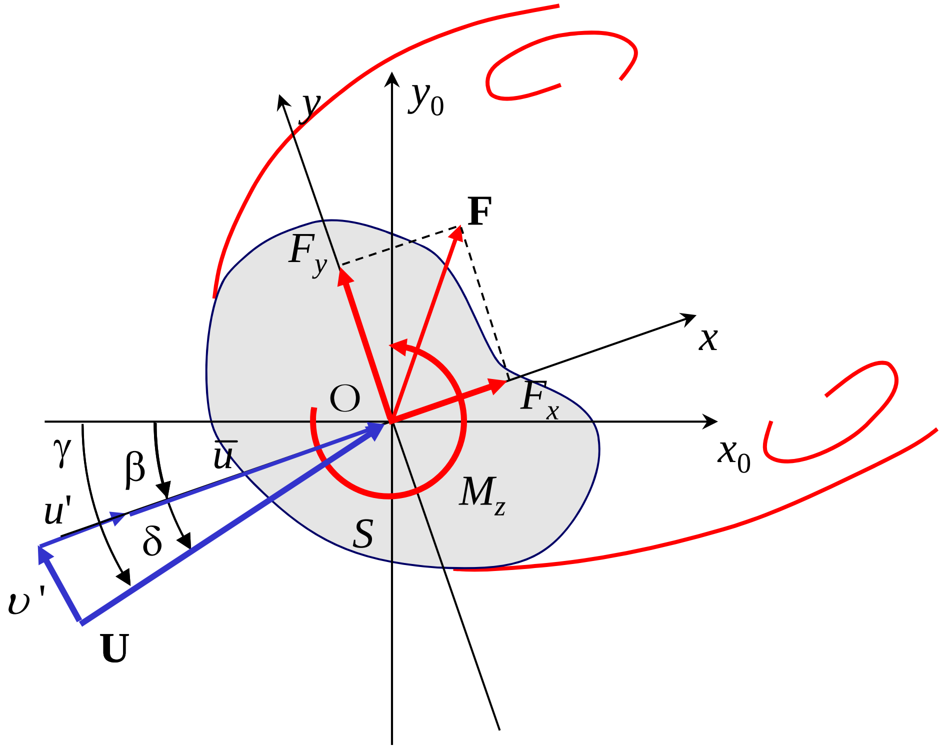


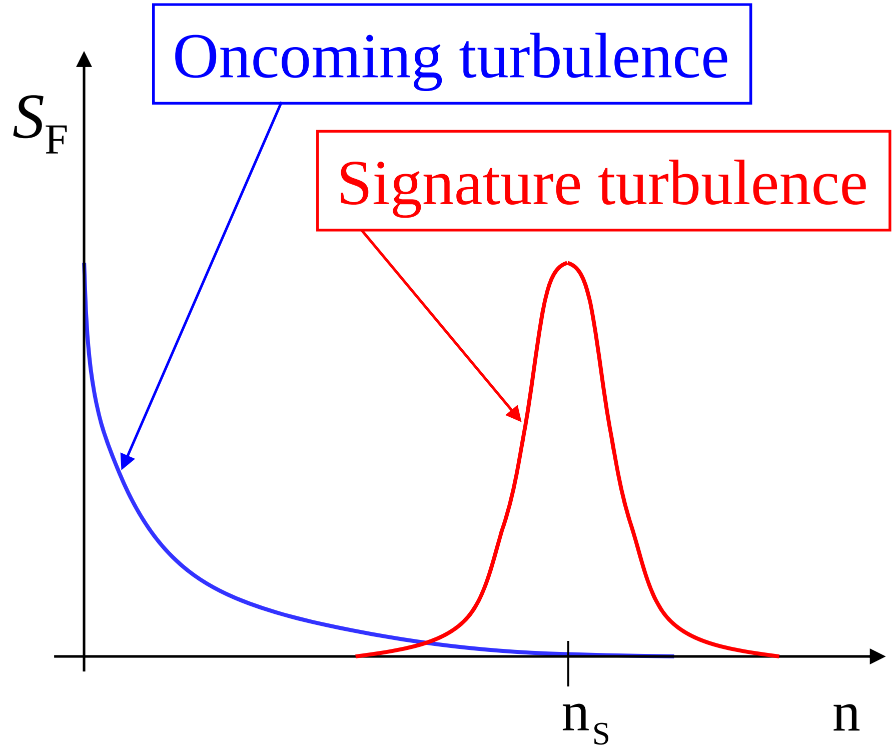
Shedding frequency

$$\boxed{n_s = \frac{\bar{u}S}{b}}$$

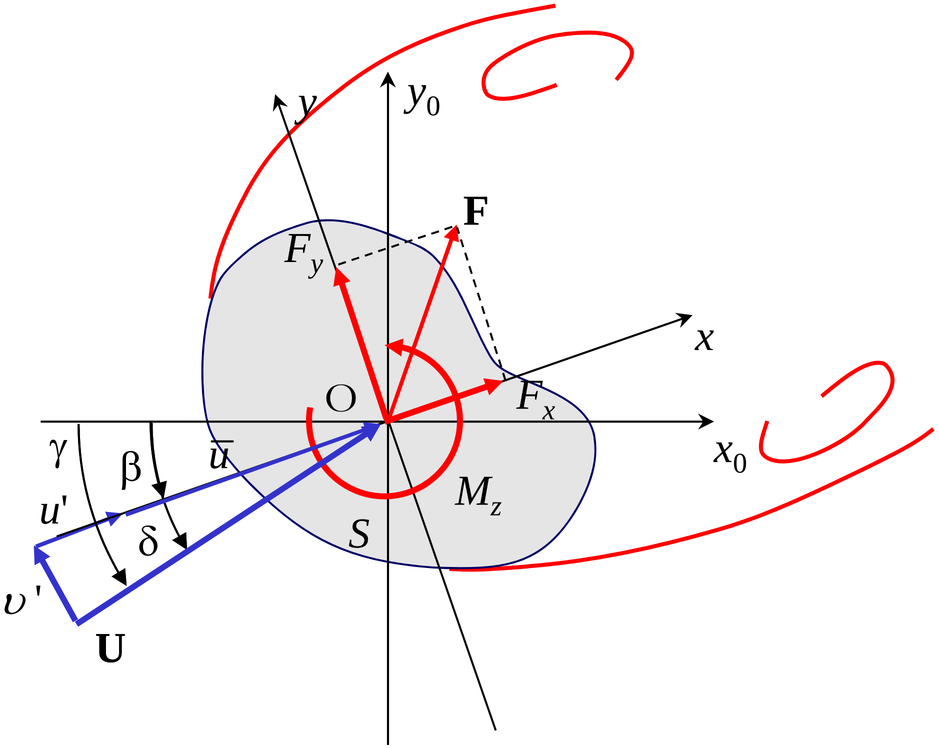
Strouhal number

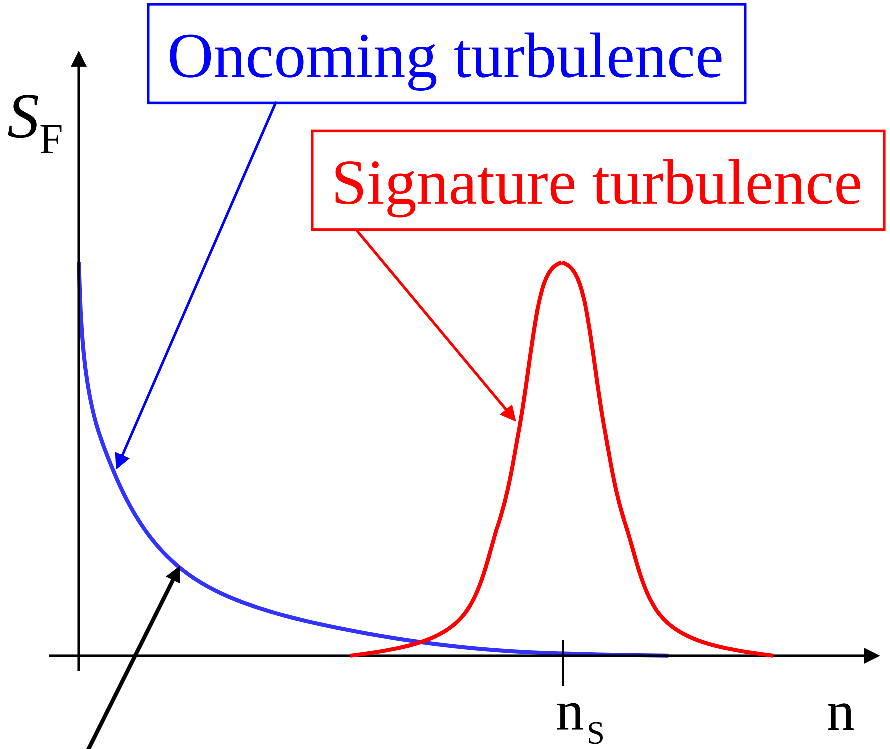
Wind induced actions on slender cylinders





Wind induced actions on slender cylinders



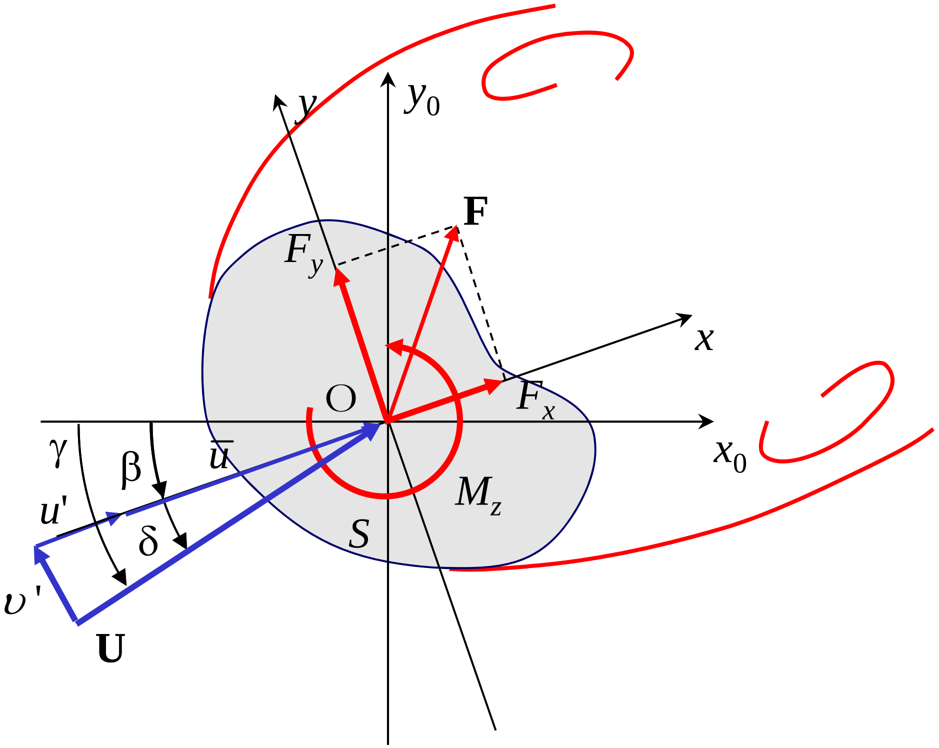


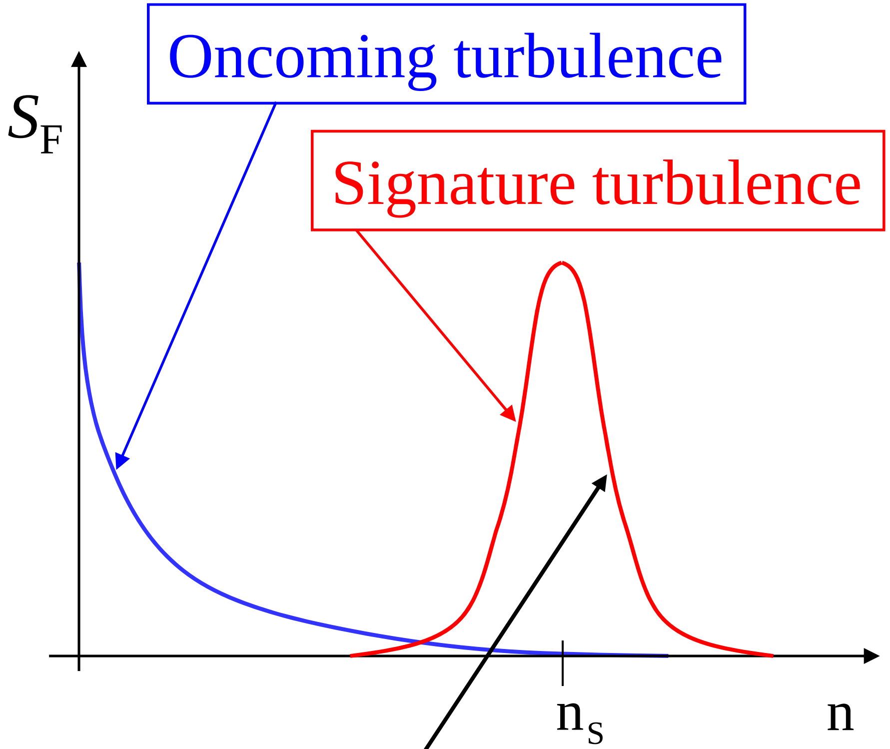
$$F'_x(t) = \rho\bar{u}bc_d u'(t) + \frac{1}{2}\rho\bar{u}b\left(c'_d - c_l\right)\upsilon'(t) + \frac{1}{2}\rho\bar{u}^2 b\tilde{c}_{ds}s^*_x(t)$$

$$F'_y(t) = \rho\bar{u}bc_l u'(t) + \frac{1}{2}\rho\bar{u}b\left(c_d + c'_l\right)\upsilon'(t) + \frac{1}{2}\rho\bar{u}^2 b\tilde{c}_{ls}s^*_y(t)$$

$$M'_z(t) = \rho\bar{u}b^2 c_m u'(t) + \frac{1}{2}\rho\bar{u}b^2 c'_m\upsilon'(t) + \frac{1}{2}\rho\bar{u}^2 b^2\tilde{c}_{ms}s^*_z(t)$$

Wind induced actions on slender cylinders



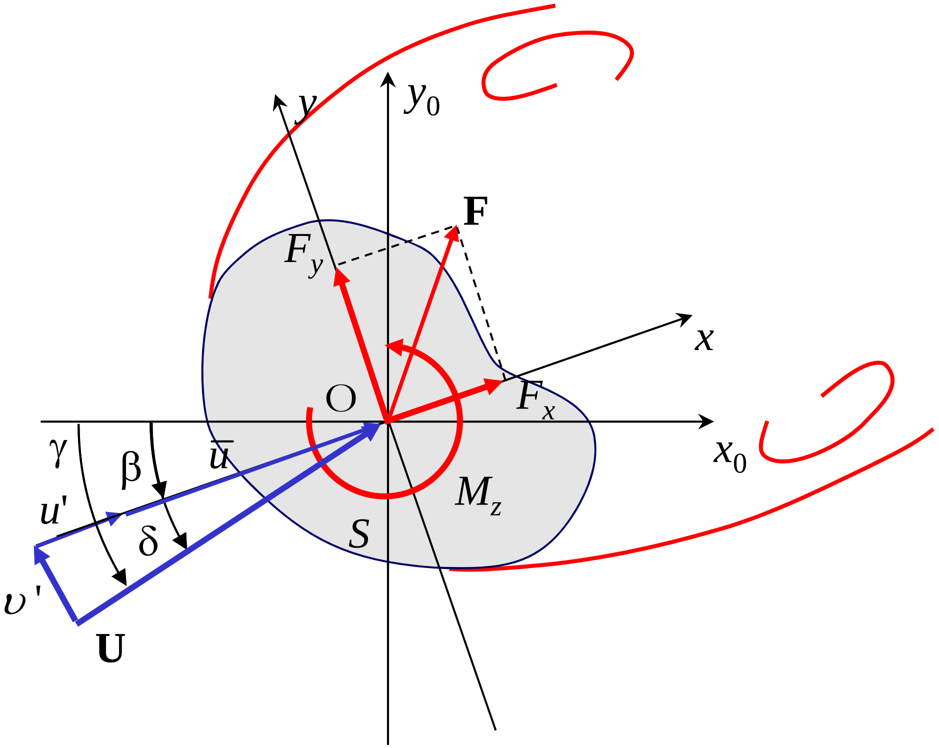


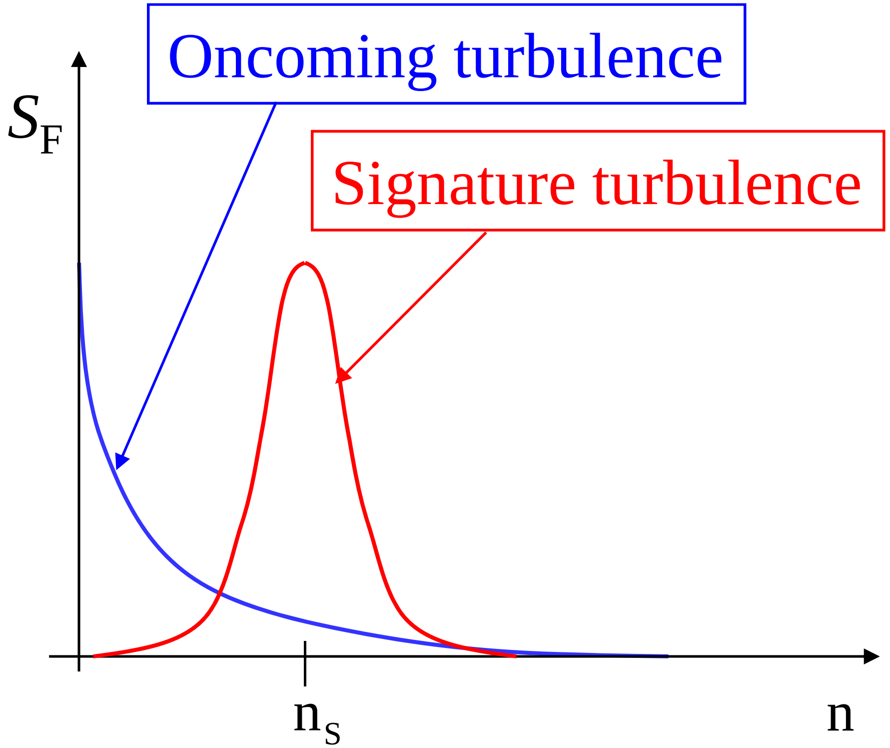
$$F'_x(t) = \rho\bar{u}bc_d u'(t) + \frac{1}{2}\rho\bar{u}b(c'_d - c_l)\upsilon'(t) \quad + \frac{1}{2}\rho\bar{u}^2 b\tilde{c}_{ds} s_x^*(t)$$

$$F'_y(t) = \rho\bar{u}bc_l u'(t) + \frac{1}{2}\rho\bar{u}b(c_d + c'_l)\upsilon'(t) \quad + \frac{1}{2}\rho\bar{u}^2 b\tilde{c}_{ls} s_y^*(t)$$

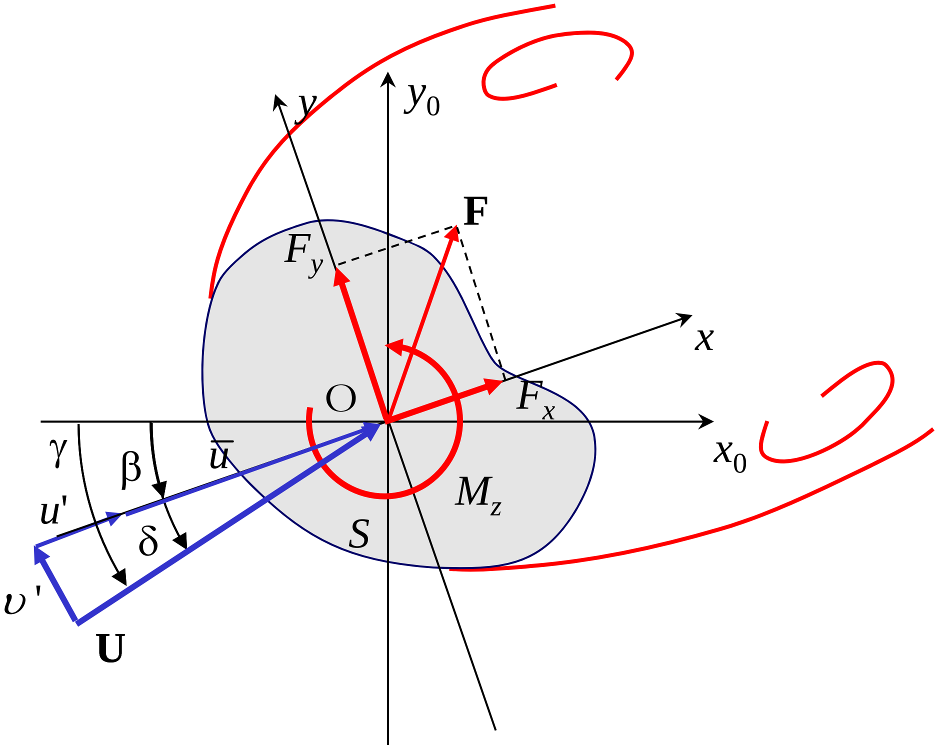
$$M'_z(t) = \rho\bar{u}b^2 c_m u'(t) + \frac{1}{2}\rho\bar{u}b^2 c'_m \upsilon'(t) \quad + \frac{1}{2}\rho\bar{u}^2 b^2\tilde{c}_{ms} s_z^*(t)$$

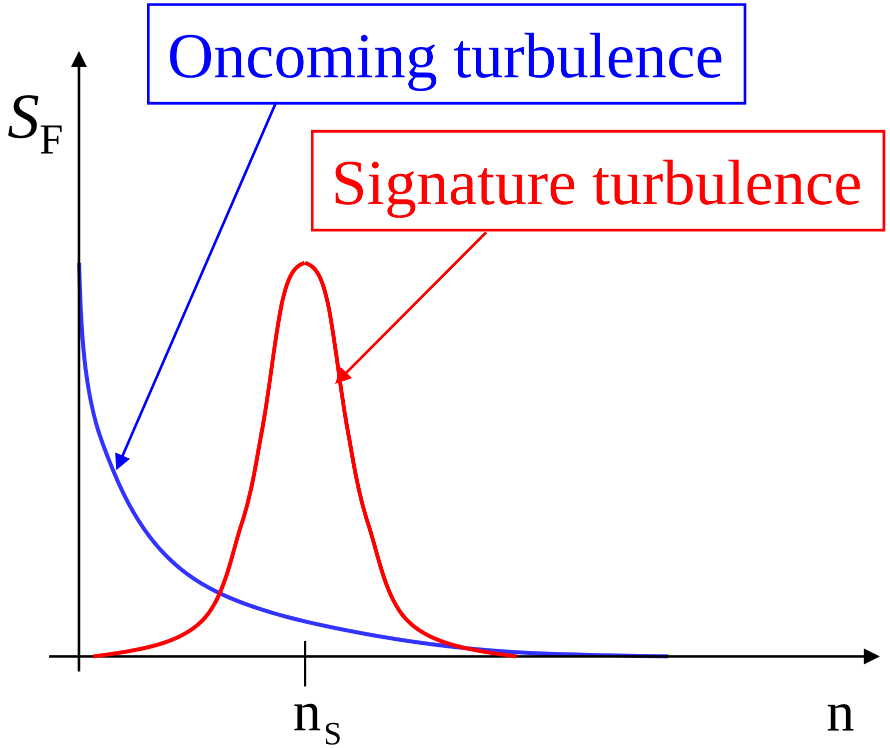
Wind induced actions on slender cylinders





Wind induced actions on slender cylinders



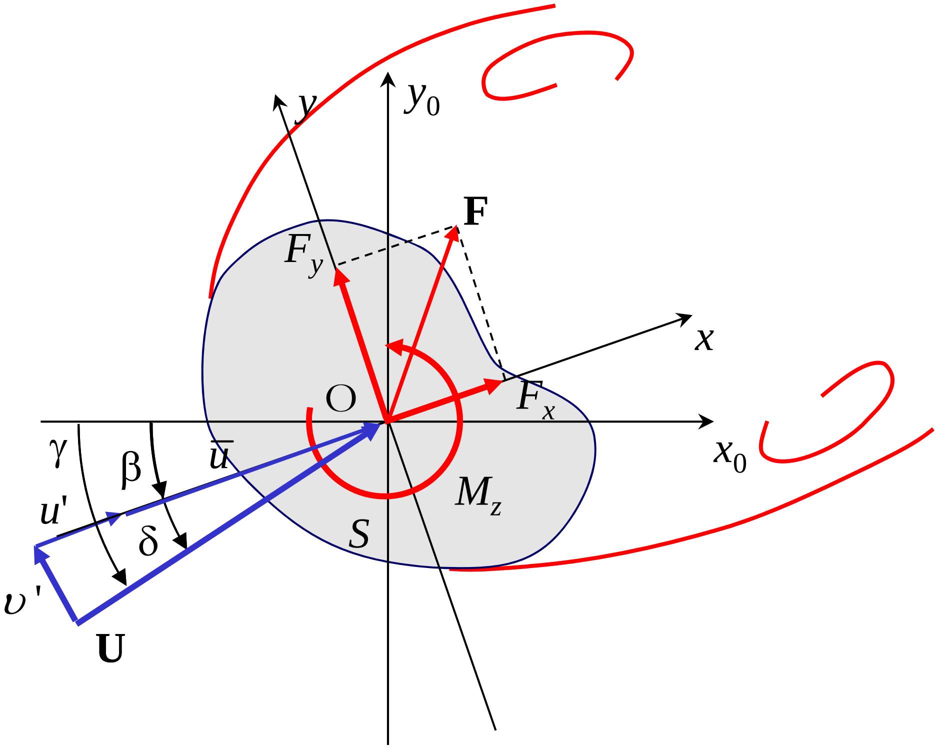


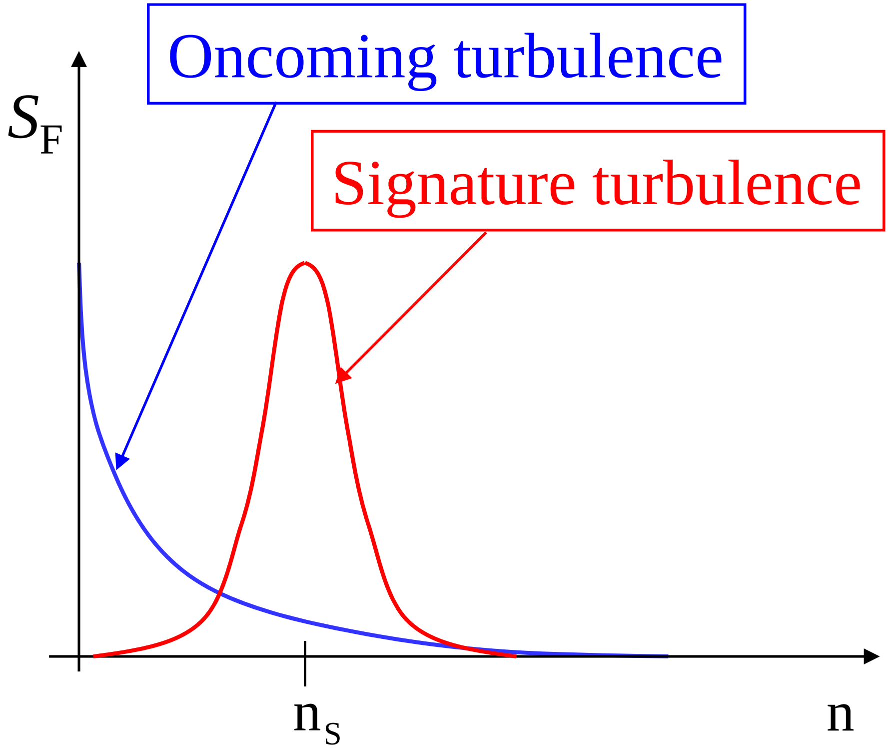
$$\tilde{F}_x'(n) = \rho \bar{u} b c_d \tilde{u}'(n) + \frac{1}{2}\rho \bar{u} b (c_d' - c_l)\tilde{\upsilon}'(n)$$

$$\tilde{F}_y'(n) = \rho \bar{u} b c_l \tilde{u}'(n) + \frac{1}{2}\rho \bar{u} b (c_d + c_l')\tilde{\upsilon}'(n)$$

$$\tilde{M}_z'(n) = \rho \bar{u} b^2 c_m \tilde{u}'(n) + \frac{1}{2}\rho \bar{u} b^2 c_m' \tilde{\upsilon}'(n)$$

Wind induced actions on slender cylinders





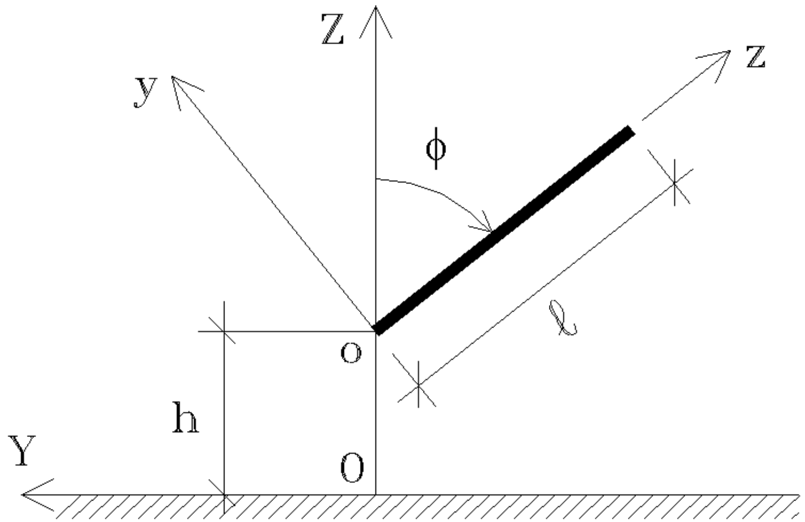
$$\tilde{F}'_x(n) = \rho \bar{u} b c_d \tilde{u}'(n) \chi_{xu}(n) + \frac{1}{2} \rho \bar{u} b \left(c'_d - c_l\right) \tilde{\upsilon}'(n) \chi_{x\upsilon}(n)$$

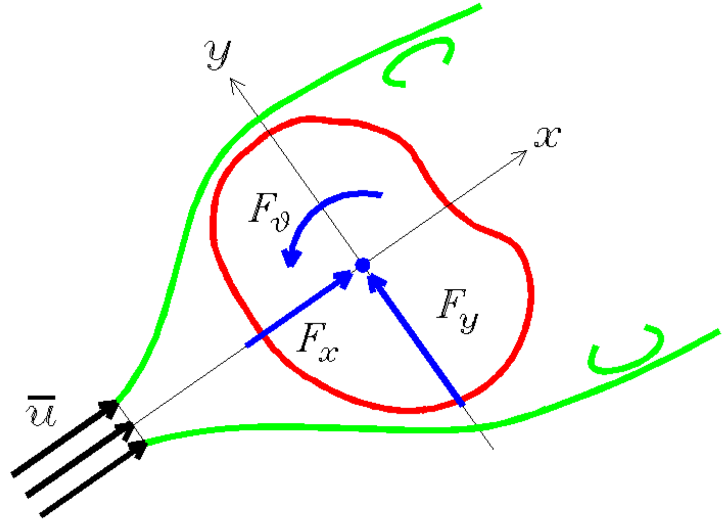
$$\tilde{F}'_y(n) = \rho \bar{u} b c_l \tilde{u}'(n) \chi_{yu}(n) + \frac{1}{2} \rho \bar{u} b \left(c_d + c'_l\right) \tilde{\upsilon}'(n) \chi_{y\upsilon}(n)$$

$$\tilde{M}'_z(n) = \rho \bar{u} b^2 c_m \tilde{u}'(n) \chi_{\vartheta u}(n) + \frac{1}{2} \rho \bar{u} b^2 c'_m \tilde{\upsilon}'(n) \chi_{\vartheta\upsilon}(n)$$

3-D WIND-EXCITED RESPONSE
OF SLENDER STRUCTURES AND STRUCTURAL ELEMENTS

Solari (1993), Piccardo & Solari (1996 - 2000)





EXCITING MECHANISMS

u = longitudinal turbulence
v = lateral turbulence
w = vertical turbulence
s = vortex shedding

3-D RESPONSE

x = alongwind response
y = crosswind response
ϑ = torsional response

GUST RESPONSE FACTOR

Alongwind response

$$\boxed{\begin{aligned} \bar{x}_{max} &= G_x \bar{x} \\ F_{x,es} &= G_x \bar{F}_x \\ G_x &= 1 + g_x \frac{\sigma_x}{\bar{x}} \end{aligned}}$$

3-D GUST RESPONSE FACTOR (Piccardo & Solari 1998)

Alongwind response

$$\overline{x}_{max} = G_x \overline{x}$$

$$F_{x,es} = G_x \overline{F}_x$$

$$G_x = 1 + g_x \frac{\sigma_x}{\overline{x}}$$

3-D response (α=x,y,ϑ)

$$\overline{\alpha}_{max} = G_\alpha \overline{\alpha}$$

$$F_{\alpha,es} = G_\alpha \lambda_\alpha \overline{F}_\alpha$$

$$G_\alpha = 1 + g_\alpha \frac{\sigma_\alpha}{\overline{\alpha}}$$

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$$\lambda_x = \lambda_y = 1; \; \lambda_\vartheta = b$$

3-D GUST RESPONSE FACTOR (Piccardo & Solari 1998)

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$\bar{\alpha}$ may be equal to zero

$$\lambda_x = \lambda_y = 1; \;\; \lambda_\vartheta = b$$

3-D GUST RESPONSE FACTOR (Piccardo & Solari 1998)

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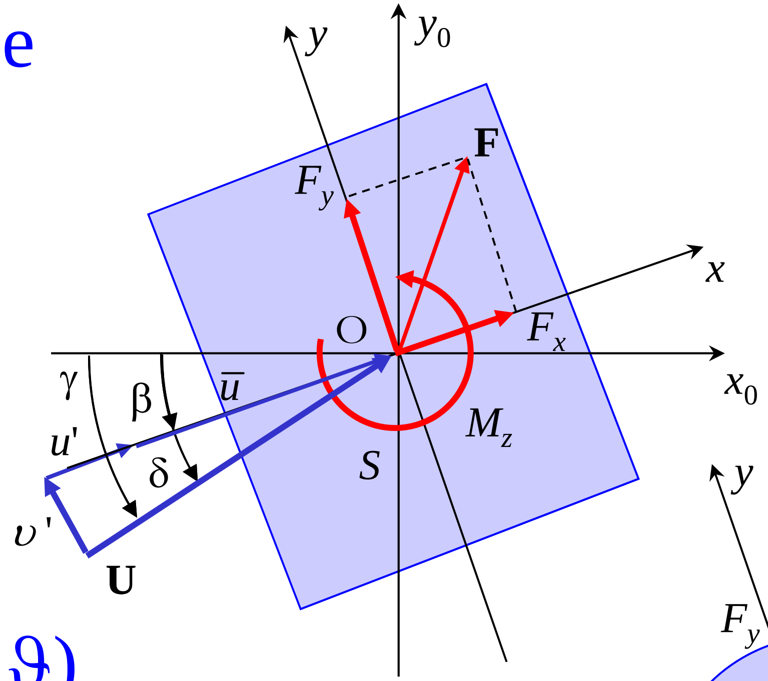
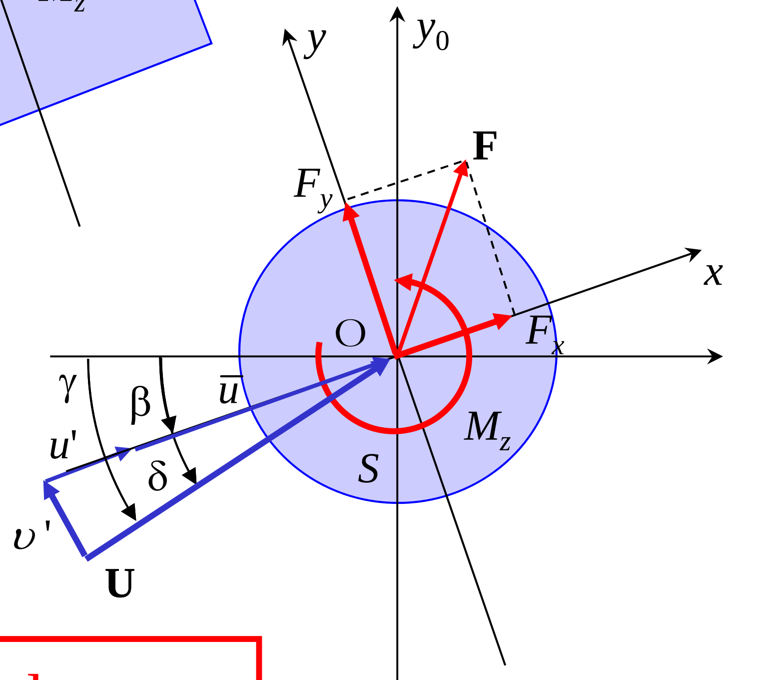
$$\lambda_x = \lambda_y = 1; \;\; \lambda_\vartheta = b$$

$\overline{\alpha}$ may be equal to zero





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Alongwind response

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3-D response (α=x,y,ϑ)

$$\bar{\alpha}_{max} = G_\alpha \bar{\alpha}_x$$

$$F_{\alpha,es} = G_\alpha \lambda_\alpha \bar{F}_x$$

$$G_\alpha = \frac{\bar{\alpha}}{\bar{\alpha}_x} + g_\alpha \frac{\sigma_\alpha}{\bar{\alpha}_x}$$

$\bar{\alpha}_x$ = generalised displacement produced applying $\lambda_\alpha \bar{F}_x$ in α direction

3-D response (α=x,y,ϑ)

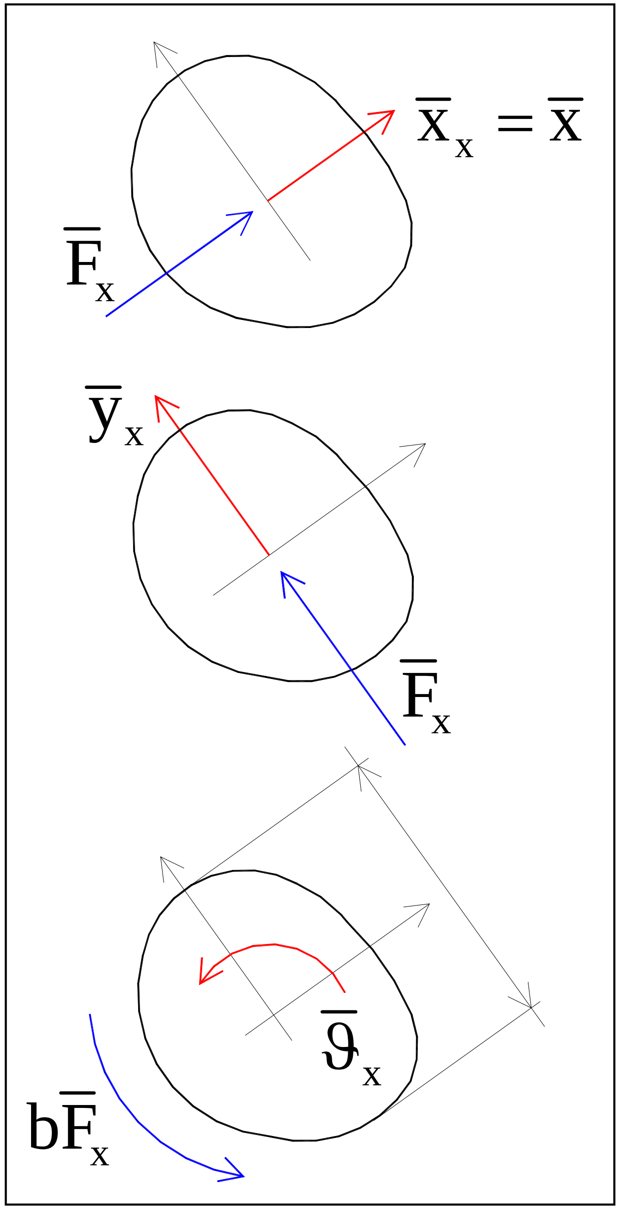
$$\bar{\alpha}_{max} = G_\alpha \bar{\alpha}$$

$$F_{\alpha,es} = G_\alpha \lambda_\alpha \bar{F}_\alpha$$

$$G_\alpha = 1 + g_\alpha \frac{\sigma_\alpha}{\bar{\alpha}}$$

$$\lambda_x = \lambda_y = 1; \; \lambda_\alpha = b$$

<u>3-D GUST RESPONSE FACTOR</u> (Piccardo & Solari 1998)



3-D response (α=x,y,ϑ)

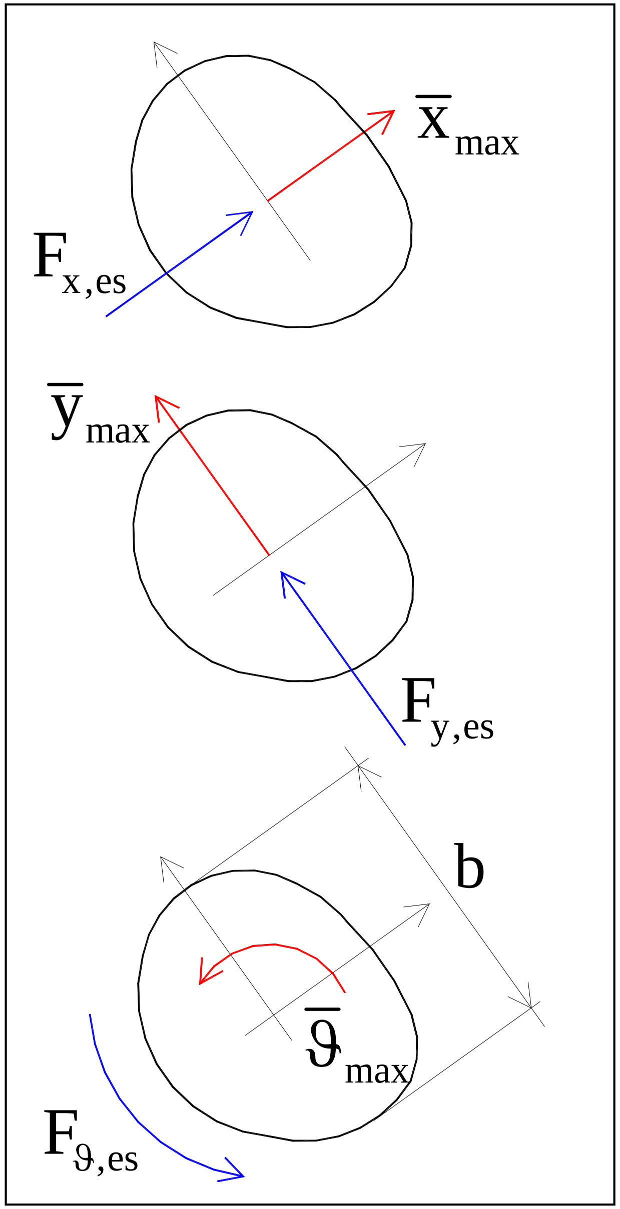
$$\bar{\alpha}_{max} = G_\alpha \bar{\alpha}_x$$

$$F_{\alpha,es} = G_\alpha \lambda_\alpha \bar{F}_x$$

$$G_\alpha = \frac{\bar{\alpha}}{\bar{\alpha}_x} + g_\alpha \frac{\sigma_\alpha}{\bar{\alpha}_x}$$

$\bar{\alpha}_x$ = generalised displacement produced applying $\lambda_\alpha \bar{F}_x$ in α direction

<u>3-D GUST RESPONSE FACTOR</u> (Piccardo & Solari 1998)



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$\overline{\alpha}_X$ = generalised displacement produced applying $\lambda_\alpha \overline{F}_x$ in α direction

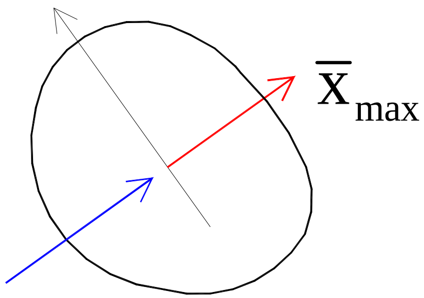
3-D equivalent static forces

$$F_{x,es} = G_x \overline{F}_x$$

$$F_{y,es} = G_y \overline{F}_x$$

$$F_{\vartheta,es} = G_\vartheta b \overline{F}_x$$

3-D GUST RESPONSE FACTOR (Piccardo & Solari 1998)



$$F_{x,es} = G_x \bar{F}_x$$

G_x alongwind gust factor

3-D response (α=x,y,ϑ)

$$\bar{\alpha}_{max} = G_\alpha \bar{\alpha}_x$$

$$F_{\alpha,es} = G_\alpha \lambda_\alpha \bar{F}_x$$

$$G_\alpha = \frac{\bar{\alpha}}{\bar{\alpha}_x} + g_\alpha \frac{\sigma_\alpha}{\bar{\alpha}_x}$$

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3-D equivalent static forces

$$F_{x,es} = G_x \bar{F}_x$$

$$F_{y,es} = G_y \bar{F}_x$$

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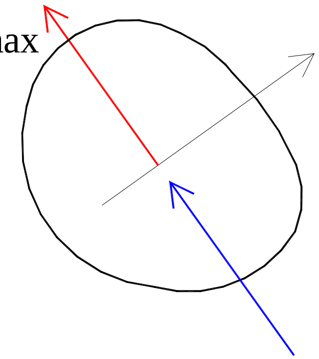
3-D GUST RESPONSE FACTOR (Piccardo & Solari 1998)

$\bar{y}_{max}$



$$F_{y,es} = G_y \bar{F}_x$$

G_y crosswind gust factor

3-D response (α=x,y,ϑ)

$$\bar{\alpha}_{max} = G_\alpha \bar{\alpha}_x$$

$$F_{\alpha,es} = G_\alpha \lambda_\alpha \bar{F}_x$$

$$G_\alpha = \frac{\bar{\alpha}}{\bar{\alpha}_x} + g_\alpha \frac{\sigma_\alpha}{\bar{\alpha}_x}$$

$\bar{\alpha}_X$ = generalised displacement produced applying $\lambda_\alpha \bar{F}_x$ in α direction

3-D equivalent static forces

$$F_{x,es} = G_x \bar{F}_x$$

$$F_{y,es} = G_y \bar{F}_x$$

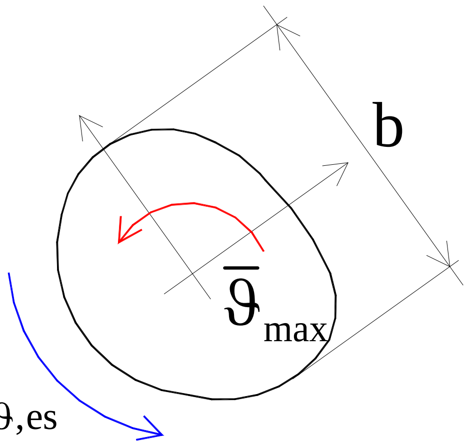
$$F_{\vartheta,es} = G_\vartheta b \bar{F}_x$$

3-D GUST RESPONSE FACTOR (Piccardo & Solari 1998)

$$F_{\vartheta,es} = G_\vartheta b \overline{F}_x$$

G_ϑ torsional gust factor

$G_\vartheta b =$ equivalent eccentricity of $\overline{F}_x$



3-D response ($\alpha = x, y, \vartheta$)

$$\overline{\alpha}_{max} = G_\alpha \overline{\alpha}_x$$

$$F_{\alpha,es} = G_\alpha \lambda_\alpha \overline{F}_x$$

$$G_\alpha = \frac{\overline{\alpha}}{\overline{\alpha}_x} + g_\alpha \frac{\sigma_\alpha}{\overline{\alpha}_x}$$

$\overline{\alpha}_X =$ generalised displacement produced applying $\lambda_\alpha \overline{F}_x$ in α direction

3-D equivalent static forces

$$F_{x,es} = G_x \overline{F}_x$$

$$F_{y,es} = G_y \overline{F}_x$$

$$F_{\vartheta,es} = G_\vartheta b \overline{F}_x$$

GUST RESPONSE FACTOR

$$\boxed{\bar{x}_{max} = G_x \bar{x}}$$

$$\boxed{G_x = 1 + 2 g_x I_u \sqrt{B_x^2 + R_x^2}}$$

3-D GUST RESPONSE FACTOR

$$\boxed{\bar{\alpha}_{max} = G_\alpha \bar{\alpha}_x}$$

$$\boxed{G_\alpha = \mu_\alpha + 2 g_\alpha I_u \sqrt{B_\alpha^2 + R_\alpha^2}}$$

3-D GUST RESPONSE FACTOR

$$\boxed{\bar{\alpha}_{max} = G_\alpha \bar{\alpha}_x} \qquad \boxed{G_\alpha = \mu_\alpha + 2g_\alpha I_u \sqrt{B_\alpha^2 + R_\alpha^2}}$$

Closed Form Solution (Piccardo & Solari, 1998, 2000)

$$\mu_\alpha = \frac{c_{\alpha u}\bar{K}_{\alpha\alpha}}{c_{xu}\bar{K}_{\alpha x}}; \quad B_\alpha^2 = \sum_\varepsilon \chi_{\alpha\varepsilon}^2 B_{\alpha\varepsilon}^2; \quad R_\alpha^2 = \sum_\varepsilon \chi_{\alpha\varepsilon}^2 R_{\alpha\varepsilon}^2; \quad \chi_{\alpha\varepsilon} = \frac{J_\varepsilon(\bar{z})c_{\alpha\varepsilon}K'_{\alpha\varepsilon}}{2I_u c_{xu}\bar{K}_{\alpha x}} \qquad (\varepsilon = u,v,w,s)$$

$$B_{\alpha\varepsilon}^2 = \frac{1}{1+0.56\tilde{\tau}_{\alpha\varepsilon}^{0.74} + 0.30\tilde{\ell}_{\alpha\varepsilon}^{0.63}}; \quad R_{\alpha\varepsilon}^2 = \frac{\pi}{4\xi_{\alpha 1}} \frac{d_u \tilde{n}_{\alpha\varepsilon}}{(1+1.5 d_u \tilde{n}_{\alpha\varepsilon})^{5/3}} C\left\{\tilde{n}_{\alpha\varepsilon}\tilde{\ell}_{\alpha\varepsilon}\right\} \qquad (\varepsilon = u,v,w)$$

$$B_{\alpha s}^2 = C\left\{\tilde{\ell}_{\alpha s}\right\} F\left\{\tilde{n}_{\alpha s}\right\}; \quad R_{\alpha s}^2 = \frac{\pi}{4\xi_{\alpha 1}} \frac{\tilde{n}_{\alpha s}}{\sqrt{\pi}\beta(z_{\alpha s})} exp\left\{-\left[\frac{1-\tilde{n}_{\alpha s}}{\beta(z_{\alpha s})}\right]^2\right\} C\left\{\tilde{\ell}_{\alpha s}\right\}$$

$$\tilde{\tau}_{\alpha\varepsilon} = \frac{\tau d_u \bar{u}(z_{\alpha\varepsilon})}{d_\varepsilon L_\varepsilon(z_{\alpha\varepsilon})}; \quad \tilde{\ell}_{\alpha\varepsilon} = \frac{k_{\alpha\varepsilon} d_u C_{r\varepsilon}\ell}{d_\varepsilon L_\varepsilon(z_{\alpha\varepsilon})}; \quad \tilde{n}_{\alpha\varepsilon} = \frac{n_{\alpha 1} d_\varepsilon L_\varepsilon(z_{\alpha\varepsilon})}{d_u \bar{u}(z_{\alpha\varepsilon})}; \quad \tilde{\ell}_{\alpha s} = \frac{k_{\alpha s}\ell}{Lb}; \quad \tilde{n}_{\alpha s} = \frac{n_{\alpha 1} b}{\Upsilon_\alpha S\bar{u}(z_{\alpha s})}$$

3-D GUST RESPONSE FACTOR

$$\boxed{\bar{\alpha}_{max} = G_\alpha \bar{\alpha}_x} \qquad \boxed{G_\alpha = \mu_\alpha + 2 g_\alpha I_u \sqrt{B_\alpha^2 + R_\alpha^2}}$$

Closed Form Solution (Piccardo & Solari, 1998, 2000)

$$\mu_\alpha = \frac{c_{\alpha u} \bar{K}_{\alpha\alpha}}{c_{xu} \bar{K}_{\alpha x}}; \quad B_\alpha^2 = \sum_\varepsilon \chi_{\alpha\varepsilon}^2 B_{\alpha\varepsilon}^2; \quad R_\alpha^2 = \sum_\varepsilon \chi_{\alpha\varepsilon}^2 R_{\alpha\varepsilon}^2; \quad \chi_{\alpha\varepsilon} = \frac{J_\varepsilon(\bar{z}) c_{\alpha\varepsilon} K'_{\alpha\varepsilon}}{2 I_u c_{xu} \bar{K}_{\alpha x}} \qquad (\varepsilon = u, v, w, s)$$

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$$B_{\alpha s}^2 = C\left\{\tilde{\ell}_{\alpha s}\right\} F\left\{\tilde{n}_{\alpha s}\right\}; \quad R_{\alpha s}^2 = \frac{\pi}{4\xi_{\alpha 1}} \frac{\tilde{n}_{\alpha s}}{\sqrt{\pi}\beta(z_{\alpha s})} exp\left\{-\left[\frac{1 - \tilde{n}_{\alpha s}}{\beta(z_{\alpha s})}\right]^2\right\} C\left\{\tilde{\ell}_{\alpha s}\right\}$$

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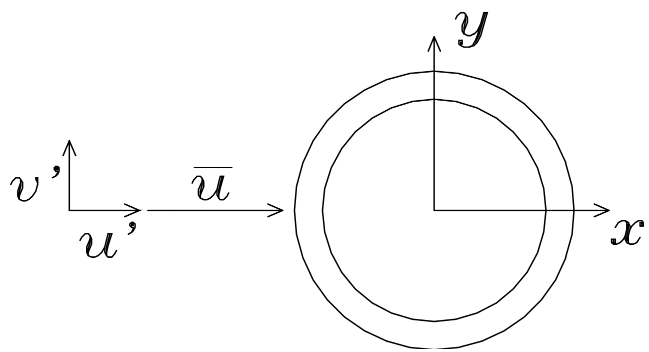
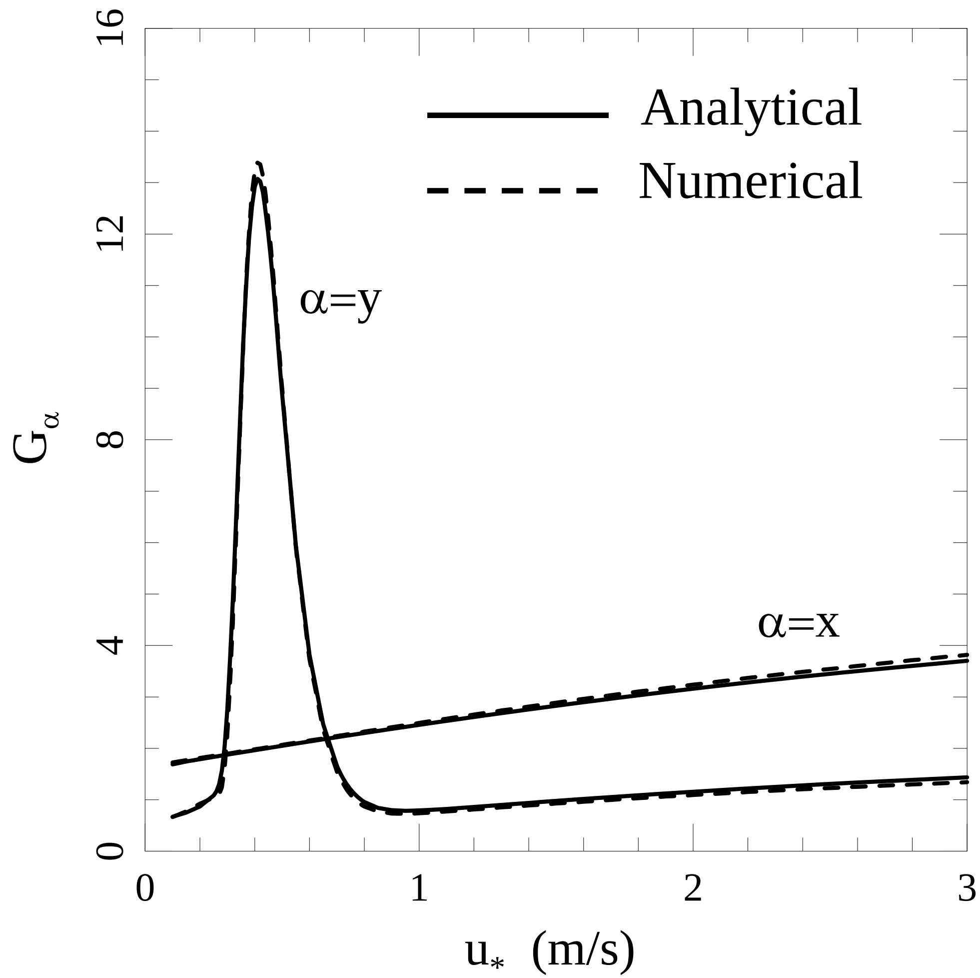
PREDICTION OF 3-D RESPONSE

Piccardo & Solari (1998, 2000)

Concrete Chimney (aspect ratio 1:32)





Full-scale measurements

Müller-Nieser (1976) -
Alongwind and Crosswind
standard deviations

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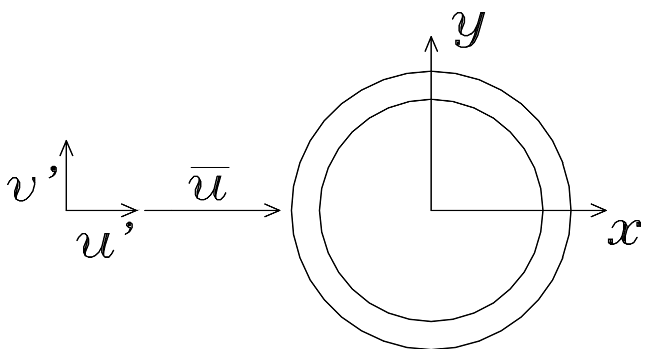
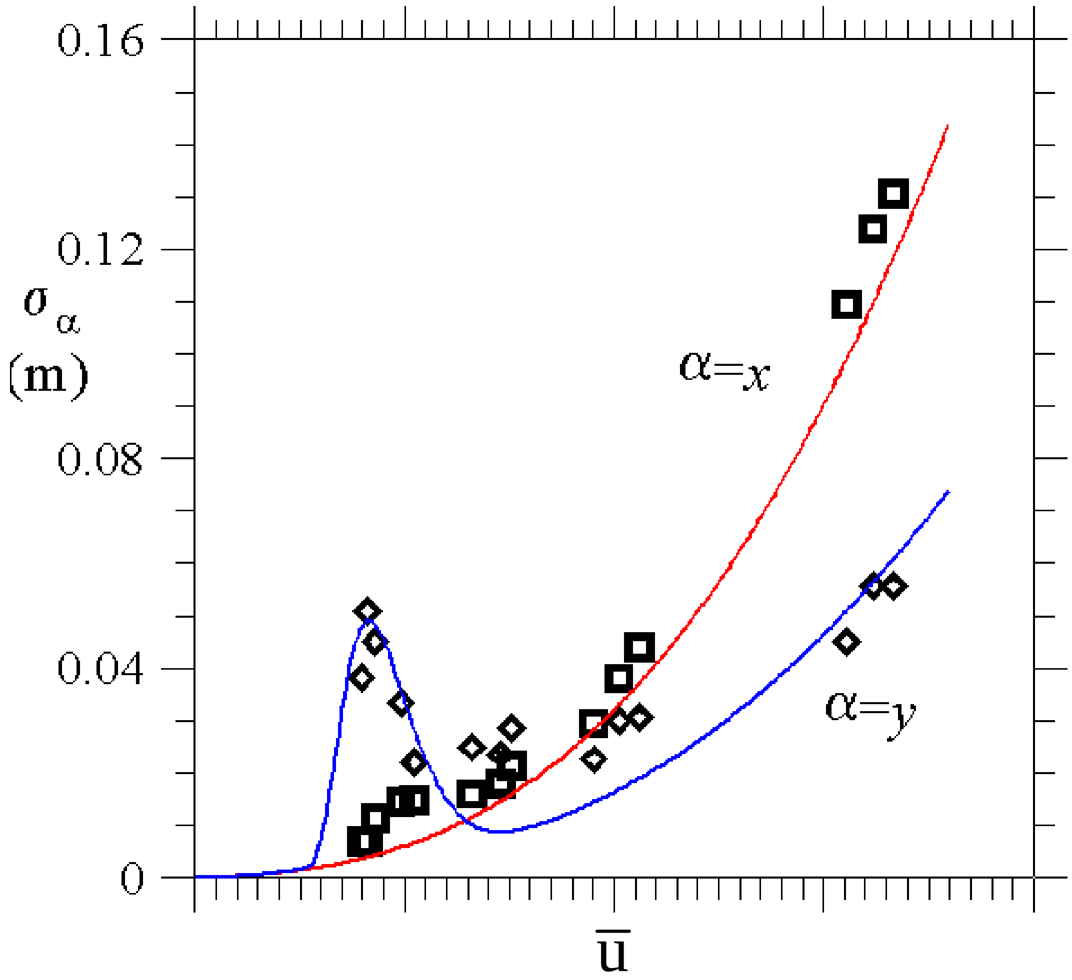




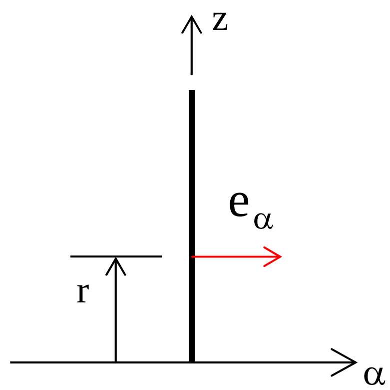
Full-scale measurements

Müller-Nieser (1976) - Alongwind and Crosswind standard deviations

3-D WIND LOAD EFFECTS

Piccardo & Solari (2002)

$$\boxed{e_\alpha(r;t) = \bar{e}_\alpha(r) + e'_{Q\alpha}(r;t) + e'_{D\alpha}(r;t); \quad \alpha = x, y, \theta}$$



3-D WIND LOAD EFFECTS

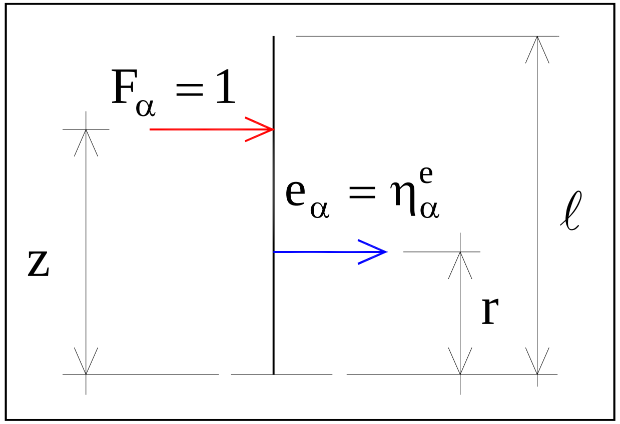
Piccardo & Solari (2002)

$$\boxed{e_\alpha(r;t) = \bar{e}_\alpha(r) + e'_{Q\alpha}(r;t) + e'_{D\alpha}(r;t); \quad \alpha = x, y, \theta}$$

$$\bar{e}_\alpha(r) = \int_0^\ell \bar{F}_\alpha(z)\,\eta^e_\alpha(r;z)\,dz$$

$$e'_{Q\alpha}(r;t) = \int_0^\ell F'_\alpha(z;t)\,\eta^e_\alpha(r;z)\,dz$$

$\eta^e_\alpha(r;z)$ =influence function of $e_\alpha(z)$



3-D WIND LOAD EFFECTS

Piccardo & Solari (2002)

$$\boxed{e_\alpha(r;t) = \bar{e}_\alpha(r) + e'_{Q\alpha}(r;t) + e'_{D\alpha}(r;t); \quad \alpha = x, y, \theta}$$

$$\bar{e}_\alpha(r) = \int_0^\ell \bar{F}_\alpha(z)\eta^e_\alpha(r;z)dz$$

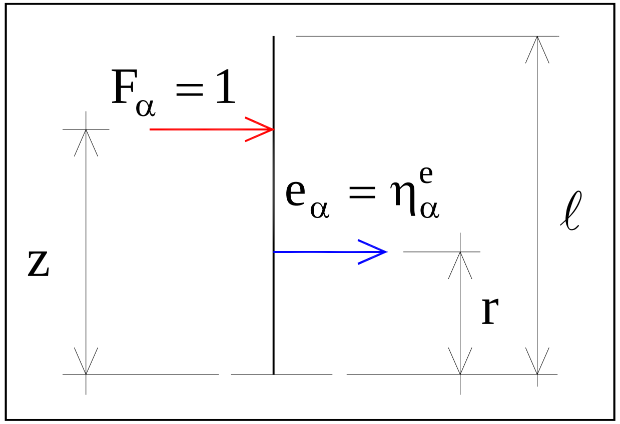
$$e'_{D\alpha}(r;t) = \int_0^\ell F'_{D\alpha}(z;t)\eta^e_\alpha(r;z)dz$$

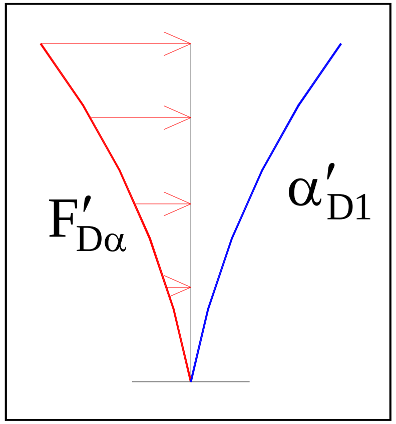
$$e'_{Q\alpha}(r;t) = \int_0^\ell F'_\alpha(z;t)\eta^e_\alpha(r;z)dz$$

$$F'_{D\alpha}(z;t) = \mu_\alpha(z)(2\pi n_{\alpha 1})^2 \alpha'_{D1}(z;t)$$

$\eta^e_\alpha(r;z)$ = influence function of $e_\alpha(z)$

$$\alpha'_{D1}(z;t) = \psi_{\alpha 1}(z)p'_{D\alpha 1}(t)$$





MEAN LOAD EFFECT

$$\bar{e}_{\alpha,\max}(r) = \bar{e}_{\alpha}(r) + g_{\alpha}^{e}(r)\,\sigma_{\alpha}^{e}(r)$$

$$\boxed{\bar{e}_{\alpha,\max}(r) = \bar{e}_{\alpha}^{x}(r)\,G_{\alpha}^{e}(r)}$$

$\bar{e}_{\alpha}^{x}(r)$ is the static effect due to the generalised force $\lambda_{\alpha}\bar{F}_{x}$

$$\lambda_{x} = \lambda_{y} = 1;\ \lambda_{\theta} = b$$

EQUIVALENT STATIC FORCE

$$\boxed{F_{\alpha eq}^{e}(z;r) = \lambda_{\alpha}\,G_{\alpha}^{e}(r)\,\bar{F}_{X}(z)}$$

MEAN LOAD EFFECT

$$\bar{e}_{\alpha,\max}(r) = \bar{e}_{\alpha}(r) + g_{\alpha}^{e}(r)\,\sigma_{\alpha}^{e}(r)$$

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3-D GUST EFFECT FACTOR

$$\boxed{G_{\alpha}^{e}(r) = \mu_{\alpha}^{e}(r) + g_{\alpha}^{e}(r)\sqrt{Q_{\alpha}^{e}(r) + D_{\alpha}^{e}(r)}}$$

EQUIVALENT STATIC FORCE

$$\boxed{F_{\alpha eq}^{e}(z;r) = \lambda_{\alpha}\,G_{\alpha}^{e}(r)\,\bar{F}_{X}(z)}$$

MEAN LOAD EFFECT

$$\bar{e}_{\alpha,\,max}(r) = \bar{e}_{\alpha}(r) + g_{\alpha}^{e}(r)\,\sigma_{\alpha}^{e}(r)$$

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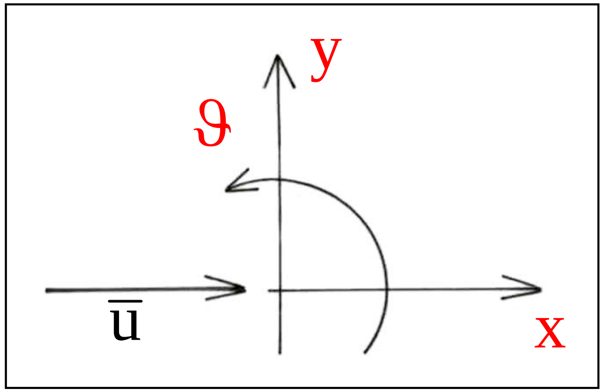
$$G_{\alpha}^{e}(r)$$



MEAN LOAD EFFECT

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$$\boxed{F_{\alpha eq}^{e}(z;r) = \lambda_{\alpha}\,G_{\alpha}^{e}(r)\,\bar{F}_{X}(z)}$$

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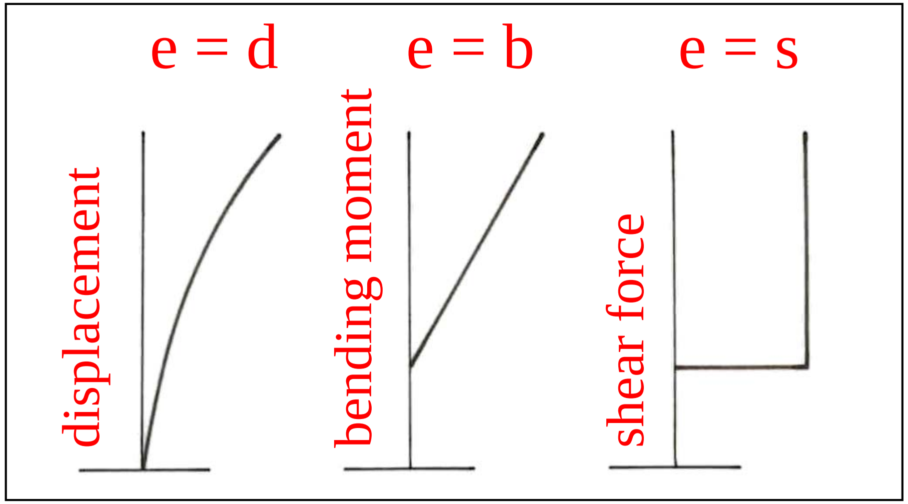
$$\boxed{G_{\alpha}^{e}(r) = \mu_{\alpha}^{e}(r) + g_{\alpha}^{e}(r)\sqrt{Q_{\alpha}^{e}(r) + D_{\alpha}^{e}(r)}}$$



$$G_{\alpha}^{e}(r)$$

MEAN LOAD EFFECT

$$\bar{e}_{\alpha,\max}(r) = \bar{e}_{\alpha}(r) + g_{\alpha}^{e}(r)\,\sigma_{\alpha}^{e}(r)$$

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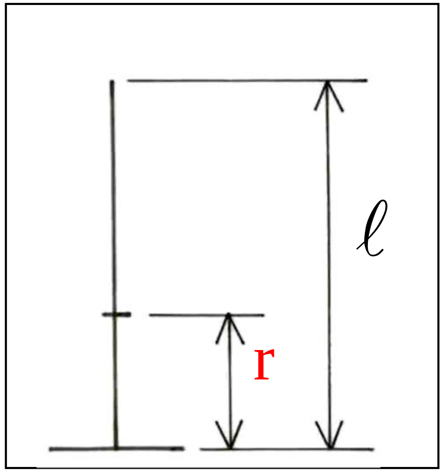
EQUIVALENT STATIC FORCE

$$\boxed{F_{\alpha eq}^{e}(z;r) = \lambda_{\alpha}\,G_{\alpha}^{e}(r)\,\bar{F}_{X}(z)}$$

3-D GUST EFFECT FACTOR

$$\boxed{G_{\alpha}^{e}(r) = \mu_{\alpha}^{e}(r) + g_{\alpha}^{e}(r)\sqrt{Q_{\alpha}^{e}(r) + D_{\alpha}^{e}(r)}}$$



$$G_{\alpha}^{e}(r)$$

EQUIVALENT STATIC FORCES

3-D GEF technique (Piccardo & Solari, 2002)

$$\boxed{F^{e}_{\alpha,es}(r,z) = \lambda_{\alpha} G^{e}_{\alpha}(r)\bar{F}_{x}(z)}$$

EQUIVALENT STATIC FORCES

3-D GEF technique (Piccardo & Solari, 2002)

$$\boxed{F^{e}_{\alpha,es}(r,z) = \lambda_{\alpha} G^{e}_{\alpha}(r)\bar{F}_{x}(z)}$$

e = d

particular case

3-D GRF technique (Piccardo & Solari, 2000)

$$\boxed{F_{\alpha,es}(z) = \lambda_{\alpha} G_{\alpha}\bar{F}_{x}(z)}$$

$$F_{\alpha,es} = F^{d}_{\alpha,es} \;;\; G_{\alpha} = G^{d}_{\alpha}$$

EQUIVALENT STATIC FORCES

3-D GEF technique (Piccardo & Solari, 2002)

$$\boxed{F^{e}_{\alpha,es}(r,z)=\lambda_{\alpha}G^{e}_{\alpha}(r)\bar{F}_{x}(z)}$$

e = d

particular case

3-D GRF technique (Piccardo & Solari, 2000)

$$\boxed{F_{\alpha,es}(z)=\lambda_{\alpha}G_{\alpha}\bar{F}_{x}(z)}$$

$$F_{\alpha,es}=F^{d}_{\alpha,es}\;;\;G_{\alpha}=G^{d}_{\alpha}$$

$\alpha = x$

(Alongwind) GRF technique (Davenport, 1967)

$$\boxed{F_{x,eq}(z)=G_{x}\bar{F}_{x}(z)}$$

$$\lambda_{x}=1$$

EQUIVALENT STATIC FORCES

3-D GEF technique (Piccardo & Solari, 2002)

$$\boxed{F^{e}_{\alpha,es}(r,z) = \lambda_{\alpha} G^{e}_{\alpha}(r) \bar{F}_{x}(z)}$$

e = d

particular case

3-D GRF technique (Piccardo & Solari, 2000)

$$\boxed{F_{\alpha,es}(z) = \lambda_{\alpha} G_{\alpha} \bar{F}_{x}(z)}$$

$$F_{\alpha,es} = F^{d}_{\alpha,es} \;;\; G_{\alpha} = G^{d}_{\alpha}$$

generalisation

$\alpha = x$

(Alongwind) GRF technique (Davenport, 1967)

$$\boxed{F_{x,eq}(z) = G_{x} \bar{F}_{x}(z)}$$

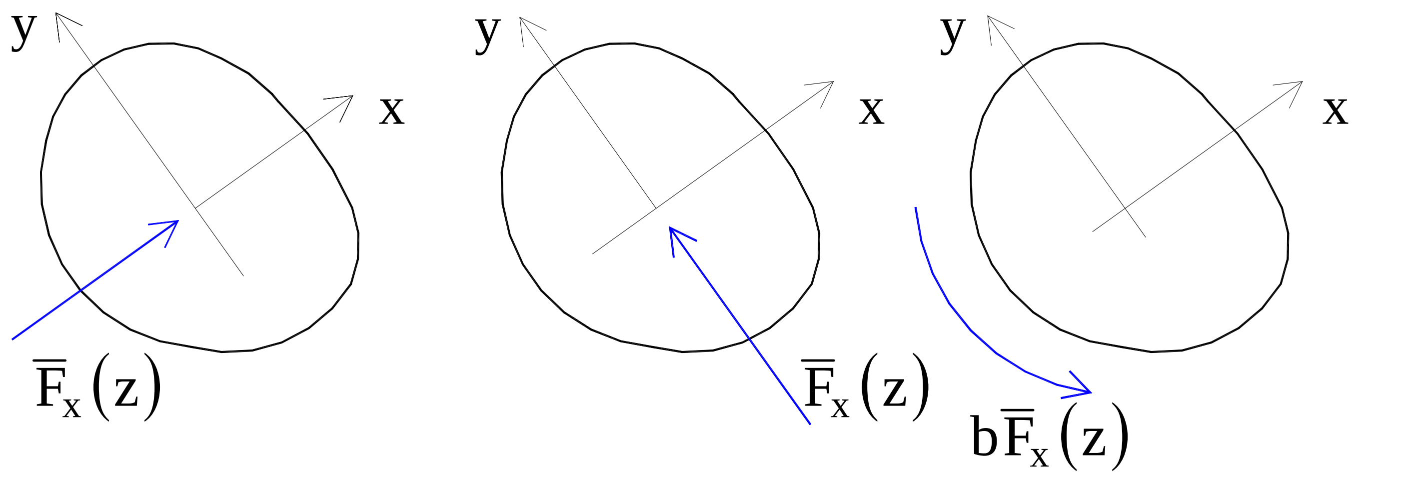
$$\lambda_{x} = 1$$

3-D EQUIVALENT STATIC FORCES

$$\boxed{F_{\alpha eq}\left(z\,;\,r\right)=\lambda_{\alpha}\,G_{\alpha}^{e}\left(r\right)\overline{F}_{X}\left(z\right)}$$

3-D MAXIMUM EFFECTS

$$\boxed{\overline{e}_{\alpha,\,max}\left(r\right)=\overline{e}_{\alpha}^{X}\left(r\right)G_{\alpha}^{e}\left(r\right)}$$

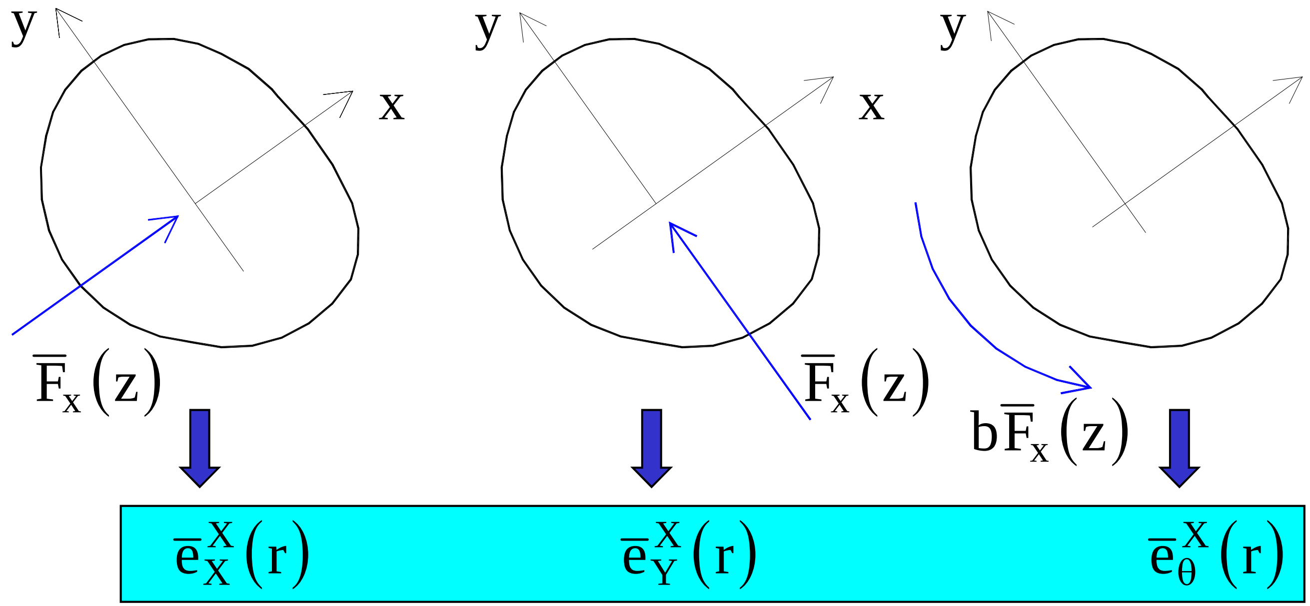


3-D EQUIVALENT STATIC FORCES

$$F_{\alpha eq}(z;r) = \lambda_{\alpha}\, G_{\alpha}^{e}(r)\, \overline{F}_{X}(z)$$

3-D MAXIMUM EFFECTS

$$\overline{e}_{\alpha,\,\max}(r) = \overline{e}_{\alpha}^{X}(r)\, G_{\alpha}^{e}(r)$$

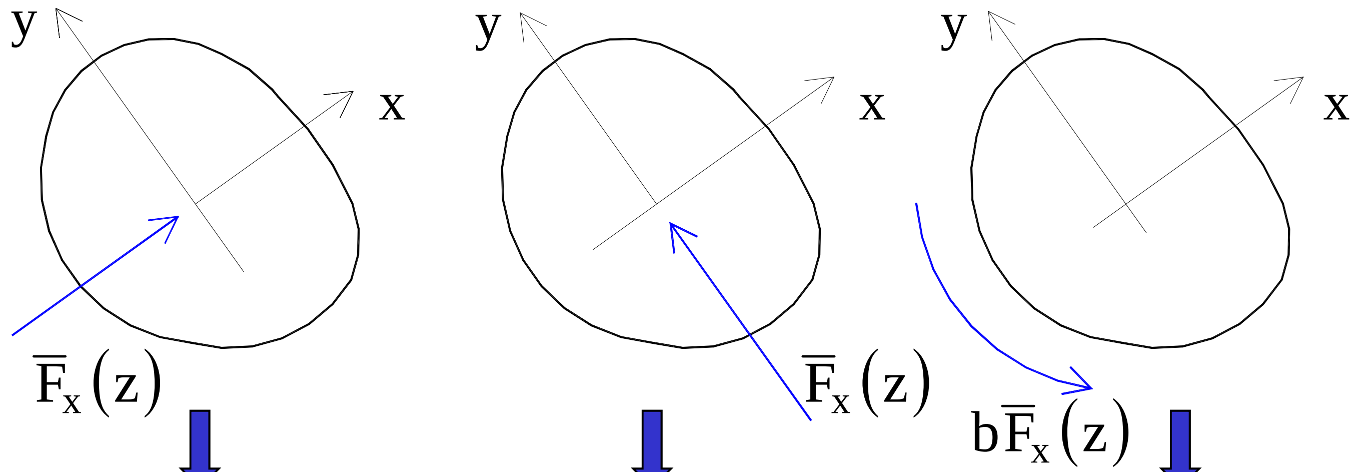


3-D EQUIVALENT STATIC FORCES

$$\boxed{F_{\alpha eq}(z;r)=\lambda_\alpha\, G^{e}_{\alpha}(r)\,\overline{F}_X(z)}$$

3-D MAXIMUM EFFECTS

$$\boxed{\bar{e}_{\alpha,\,\max}(r)=\bar{e}^{X}_{\alpha}(r)\,G^{e}_{\alpha}(r)}$$



$\bar{e}^{X}_{X}(r)$ $\bar{e}^{X}_{Y}(r)$ $\bar{e}^{X}_{\theta}(r)$

$$\bar{e}_{X,\,\max}(r)=\bar{e}^{X}_{X}\,G^{e}_{X} \qquad \bar{e}_{Y,\,\max}(r)=\bar{e}^{X}_{Y}\,G^{e}_{Y} \qquad \bar{e}_{\theta,\,\max}(r)=\bar{e}^{X}_{\theta}\,G^{e}_{\theta}$$

3-D GUST EFFECT FACTOR

$$\boxed{\overline{e}_{\alpha,max}(r)=G_{\alpha}^{e}(r)e_{\alpha}^{x}(r)}\qquad\boxed{G_{\alpha}^{e}(r)=\mu_{\alpha}^{e}(r)+2g_{\alpha}^{e}(r)I_{u}\sqrt{\left[B_{\alpha}^{e}(r)\right]^{2}+\left[R_{\alpha}^{e}(r)\right]^{2}}}$$

Closed Form Solution (Piccardo & Solari, 2002)

$$\mu_{\alpha}^{e}(r)=\frac{c_{\alpha u}\overline{K}_{\alpha\alpha}^{e}(r)}{c_{xu}\overline{K}_{\alpha x}^{e}(r)};\quad \left[B_{\alpha}^{e}(r)\right]^{2}=\sum_{\varepsilon}\left[\chi_{\alpha\varepsilon}^{e}(r)\right]^{2}\left[B_{\alpha\varepsilon}^{e}(r)\right]^{2};\quad \left[R_{\alpha}^{e}(r)\right]^{2}=\sum_{\varepsilon}\left[\phi_{\alpha\varepsilon}^{e}(r)\right]^{2}\left[R_{\alpha\varepsilon}^{d}(r)\right]^{2}\quad (\varepsilon=u,v,w,s)$$

$$\chi_{\alpha\varepsilon}^{e}(r)=\frac{J_{\varepsilon}(\ell)c_{\alpha\varepsilon}K'^{e}_{\alpha\varepsilon}(r)}{2I_{u}c_{xu}\overline{K}_{\alpha x}^{e}(r)};\quad \phi_{\alpha\varepsilon}^{e}(r)=\frac{J_{\varepsilon}(\ell)c_{\alpha\varepsilon}K'^{d}_{\alpha\varepsilon}(r)m_{\alpha 1}^{e}(r)}{2I_{u}c_{xu}\overline{K}_{\alpha x}^{e}(r)m_{\alpha 1}^{d}(r)}$$

$$\left[B_{\alpha\varepsilon}^{e}(r)\right]^{2}=\frac{1}{1+0.56\left[\tilde{\tau}_{\alpha\varepsilon}^{e}(r)\right]^{0.74}+0.30\left[\tilde{\ell}_{\alpha\varepsilon}^{e}(r)\right]^{0.63}}$$

$$\left[R_{\alpha\varepsilon}^{d}(r)\right]^{2}=\frac{\pi}{4\xi_{\alpha 1}}\ \frac{d_{u}\tilde{n}_{\alpha\varepsilon}^{d}(r)}{\left[1+1.5d_{u}\tilde{n}_{\alpha\varepsilon}^{d}(r)\right]^{5/3}}C\left\{\tilde{n}_{\alpha\varepsilon}^{d}(r)\tilde{\ell}_{\alpha\varepsilon}^{d}(r)\right\}$$

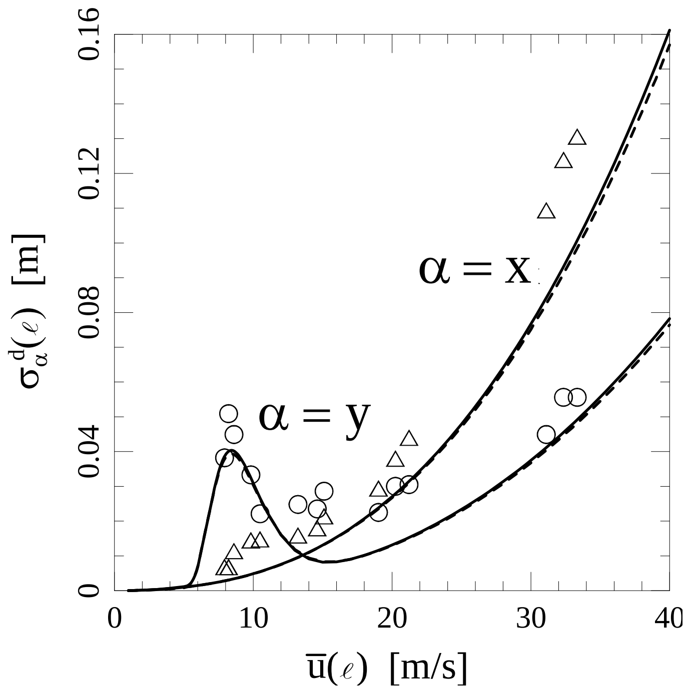
$$\tilde{\tau}_{\alpha\varepsilon}^{e}(r)=\frac{\tau d_{u}\overline{u}\left[z_{\alpha\varepsilon}^{e}(r)\right]}{d_{\varepsilon}L_{\varepsilon}\left[z_{\alpha\varepsilon}^{e}(r)\right]};\quad \tilde{\ell}_{\alpha\varepsilon}^{e}(r)=\frac{k_{\alpha\varepsilon}^{e}(r)d_{u}C_{z\varepsilon}\ell}{d_{\varepsilon}L_{\varepsilon}\left[z_{\alpha\varepsilon}^{e}(r)\right]};\quad \tilde{n}_{\alpha\varepsilon}^{d}(r)=\frac{n_{\alpha 1}d_{\varepsilon}L_{\varepsilon}\left[z_{\alpha\varepsilon}^{d}(r)\right]}{d_{u}\overline{u}\left[z_{\alpha\varepsilon}^{d}(r)\right]}$$

$$\left[B_{\alpha s}^{e}(r)\right]^{2}=C\left\{\tilde{\ell}_{\alpha s}^{e}(r)\right\}F\left\{\tilde{n}_{\alpha s}^{e}(r)\right\};\quad \left[R_{\alpha s}^{d}(r)\right]^{2}=\frac{\pi}{4\xi_{\alpha 1}}\frac{\tilde{n}_{\alpha s}^{d}(r)}{\sqrt{\pi}\beta\left[z_{\alpha s}^{d}(r)\right]}exp\left\{-\left[\frac{1-\tilde{n}_{\alpha s}^{d}(r)}{\beta\left[z_{\alpha s}^{d}(r)\right]}\right]^{2}\right\}C\left\{\tilde{\ell}_{\alpha s}^{d}(r)\right\}$$

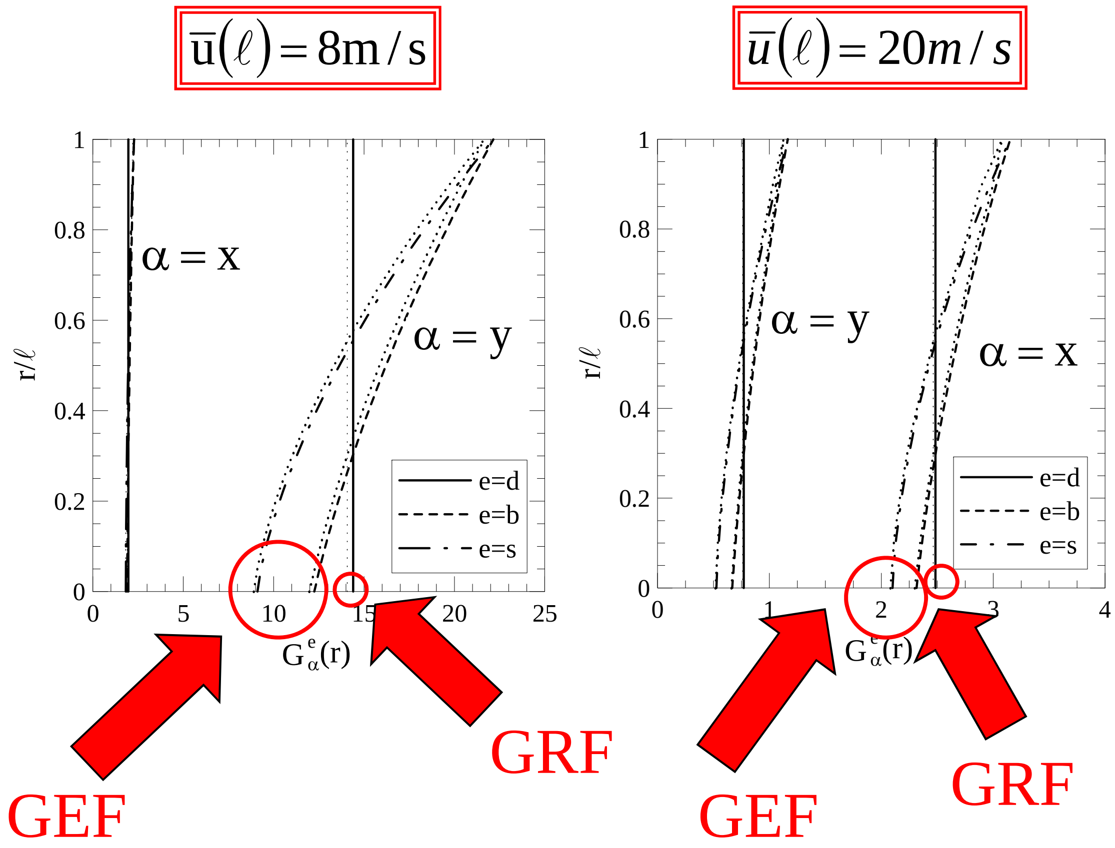
$$\tilde{\ell}_{\alpha s}^{e}(r)=\frac{k_{\alpha s}^{e}(r)\ell}{Lb};\quad \tilde{n}_{\alpha s}^{e}(r)=\frac{n_{\alpha 1}b}{\Upsilon_{\alpha}S\overline{u}\left[z_{\alpha s}^{e}(r)\right]}$$

Concrete Chimney: Mueller & Nieser (1976)
Piccardo & Solari (2002)

3-D RESPONSE



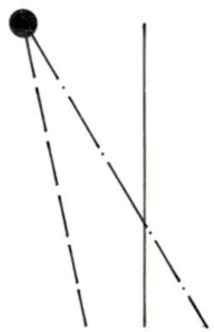
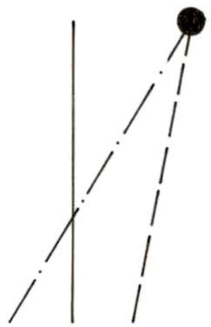
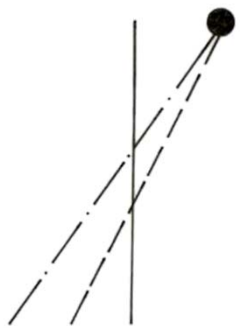
3-D GUST EFFECT FACTORS



ASSESSMENT OF GENERAL TENDENCIES

Solari & Repetto (2002)

3-D Gust Effect Factor - Resonant Response

shear - type structures		flexural - type structures
rough terrain	smooth terrain	
		

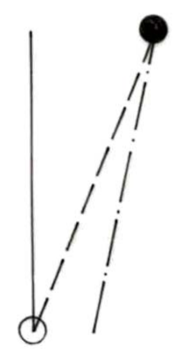
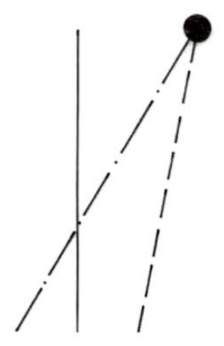
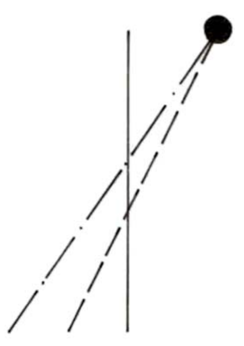
——— displacements   --------- bending moments   -·-·-·- shears

GRF safe	GRF unsafe

ASSESSMENT OF GENERAL TENDENCIES

Solari & Repetto (2002)

3-D Gust Effect Factor - Quasi-static Response

dominant buffeting		dominant wake	
low-rise str.	high-rise str.	shear-type str.	flexural-type str.
			

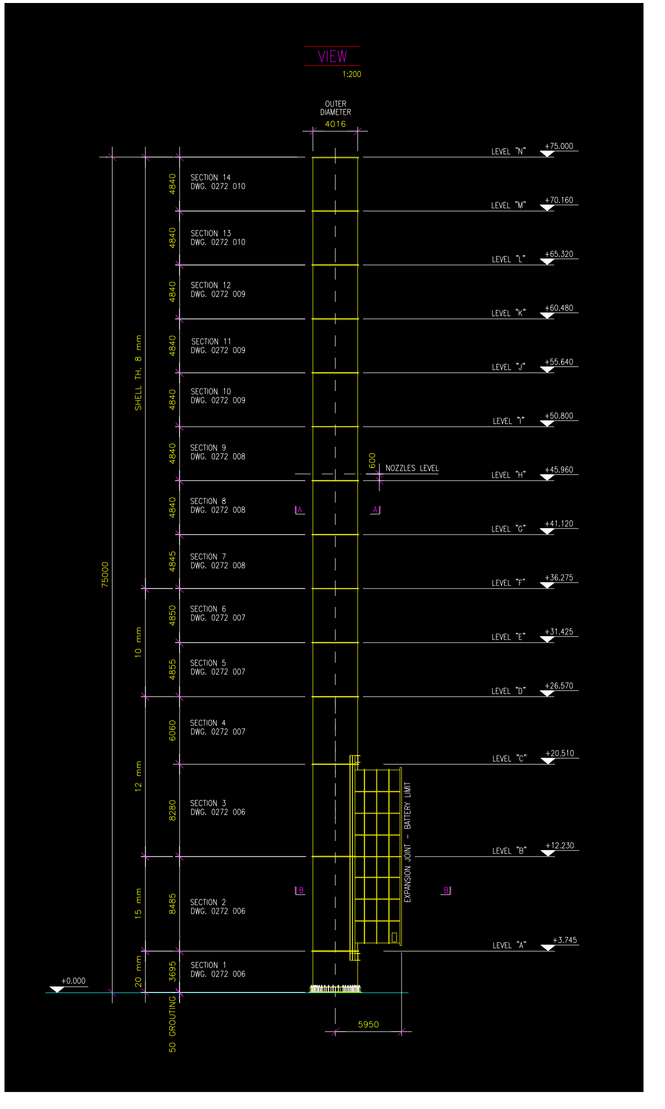
——— displacements

--------- bending moments

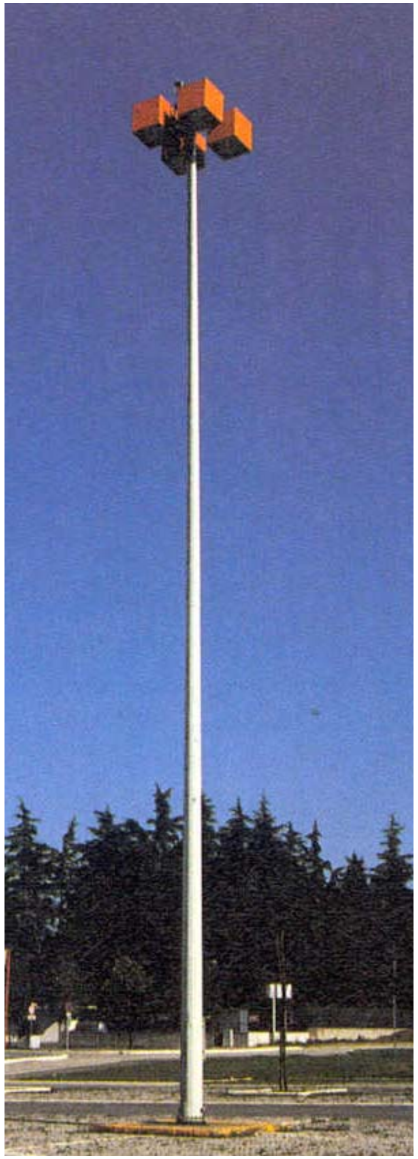
-·-·-·-·- shears

GRF safe	GRF unsafe

Centrale termoelettrica Enelpower Ballylumford, Irlanda

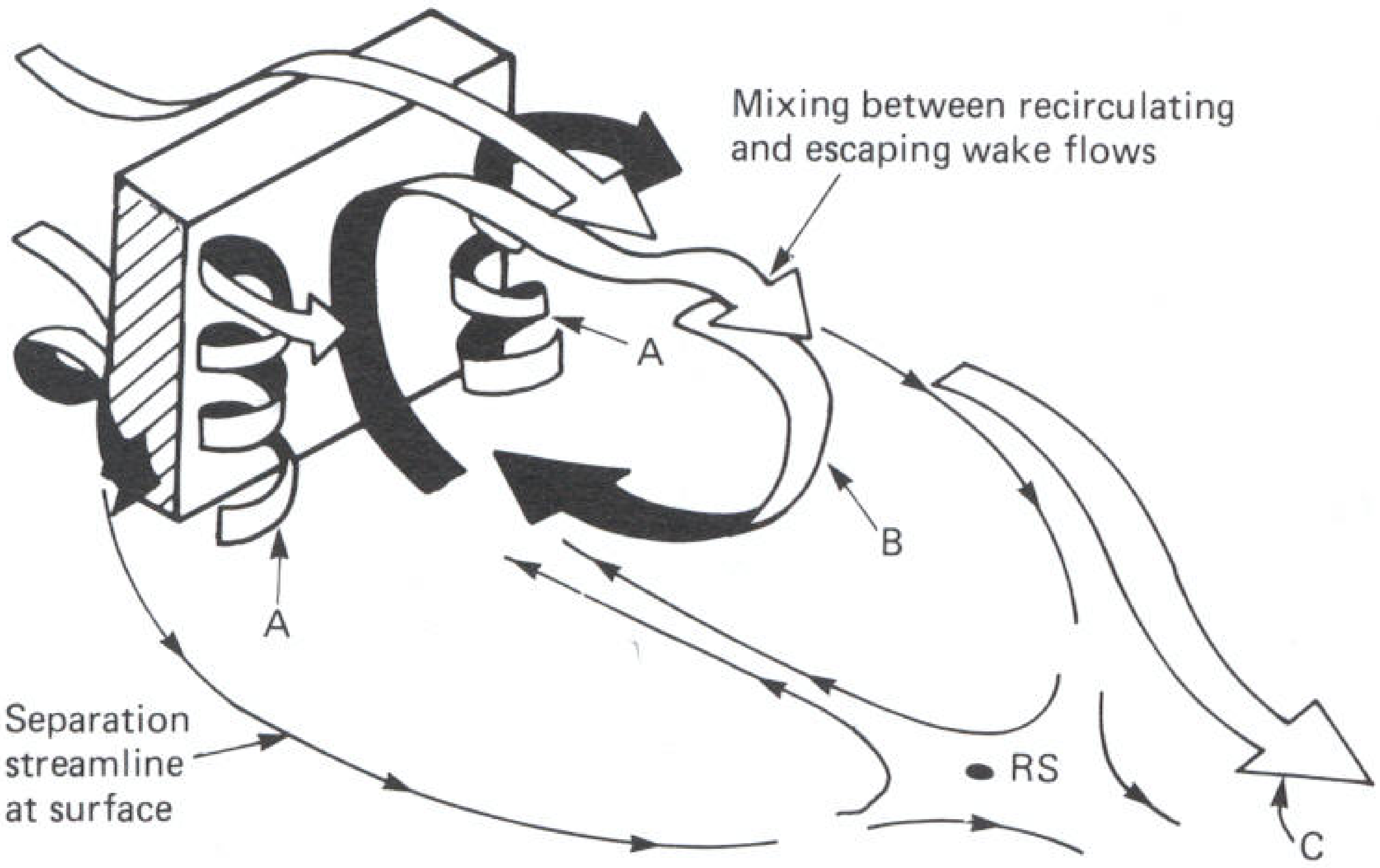


Poles and monotubular towers



Dockers, Calata Sanità, Genoa

3-D WIND-EXCITED RESPONSE OF THREE-DIMENSIONAL BLUFF-BODIES



Historical Area, Fiera di Milano