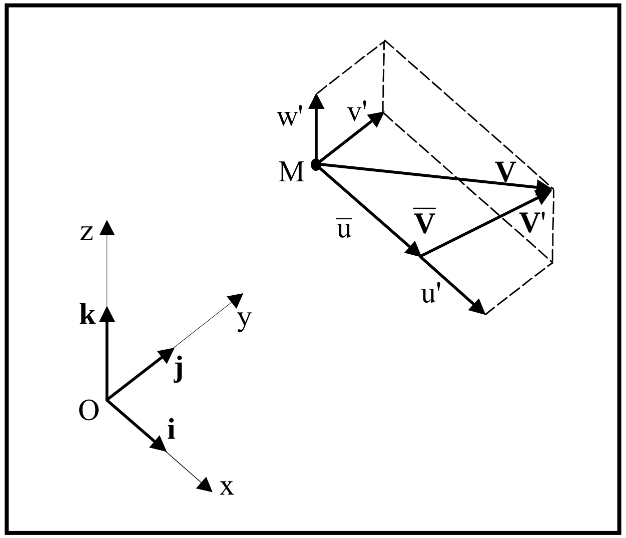
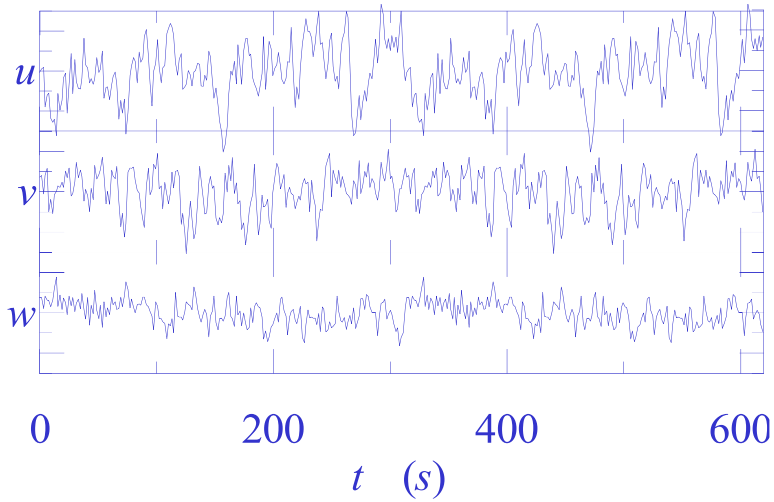
COE Program TPU
Wind Effects on Buildings and Urban Environment

# Wind Velocity

- Wind Velocity
- Local Pressure
- Resultant Force
- Dynamic Response
- Wind Load Effects
- Equiv Static Forces
- Applications




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

$$\bar{\mathbf{V}} = \mathbf{i}\bar{u}$$

$$\bar{\mathbf{V}}'(t) = \mathbf{i}u'(t) + \mathbf{j}v'(t) + \mathbf{k}w'(t)$$

$\bar{u}$ = mean wind velocity

u’ = longitudinal turbulence
v’ = lateral turbulence
w’ = vertical turbulence

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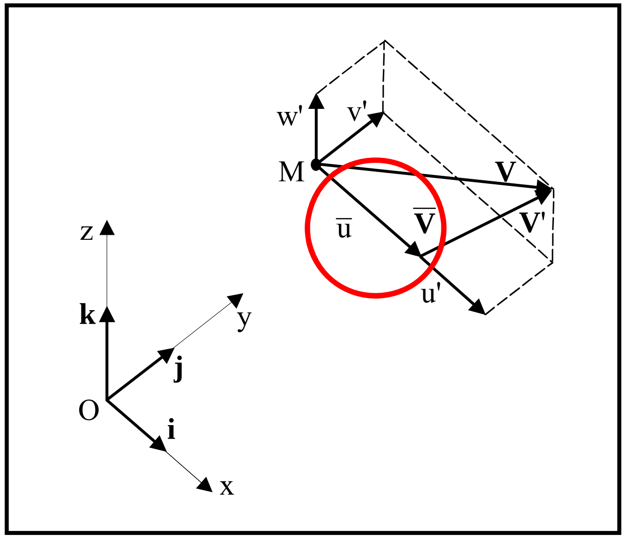


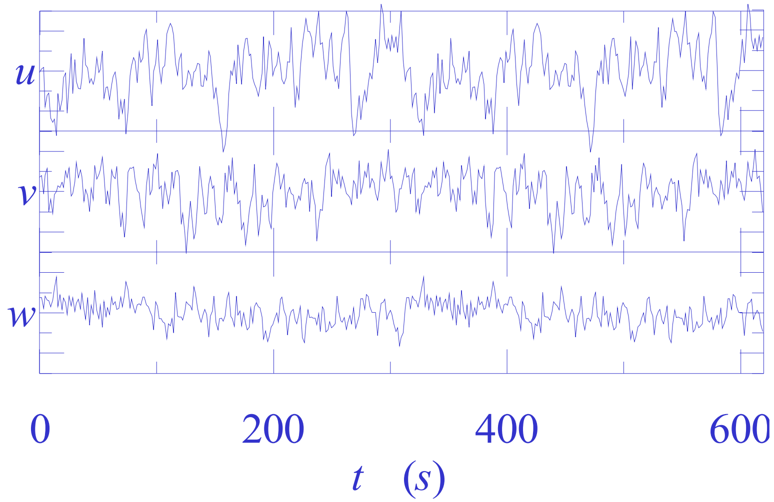


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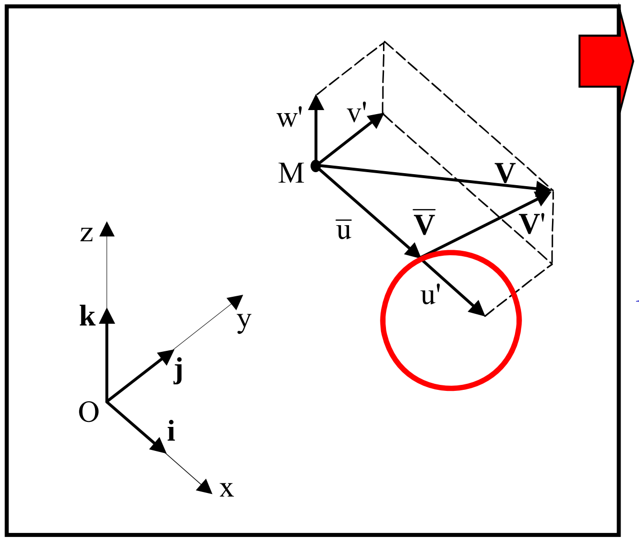


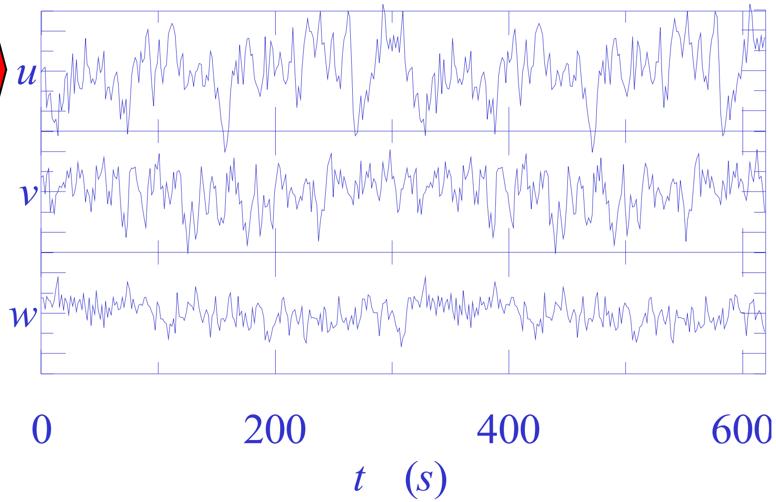


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ū = mean wind velocity

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- Literature in ’60s
- Literature in ’70s
- Research Project
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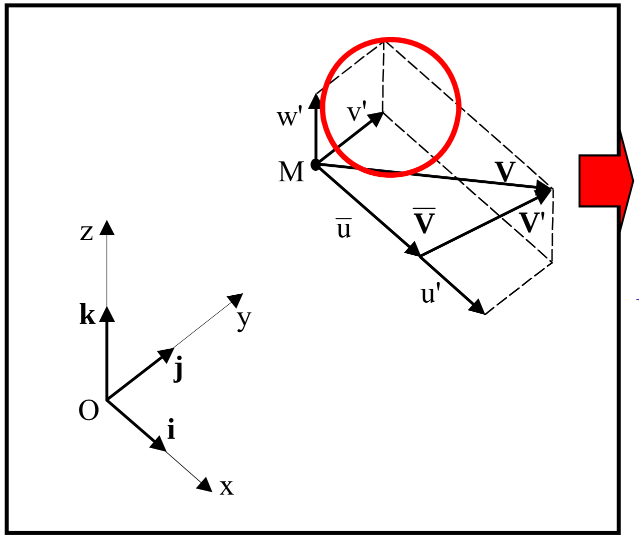


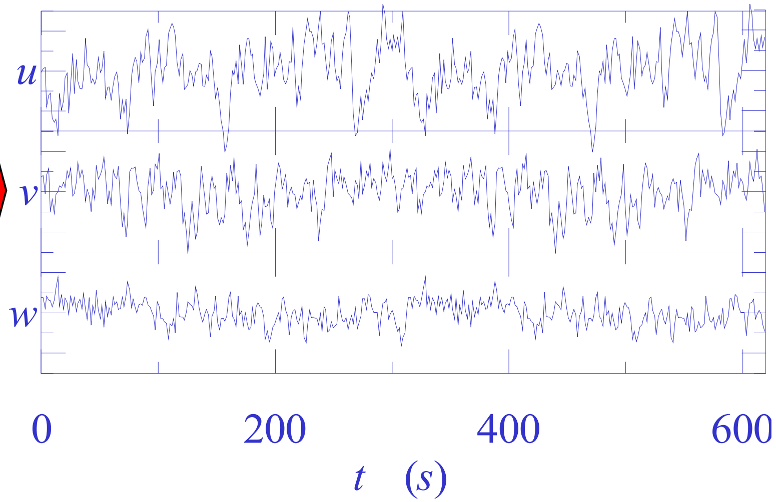


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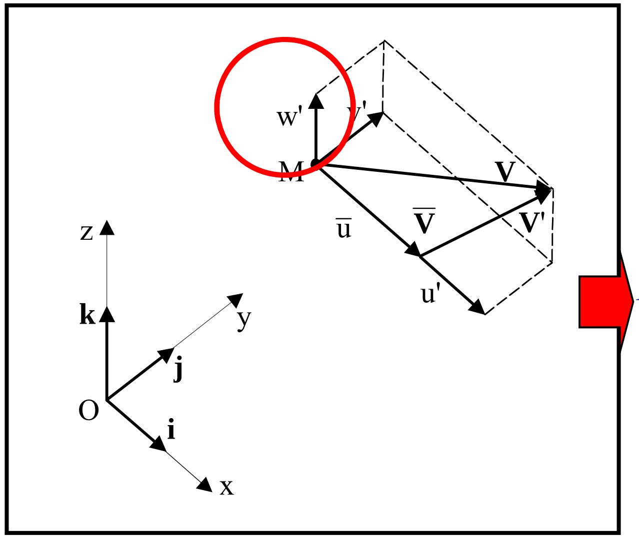


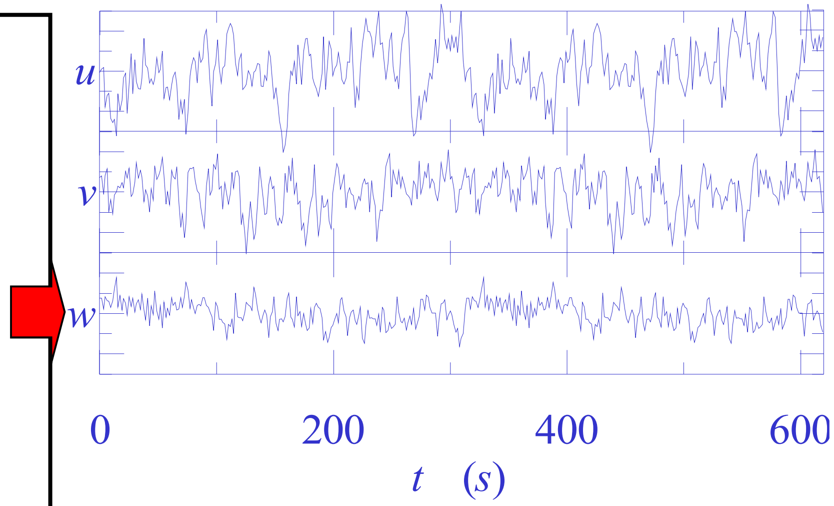


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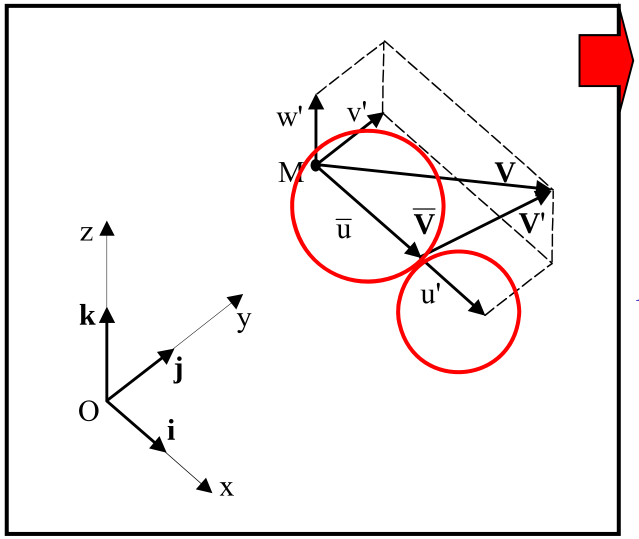


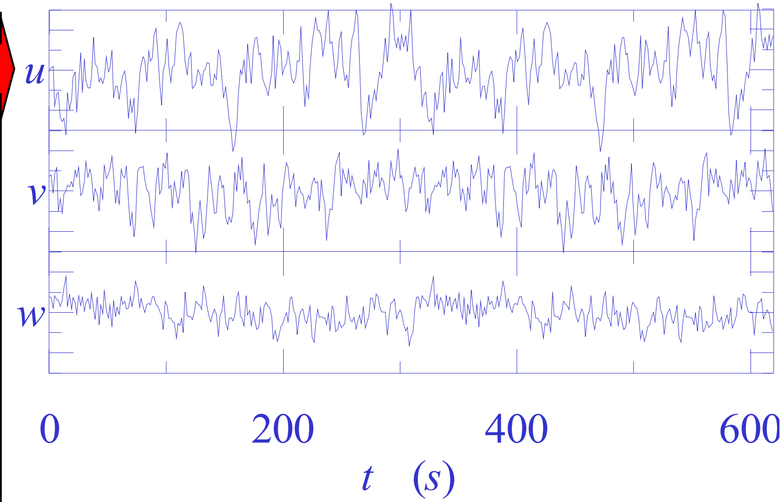


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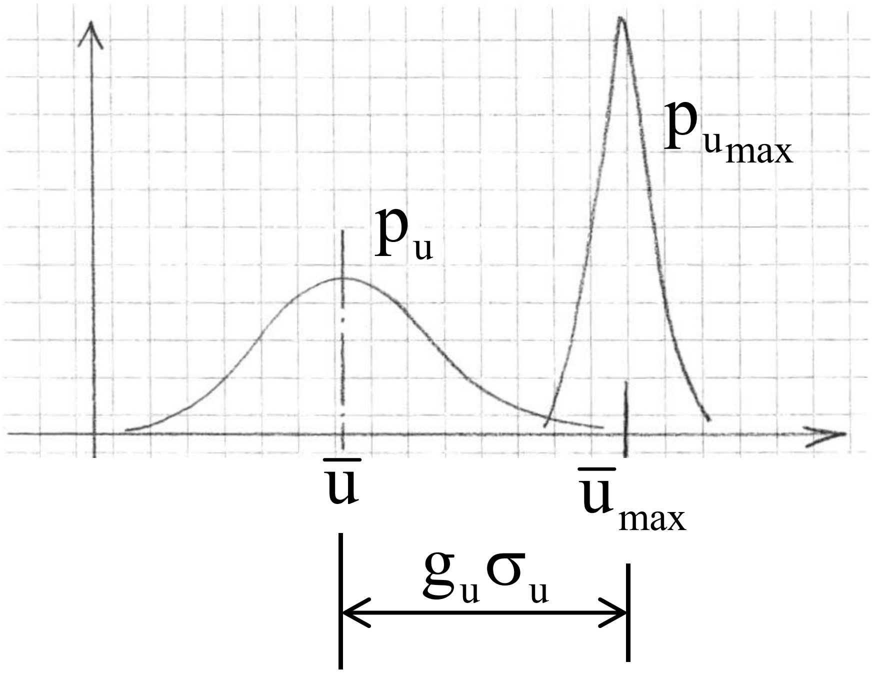
$$\boxed{u(t) = \bar{u} + u'(t)}$$

**Maximum wind velocity**

$$\bar{u}_{max} = \bar{u} + g_u \sigma_u$$



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$$\boxed{u(t) = \overline{u} + u'(t)}$$

**Maximum wind velocity**

$$\overline{u}_{max} = \overline{u} + g_u \sigma_u = \overline{u}\left(1 + g_u \underbrace{\frac{\sigma_u}{\overline{u}}}_{I_u}\right) = \overline{u}\left(1 + g_u I_u\right) \Rightarrow$$

# Wind Velocity



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

**Maximum wind velocity**

$$\bar{u}_{max} = \bar{u} + g_u \sigma_u = \bar{u}\left(1 + g_u \frac{\sigma_u}{\bar{u}}\right) = \bar{u}\underbrace{\left(1 + g_u I_u\right)}_{G_u} \Rightarrow$$

**Velocity gust factor**

$$\boxed{G_u = 1 + g_u I_u} \Rightarrow \boxed{\bar{u}_{max} = \bar{u} G_u}$$

# Wind Velocity



## Maximum wind velocity

$$\boxed{\bar{u}_{max} = \bar{u} G_u} \qquad \boxed{G_u = 1 + g_u I_u}$$

## Closed form solution (Solari 1993)

$$g_u(z) = \sqrt{P_0(z)} \sqrt{1.175 + 2\ell n \left[ \tilde{T} \sqrt{\frac{P_1(z)}{P_0(z)}} \right]}$$

$$P_0 = \frac{1}{1 + 0.56\tilde{\tau}^{0.74}} \; ; \; \frac{P_1}{P_0} = \frac{0.032}{\tilde{\tau}^{1.44}} \; ; \; \tilde{T} = \frac{T\bar{u}(z)}{L_u(z)} \; ; \; \tilde{\tau} = \frac{\tau\bar{u}(z)}{L_u(z)}$$

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## Maximum wind velocity

$$\boxed{\bar{u}_{max} = G_u \bar{u}} \qquad \boxed{G_u = 1 + g_u I_u}$$

## Example

$$z_0 = 0.05\ \mathrm{m};\ z = 10\ \mathrm{m};\ \bar{u}(z) = 25\ \mathrm{m/s};\ \rho = 1.25\ \mathrm{kg/m^3}$$

$$I_u = 1/\ln(z/z_0) = 1/\ln(10/0.05) = 0.19;\ g_u = 2.79$$

$$G_u = 1 + g_u I_u = 1 + 2.79 \times 0.19 = 1.53$$

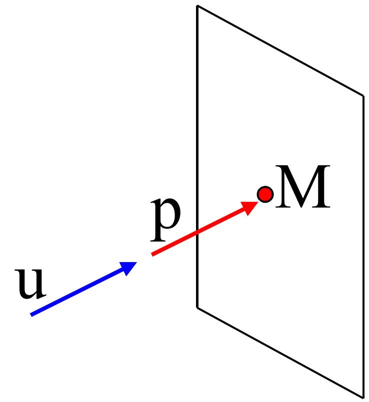
$$\bar{u}_{max} = \bar{u} G_u = 25 \times 1.53 = 38.25\ \mathrm{m/s}$$

# Local Pressure



## Mean pressure

$$\bar{p} = \frac{1}{2}\rho \bar{u}^2 \bar{c}_p$$



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## Mean pressure

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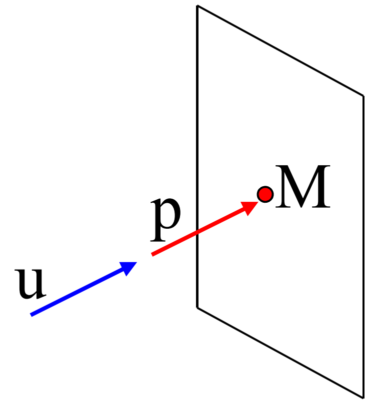


## QUASI-STEADY THEORY
## Instantaneous pressure

$$p(t) = \frac{1}{2}\rho u^2(t)\overline{c}_p = \frac{1}{2}\rho\left[\overline{u} + u'(t)\right]^2 \overline{c}_p$$

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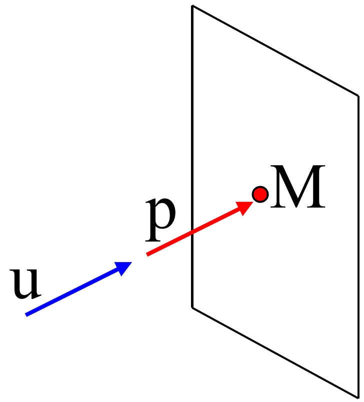
## Mean pressure

$$\overline{p} = \frac{1}{2}\rho\overline{u}^2\overline{c}_p$$




## QUASI-STEADY THEORY

## Instantaneous pressure

$$p(t) = \frac{1}{2}\rho u^2(t)\overline{c}_p = \frac{1}{2}\rho\left[\overline{u} + u'(t)\right]^2\overline{c}_p = \frac{1}{2}\rho\overline{u}^2\left[1 + \frac{2u'(t)}{\overline{u}} + \cancelto{\approx 0}{\frac{u'^2(t)}{\overline{u}^2}}\right]\overline{c}_p \Rightarrow$$

$$\boxed{p(t) = \overline{p} + p'(t)} \qquad \text{where} \quad p'(t) = \rho\overline{u}u'(t)\overline{c}_p$$

# Local Pressure

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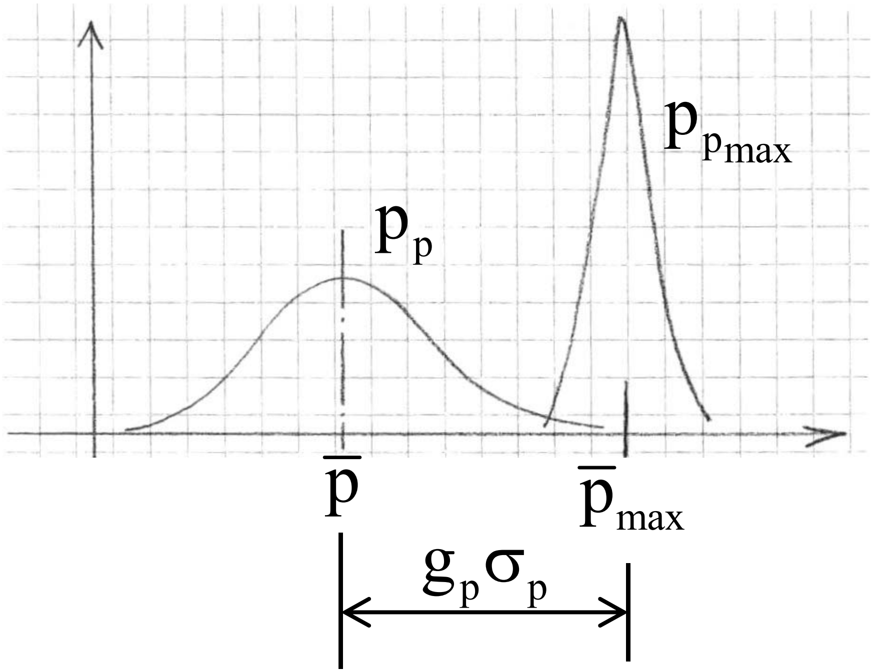
$$\boxed{p(t) = \overline{p} + p'(t)}$$

**Maximum local pressure**

$$\overline{p}_{max} = \overline{p} + g_p \sigma_p$$



# Local Pressure

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$$\boxed{p(t) = \bar{p} + p'(t)}$$

**Maximum local pressure**

$$\bar{p}_{max} = \bar{p} + g_p \sigma_p = \bar{p} \underbrace{\left( 1 + g_p \frac{\sigma_p}{\bar{p}} \right)}_{G_p}$$

**Gust factor of the local pressure**

$$\boxed{G_p = 1 + g_p \frac{\sigma_p}{\bar{p}}} \Rightarrow \boxed{\bar{p}_{max} = \bar{p} G_p}$$

# Local Pressure



$$\boxed{p(t) = \overline{p} + p'(t)}$$

**Maximum local pressure**

$$\overline{p}_{max} = \overline{p} + g_p \sigma_p = \overline{p}\left(1 + g_p \frac{\sigma_p}{\overline{p}}\right)$$

**Gust factor of the local pressure**

$$\boxed{G_p = 1 + g_p \frac{\sigma_p}{\overline{p}}} \quad \Rightarrow \quad \boxed{\overline{p}_{max} = \overline{p} G_p}$$

$$p'(t) \propto u'(t) \Rightarrow g_p = g_u$$

$$\sigma_p / \overline{p} = 2\sigma_u / \overline{u} = 2I_u \Rightarrow \boxed{G_p = 1 + 2g_u I_u}$$

# Local Pressure



$$\boxed{p(t) = \overline{p} + p'(t)}$$

**Maximum local pressure**

$$\boxed{\overline{p}_{max} = \overline{p} G_p} \qquad \boxed{G_p = 1 + 2 g_u I_u}$$

**Example**

$$\overline{c}_p = 1$$

$$\overline{p} = \frac{1}{2}\rho\overline{u}^2\overline{c}_p = \frac{1}{2}\times 1.25\times 25^2\times 1 = 390.625\ \mathrm{N/m^2}$$

$$G_p = 1 + 2g_u I_u = 1 + 2\times 2.79\times 0.19 = 2.06$$

$$\overline{p}_{max} = \overline{p}G_p = 390.625\times 2.06 = 804.8\ \mathrm{N/m^2}$$

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# Local Pressure



## Maximum wind velocity

$$\boxed{u(t) = \bar{u} + u'(t)} \qquad \boxed{\bar{u}_{max} = \bar{u} G_u} \qquad \boxed{G_u = 1 + g_u I_u}$$

## Maximum local pressure

$$\boxed{p(t) = \bar{p} + p'(t)} \qquad \boxed{\bar{p}_{max} = \bar{p} G_p} \qquad \boxed{G_p = 1 + 2 g_u I_u}$$

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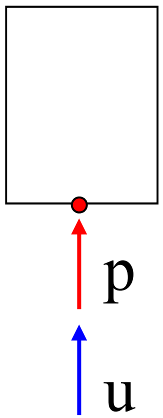


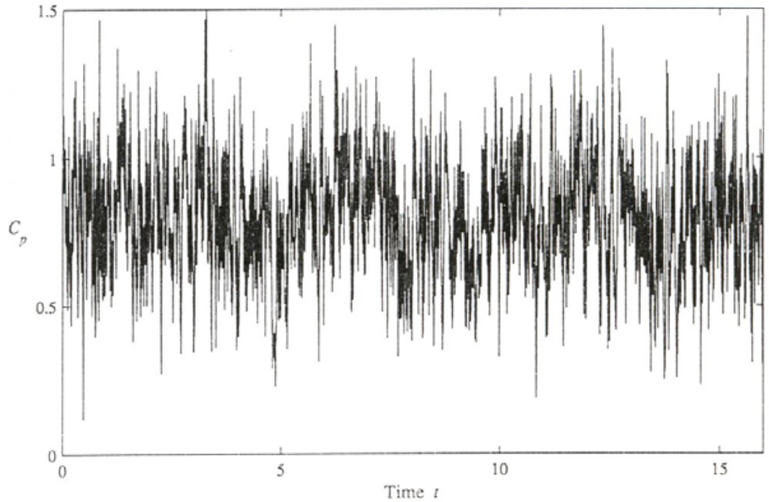


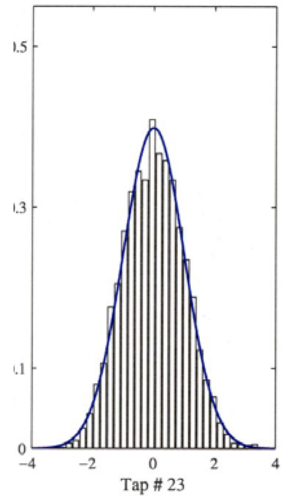

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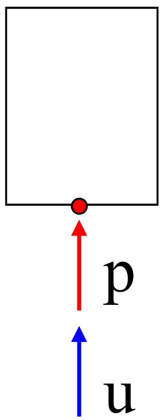
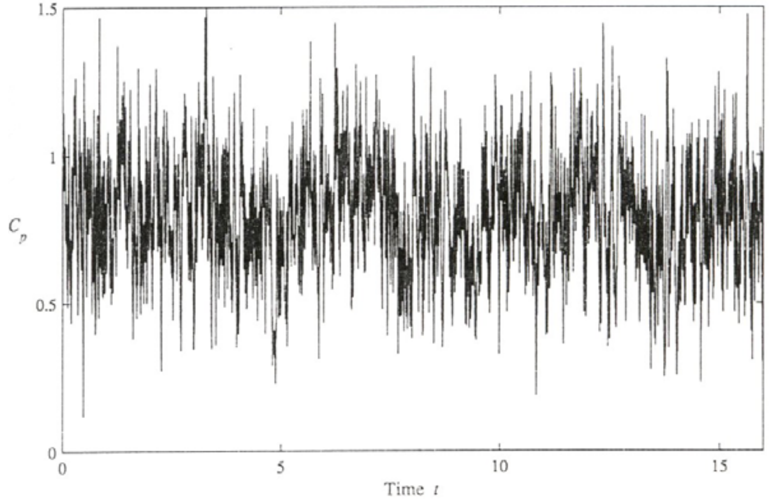
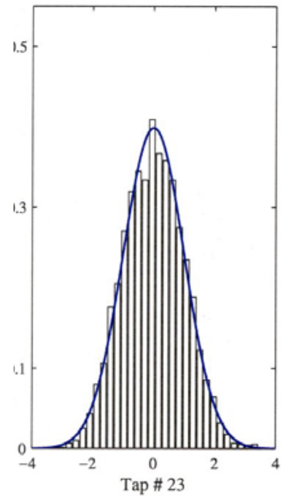
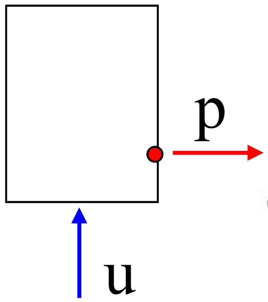
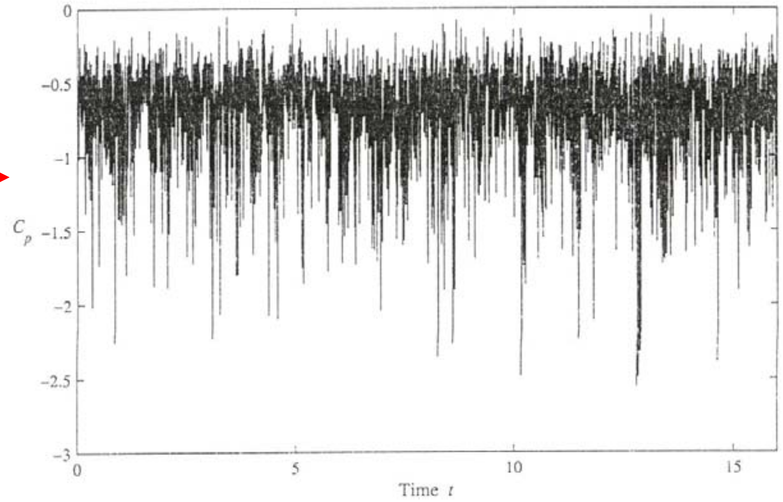
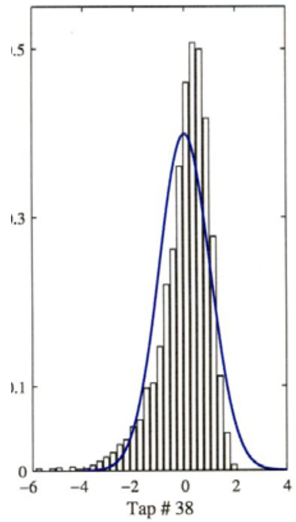


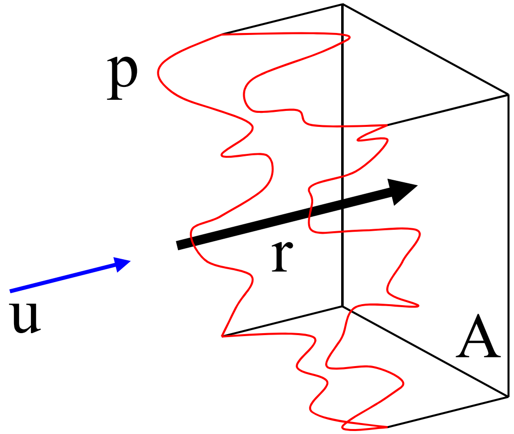



# Resultant Force






$$r(t) = \int_A p(M,t)\,dA$$

$$p(M,t) = \overline{p}(M) + p'(M,t) \Rightarrow$$

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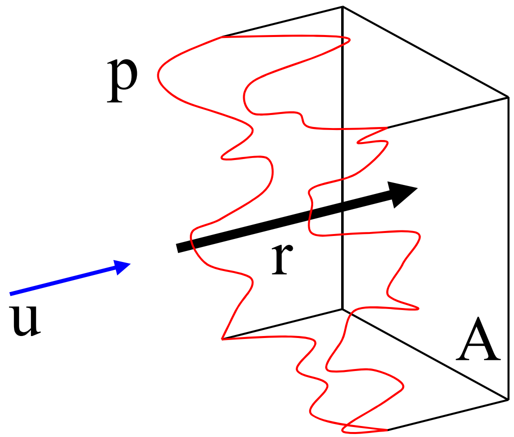


$$r(t) = \int_A p(M,t)\,dA$$

$$p(M,t) = \overline{p}(M) + p'(M,t) \Rightarrow$$

$$\boxed{r(t) = \overline{r} + r'(t)}$$

$$\overline{r} = \int_A \overline{p}(M)\,dA \qquad r'(t) = \int_A p'(M,t)\,dA$$

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$$\boxed{r(t) = \overline{r} + r'(t)}$$

$$\overline{r} = \underbrace{\frac{1}{2}\rho u^2 \overline{c}_p}_{\overline{p}} A$$

# Resultant Force



$$\boxed{r(t) = \overline{r} + r'(t)}$$

$$\overline{r} = \frac{1}{2}\rho u^2 \overline{c}_p A \qquad r'(t) = \rho \overline{u}\,\overline{c}_p \int_A u'(M,t)\, dA$$

$$S_r(n) = \left(\rho \overline{u}\,\overline{c}_p A\right)^2 S_u(n)\chi(n)$$

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# Resultant Force

$$\boxed{r(t)=\overline{r}+r'(t)}$$

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$$S_r(n)=\left(\rho\overline{u}\,\overline{c}_p A\right)^2 S_u(n)\chi(n)$$

<u>**Aerodynamic admittance function**</u>

$$\boxed{\chi(n)=\frac{1}{A^2}\int_A\int_A Coh_{uu}(M,M';n)\,dA\,dA'}$$

$$\xrightarrow{\;u\;}\boxed{\chi}\xrightarrow{\;r\;}$$

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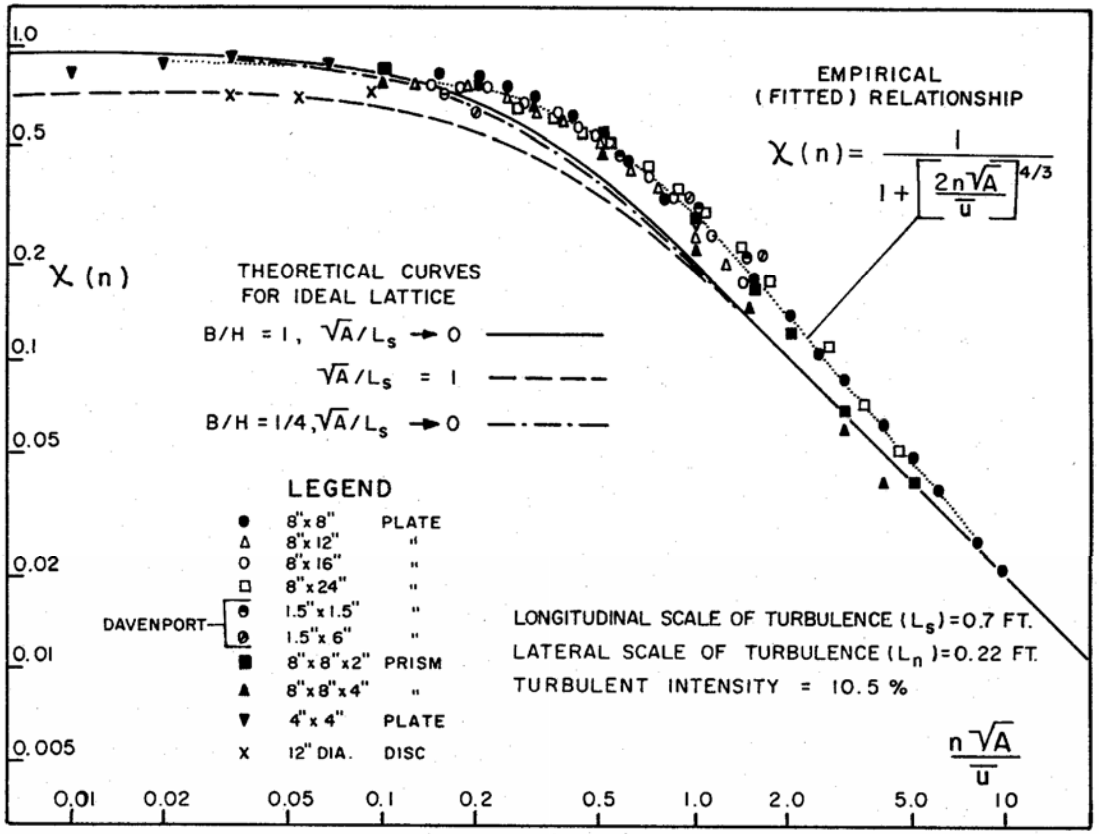
## Aerodynamic admittance function
## Experimental analysis (Vickery 1966)



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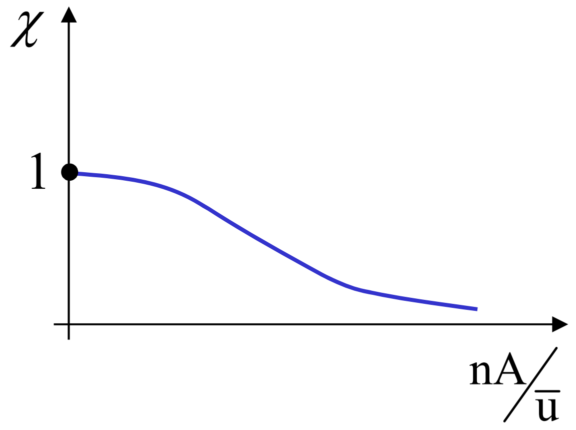
## Aerodynamic admittance function
## Closed form solution (Solari 1993)

$$\boxed{\chi(n)\frac{1}{A^2}\int_A\int_A \mathrm{Coh}_{uu}(M,M';n)\,dA\,dA'}$$

$$\boxed{\mathrm{Coh}_{uu}(M,M';n)=\exp\left\{-\frac{2n\sqrt{c_{uy}^2\left|y-y'\right|^2+c_{uz}^2\left|z-z'\right|^2}}{\bar{u}}\right\}}$$

$$\boxed{\chi(n)\cong C\left\{0.4\frac{nc_{uy}b}{\bar{u}}\right\}C\left\{0.4\frac{nc_{uz}h}{\bar{u}}\right\}}$$

$$C\{\eta\}=\frac{1}{\eta}-\frac{1}{2\eta^2}\left(1-e^{-2\eta}\right)\ \text{for}\ \eta>0;\ C\{0\}=1$$



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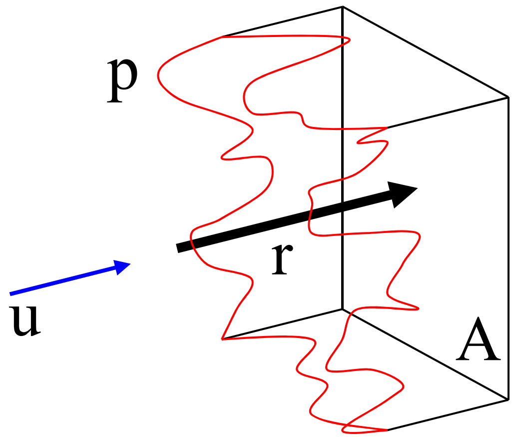
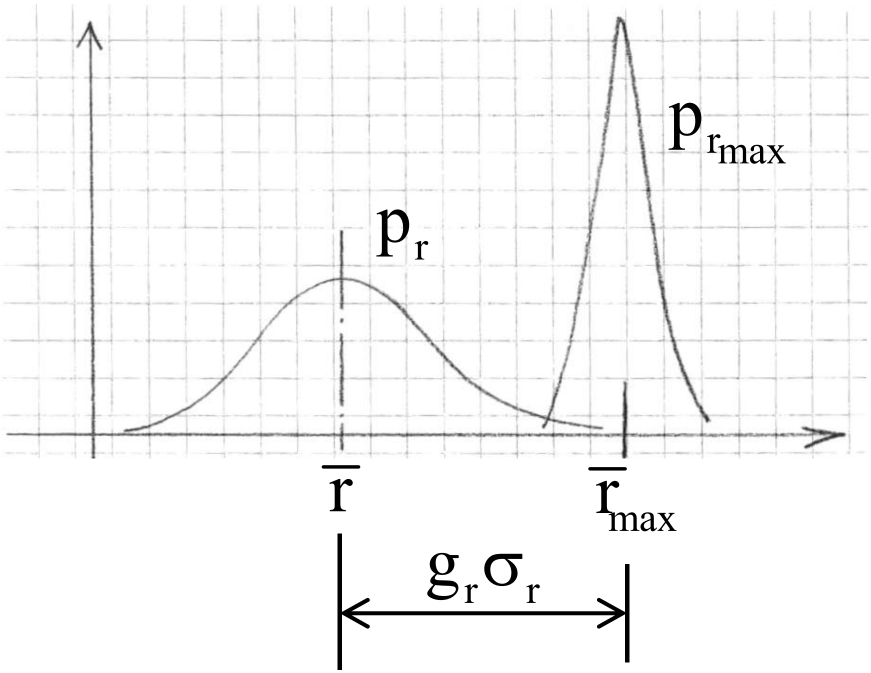
$$\boxed{r(t) = \overline{r} + r'(t)}$$




## Maximum resultant force

$$\overline{r}_{max} = \overline{r} + g_r \sigma_r$$



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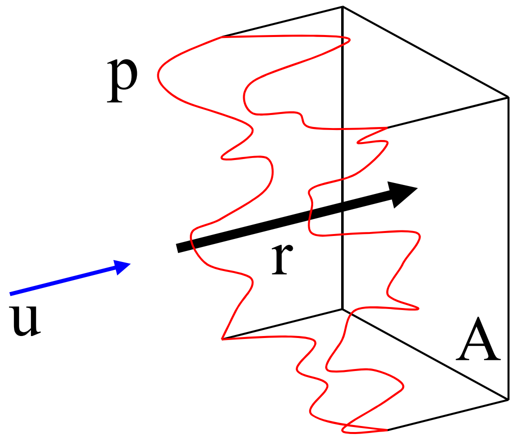


**Maximum resultant force**

$$\overline{r}_{max} = \overline{r} + g_r \sigma_r = \overline{r}\underbrace{\left(1 + g_r \frac{\sigma_r}{\overline{r}}\right)}_{G_r}$$

**Gust factor of the resultant force**

$$\boxed{G_r = 1 + g_r \frac{\sigma_r}{\overline{r}}} \Rightarrow \boxed{\overline{r}_{max} = \overline{r} G_r}$$

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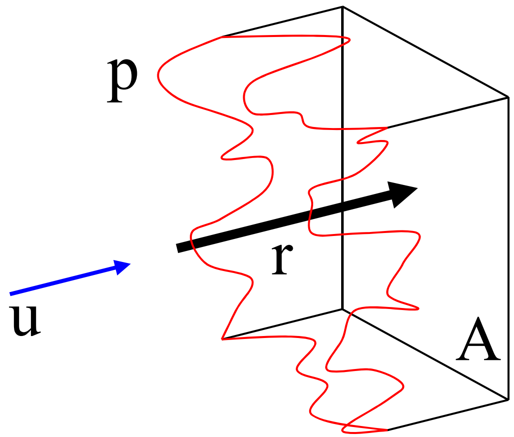
$$\boxed{r(t) = \overline{r} + r'(t)}$$




## Maximum resultant force

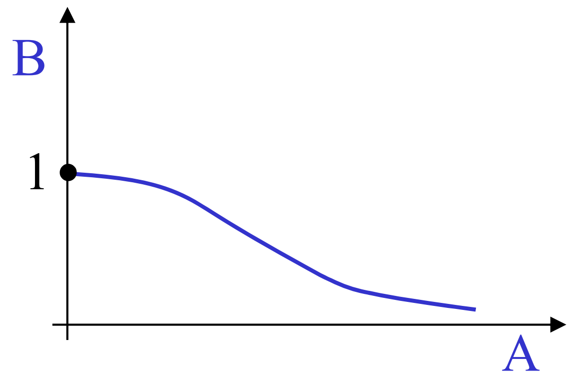
$$\overline{r}_{max} = \overline{r} + g_r\sigma_r = \overline{r}\left(1 + g_r\frac{\sigma_r}{\overline{r}}\right)$$

## Gust factor of the resultant force

$$\boxed{G_r = 1 + g_r\frac{\sigma_r}{\overline{r}}} \Rightarrow \boxed{\overline{r}_{max} = \overline{r}G_r}$$

$$\boxed{G_r = 1 + 2g_r I_u B}$$

$$B = \frac{1}{2I_u}\frac{\sigma_r}{\overline{r}} = \frac{1}{\sigma_u}\sqrt{\int_0^\infty S_u(n)\chi(n)\,dn}$$



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# Resultant Force



## Maximum resultant force

$$\boxed{\bar{r}_{max} = \bar{r} G_r} \qquad \boxed{G_r = 1 + 2 g_r I_u B}$$

## Closed form solution (Solari 1993)

$$B^2 = \frac{1}{1 + 0.56\tilde{\tau}^{0.74} + 0.29\tilde{L}_0^{0.63}}$$

$$\tilde{\tau} = \frac{\tau \bar{u}}{L_u}; \; \tilde{L}_0 = 0.5\left(\tilde{b} + \tilde{h}\right); \tilde{b} = \frac{c_{uy} b}{L_u}; \tilde{h} = \frac{c_{uz} h}{L_u}$$

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## Maximum resultant force

$$\boxed{\bar{r}_{max} = \bar{r}G_r} \qquad \boxed{G_r = 1 + 2g_r I_u B}$$

## Closed form solution (Solari 1993)

$$g_r = \sqrt{2\ln(\nu_r T)} + \frac{0.5772}{\sqrt{2\ln(\nu_r T)}};\ \nu_r = \frac{\bar{u}}{L_u}\frac{B_1}{B}$$

$$\frac{B_1}{B} = \frac{1}{\sqrt{31.25\tilde{\tau}^{1.44} + 1.23\tilde{L}_1^{1.23}}}$$

$$\tilde{L}_1 = 0.04\left(\tilde{b} + \tilde{h}\right) + 0.92\sqrt{\tilde{b}\tilde{h}}$$

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## Maximum wind velocity

$$\boxed{u(t) = \bar{u} + u'(t)} \qquad \boxed{\bar{u}_{max} = \bar{u} G_u} \qquad \boxed{G_u = 1 + g_u I_u}$$

## Maximum local pressure

$$\boxed{p(t) = \bar{p} + p'(t)} \qquad \boxed{\bar{p}_{max} = \bar{p} G_p} \qquad \boxed{G_p = 1 + 2 g_u I_u}$$

## Maximum resultant force

$$\boxed{r(t) = \bar{r} + r'(t)} \qquad \boxed{\bar{r}_{max} = \bar{r} G_r} \qquad \boxed{G_r = 1 + 2 g_r I_u B}$$

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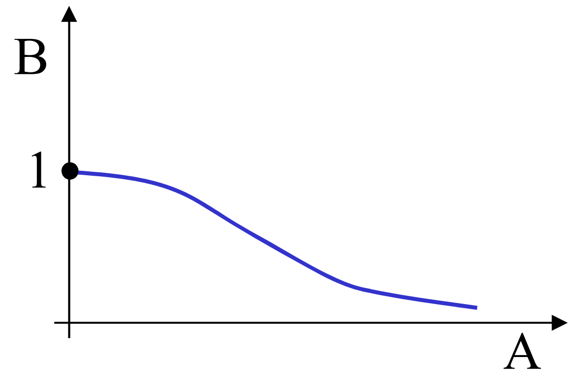
## Equivalent pressure

$$\boxed{p_{eq} = \frac{\bar{r}_{max}}{A} = \frac{G_r \bar{r}}{A}} \Rightarrow$$

$$\boxed{p_{eq} = \bar{p} G_r}$$

$$\boxed{G_r = 1 + 2 g_r I_u B}$$



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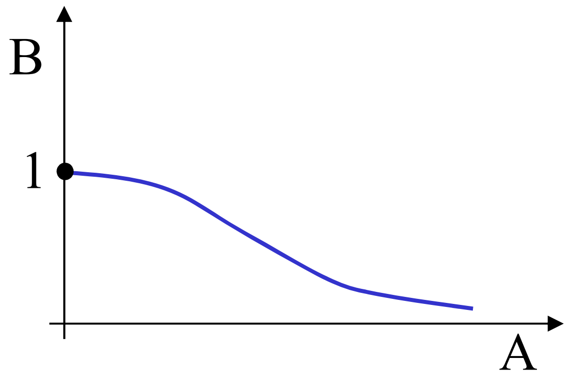
## Maximum local pressure

$$\boxed{\bar{p}_{max} = \bar{p} G_p} \qquad \boxed{G_p = 1 + 2 g_u I_u}$$

## Equivalent pressure

$$\boxed{p_{eq} = \frac{\bar{r}_{max}}{A} = \frac{G_r \bar{r}}{A}} \Rightarrow$$

$$\boxed{p_{eq} = \bar{p} G_r} \qquad \boxed{G_r = 1 + 2 g_r I_u B}$$




$$A \to 0 \Rightarrow B \to 1 \Rightarrow G_r = 1 + 2 g_r I_u \Rightarrow p_{eq} \to \bar{p}_{max}$$

# Resultant Force

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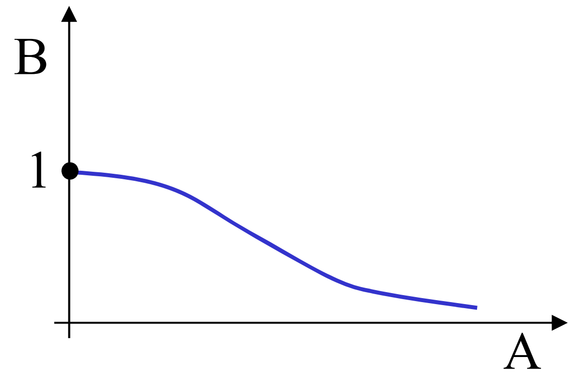
## Maximum local pressure

$$\boxed{\bar{p}_{max} = \bar{p}G_p} \qquad \boxed{G_p = 1 + 2g_u I_u}$$

## Equivalent pressure

$$\boxed{p_{eq} = \frac{\bar{r}_{max}}{A} = \frac{G_r \bar{r}}{A}} \Rightarrow$$

$$\boxed{p_{eq} = \bar{p}G_r} \qquad \boxed{G_r = 1 + 2g_r I_u B}$$




$$A \to 0 \Rightarrow B \to 1 \Rightarrow G_r = 1 + 2g_r I_u \Rightarrow p_{eq} \to \bar{p}_{max}$$

$$A \to \infty \Rightarrow B \to 0 \Rightarrow G_r = 1 \Rightarrow p_{eq} \to \bar{p}$$

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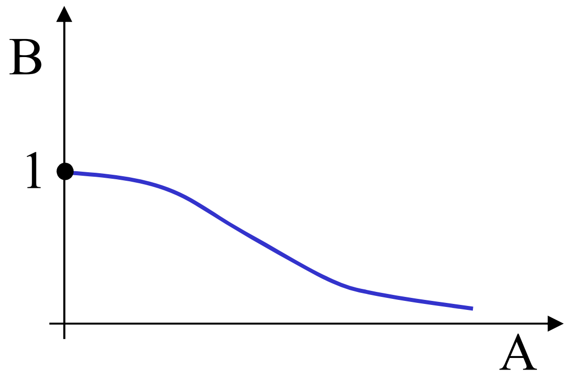
## Maximum local pressure

$$\boxed{\bar{p}_{max} = \bar{p} G_p} \qquad \boxed{G_p = 1 + 2 g_u I_u}$$

## Equivalent pressure

$$\boxed{p_{eq} = \frac{\bar{r}_{max}}{A} = \frac{G_r \bar{r}}{A}} \Rightarrow$$




$$\boxed{p_{eq} = \bar{p} G_r} \qquad \boxed{G_r = 1 + 2 g_r I_u B}$$

$$A \to 0 \Rightarrow B \to 1 \Rightarrow G_r = 1 + 2 g_r I_u \Rightarrow p_{eq} \to \bar{p}_{max}$$

$$A \to \infty \Rightarrow B \to 0 \Rightarrow G_r = 1 \Rightarrow p_{eq} \to \bar{p}$$

$$\boxed{\bar{p} \le p_{eq} \le \bar{p}_{max}}$$

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## Equivalent pressure

$$\boxed{p_{eq} = \bar{p} G_r} \qquad \boxed{G_r = 1 + 2 g_r I_u B}$$

## Example

$$b = h = 4\ \mathrm{m};\ h_0 = 10\ \mathrm{m};\ \bar{u}(z) = 25\ \mathrm{m/s};\ \rho = 1.25\ \mathrm{kg/m^3}$$

$$I_u = 0.19;\ L_u = 63\ \mathrm{m};\ c_{uy} = c_{uz} = 10;\ \tau = 1\ \mathrm{s};\ T = 600\ \mathrm{s}$$

$$\tilde{b} = c_{uy} b / L_u = 10 \times 4 / 63 = 0.635$$

$$\tilde{h} = c_{uz} h / L_u = 10 \times 4 / 63 = 0.635$$

$$\tilde{L}_0 = 0.5\left(\tilde{b} + \tilde{h}\right) = 0.5 \times (0.635 + 0.635) = 0.635$$

$$\tilde{L}_1 = 0.04\left(\tilde{b} + \tilde{h}\right) + 0.92\sqrt{\tilde{b}\tilde{h}} =$$

$$= 0.04 \times (0.635 + 0.635) + 0.92 \times \sqrt{0.635 \times 0.635} = 0.635$$

$$\tilde{\tau} = \tau \bar{u} / L_u = 1 \times 25 / 63 = 0.4$$

# Resultant Force



## Equivalent pressure

$$\boxed{p_{eq} = \overline{p} G_r} \qquad \boxed{G_r = 1 + 2 g_r I_u B}$$

## Example

$$B^2 = 0.66;\ B_1^2 = 0.074$$

$$\nu_r = \overline{u} / L_u \left( B_1 / B \right) = 25 / 63 \times \left( 0.272 / 0.812 \right) = 0.13 \text{ Hz}$$

$$g_r = 3.15;\ G_r = 1 + 2 g_r I_u B = 1 + 2 \times 3.15 \times 0.19 \times 0.812 = 1.97$$

$$p_{eq} = \overline{p} G_r = 390.625 \times 1.97 = 770.5 \text{ N} / \text{m}^2$$

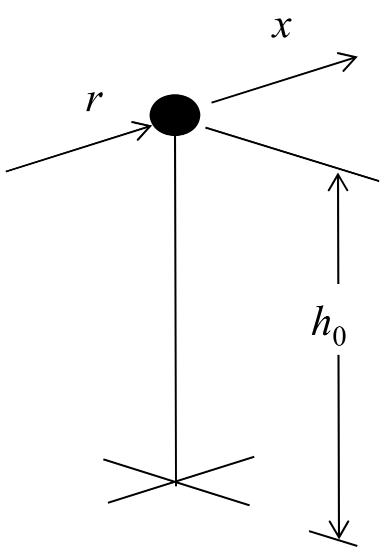
$$\overline{p} = 390.625 \text{ N} / \text{m}^2 < p_{eq} = 770.5 \text{ N} / \text{m}^2 < \overline{p}_{max} = 804.8 \text{ N} / \text{m}^2$$

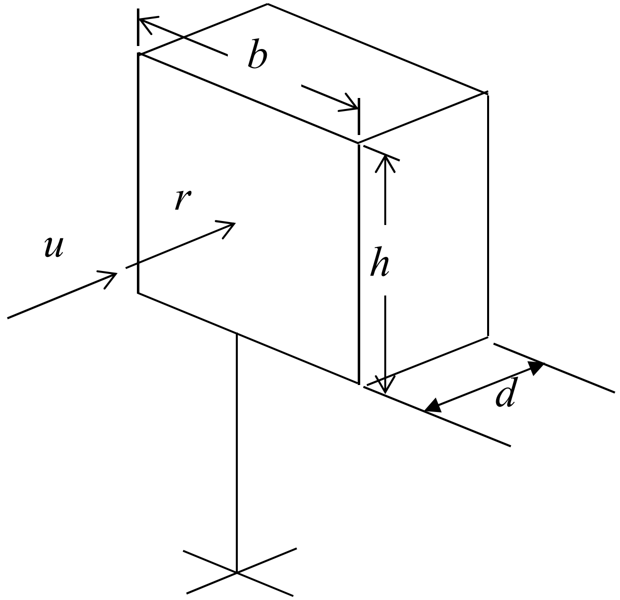
# Dynamic Response



## <u>Single-Degree-Of-Freedom System</u> (SDOF)

## POINT-LIKE MODEL



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## Resultant force

$$\boxed{r(t) = \overline{r} + r'(t)}$$

$$\overline{r} = \frac{1}{2}\rho\overline{u}^2\overline{c}_P A; \qquad S_r(n) = \left(\rho\overline{u}\,\overline{c}_P A\right)^2 S_u(n)\chi(n)$$

$$\xrightarrow{\;u\;} \boxed{\chi} \xrightarrow{\;r\;}$$

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## Resultant force

$$\boxed{r(t) = \bar{r} + r'(t)}$$

$$\bar{r} = \frac{1}{2}\rho\bar{u}^2\bar{c}_P A; \qquad S_r(n) = \left(\rho\bar{u}\bar{c}_P A\right)^2 S_u(n)\chi(n)$$

$$\xrightarrow{u} \boxed{\chi} \xrightarrow{r} \boxed{H} \xrightarrow{x}$$

## Dynamic response

$$\boxed{x(t) = \bar{x} + x'(t)}$$

$$\bar{x} = \frac{\bar{r}}{k} = \frac{\bar{r}}{m(2\pi n_0)^2}; \qquad S_x(n) = \left|H(n)\right|^2 S_r(n)$$

$$H(n) = \frac{1}{m(2\pi n_0)^2}\frac{1}{1 - \frac{n^2}{n_0^2} + 2i\xi\frac{n}{n_0}}$$

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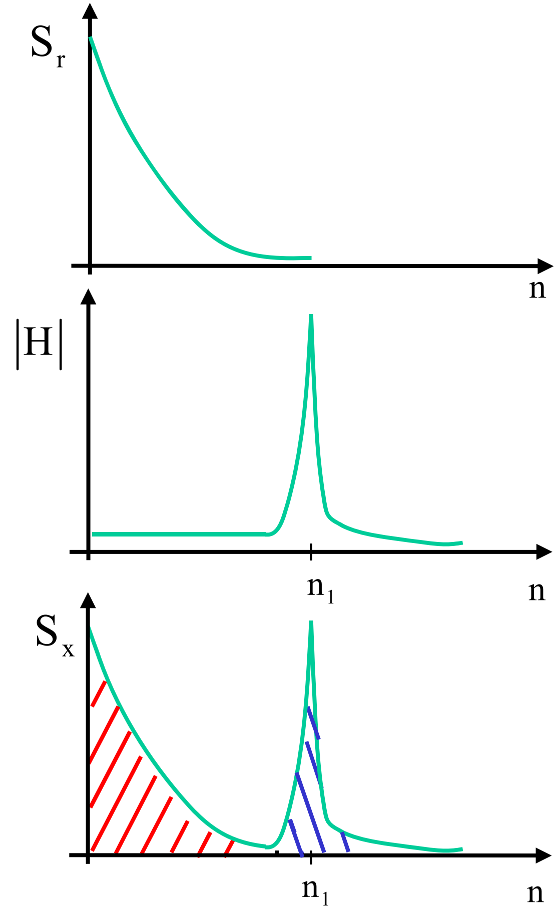

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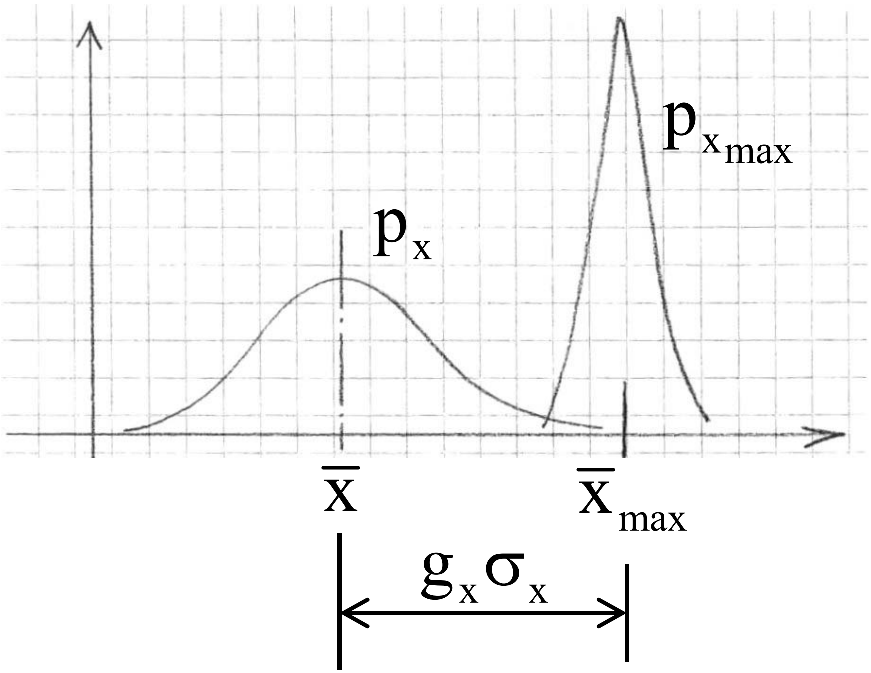
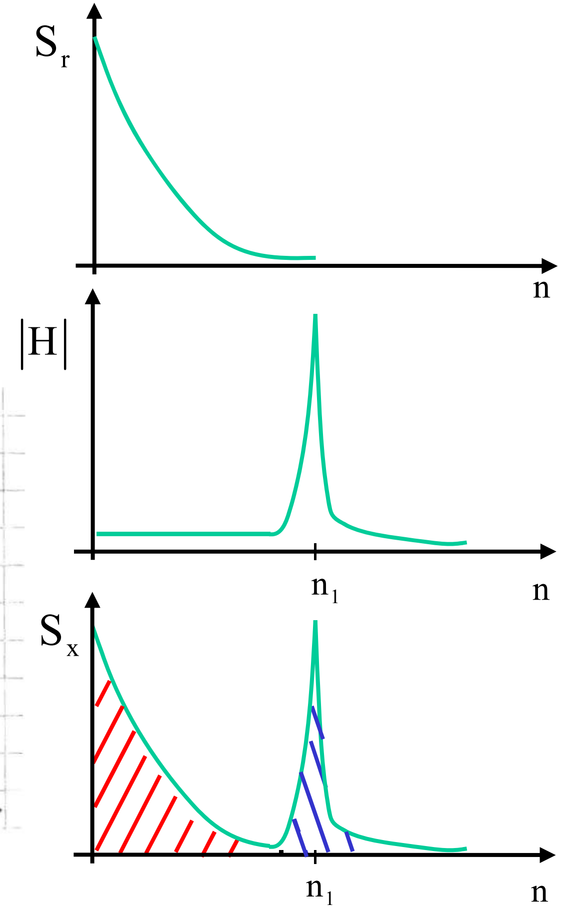
$$\boxed{x(t) = \bar{x} + x'(t)}$$

**Maximum dynamic response**

$$\bar{x}_{max} = \bar{x} + g_x \sigma_x$$



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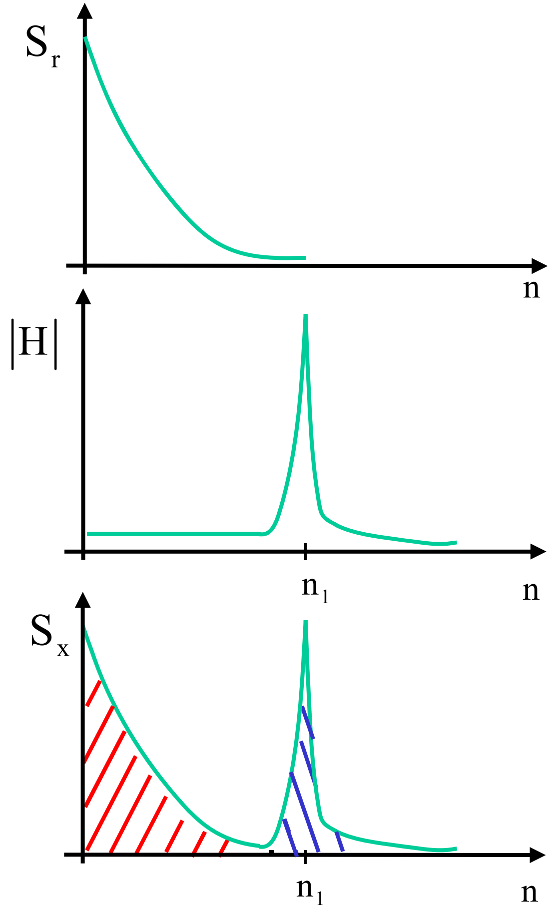
$$x(t) = \bar{x} + x'(t)$$

## Maximum dynamic response

$$\bar{x}_{max} = \bar{x} + g_x \sigma_x = \bar{x}\underbrace{\left(1 + g_x \frac{\sigma_x}{\bar{x}}\right)}_{G_x}$$

## Gust Response Factor

$$\boxed{G_x = 1 + g_x \frac{\sigma_x}{\bar{x}}} \quad \Rightarrow \quad \boxed{\bar{x}_{max} = \bar{x} G_x}$$



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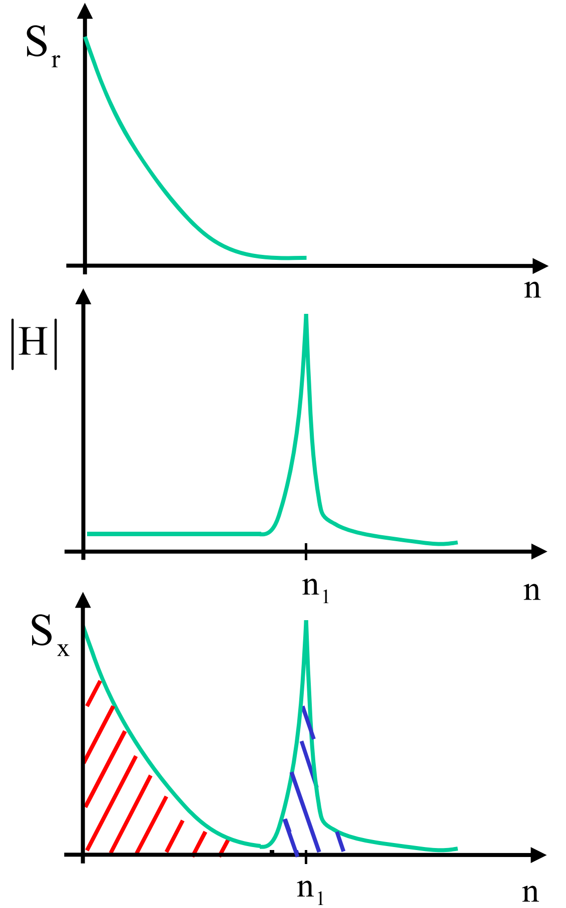
$$\boxed{x(t) = \overline{x} + x'(t)}$$

## Maximum dynamic response

$$\overline{x}_{max} = \overline{x} + g_x \sigma_x = \overline{x}\left(1 + g_x \frac{\sigma_x}{\overline{x}}\right)$$




## Gust Response Factor

$$\boxed{G_x = 1 + g_x \frac{\sigma_x}{\overline{x}}} \quad \Rightarrow \quad \boxed{\overline{x}_{max} = \overline{x} G_x}$$

$$\boxed{G_x = 1 + 2 g_x I_u \sqrt{B^2 + R^2}}$$

$$B = \frac{1}{2I_u} \frac{\sigma_{Bx}}{\overline{x}} = \frac{1}{\sigma_u} \sqrt{\int_0^\infty S_u(n) \chi(n) dn}$$

$$R = \frac{1}{2I_u} \frac{\sigma_{Rx}}{\overline{x}} = \frac{1}{\sigma_u} \sqrt{\frac{\pi n_0}{4\xi} S_u(n_0) \chi(n_0)}$$

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## Maximum dynamic response

$$\boxed{\bar{x}_{max} = \bar{x} G_x} \qquad \boxed{G_x = 1 + 2 g_x I_u \sqrt{B^2 + R^2}}$$

## Closed Form Solution (Solari 1993)

$$B^2 = \frac{1}{1 + 0.56\tilde{\tau}^{0.74} + 0.29\tilde{L}_0^{0.63}}$$

$$R^2 = \frac{\pi}{4\xi} \frac{6.868\tilde{n}_0}{[1 + 10.302\tilde{n}_0]^{5/3}} C\{0.4\tilde{n}_0\tilde{b}\} C\{0.4\tilde{n}_0\tilde{h}\}$$

$$\tilde{\tau} = \frac{\tau\bar{u}}{L_u};\ \tilde{L}_0 = 0.5\left(\tilde{b} + \tilde{h}\right);\ \tilde{b} = \frac{c_{uy} b}{L_u};\ \tilde{h} = \frac{c_{uz} h}{L_u};\ \tilde{n}_0 = \frac{n_0 L_u}{\bar{u}}$$

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## Maximum dynamic response

$$\boxed{\bar{x}_{max} = \bar{x} G_x} \qquad \boxed{G_x = 1 + 2 g_x I_u \sqrt{B^2 + R^2}}$$

## Closed Form Solution (Solari 1993)

$$g_x = \sqrt{2\ln(\nu_x T)} + \frac{0.5772}{\sqrt{2\ln(\nu_x T)}}$$

$$\nu_x = \sqrt{\frac{\nu_r^2 B_1^2 + n_0^2 R^2}{B^2 + R^2}} \simeq n_0 \sqrt{\frac{R^2}{B^2 + R^2}}$$

# Dynamic Response



## Maximum wind velocity

$$\boxed{u(t)=\overline{u}+u'(t)} \quad \boxed{\overline{u}_{max}=\overline{u}G_u} \quad \boxed{G_u=1+g_uI_u}$$

## Maximum local pressure

$$\boxed{p(t)=\overline{p}+p'(t)} \quad \boxed{\overline{p}_{max}=\overline{p}G_p} \quad \boxed{G_p=1+2g_uI_u}$$

## Maximum resultant force

$$\boxed{r(t)=\overline{r}+r'(t)} \quad \boxed{\overline{r}_{max}=\overline{r}G_r} \quad \boxed{G_r=1+2g_rI_uB}$$

## Maximum dynamic response

$$\boxed{x(t)=\overline{x}+x'(t)} \quad \boxed{\overline{x}_{max}=\overline{x}G_x} \quad \boxed{G_x=1+2g_xI_u\sqrt{B^2+R^2}}$$

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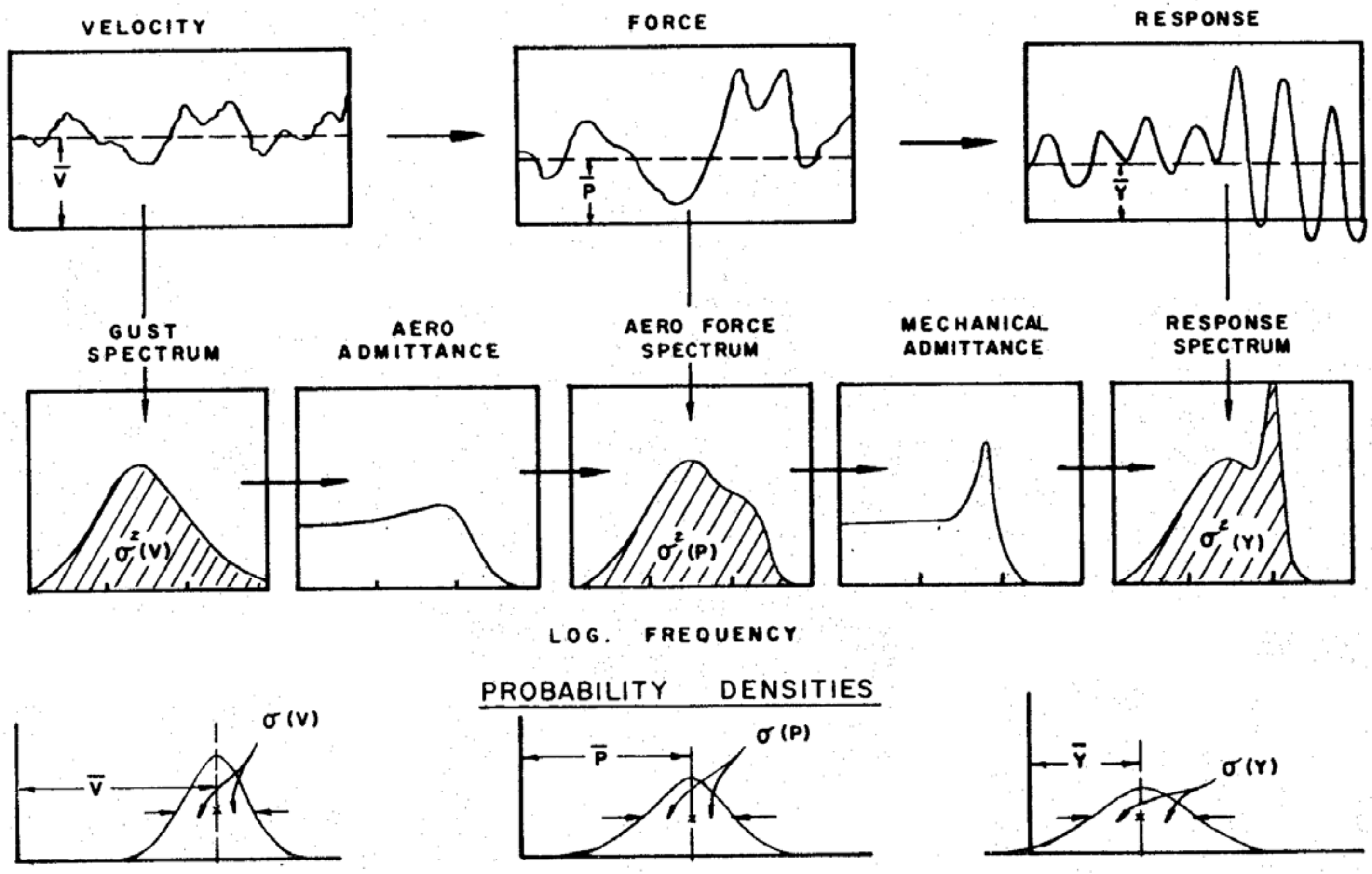
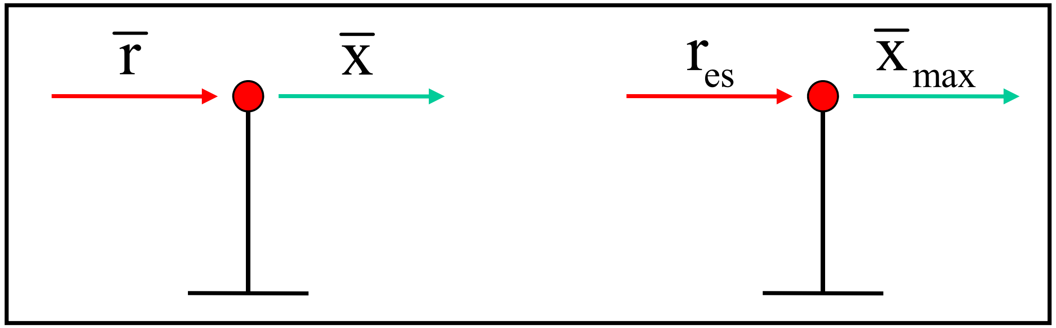
## Davenport chain



# Dynamic Response



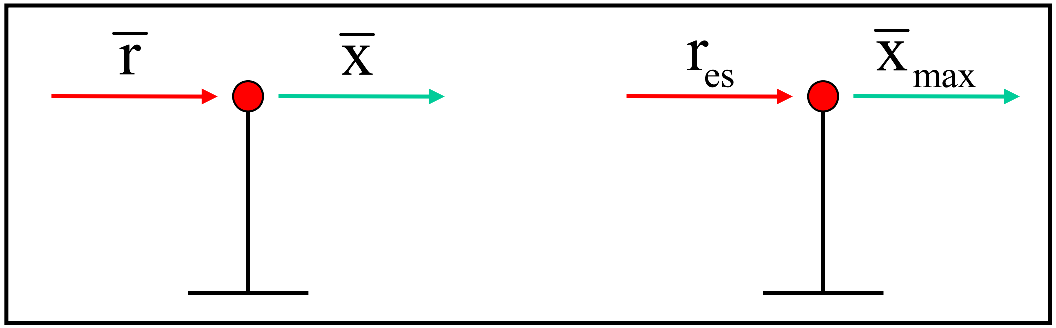



**EQUIVALENT STATIC FORCE**

$$\boxed{\bar{x}_{max} = \bar{x} G_x} \Rightarrow \boxed{r_{es} = \bar{r} G_x}$$

# Dynamic Response






## EQUIVALENT STATIC FORCE

$$\boxed{\bar{x}_{max} = \bar{x} G_x} \quad \Rightarrow \quad \boxed{r_{es} = \bar{r} G_x}$$

## Equivalent static pressure

$$\boxed{p_{es} = \frac{r_{es}}{A}} \quad \Rightarrow \quad \boxed{p_{es} = \bar{p} G_x}$$

# Dynamic Response



## Maximum local pressure

$$\boxed{\bar{p}_{max} = \bar{p} G_p}$$

$$\boxed{G_p = 1 + 2 g_u I_u}$$

# Dynamic Response



## Maximum local pressure

$$\boxed{\bar{p}_{max} = \bar{p} G_p} \qquad \boxed{G_p = 1 + 2 g_u I_u}$$

## Equivalent pressure

$$\boxed{p_{eq} = \bar{p} G_r} \qquad \boxed{G_r = 1 + 2 g_r I_u B} \qquad B \leq 1$$

$$A \to 0 \Rightarrow B \to 1 \Rightarrow G_r = 1 + 2 g_r I_u \Rightarrow p_{eq} \to \bar{p}_{max}$$

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## Maximum local pressure

$$\boxed{\bar{p}_{max} = \bar{p} G_p} \qquad \boxed{G_p = 1 + 2 g_u I_u}$$

## Equivalent pressure

$$\boxed{p_{eq} = \bar{p} G_r} \qquad \boxed{G_r = 1 + 2 g_r I_u B} \qquad B \le 1$$

$$A \to 0 \Rightarrow B \to 1 \Rightarrow G_r = 1 + 2 g_r I_u \Rightarrow p_{eq} \to \bar{p}_{max}$$

## Equivalent static pressure

$$\boxed{p_{es} = \bar{p} G_x} \qquad \boxed{G_x = 1 + 2 g_x I_u \sqrt{B^2 + R^2}} \qquad R \ge 0$$

$$n_0, \xi \to \infty \Rightarrow R \to 0 \Rightarrow G_x = 1 + 2 g_x I_u B \Rightarrow p_{es} \to p_{eq}$$

# Dynamic Response



## Equivalent static pressure

$$\boxed{p_{es} = \overline{p}G_x} \qquad \boxed{G_x = 1 + 2g_x I_u \sqrt{B^2 + R^2}}$$

## Example

$k = 60000\ \mathrm{N/m};\ m = 3000\ \mathrm{kg}$

$\omega_0 = \sqrt{k/m} = \sqrt{60000/3000} = 4.47\ \mathrm{rad/s}$

$n_0 = \omega_0 / 2\pi = 4.47/2\pi = 0.71\ \mathrm{Hz};\ \xi = 0.02$

$B^2 = 0.66;\ R^2 = 1.96$

$\nu_x = n_0\sqrt{R^2/\left(B^2 + R^2\right)} = 0.71\sqrt{1.96/\left(0.66 + 1.96\right)} = 0.61\ \mathrm{Hz}$

$g_x = 3.60;\ G_x = 1 + 2g_x I_u\sqrt{B^2 + R^2} = 1 + 2\times 3.60 \times 0.19 \times \sqrt{0.66 + 1.96} = 3.60$

$p_{se} = \overline{p}G_x = 390.625 \times 3.60 = 1253.8\ \mathrm{N/m^2}$

# Dynamic Response



## Equivalent static pressure

$$\boxed{p_{es} = \overline{p} G_x}$$

$$\boxed{G_x = 1 + 2 g_x I_u \sqrt{B^2 + R^2}}$$

## Example

$\overline{p} = 391 \, N/m^2$ → $\overline{p}_{max} = 805 \, N/m^2$ → $\overline{p}_{eq} = 770 \, N/m^2$ → $p_{es} = 1254 \, N/m^2$

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| $P_{es}$ | | Size | |
|---|---|---|---|
| | | Small | Large |
| Damping & Frequency | Large | | Small $G_x$ |
| | Small | Large $G_x$ | |

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## Gust Response Factor

$$\boxed{p_{es} = \overline{p} G_x} \qquad \boxed{G_x = 1 + 2 g_x I_u \sqrt{B^2 + R^2}}$$

## Dynamic coefficient

$$p_{es} = \overline{p} G_x = \overline{p} G_x \frac{G_p}{G_p} = \overline{p} G_p \frac{G_x}{G_p} = \overline{p}_{max} C_d$$

$$C_d = \frac{G_x}{G_p} = \frac{1 + 2 g_x I_u \sqrt{B^2 + R^2}}{1 + 2 g_u I_u}$$

$$\boxed{p_{es} = \overline{p}_{max} C_d}$$

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| $P_{es}$ | | Size: Small | Size: Large |
|---|---|---|---|
| Damping & Frequency | Large | | Small<br>$C_d < 1$ |
| Damping & Frequency | Small | Large<br>$C_d > 1$ | |

$\boxed{C_d = 1}$

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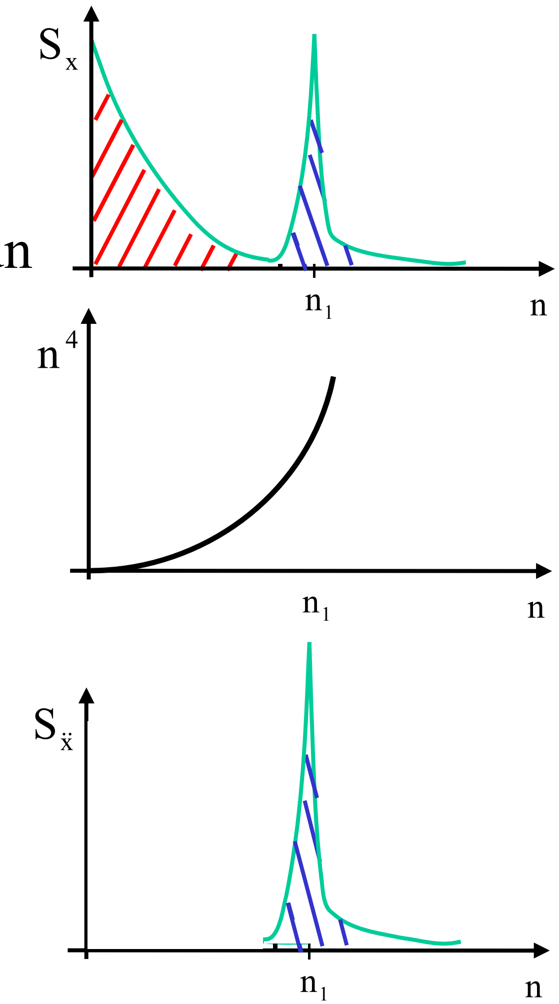
## Acceleration

$$S_{\ddot{x}}(n) = (2\pi n)^4 S_x(n)$$

$$\sigma_{\ddot{x}}^2 = \int_0^\infty S_{\ddot{x}}(n)\,dn = \int_0^\infty (2\pi n)^4 S_x(n)\,dn$$



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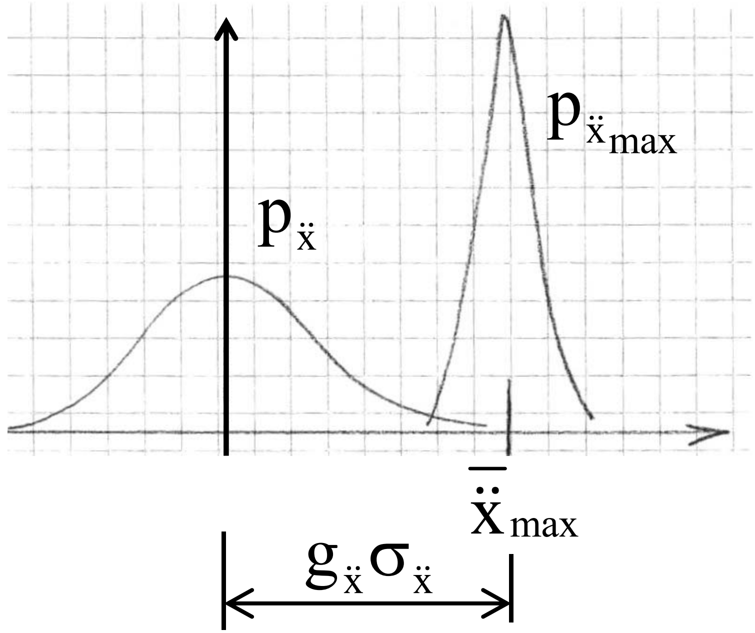
## Maximum acceleration

$$\boxed{\bar{\ddot{x}}_{max} = g_{\ddot{x}}\sigma_{\ddot{x}}}$$

$$g_{\ddot{x}} = \sqrt{2\ln(n_0 T)} + \frac{0.5772}{\sqrt{2\ln(n_0 T)}}$$

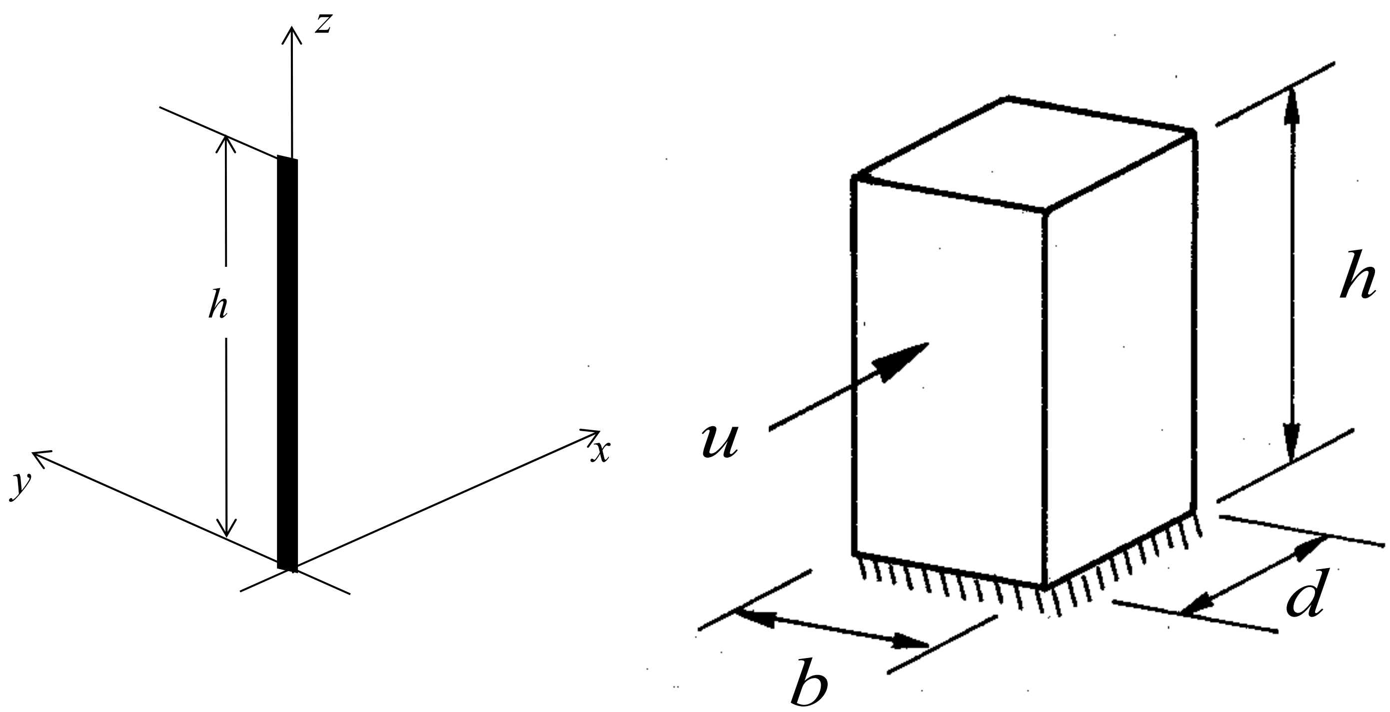


# Dynamic Response



## Continuous Cantilever Beam System

## VERTICAL MODEL



# Dynamic Response

- Wind Velocity
- Local Pressure
- Resultant Force
- Dynamic Response
- Wind Load Effects
- Equiv Static Forces
- Applications

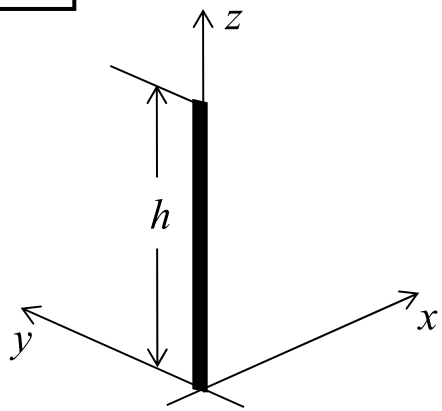
$$\boxed{x(z;t) = \overline{x}(z) + x'(z;t)}$$

## Maximum alongwind displacement

$$\overline{x}_{max}(z) = \overline{x}(z) + g_x(z)\sigma_x(z) = \overline{x}(z)\underbrace{\left[1 + g_x(z)\frac{\sigma_x(z)}{\overline{x}(z)}\right]}_{G_x(z)}$$

## Gust Response Factor

$$\boxed{G_x(z) = 1 + g_x(z)\frac{\sigma_x(z)}{\overline{x}(z)}} \Rightarrow \boxed{\overline{x}_{max}(z) = \overline{x}(z)G_x(z)}$$



# Dynamic Response

Wind Velocity
Local Pressure
Resultant Force
Dynamic Response
Wind Load Effects
Equiv Static Forces
Applications

$$\boxed{x(z;t) = \bar{x}(z) + x'(z;t)}$$

## Maximum alongwind displacement

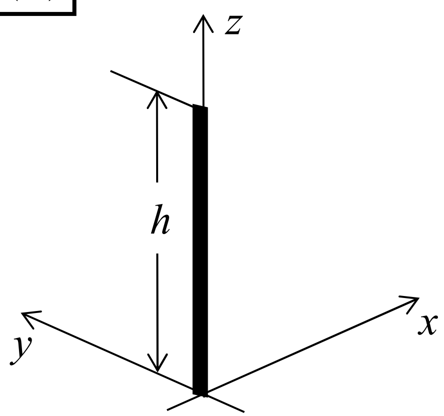
$$\bar{x}_{max}(z) = \bar{x}(z) + g_x(z)\sigma_x(z) = \bar{x}(z)\underbrace{\left[1 + g_x(z)\frac{\sigma_x(z)}{\bar{x}(z)}\right]}_{\mathrm{G_x(z)}}$$

## Gust Response Factor

$$\boxed{G_x(z) = 1 + g_x(z)\frac{\sigma_x(z)}{\bar{x}(z)}} \Rightarrow \boxed{\bar{x}_{max}(z) = \bar{x}(z)G_x(z)}$$

$$\boxed{G_x(z) = 1 + 2g_x(z)I_u\sqrt{B^2(z) + R^2(z)}}$$

$$B(z) = \frac{1}{2I_u}\frac{\sigma_{Bx}(z)}{\bar{x}(z)} \qquad R(z) = \frac{1}{2I_u}\frac{\sigma_{Rx}(z)}{\bar{x}(z)}$$



# Dynamic Response

Wind Velocity
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## Classical Modal Analysis

$$\bar{x}(z) = \sum_k \frac{\psi_{xk}(z)}{m_{xk}(2\pi n_{xk})^2} \int_0^h \bar{F}_x(\zeta)\psi_{xk}(\zeta)\mathrm{d}\zeta$$

$$\sigma_{Bx}(z) = \sum_k \frac{\psi_{xk}(z)}{m_{xk}(2\pi n_{xk})^2} \sqrt{\int_0^\infty \left[\int_0^h\int_0^h S_{F_xF_x}(\zeta,\zeta';n)\psi_{xk}(\zeta)\psi_{xk}(\zeta')\mathrm{d}\zeta\mathrm{d}\zeta'\right]dn}$$

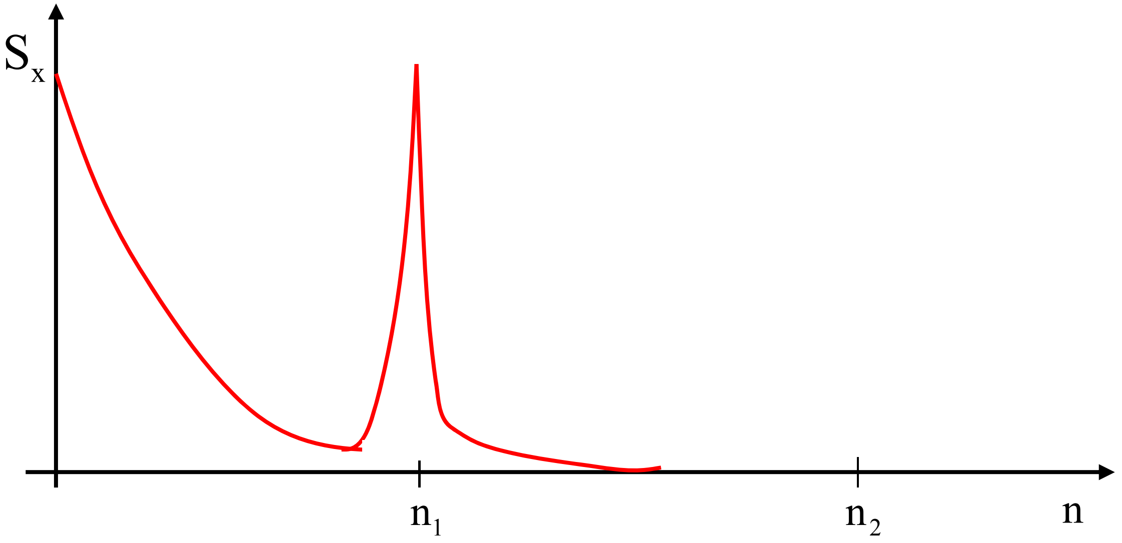
$$\sigma_{Rx}(z) = \sum_k \frac{\psi_{xk}(z)}{m_{xk}(2\pi n_{xk})^2} \sqrt{\int_0^h\int_0^h S_{F_xF_x}(\zeta,\zeta';n_{xk})\psi_{xk}(\zeta)\psi_{xk}(\zeta')\mathrm{d}\zeta\mathrm{d}\zeta'} \sqrt{\frac{\pi n_{xk}}{4\xi_{xk}}}$$

$\bar{F}_x(\zeta), S_{F_xF_x}(\zeta,\zeta';n) =$ mean value and psdf of the alongwind force

$\mathrm{n_{xk}}, \mathrm{m_{xk}}, \xi_{\mathrm{xk}}, \psi_{\mathrm{xk}}(\mathrm{z}) = \mathrm{k^{th}}$ natural frequency, modal mass, modal damping and modal shape

# Dynamic Response

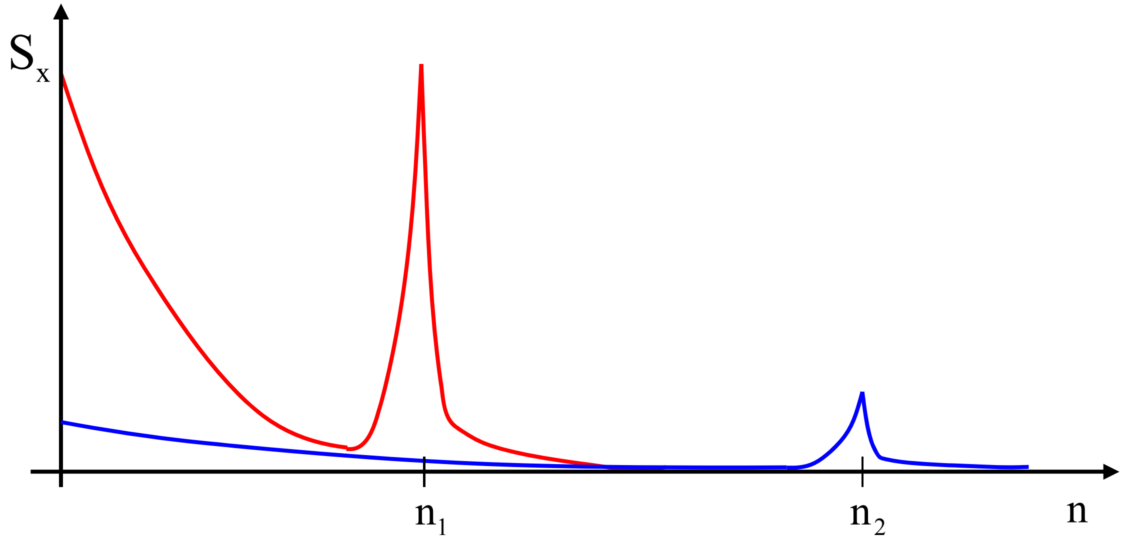





**The second mode of vibration is well separated from the first one ⇒**

# Dynamic Response






**The second mode of vibration is well separated from the first one ⇒**

**Only the first mode of vibration contributes to the dynamic response ⇒**

# Dynamic Response

- Wind Velocity
- Local Pressure
- Resultant Force
- Dynamic Response
- Wind Load Effects
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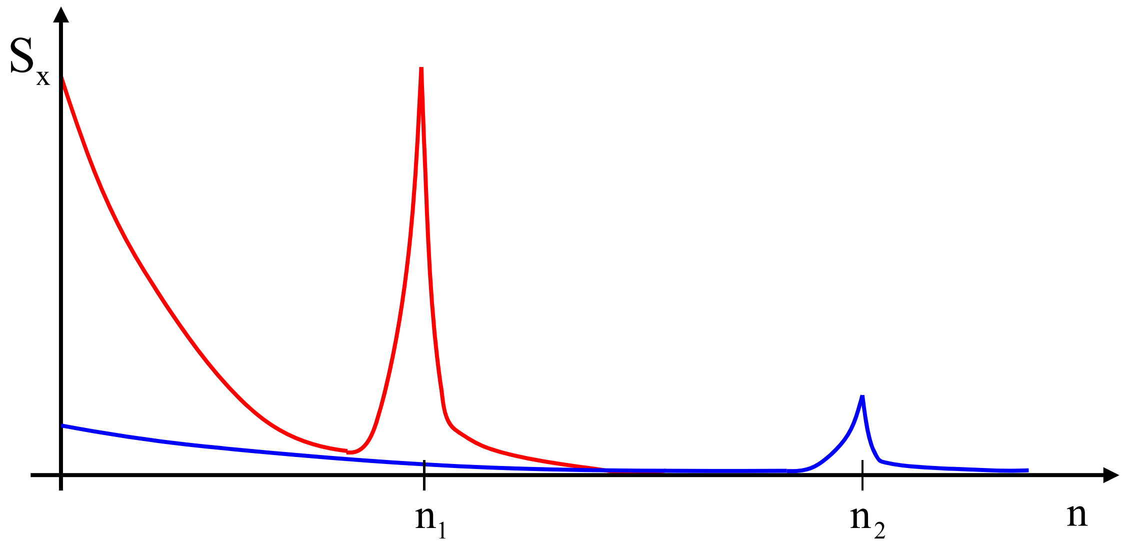


**The second mode of vibration is well separated from the first one ⇒**

**Only the first mode of vibration contributes to the dynamic response ⇒**

**The Gust Response Factor returns to be a constant quantity**

# Dynamic Response

Wind Velocity
Local Pressure
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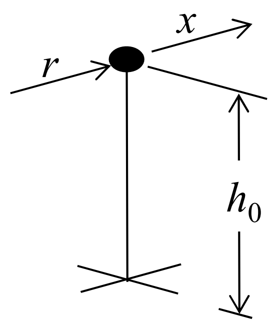
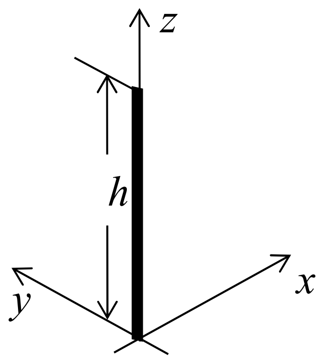
## Maximum alongwind displacement

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




## Equivalent static force

$$G_x = 1 + 2 g_x I_u \sqrt{B^2 + R^2}$$




## Closed Form Solution (Solari 1993)

$$B^2 = \frac{1}{1 + 0.56\tilde{\tau}^{0.74} + 0.29\tilde{L}_0^{0.63}}$$

$$R^2 = \frac{\pi}{4\xi} \frac{6.868\tilde{n}_0}{\left[1 + 10.302\tilde{n}_0\right]^{5/3}} C\left\{0.4\tilde{n}_0\tilde{b}\right\} C\left\{0.4\tilde{n}_0\tilde{h}\right\}$$

$$\tilde{\tau} = \frac{\tau\bar{u}}{L_u(h_0)};\ \tilde{L}_0 = \frac{1}{2}\left(\tilde{b} + \tilde{h}\right);\ \tilde{b} = \frac{c_{uy} b}{L_u(h_0)};\ \tilde{h} = \frac{c_{uz} h}{L_u(h_0)};\ \tilde{n}_0 = \frac{n_0 L_u(h_0)}{\bar{u}(h_0)}$$

# Wind Load Effects

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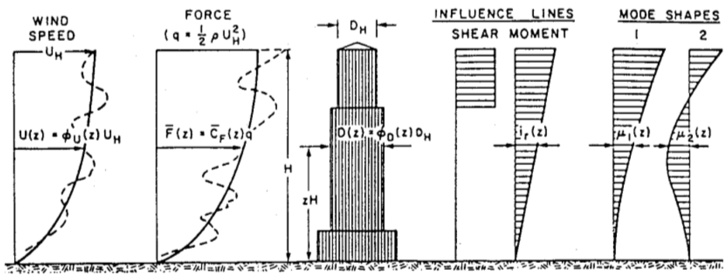
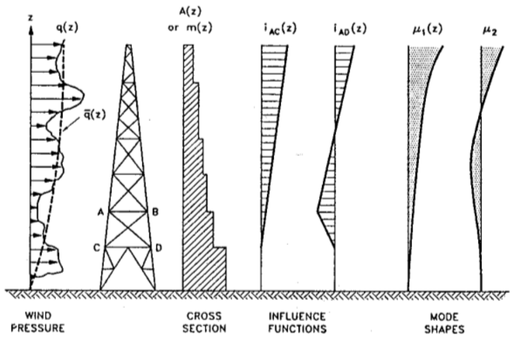
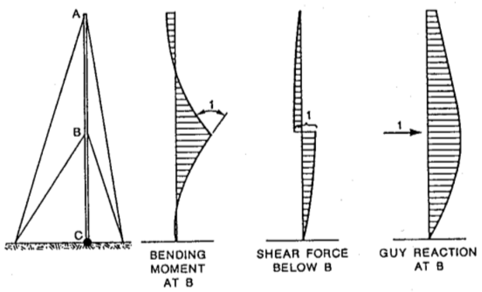



ESDU (1976)
ECCS (1978)

Kasperski (1992)
Holmes (1994)
Davenport (1995)
Dyrbye & Hansen (1997)
Zhou et al (1999)
Holmes (2001)
Zhou & Kareem (2001)
Piccardo & Solari (2002)
Holmes (2004)

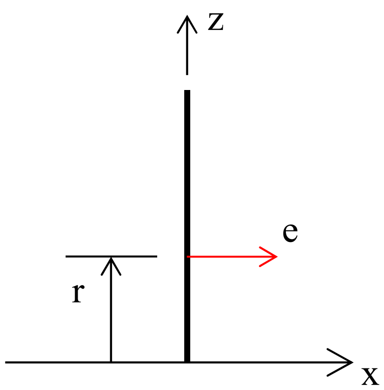
# Wind Load Effects



$$\boxed{e(r;t) = \bar{e}(r) + e'(r;t)}$$

**Maximum wind load effect**

$$\bar{e}_{max}(r) = \bar{e}(r) + g_e(r)\sigma_e(r)$$



# Wind Load Effects

- Wind Velocity
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- Applications

$$\boxed{e(r;t)=\bar{e}(r)+e'(r;t)}$$

## Maximum wind load effect

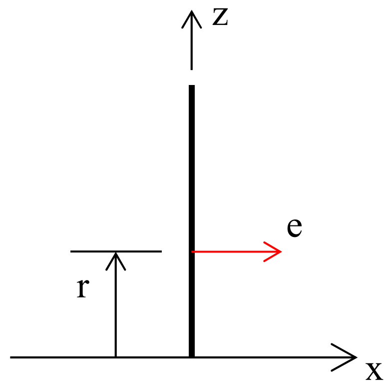
$$\bar{e}_{max}(r)=\bar{e}(r)+g_e(r)\sigma_e(r)=\bar{e}(r)\underbrace{\left[1+g_e(r)\frac{\sigma_e(r)}{\bar{e}(r)}\right]}_{G_e(r)}$$

## Gust Effect Factor

$$\boxed{G_e(r)=1+g_e(r)\frac{\sigma_e(r)}{\bar{e}(r)}} \Rightarrow \boxed{\bar{e}_{max}(r)=G_e(r)\bar{e}(r)}$$

$$\boxed{G_e(r)=1+2g_e(r)I_u\sqrt{\left[B_e(r)\right]^2+\left[R_e(r)\right]^2}}$$

$$B_e(r)=\frac{1}{2I_u}\frac{\sigma_{Be}(r)}{\bar{e}(r)} \qquad R_e(r)=\frac{1}{2I_u}\frac{\sigma_{Re}(r)}{\bar{e}(r)}$$



# Wind Load Effects



## INFLUENCE FUNCTION TECHNIQUE

$$\boxed{e(r;t) = \bar{e}(r) + e'_B(r;t) + e'_R(r;t)}$$

# Wind Load Effects

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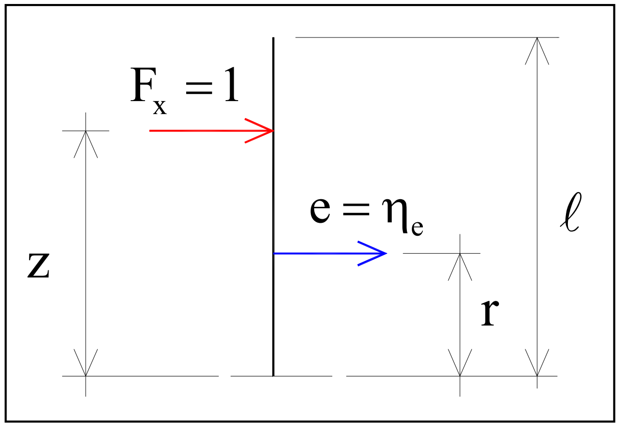
## INFLUENCE FUNCTION TECHNIQUE

$$\boxed{e(r;t) = \bar{e}(r) + e'_B(r;t) + e'_R(r;t)}$$

$$\bar{e}(r) = \int_0^{\ell} \bar{F}_x(z)\eta_e(r;z)dz$$

$$e'_B(r;t) = \int_0^{\ell} F'_x(z;t)\eta_e(r;z)dz$$

$\eta_e(r;z) =$ influence function of $e(r)$



# Wind Load Effects

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## INFLUENCE FUNCTION TECHNIQUE

$$\boxed{e(r;t) = \bar{e}(r) + e'_B(r;t) + e'_R(r;t)}$$

$$\bar{e}(r) = \int_0^\ell \bar{F}_x(z)\eta_e(r;z)\,dz$$

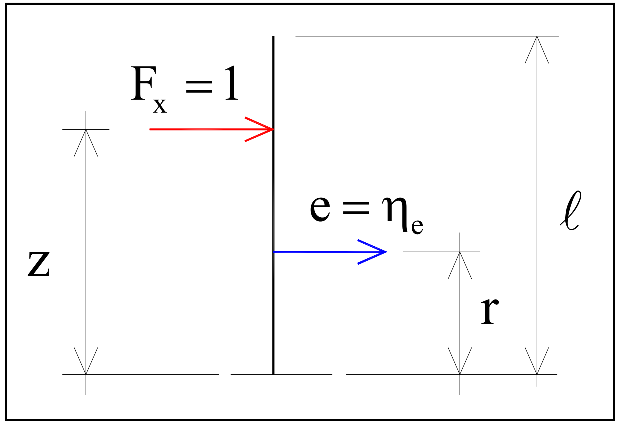
$$e'_B(r;t) = \int_0^\ell F'_x(z;t)\eta_e(r;z)\,dz$$

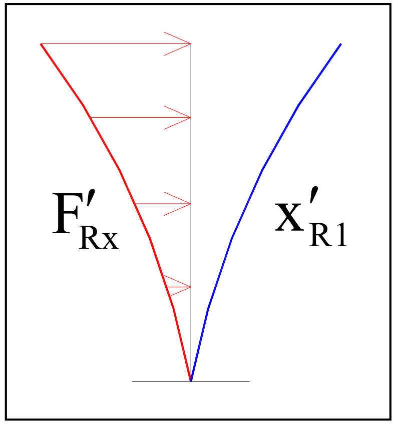
$\eta_e(r;z) =$ influence function of $e(r)$

$$e'_R(r;t) = \int_0^\ell F'_{Rx}(z;t)\eta_e(r;z)\,dz$$

$$F'_{Rx}(z;t) = \mu_x(z)(2\pi n_{x1})^2 x'_{R1}(z;t)$$

$$x'_{R1}(z;t) = \psi_{x1}(z)p'_{Rx1}(t)$$



# Wind Load Effects

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## Influence Function Technique

$$\bar{e}(r) = \int_0^h \bar{F}_x(z)\,\eta_e(r;z)\,\mathrm{d}z$$

$$\sigma_{Be}(r) = \sqrt{\int_0^\infty \left[\int_0^h \int_0^h S_{F_xF_x}(z,z';n)\,\eta_e(r;z)\,\eta_e(r;z')\,\mathrm{d}z\mathrm{d}z'\right] dn}$$

$$\sigma_{Re}(r) = \frac{m_e(r)}{m_{x1}} \sqrt{\int_0^h \int_0^h S_{F_xF_x}(z,z';n_{x1})\,\psi_{x1}(z)\,\psi_{x1}(z')\,\mathrm{d}z\mathrm{d}z'} \sqrt{\frac{\pi n_{x1}}{4\xi_{x1}}}$$

$$m_e(r) = \int_0^h m(z)\,\psi_{x1}(z)\,\eta_e(r;z)\,\mathrm{d}z$$

*$\eta_e(r,z)$* is the influence function of *$e(r)$*, i.e. the value of *$e$* at height *$r$* due to a unit static force at height *$z$*

# Wind Load Effects

- Wind Velocity
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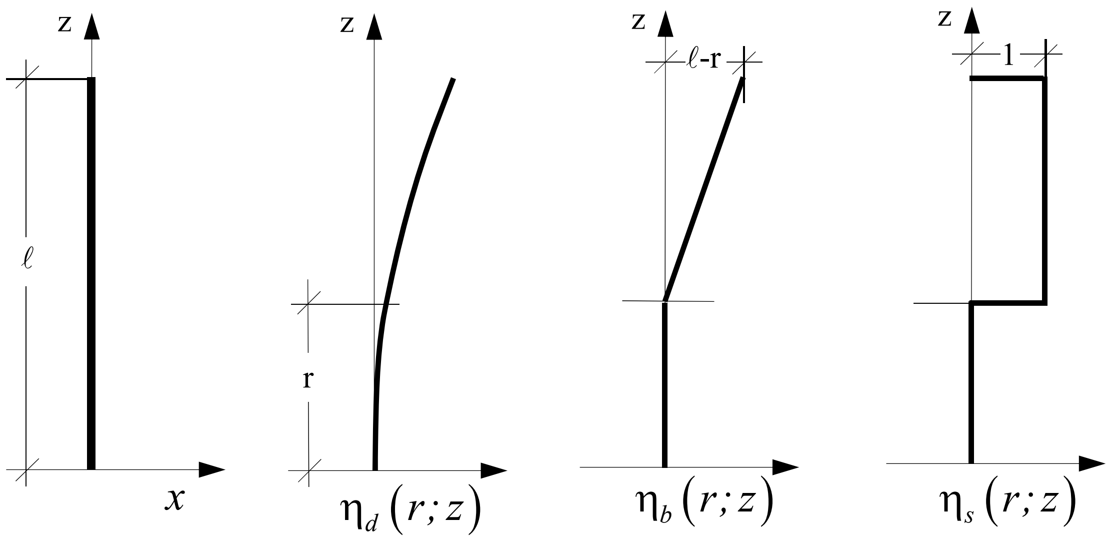
## Main Influence Functions (IF) for vertical structures



# Wind Load Effects

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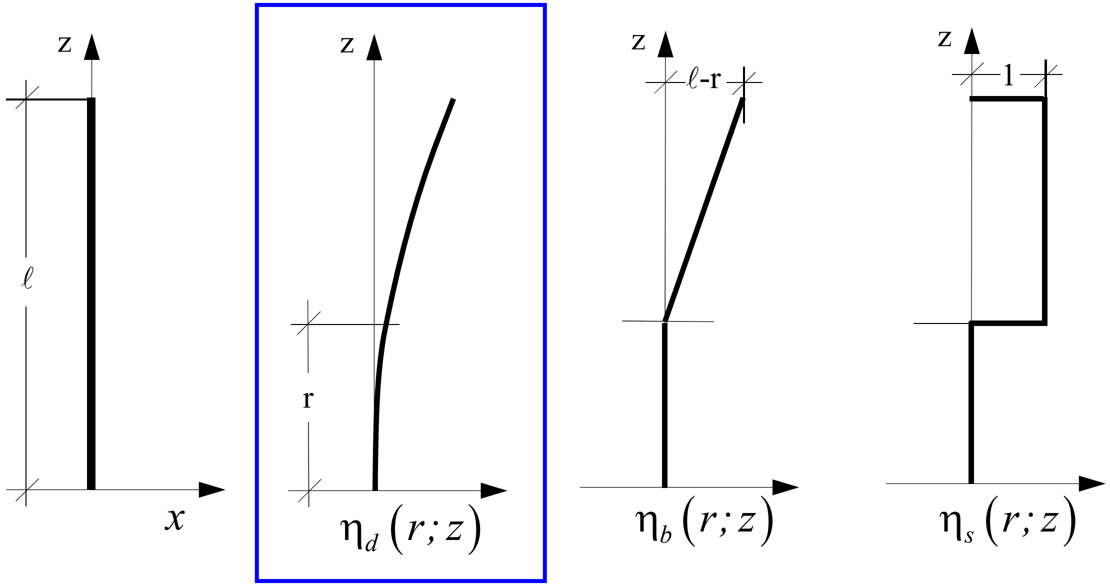
## Main Influence Functions (IF) for vertical structures




## Displacement IF (*e*=*d*)

$$\eta_d(r;z) = \frac{\psi_{x1}(r)\psi_{x1}(z)}{m_{x1}(2\pi n_{x1})^2}$$

# Wind Load Effects

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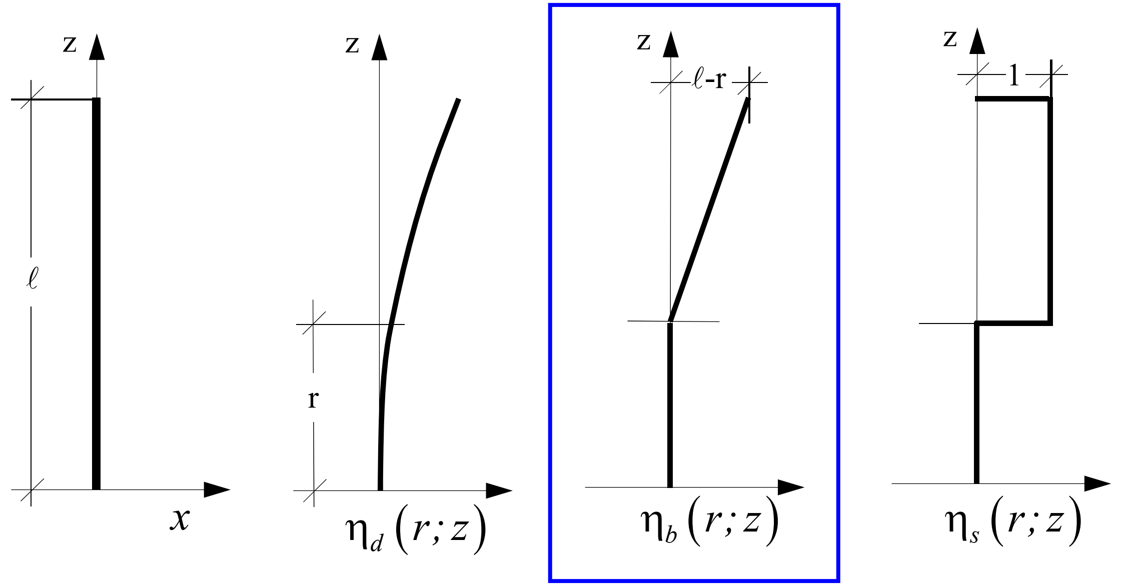
## Main Influence Functions for vertical structures




### Bending Moment IF (*e*=*b*)

$$\eta_b(r;z) = (z-r)H(z-r)$$

$H(\bullet)$ = Heaviside's function

# Wind Load Effects

Wind Velocity
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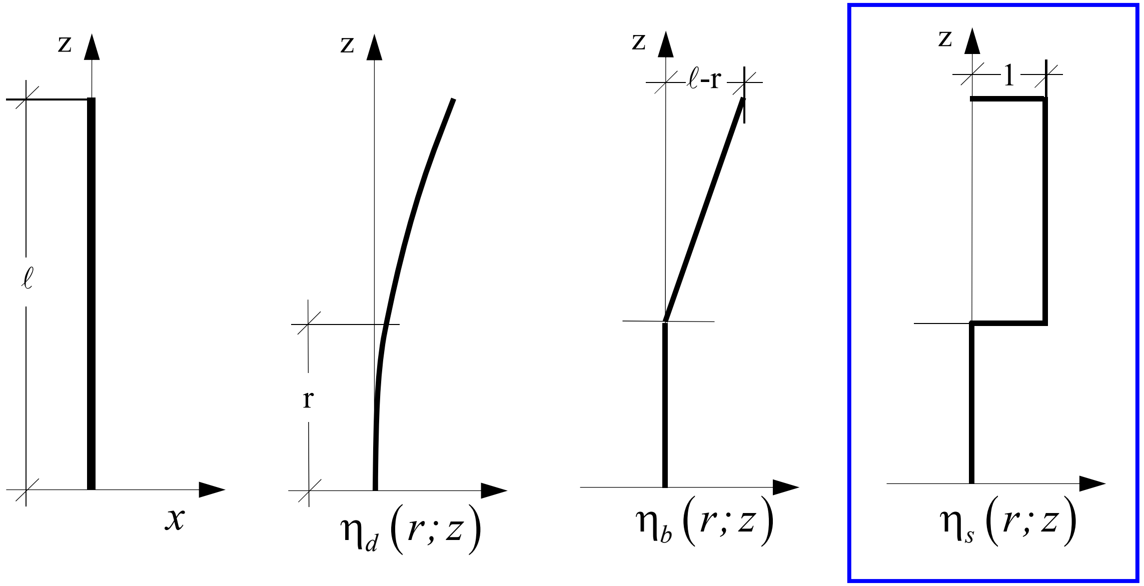
## Main Influence Functions for vertical structures




**Shear force IF (*e*=*s*)**

$$\eta_s(r;z) = H(z-r)$$

$H(\bullet)$ = Heaviside's function

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# Wind Load Effects

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## Maximum load effect

$$\boxed{\bar{e}_{max}(r) = G_e(r)\bar{e}(r)} \qquad \boxed{G_e(r) = 1 + 2g_e(r) I_u \sqrt{[B_e(r)]^2 + [R_e(r)]^2}}$$

## Closed Form Solution (Piccardo & Solari 2002)

$$[B_e(r)]^2 = \left[\frac{K'_e(r)}{\bar{K}_e(r)}\right]^2 \frac{1}{1 + 0.56[\tilde{\tau}_e(r)]^{0.74} + 0.30[\tilde{\ell}_e(r)]^{0.63}}$$

$$[R_e(r)]^2 = \left[\frac{K'_d(r) m_{e1}(r)}{\bar{K}_e(r) m_{d1}(r)}\right]^2 \frac{\pi}{4\xi_{x1}} \frac{d_u \tilde{n}_d(r)}{[1 + 1.5 d_u \tilde{n}_d(r)]^{5/3}} C\{\tilde{n}_d(r)\tilde{\ell}_d(r)\}$$

$$\tilde{\tau}_e(r) = \frac{\tau \bar{u}[z_e(r)]}{L_u[z_e(r)]}; \quad \tilde{\ell}_e(r) = \frac{k_e(r) C_z \ell}{L_u[z_e(r)]}; \quad \tilde{n}_d(r) = \frac{n_{x1} L_u[z_d(r)]}{\bar{u}[z_d(r)]}$$

# Wind Load Effects

Wind Velocity
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## Gust Response Factor Technique

$$\boxed{\bar{x}_{max}(z) = \bar{x}(z) G_x}$$

$$\boxed{G_x = 1 + 2 g_x I_u \sqrt{B^2 + R^2}}$$

## Gust Effect Factor Technique

$$\boxed{\bar{e}_{max}(r) = \bar{e}(r) G_e(r)}$$

$$\boxed{G_e(r) = 1 + 2 g_e(r) I_u \sqrt{[B_e(r)]^2 + [R_e(r)]^2}}$$

# Wind Load Effects

Wind Velocity
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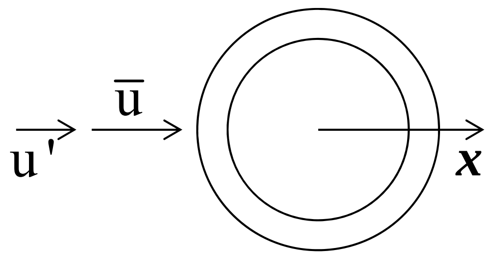
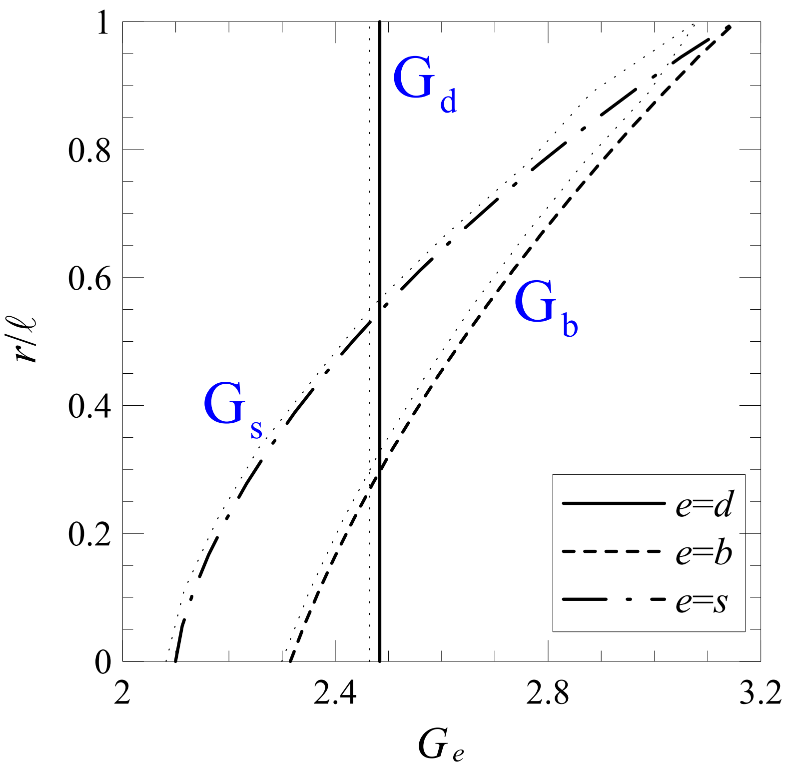
Applications

## Concrete Chimney (aspect ratio 1:32)

**Full-scale measurements (Muller & Nieser 1976)**

## Gust Response Factor & Gust Effect Factor



# Equivalent Static Forces



1) **Gust Effect Factor Technique**
2) **Load Combination Technique**
3) **Global Loading Technique**

# Equivalent Static Forces

Wind Velocity
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## Gust Response Factor Technique

$$\boxed{\bar{x}_{max}(z) = \bar{x}(z)\,G_x}$$

$$\boxed{G_x = 1 + 2 g_x I_u \sqrt{B^2 + R^2}}$$

## Gust Effect Factor Technique

$$\boxed{\bar{e}_{max}(r) = \bar{e}(r)\,G_e(r)}$$

$$\boxed{G_e(r) = 1 + 2 g_e(r) I_u \sqrt{\left[B_e(r)\right]^2 + \left[R_e(r)\right]^2}}$$

# Equivalent Static Forces

Wind Velocity
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## Gust Response Factor Technique

$$\boxed{\bar{x}_{max}(z) = \bar{x}(z) G_x} \Rightarrow \boxed{F_{es}(z) = \bar{F}_x(z) G_x}$$

$$\boxed{G_x = 1 + 2 g_x I_u \sqrt{B^2 + R^2}}$$

## Gust Effect Factor Technique

$$\boxed{\bar{e}_{max}(r) = \bar{e}(r) G_e(r)} \Rightarrow \boxed{F_{e,es}(r,z) = \bar{F}_x(z) G_e(r)}$$

$$\boxed{G_e(r) = 1 + 2 g_e(r) I_u \sqrt{[B_e(r)]^2 + [R_e(r)]^2}}$$

# Equivalent Static Forces

Wind Velocity
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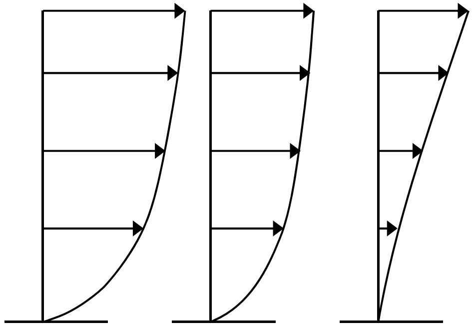
## Load Combination Technique

Equivalent static force:



$\bar{F}_x$ $\quad F^e_{Bx,es}$ $\quad F_{Rx,es}$

$$F^e_{x,es} = \bar{F}_x \cup F^e_{Bx,es} \cup F_{Rx,es}$$

$\bar{F}_x$ = Mean static force

$F^e_{Bx,es}$ = Eq. quasi-static force

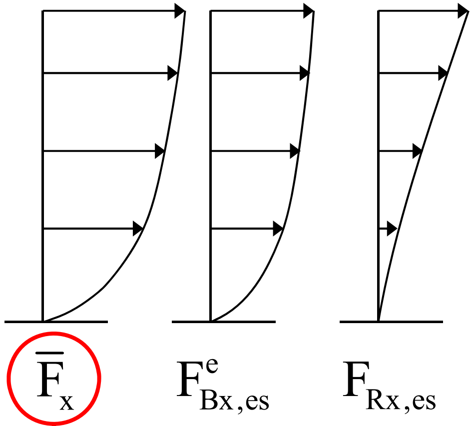
$F_{Rx,es}$ = Eq. resonant force

# Equivalent Static Forces

- Wind Velocity
- Local Pressure
- Resultant Force
- Dynamic Response
- Wind Load Effects
- Equiv Static Forces
- Applications

## Load Combination Technique

Equivalent static force:




$$F^e_{x,es} = \bar{F}_x \cup F^e_{Bx,es} \cup F_{Rx,es}$$

$\bar{F}_x$ = Mean static force

$F^e_{Bx,es}$ = Eq. quasi-static force

$F_{Rx,es}$ = Eq. resonant force

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

# Equivalent Static Forces

Wind Velocity
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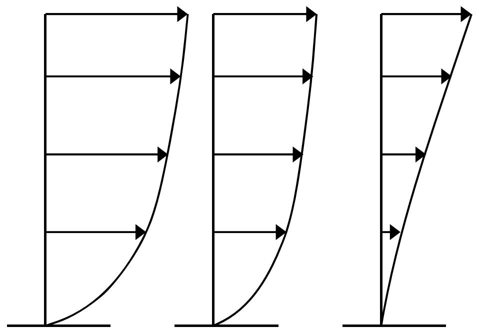
## Load Combination Technique

Equivalent static force:




$$F^e_{x,es} = \bar{F}_x \cup F^e_{Bx,es} \cup F_{Rx,es}$$

$\bar{F}_x$ = Mean static force

$F^e_{Bx,es}$ = Eq. quasi-static force

$F_{Rx,es}$ = Eq. resonant force

$$F_{Rx,es}(z) = \mu(z)(2\pi n_{x1})^2 \sigma_{Rx}(z) = 2\mu(z)(2\pi n_{x1})^2 \bar{x}(z) I_u R_x$$

# Equivalent Static Forces

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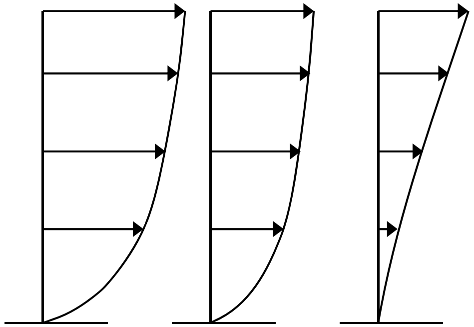
## Load Combination Technique

Equivalent static force:



$\bar{F}_x$ $\quad F^e_{Bx,es}$ $\quad F_{Rx,es}$

$$F^e_{x,es} = \bar{F}_x \cup F^e_{Bx,es} \cup F_{Rx,es}$$

$\bar{F}_x$ = Mean static force

$F^e_{Bx,es}$ = Eq. quasi-static force

$F_{Rx,es}$ = Eq. resonant force

?

# Equivalent Static Forces

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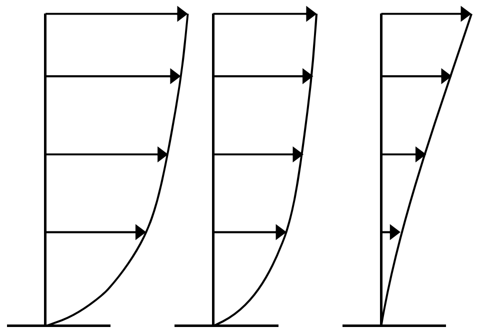
## Load Combination Technique

Equivalent static force:



$\bar{F}_x$ $\quad F^e_{Bx,es}$ $\quad F_{Rx,es}$

$$F^e_{x,es} = \bar{F}_x \cup F^e_{Bx,es} \cup F_{Rx,es}$$

$\bar{F}_x$ = Mean static force

$F^e_{Bx,es}$ = Eq. quasi-static force

$F_{Rx,es}$ = Eq. resonant force

Load Response Correlation Method (Kasperski, 1992)

$$F^e_{Bx,es}(r;z) = 2\bar{F}_x(z) I_u B_e(r) \Delta_e(r;z)$$

$$\Delta_e(r;z) = \frac{\bar{e}(r)}{\bar{F}_x(z)\left[\sigma_{Be}(r)\right]^2} \int_0^\infty \left[\int_0^h S_{F_xF_x}(z,z';n)\,\eta_e(r;z)\,dz'\right] dn$$

Wind Velocity
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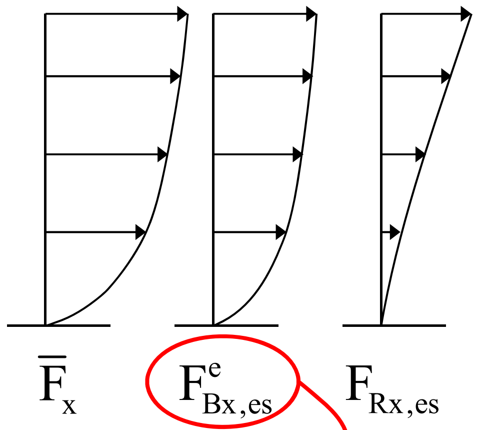
# Equivalent Static Forces

## Load Combination Technique

Equivalent static force:




$$F^e_{x,es} = \bar{F}_x \cup F^e_{Bx,es} \cup F_{Rx,es}$$

$\bar{F}_x$ = Mean static force

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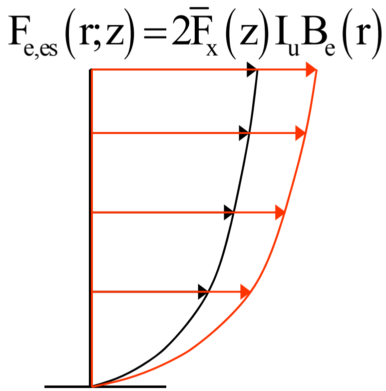
## GEF Technique




$$F_{e,es}(r;z) = \bar{F}_x(z) G_e(r)$$

$$G_e(r) = 1 + 2g_e(r) I_u \sqrt{[B_e(r)]^2 + [R_e(r)]^2}$$

$$F_{e,es}(r;z) = 2\bar{F}_x(z) I_u B_e(r)$$

# Equivalent Static Forces

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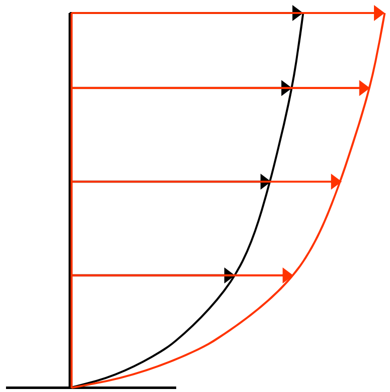
## Load Combination Technique

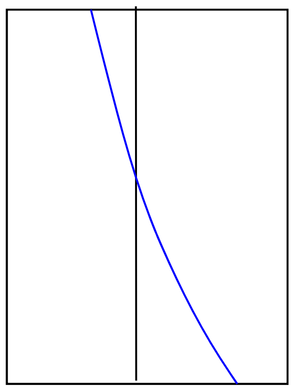
### GEF technique

$$F_{e,es}(r;z) = 2\bar{F}_x(z)\, I_u B_e(r)$$



### LRC factor

$$\Delta_e(r,z)$$



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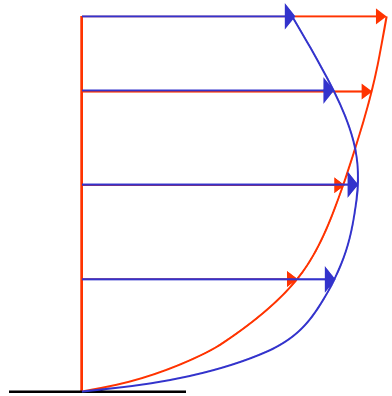
### LRC method

$$F_{e,es}(r;z) = 2\bar{F}_x(z)\, I_u B_e(r)\, \Delta_e(r,z)$$



# Equivalent Static Forces



## Global Loading Technique

$$\boxed{F_{x,es}(z) = \overline{F}_x(h)\sum_{k=0}^{n-1} q_k \left(\frac{z}{h}\right)^k}$$

$q_k$ $(k = 0, 1, 2, \ldots, n-1)$ = n non-dimensional coefficients used to impose the correct fulfillment of n specified maximum load effects

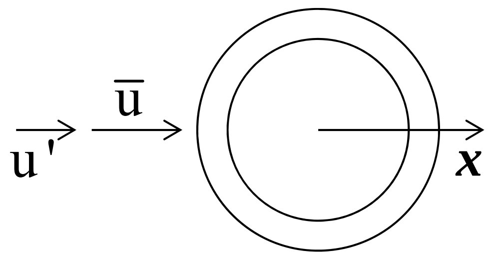
# Applications

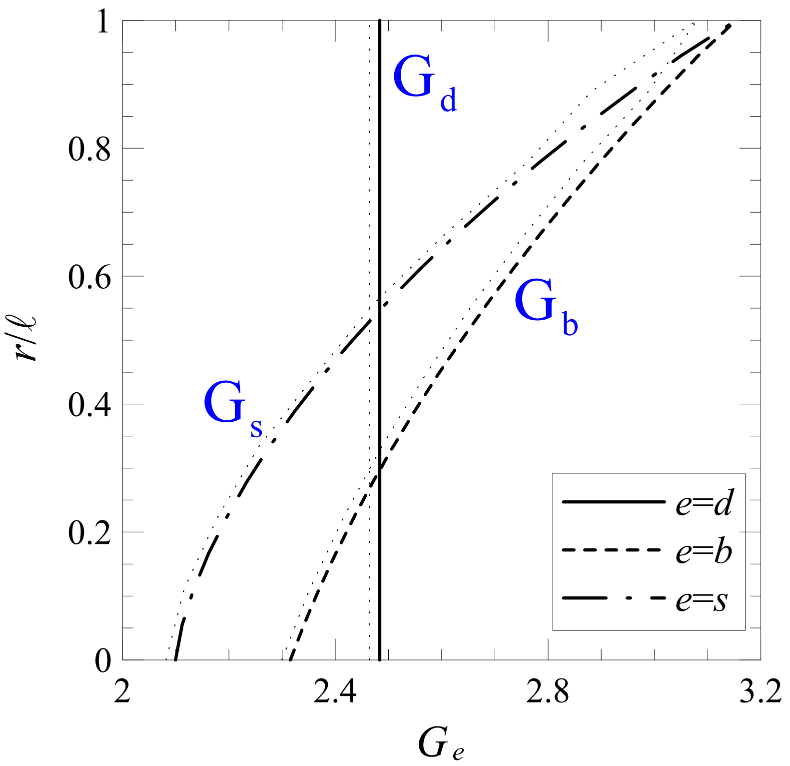
- Wind Velocity
- Local Pressure
- Resultant Force
- Dynamic Response
- Wind Load Effects
- Equiv Static Forces
- Applications

## Concrete Chimney (aspect ratio 1:32)

**Full-scale measurements (Muller & Nieser 1976)**

## Gust Response Factor & Gust Effect Factor



# Applications

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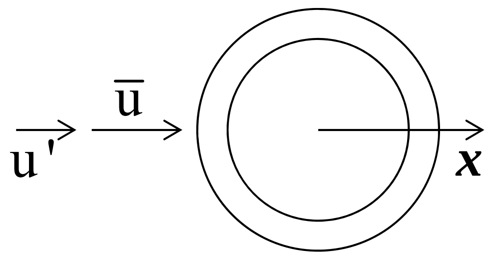
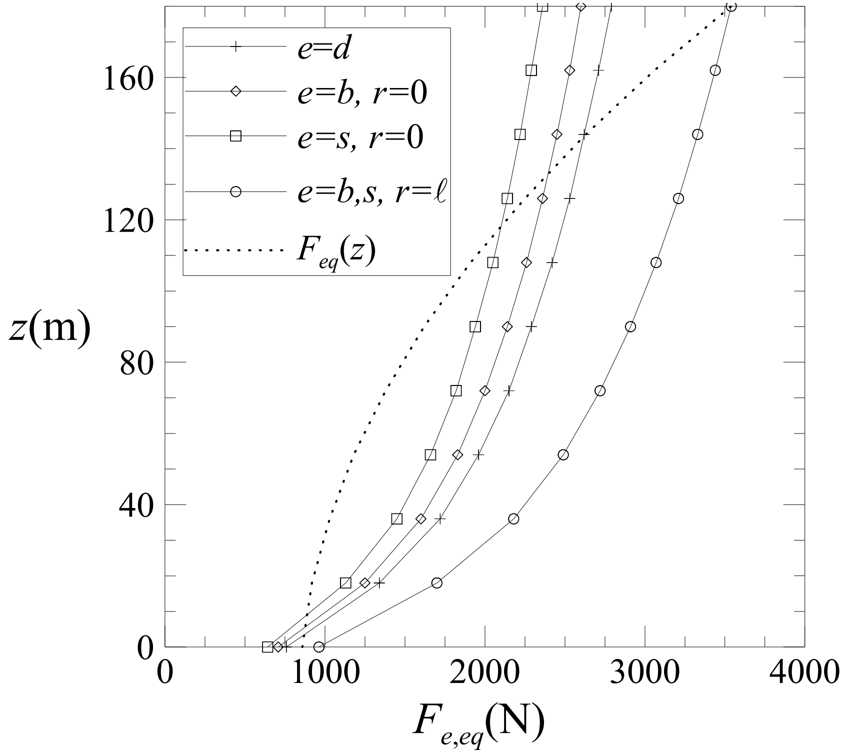
Applications

## Concrete Chimney (aspect ratio 1:32)

**Full-scale measurements (Muller & Nieser 1976)**

## Global Equivalent Static Forces



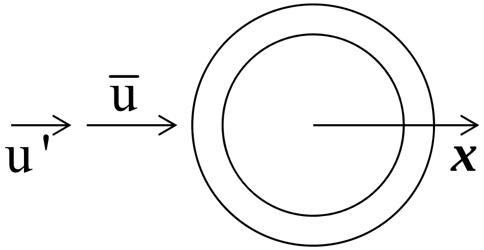
# Applications

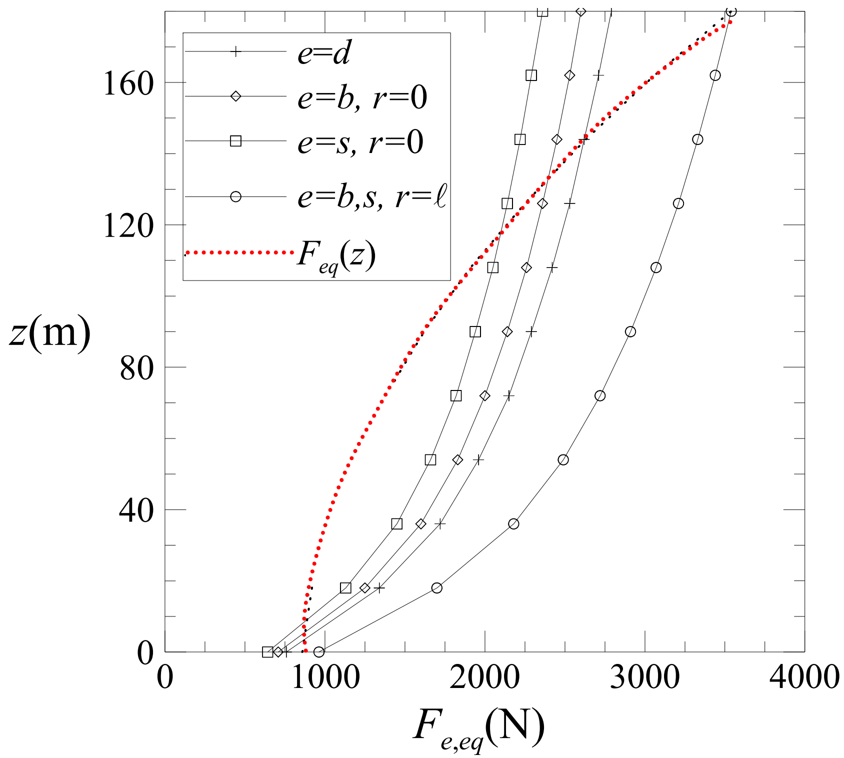


## Concrete Chimney (aspect ratio 1:32)

**Full-scale measurements (Muller & Nieser 1976)**

## Global Equivalent Static Forces



# Applications

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## Concrete Chimney (aspect ratio 1:32)

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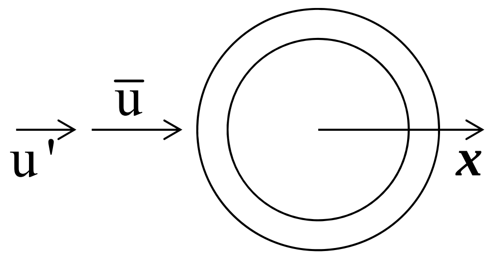
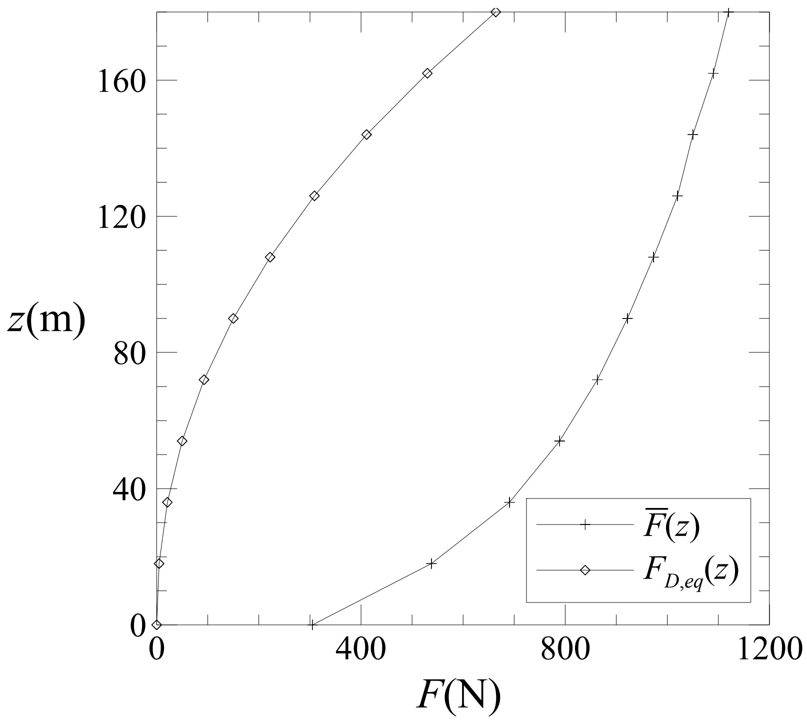
## Mean and Resonant Static Forces



# Applications



## Concrete Chimney (aspect ratio 1:32)

**Full-scale measurements (Muller & Nieser 1976)**

## Quasi-static Equivalent Static Forces