Lecture 5

Dynamic Wind Forces and Wind Loads

Tokyo Polytechnic University
The 21st Century Center of Excellence Program

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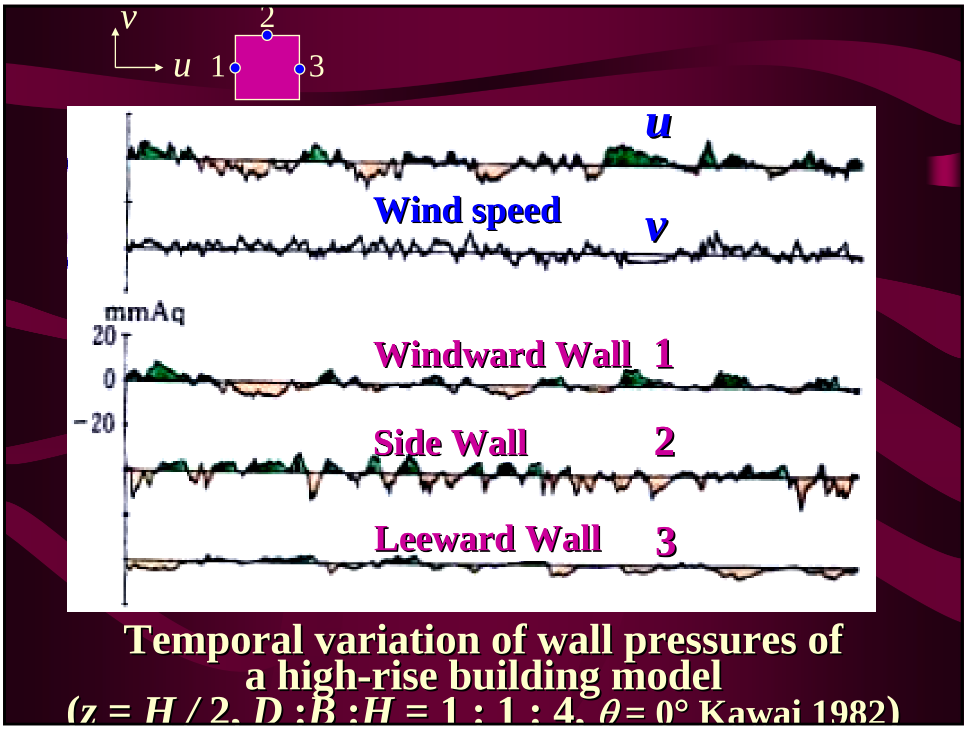
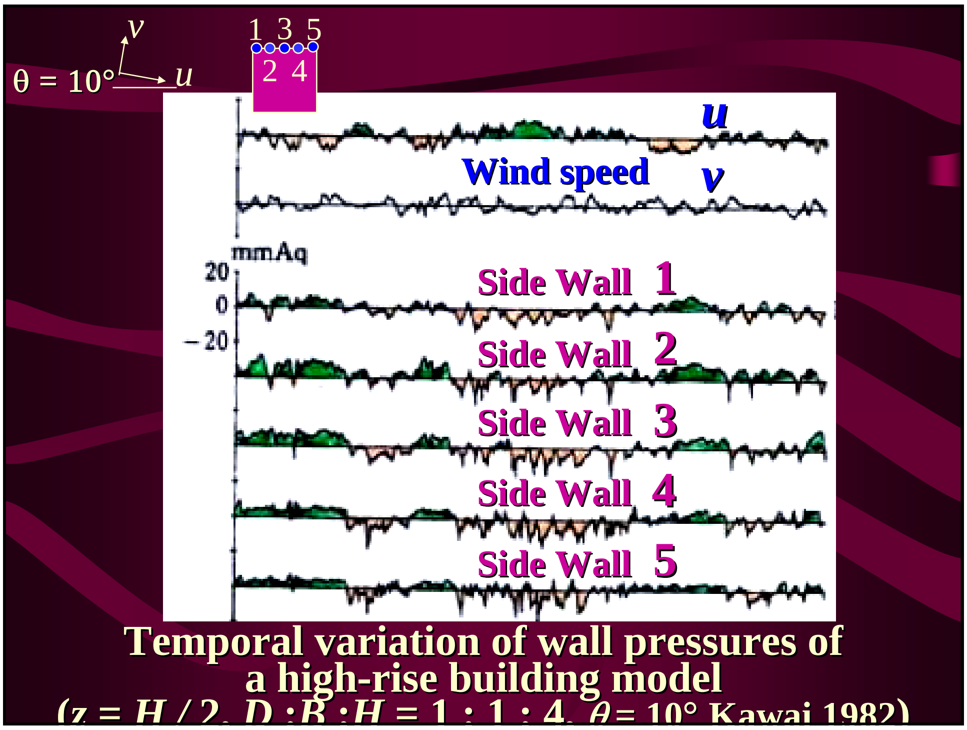
Temporal Variation of Wind Pressures


v
u
1
2
3
u
Wind speed
v
mmAq
20
0
−20
Windward Wall 1
Side Wall 2
Leeward Wall 3
Temporal variation of wall pressures of
a high-rise building model
(z = H / 2, D : B : H = 1 : 1 : 4, θ = 0° Kawai 1982)


θ = 10°
v
u
1 3 5
2 4
u
Wind speed
v
mmAq
20
0
−20
Side Wall 1
Side Wall 2
Side Wall 3
Side Wall 4
Side Wall 5
Temporal variation of wall pressures of
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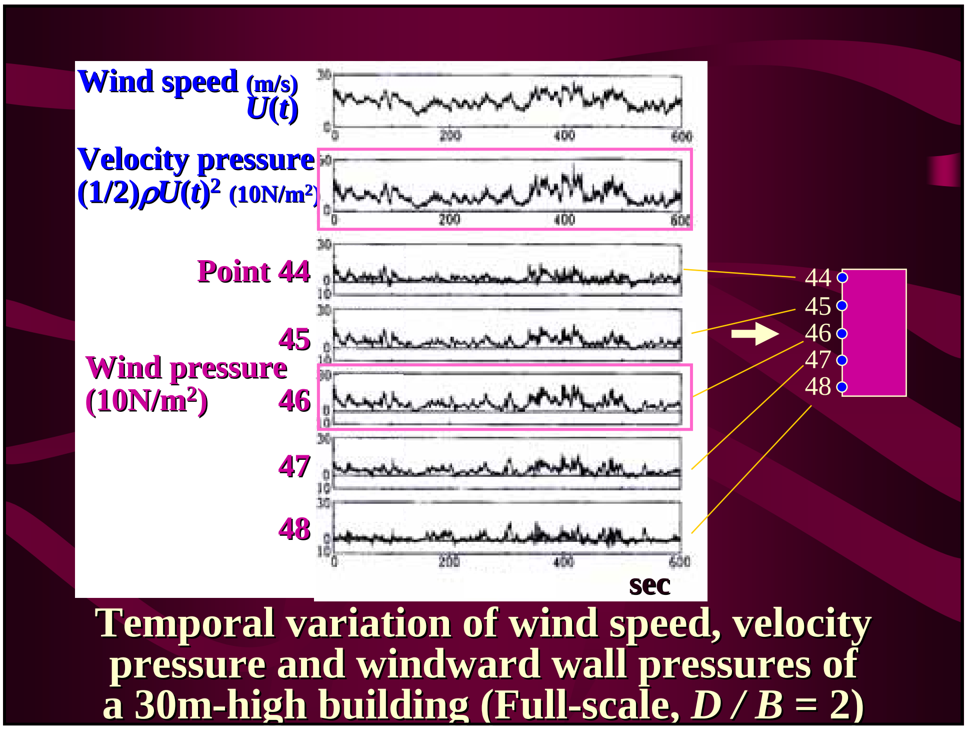
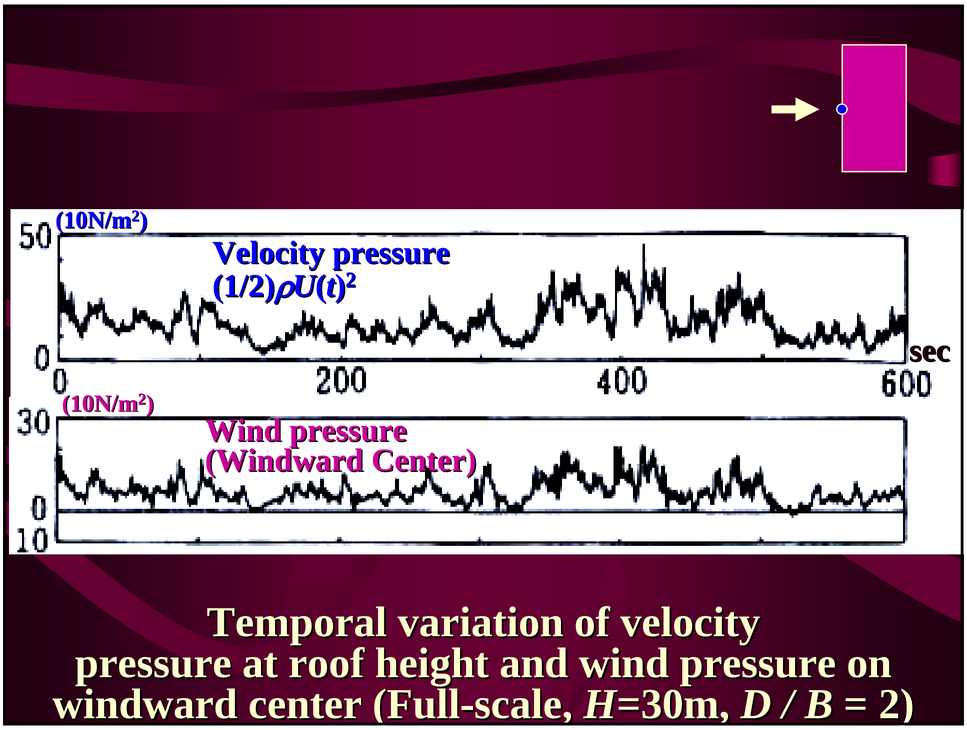
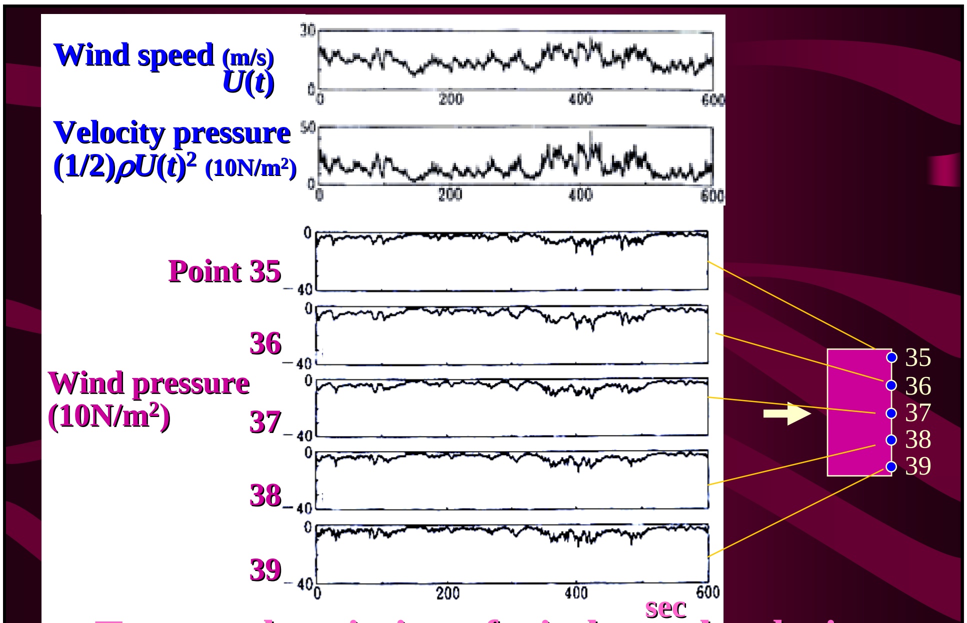
(z = H / 2, D : B : H = 1 : 1 : 4, θ = 10° Kawai 1982)



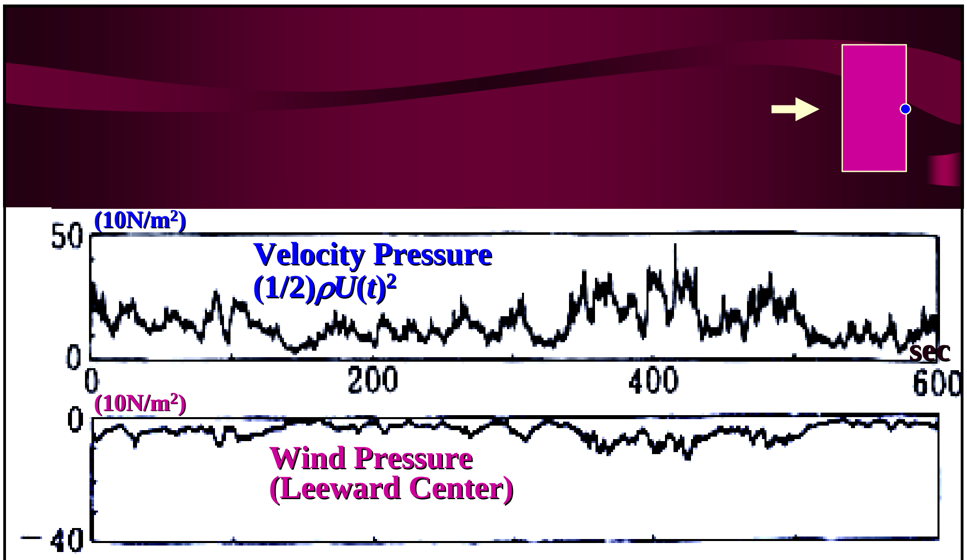
Temporal variation of wind speed, velocity pressure and windward wall pressures of a 30m-high building (Full-scale, *D* / *B* = 2)



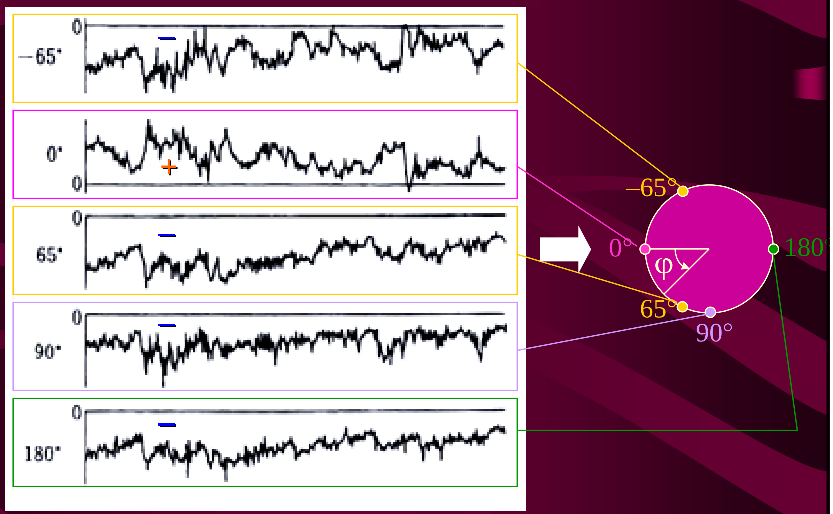
Temporal variation of velocity pressure at roof height and wind pressure on windward center (Full-scale, *H*=30m, *D* / *B* = 2)



Temporal variation of wind speed, velocity pressure and leeward wall pressures of a 30m-high building (Full-scale, *D* / *B* = 2)



Temporal variation of velocity pressure at roof height and wind pressure on leeward center (Full-scale, *H*=30m, *D* / *B* = 2)



Temporal variation of wind pressures of a 200m-high RC chimney (Full-scale, 0.7*H*, *H* / *D* = 13.2)

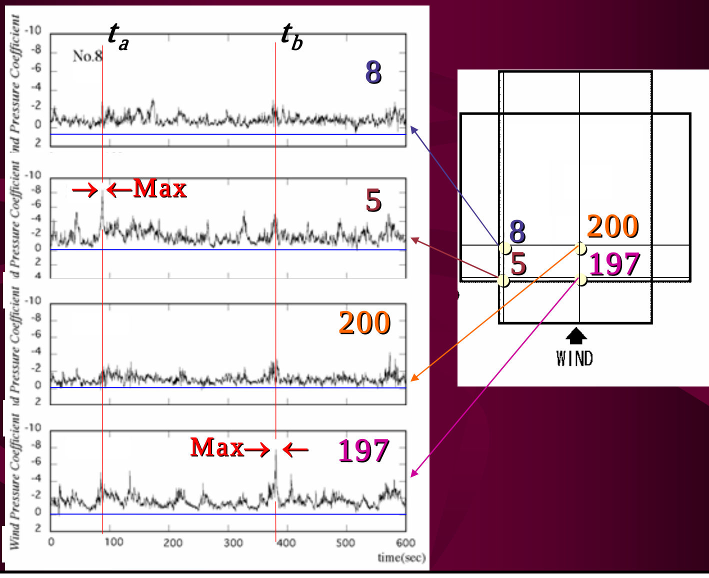
Fluctuating Pressure Coefficient C_p'

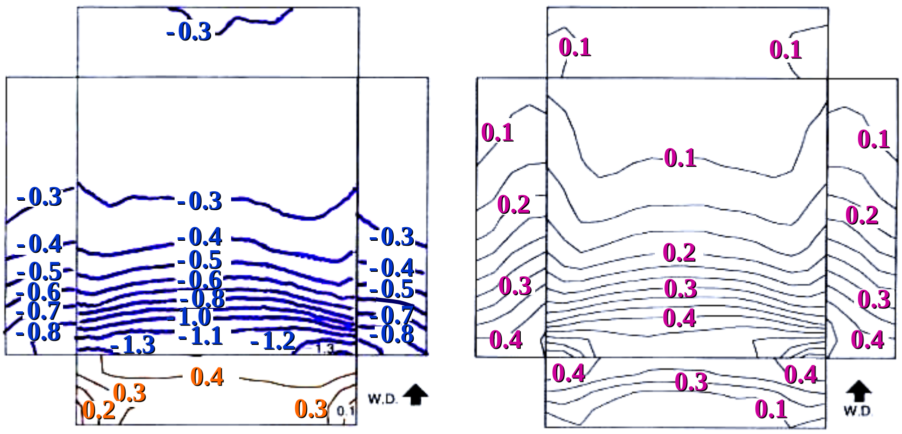
$$C_p' = \frac{\sigma_p}{\frac{1}{2}\rho U_R^{\,2}} = \frac{\sigma_p}{q_R}$$

$$\sigma_p = \sqrt{\overline{(p - \bar{p})^2}}$$

- p : Wind pressure
- $\bar{p}$: Mean wind pressure
- ρ : Air density
- U_R : Reference wind speed
- q_R : Reference velocity pressure

Temporal Variations of Fluctuating Pressures on Roof

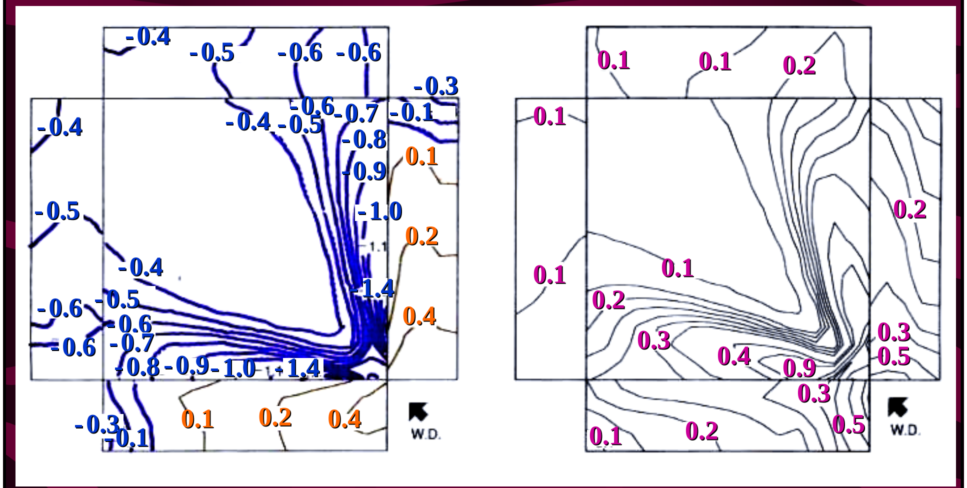




(a) Mean pressure coefficient C_p

(b) Fluctuating pressure coefficient C_p'

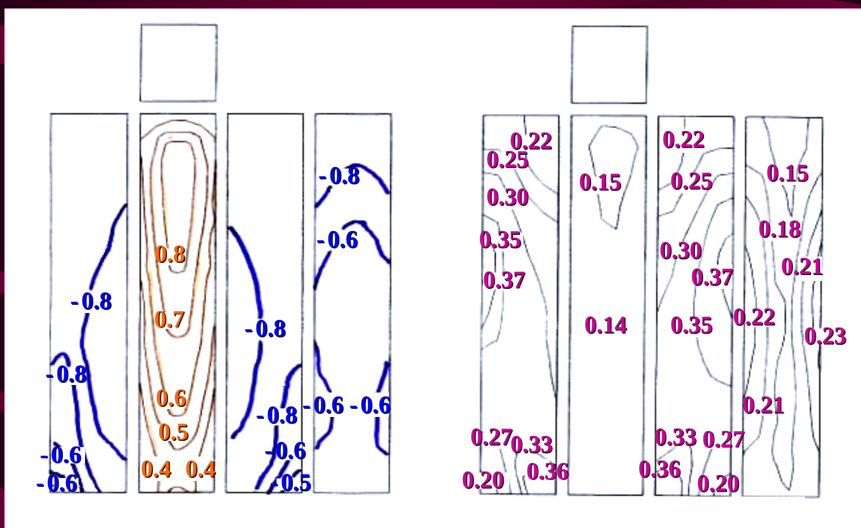
Pressure distributions on a low-rise building model ($\theta = 0°$, $D : B : H = 4 : 4 : 1$)



(a) Mean pressure coefficient C_p

(b) Fluctuating pressure coefficient C_p'

Pressure distributions on a low-rise building model (θ = 45°, D : B : H = 4 : 4 : 1)



(a) Mean pressure coefficient C_p

(b) Fluctuating pressure coefficient C_p'

Pressure distributions on a high-rise building model (θ = 0°, D : B : H = 1 : 1 : 5)

Pressures in Unsteady Flow Fields

Unsteady / Irrotational / Ideal Flow

Generalized Bernoulli's Equation

(Blasius Equation)

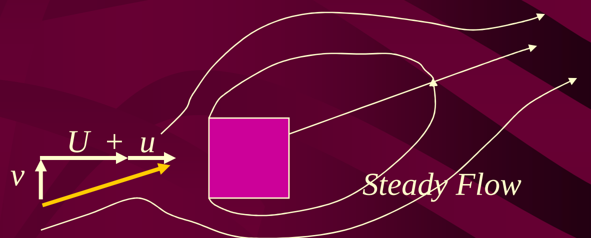
$$\frac{\partial \phi}{\partial t} + \frac{1}{2}U^2 + \frac{P}{\rho} + \Omega = n(t)$$

ρ : Fluid density
U : Flow velocity
P : Pressure
ϕ : Velocity potential
Ω : External force potential = gz
$n(t)$: Time function

Quasi-steady Assumption
and
Fluctuating Pressures

Quasi-steady Assumption

- The flow field at every moment is the same as the steady flow field for the wind speed and the wind direction upstream of its instance.



- Fluctuating pressure on a structure follows the variations in longitudinal wind velocity upstream. (a narrow sense)

Quasi-steady Assumption (a narrow sense)

- Fluctuating pressure

Mean Pressure Coefficient

$$p(t) = C_p \frac{1}{2} \rho U(t)^2$$

$$= C_p \frac{1}{2} \rho \{U + u(t)\}^2$$

$U^2 + 2u(t)U + \cancel{u(t)^2}$

$u(t) << U$

$$\approx C_p \frac{1}{2} \rho U^2 \{1 + 2\frac{u(t)}{U}\}$$

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

$$= \bar{p}\{1 + \frac{p'(t)}{\bar{p}}\}$$

$\sigma_p/p \approx 2\sigma_u/U$

$I_p \approx 2I_u$

Quasi-steady Assumption (a narrow sense)

- Fluctuating pressure:

$$u(t) << U \quad \rightarrow \quad u(t)^2 \approx 0$$

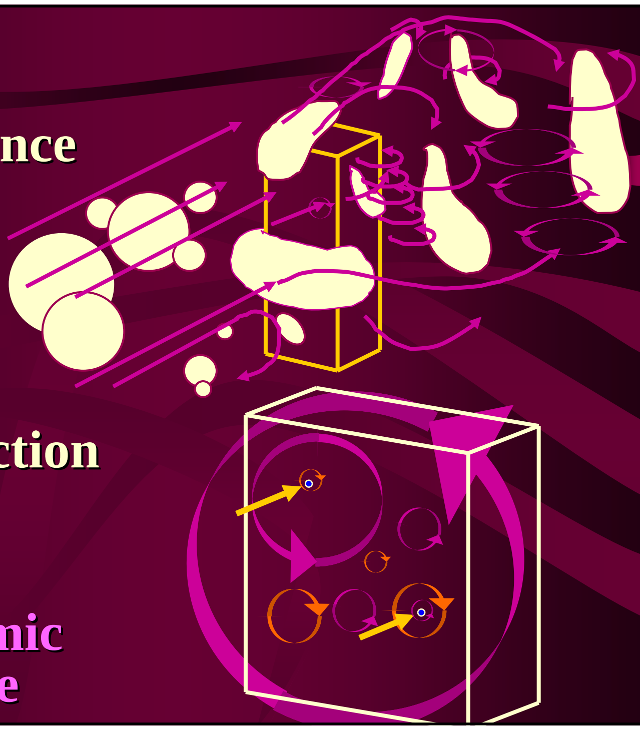
$$p(t) = \bar{p} + p'(t)$$

$$\bar{p} = C_p \frac{1}{2} \rho U^2$$: Mean Pressure

$$p'(t) \approx C_p \rho U u(t)$$: Fluctuating Component

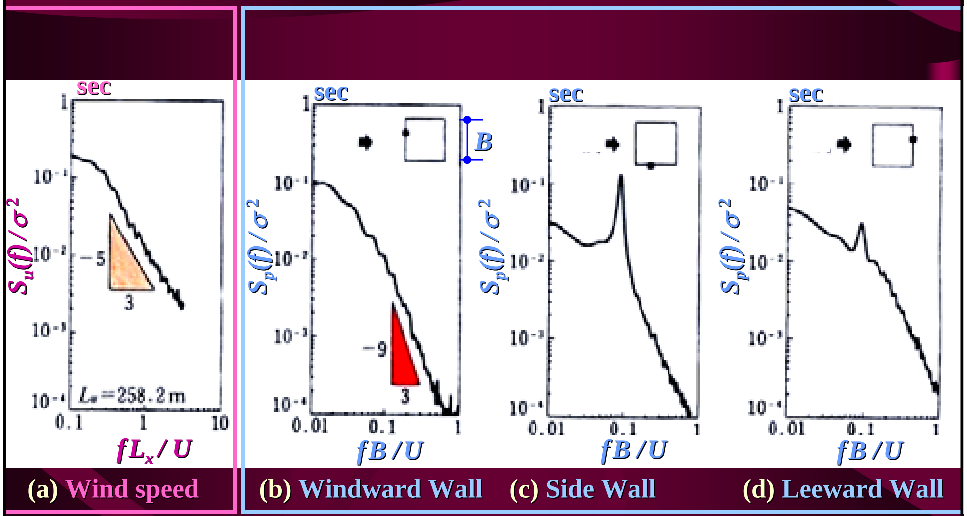
Spatial Scale
of
Pressure Fluctuation

- Distortion of Turbulence



- Size Reduction Effect

➡ Aerodynamic Admittance



Power spectral densities of fluctuating wind speed and wind pressures

Reduced Frequency :

$$\frac{\textit{Building Size}}{\textit{Spatial Scale of Fluctuation}} = \frac{B}{L_f}$$

similar to Eddy Size of Turbulence

$$= \frac{B}{T_f U}$$

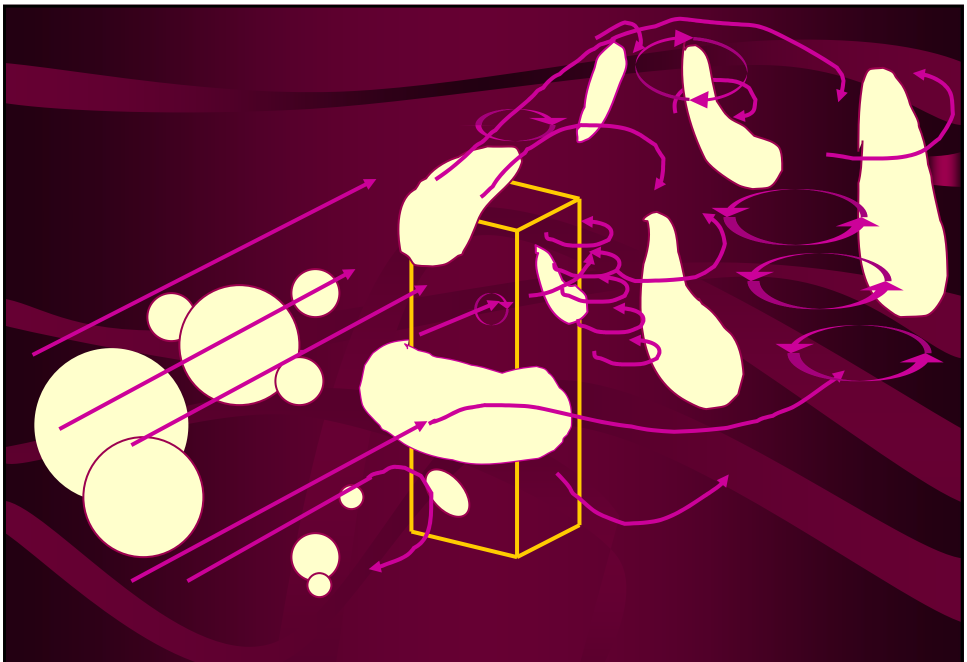
Temporal Scale of Fluctuation

$$= \frac{fB}{U}$$

f : **Fluctuating Frequency**

$$T_f = \frac{1}{f}$$

$\frac{fB}{U}$: **Reduced Frequency**



Schematic view of distortion of turbulence

- **Power spectral density of fluctuating pressure $S_p(f)$:**

$$S_p(f) = \rho^2 U^2 |\chi(f)|^2 S_u(f)$$

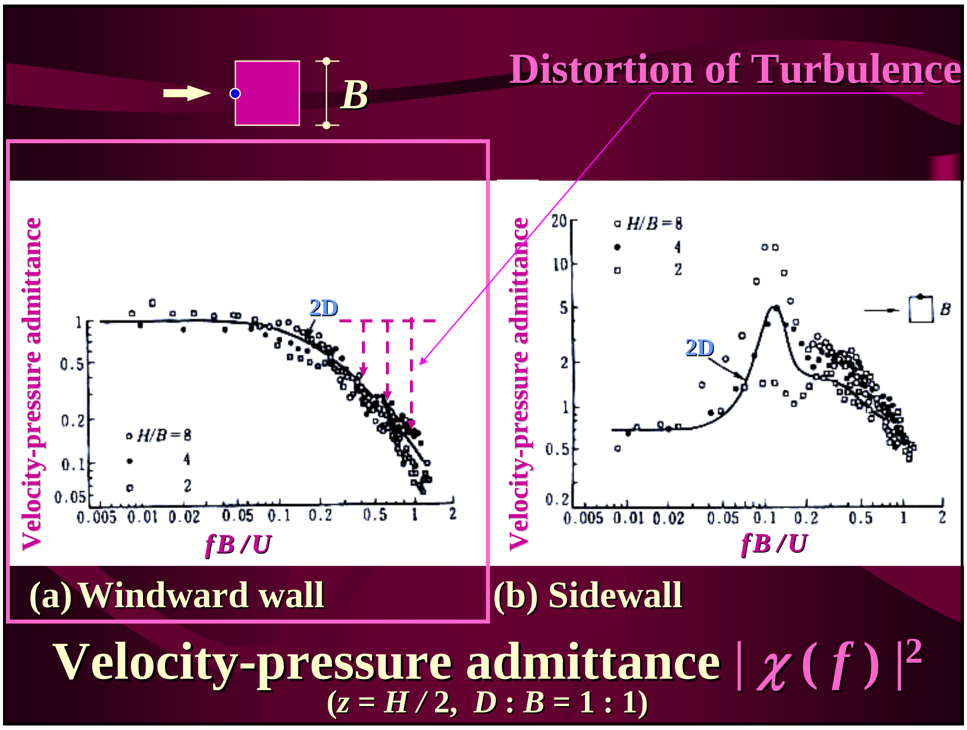
$S_u(f)$: **Power spectral density of fluctuating wind speed**

$|\chi(f)|^2$: **Velocity-pressure admittance**

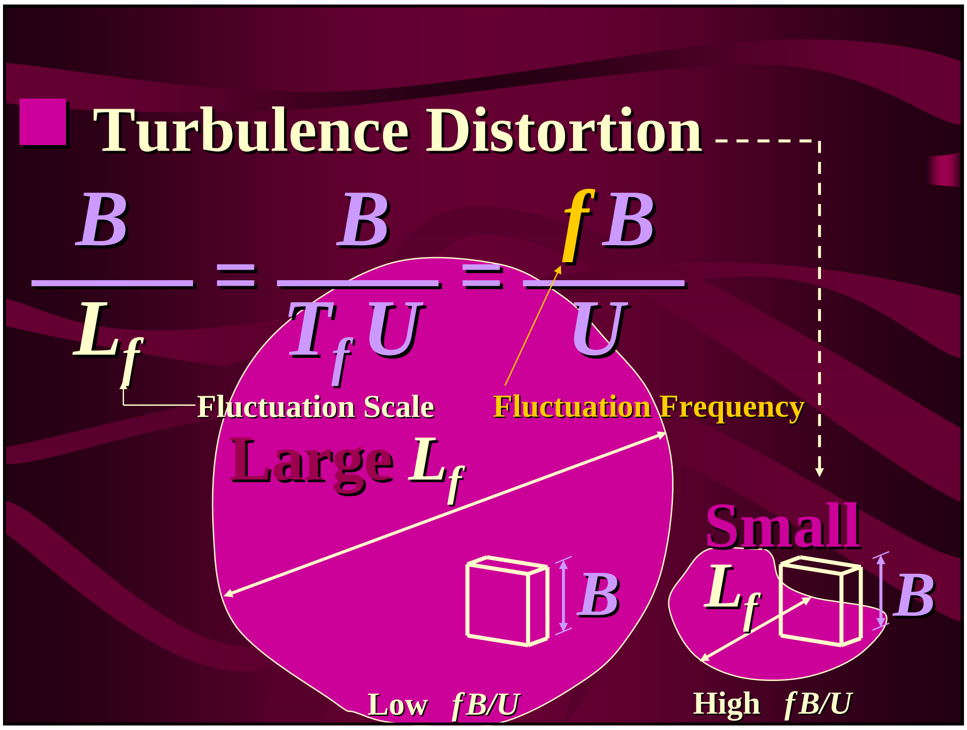
ρ : **Air density**

U : **Wind speed**

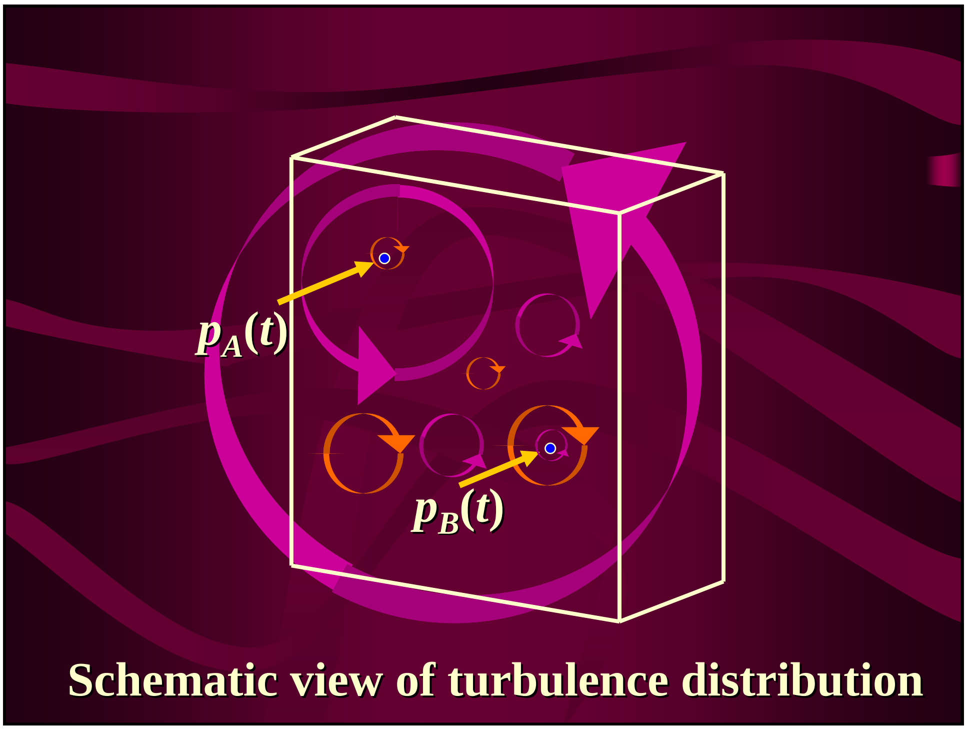
Quasi-steady: $p'(t) = C_p \rho U u(t)$

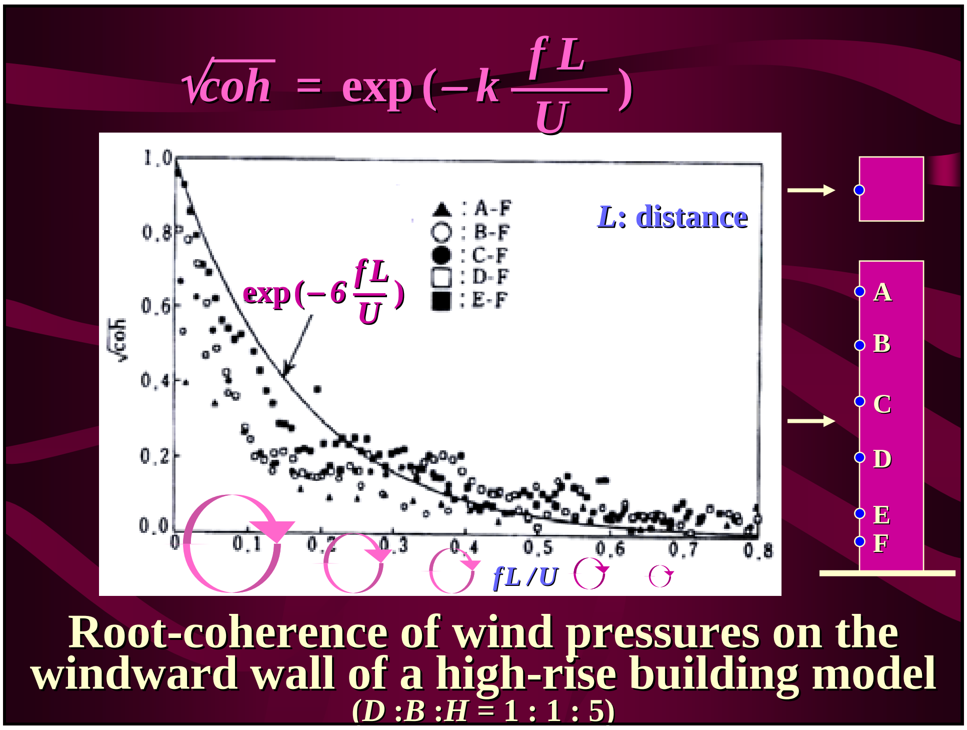


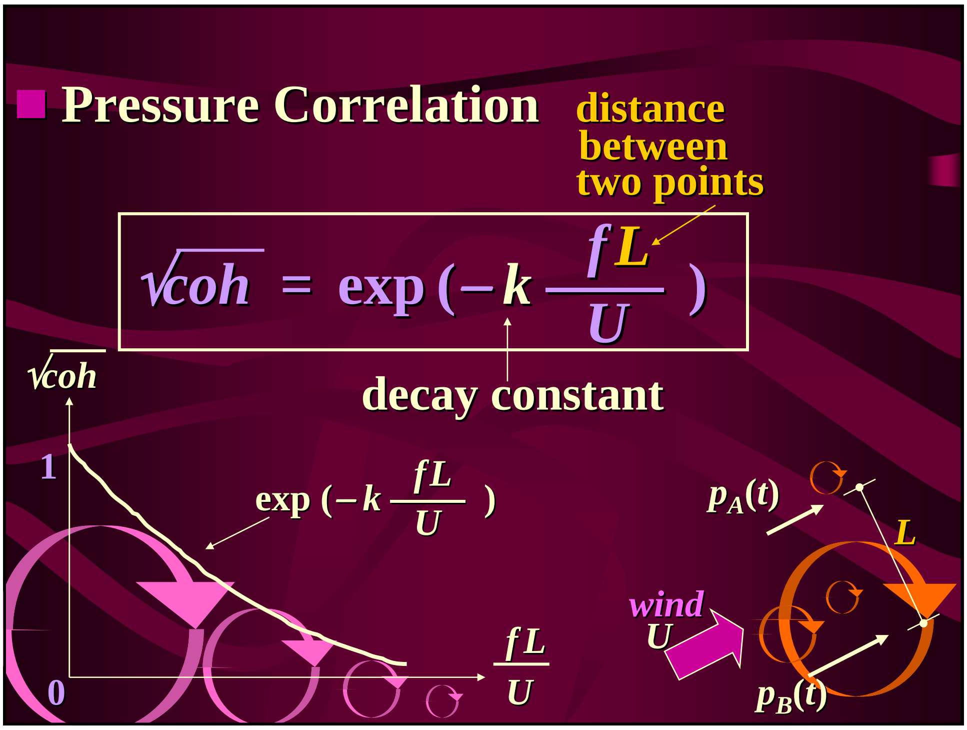
B
Distortion of Turbulence
Velocity-pressure admittance
2D
H/B=8
4
2
fB/U
(a) Windward wall
(b) Sidewall
Velocity-pressure admittance | χ (f) |²
(z = H / 2, D : B = 1 : 1)



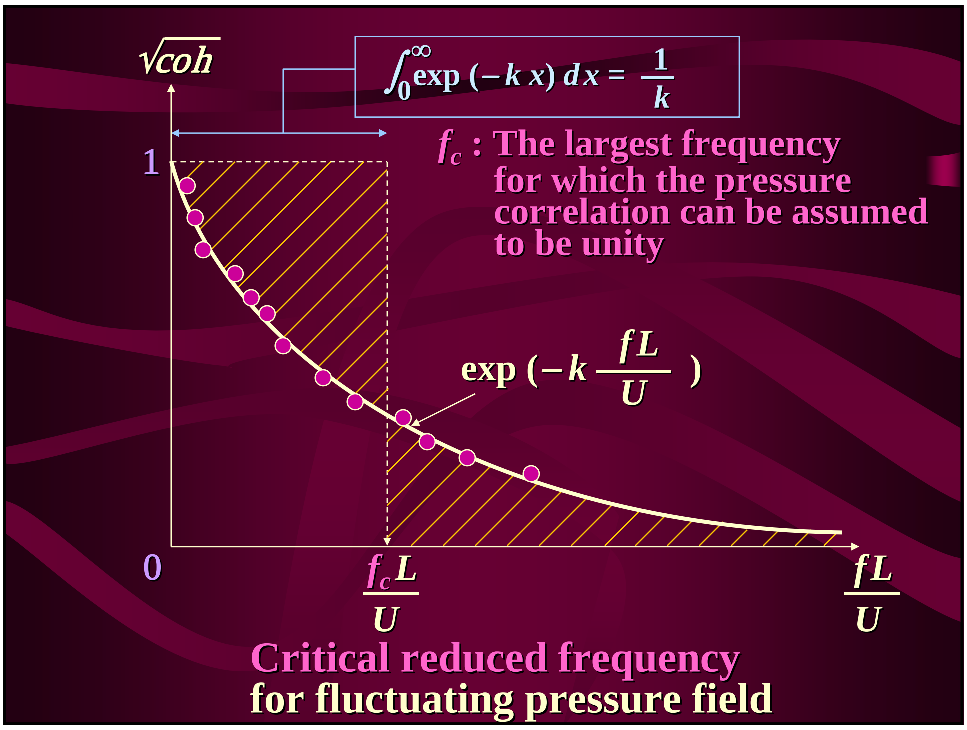
Turbulence Distortion
B / L_f = B / (T_f U) = f B / U
Fluctuation Scale
Fluctuation Frequency
Large L_f
B
Small
L_f
B
Low fB/U
High fB/U


$p_A(t)$
$p_B(t)$
Schematic view of turbulence distribution


$\sqrt{coh} = \exp(-k \frac{fL}{U})$
$\exp(-6\frac{fL}{U})$
▲ : A-F
○ : B-F
● : C-F
□ : D-F
■ : E-F
L: distance
√coh
fL/U
A
B
C
D
E
F
Root-coherence of wind pressures on the windward wall of a high-rise building model
(D :B :H = 1 : 1 : 5)



Pressure Correlation
distance between two points
$\sqrt{coh} = \exp\left(-k \frac{fL}{U}\right)$
decay constant
$\sqrt{coh}$
1
$\exp\left(-k \frac{fL}{U}\right)$
0
$\frac{fL}{U}$
$p_A(t)$
L
wind
U
$p_B(t)$



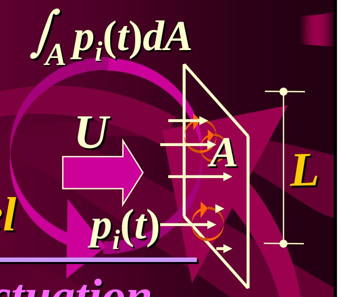
$\sqrt{coh}$
$\int_0^\infty \exp(-k\,x)\,dx = \frac{1}{k}$
1
f_c : The largest frequency for which the pressure correlation can be assumed to be unity
$\exp\left(-k \frac{fL}{U}\right)$
0
$\frac{f_c L}{U}$
$\frac{fL}{U}$
Critical reduced frequency for fluctuating pressure field

Critical Frequency f_c and Equivalent Averaging Time T_c for Panel Pressure of Size L

$$\frac{f_c L}{U} = \frac{L}{T_c U}$$

$$= \frac{\text{Size of Panel}}{\text{Critical Size of Fluctuation}}$$

$$= \frac{1}{k}$$



Decay Constant

$k = 0$: Fully Correlated

$k = \infty$: No Correlation

Note: Exactly speaking, we have to consider two dimensional (area) correlations for panel pressures.

Size Reduction Factor (Spatial Averaging Effects)

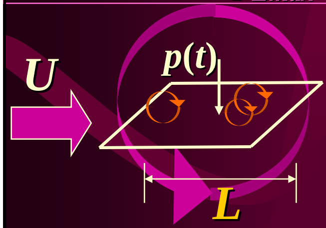
Size L acts as a low-pass filter.

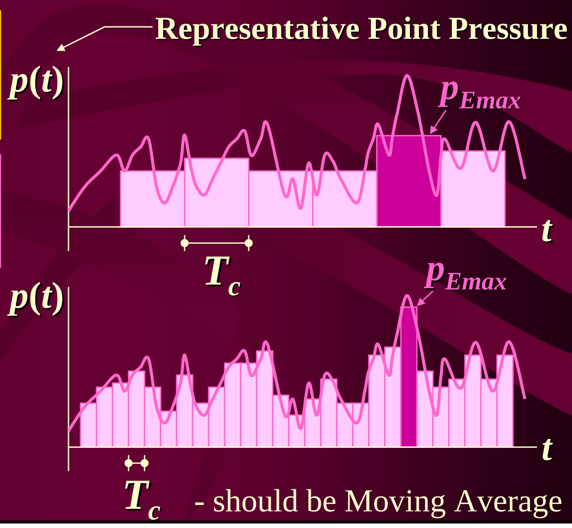
Larger L → Smaller f_c (Larger T_c)

Maximum Panel Pressure (Spatial Average)

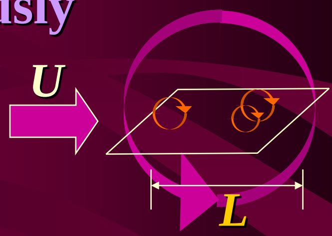
↓

Equivalent Temporal Average Maximum Pressure p_{Emax}





- Equivalent averaging time T_c of the minimum size of fluctuating gust acting simultaneously on the panel

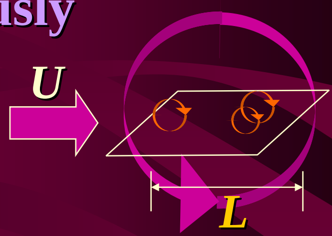


$$T_c = \frac{kL}{U}$$

ex. $L = 1\text{m}$, $U = 40\text{m/s}$, $k = 8$

$$T_c = \frac{8 \times 1}{40} = 0.2 \text{ sec}$$

- Equivalent averaging time T_c of the minimum size of fluctuating gust acting simultaneously on the panel



$$T_c = \frac{kL}{U}$$

ex. $L = 10\text{m}$, $U = 30\text{m/s}$, $k = 8$

$$T_c = \frac{8 \times 10}{30} = 2.7 \text{ sec}$$

Temporal Variation of Internal Pressure

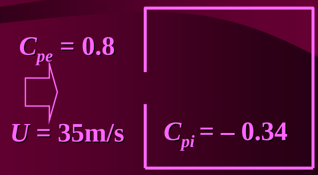
- Necessary time T_c (sec) to reach equilibrium after giving a pressure difference Δp (Pa) at an opening (T.V. Lawson, 1980)

$$T_c = 1.2 \times 10^{-4} \frac{B}{A} \sqrt{\Delta p}$$

B : Volume of a room (m^3)
A : Area of an opening (m^2)

- **ex.**

  $C_{pe} = 0.8$, $C_{pi} = -0.34$,
  $U = 35$ m/s
  $\rightarrow \Delta p = 860$ Pa



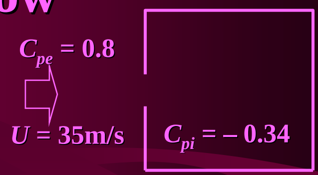
  B : Volume of a room = 200 m^3
  A : Area of an opening = 0.02 m^2

$$T_c = 1.2 \times 10^{-4} \, \frac{200}{0.02}\sqrt{860} = 35 \text{ sec}$$

The internal pressure cannot respond to the external pressure fluctuation with a shorter period than T_c → *Time Constant*

- **ex. a broken glass window**

  $C_{pe} = 0.8$, $C_{pi} = -0.34$,
  $U = 35$ m/s
  $\rightarrow \Delta p = 860$ Pa



  B : Volume of a room = 200 m^3
  A : Area of an opening = 1 m^2

$$T_c = 1.2 \times 10^{-4} \, \frac{200}{1}\sqrt{860} = 0.7 \text{ sec}$$

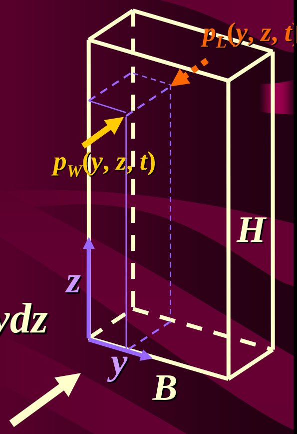
The internal pressure can respond high-frequency external pressure fluctuations !

Temporal Variation
of
Wind Forces

General Buildings

■ **Along-wind Force:**

$$F_D(t) = \int_0^H \int_0^B \{p_W(y,z,t) - p_L(y,z,t)\} dydz$$
$$= \int_0^H \int_0^B \{\bar{p}_W(y,z,t) - \bar{p}_L(y,z,t)\} dydz + \int_0^H \int_0^B \{p'_W(y,z,t) - p'_L(y,z,t)\} dydz$$
$$= \bar{F}_D(t) + F_D'(t)$$



■ **Quasi-steady assumption & $u(t)/U << 1$**

$$F_D'(t) = C_D \rho U u(t) BH$$
$$S_D(f) = (C_D \rho UBH)^2 S_u(f)$$

■ **Power Spectrum of Along-wind Force**

Size Reduction Effect & Distortion of Turbulence

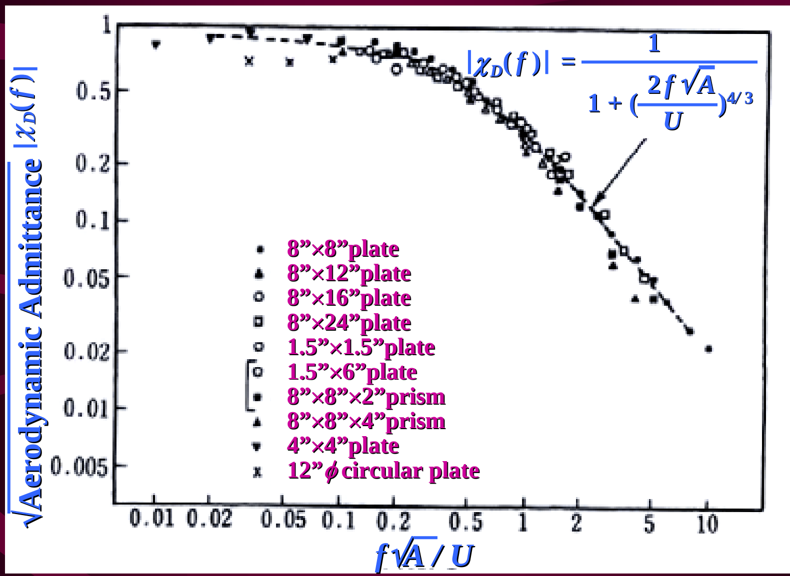
$$S_D(f) = 4C_D^2 \frac{S_u(f)}{U^2} |\chi_D(f)|^2$$

$|\chi_D(f)|^2$: **Aerodynamic admittance**

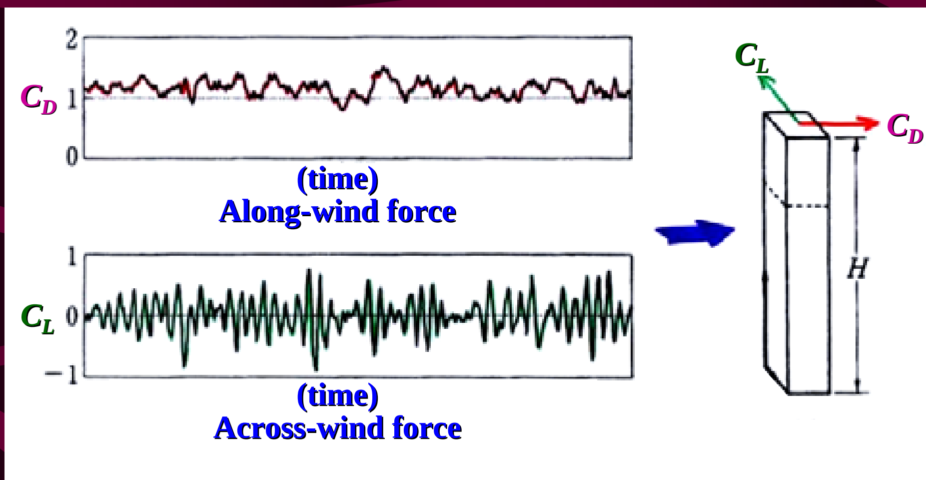
e.g. Vickery (1968)

$$|\chi_D(f)| = \frac{1}{1 + \left(\frac{2f\sqrt{A}}{U}\right)^{4/3}}$$

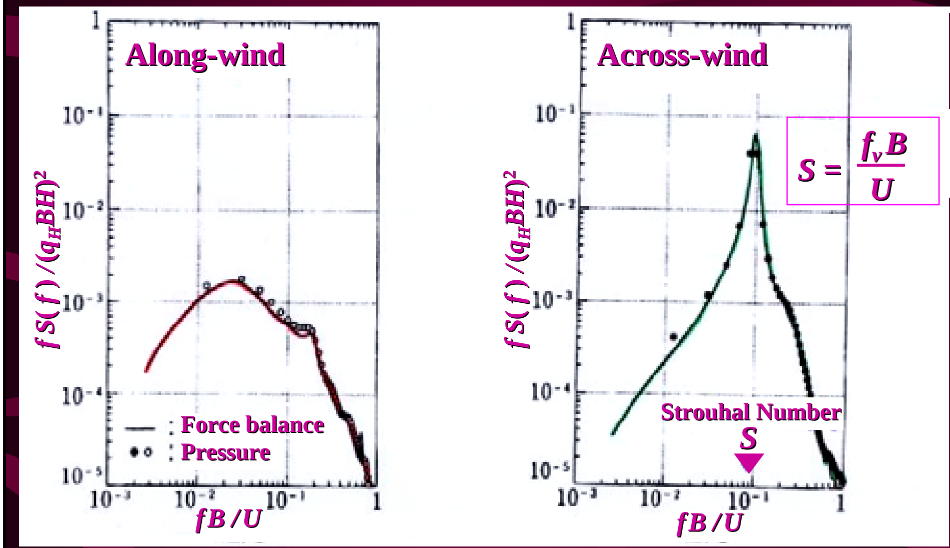
A : Projected Area



Aerodynamic admittance of plates and prisms (Vickery 1968)



Temporal variation of wind forces acting on a high-rise building model (2*H*/3, Wind tunnel)



Power spectra of wind forces acting on a high-rise building model

(2*H*/3, Wind tunnel, Kikuchi & Hibi 1995)

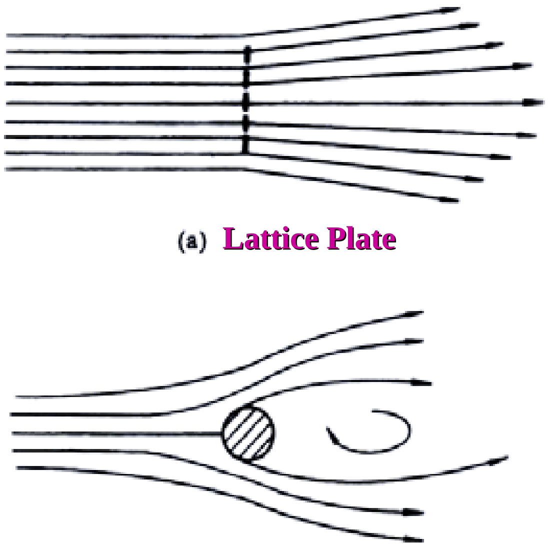
■ Fluctuating Wind Force Coefficient

$$C_D' = \frac{\sigma_D}{\frac{1}{2}\rho U_R^2 A}$$

$$C_L' = \frac{\sigma_L}{\frac{1}{2}\rho U_R^2 A}$$

σ_D, σ_L : Standard deviation of F_D and F_L
ρ : Air density
U_R : Reference wind speed
A : Projected area

Line-like Structures

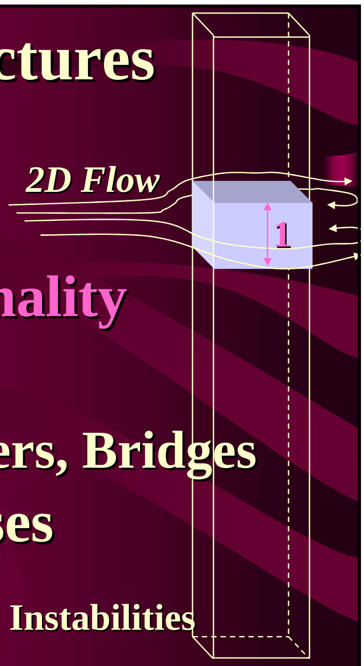


(a) Lattice Plate

(b) Cylinder / Prism

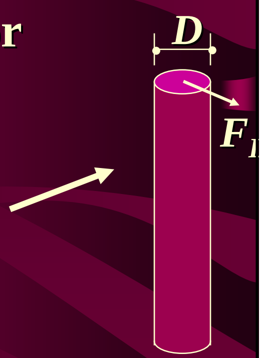
Line-like Structures

Line-like Structures



- **Local Two Dimensionality**
  - Strip Theory
- **Masts, Chimneys, Towers, Bridges**
- **Across-wind Responses**
  (except lattice towers)
  Vortex-resonance, Aerodynamic Instabilities

- **Across-wind Force Spectrum for a circular chimney**
  (Marukawa, Tamura et al., 1984)



$$S_L(f) = \left(\frac{1}{2}\rho U^2 D C_L'\right)^2 \times \left[\frac{k}{2\pi}\left\{\frac{\lambda f_s}{(f+f_s)^2+\lambda^2 f_s^2}+\frac{\lambda f_s}{(f-f_s)^2+\lambda^2 f_s^2}\right\} + \frac{2d}{U}\left\{1+\frac{70.8}{(1-k)^2}\left(\frac{fd}{U}\right)^2\right\}^{-5/6}\right]$$

Strouhal Component

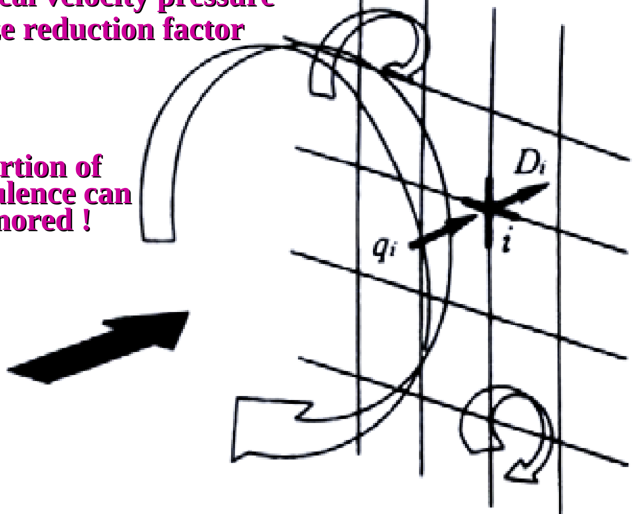
Gust Component

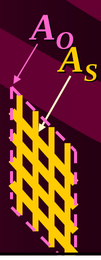
Lattice Structures

Lattice structures

- Local velocity pressure
- Size reduction factor

Distortion of turbulence can be ignored !





Solidity Ratio $\phi = A_S / A_O$ (less than ≈ 0.6)
A_S : Projected Area, A_O : Outline Area

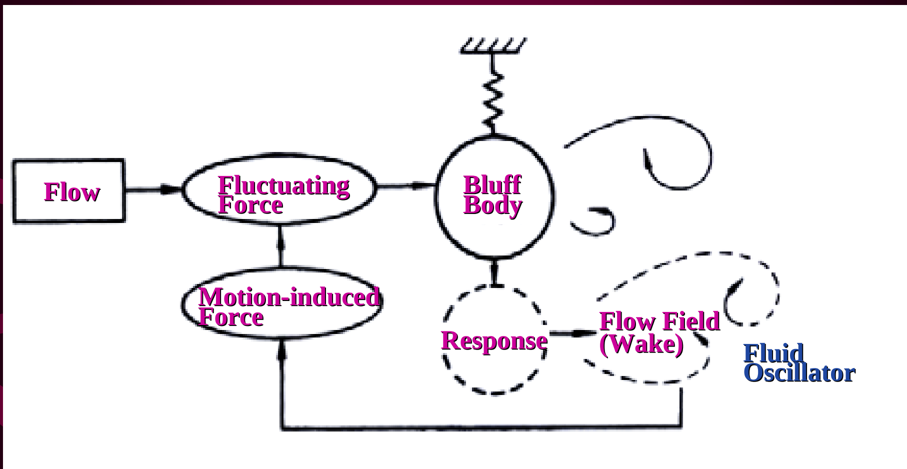
Lattice Structures

- Diameters of individual members are small.
  - → Momentum loss is small.
  - → Along-wind Force only for whole structure
  - (Across-wind forces can act on individual members)
  - → Total Along-wind Force D
    - = Sum of Along-wind Forces of Individual Members D_i
    - (governed by local velocity pressure q_i)

→ **Lattice Plate Theory** *Simplest !*

- Size-reduction Factor
- Aerodynamic Admittance

Motion-induced Wind Forces



Generation of motion-induced fluid force

■ Motion-induced Wind Forces: F_M

✧ Along-wind motion : F_M generally acts to suppress the motion.

Positive aerodynamic damping

✧ Across-wind motion : F_M occasionally acts to stimulate the motion.

Negative aerodynamic damping

→ *Flutters*

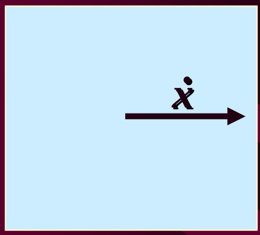
■ Unsteady flow / Vibrating body with an acceleration $\dot{U}$

-- accompanies inertial force / resistance $F_A \propto \dot{U}$

-- $F_A / \dot{U} = M_A$: Virtual mass (Additional mass)

Along-wind Motion

Mean Wind Speed U — Fluctuating Wind Speed u



$U_{rel} = U + u - \dot{x}$ — $\dot{x}$

Relative Wind Speed

$$M\ddot{x} + C\dot{x} + Kx = C_D \frac{1}{2}\rho U_{rel}{}^2 A$$

$$= C_D \frac{A}{2}\rho (U + u - \dot{x})^2$$

$$\approx C_D \frac{A}{2}\rho (U^2 + 2Uu - 2U\dot{x})$$

Along-wind Motion

$$M\ddot{x} + C\dot{x} + Kx = C_D \frac{A}{2}\rho (U^2 + 2Uu - 2U\dot{x})$$

Damping Term

$$(C + \rho C_D A U)\,\dot{x}$$

Aerodynamic Damping Ratio ζ_a

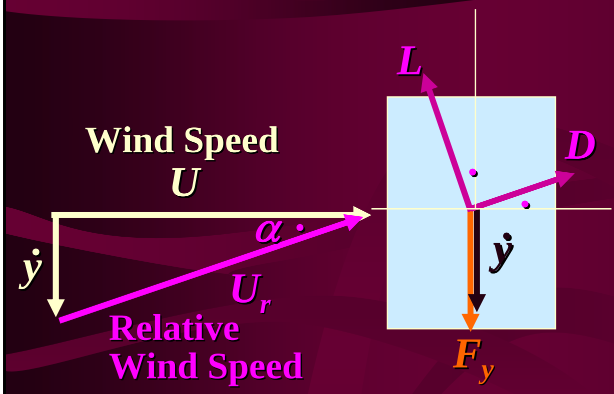
$$\zeta_a = \frac{\rho C_D A U}{2\omega_0 M}$$

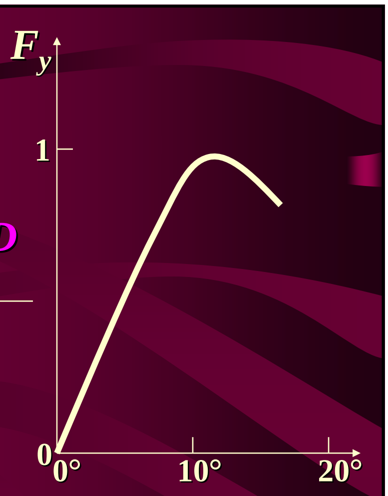
← *always positive*

$$\omega_0 = \sqrt{K/M}$$

Generally small and negligible

Across-wind Motion





$$\alpha \approx \dot{y}/U$$

$$-F_y = L\cos\alpha + D\sin\alpha = \frac{\rho}{2}AU_r^2(C_L\cos\alpha + C_D\sin\alpha)$$

$$= \frac{\rho}{2}AU^2(C_L + C_D\tan\alpha)\sec\alpha$$

Across-wind Motion

Derivative of F_y by α near $\alpha = 0$:

$$\frac{dF_y}{d\alpha} \approx -\frac{\rho}{2}AU^2\left(\frac{\partial C_L}{\partial \alpha} + C_D\right)$$

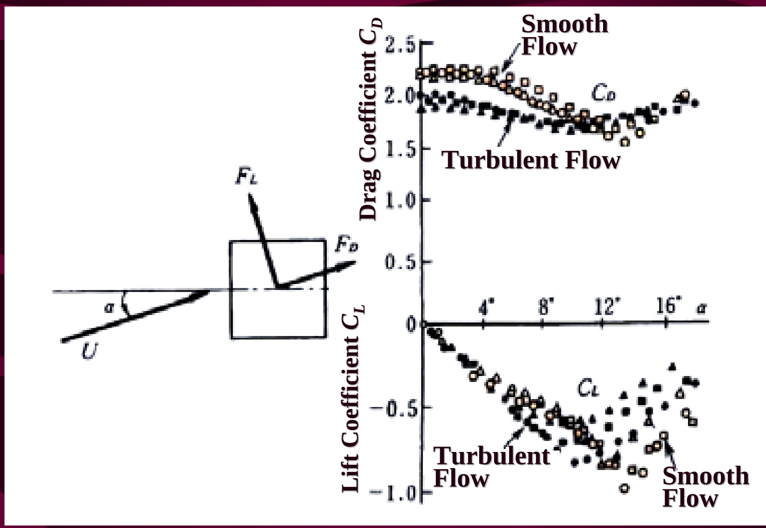
Unsteady force near $\alpha = 0$ $(\alpha \approx \dot{y}/U)$

$$F_y \approx -\frac{\rho}{2}AU\left(\frac{\partial C_L}{\partial \alpha} + C_D\right)\dot{y}$$

Aerodynamic Damping Ratio

$$\zeta_a = \frac{\rho AU}{4\omega_0 M}\left(\frac{\partial C_L}{\partial \alpha} + C_D\right)$$

can be negative



Variations of mean drag and lift coefficients with attacking angle (2D)

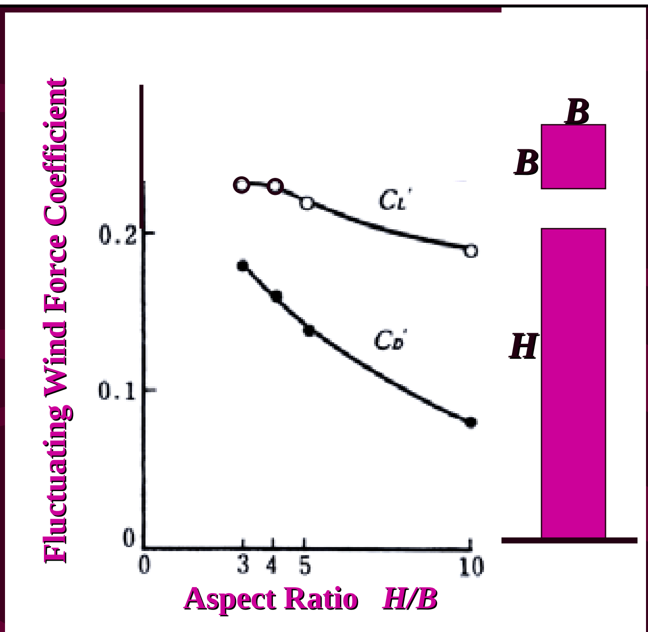
- **Unsteady Flow / Vibrating Body**

$$\frac{\partial \phi}{\partial t}$$ in Blasius Eq. : Unsteady term

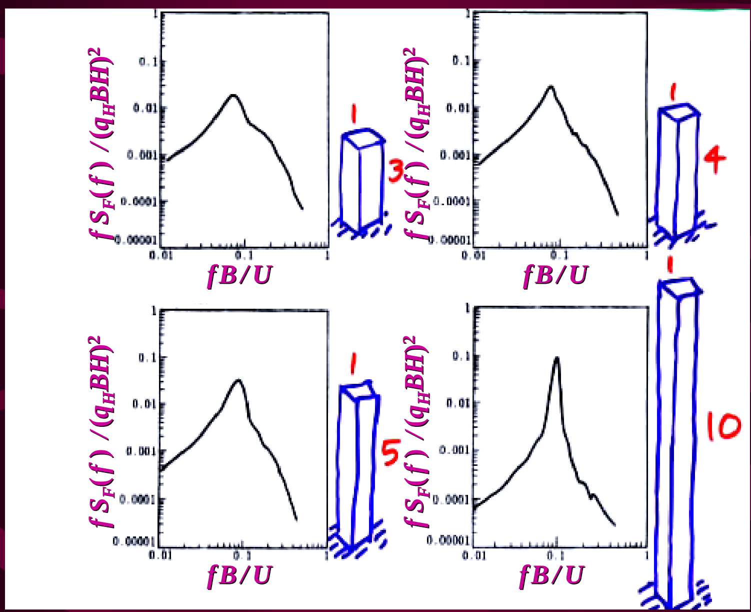
→ Inertial resistance
→ Virtual mass : M_A

ex. 2D circular cylinder
M_A = Fluid mass of the same volume

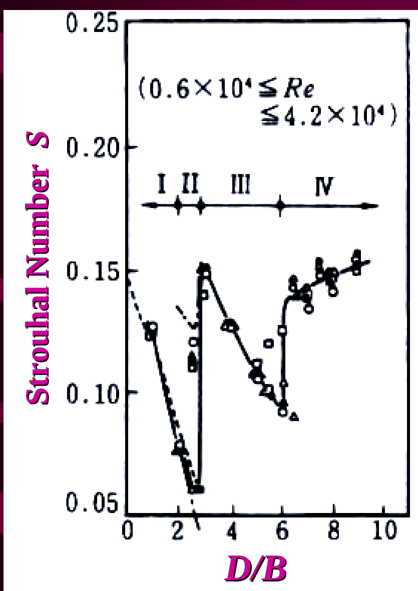
Fluctuating Wind Forces Acting on Basic Sectional Shapes

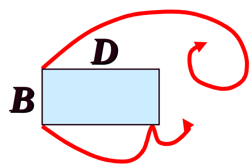


Fluctuating wind force coefficients vs. aspect ratio of square prisms (Turbulent boundary layer flow)



Power spectra of across-wind forces on 3D prisms
(1st mode generalized force, Turbulent shear layer flow)





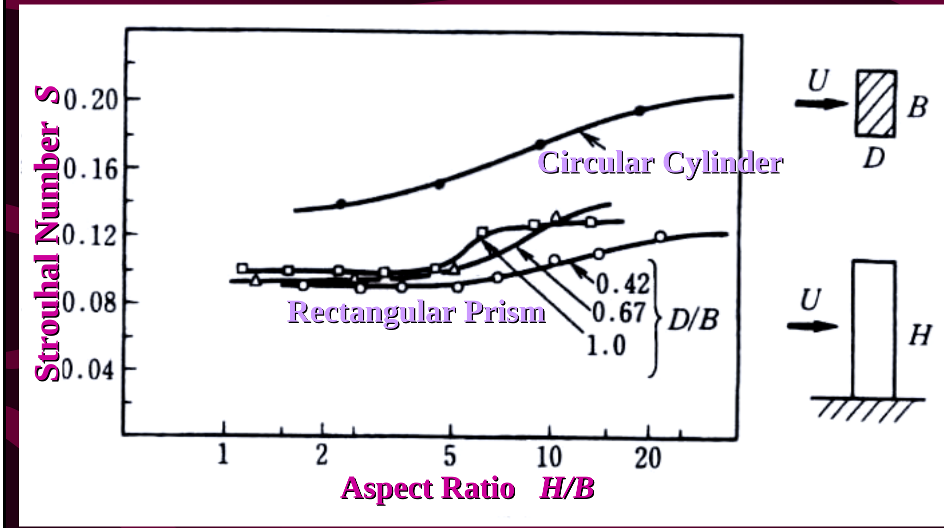
I Always separated

II Separated in terms of temporal average (Occasionally reattached)

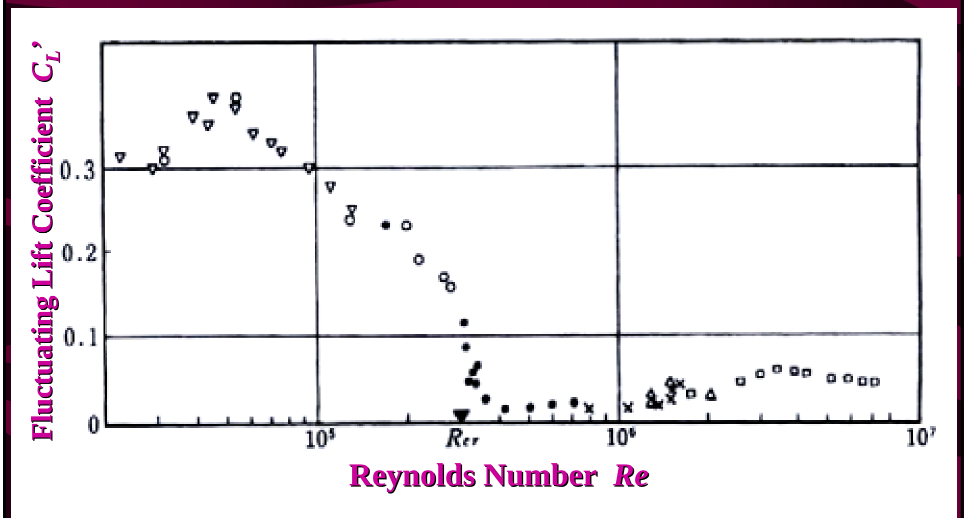
III Reattached in terms of temporal average (Occasionally separated)

IV Always reattached

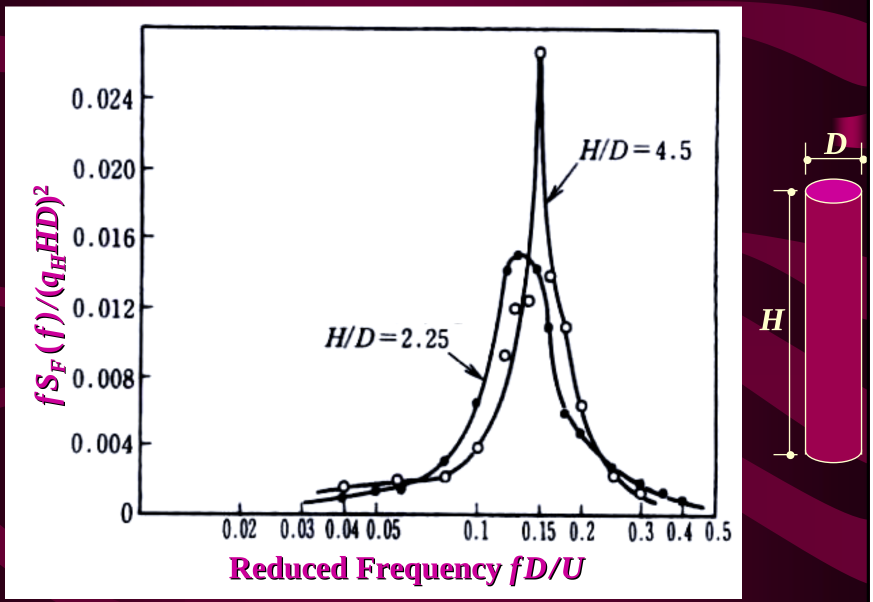
Strouhal number vs. side ratio of prisms
(2D, Smooth Flow, Okajima 1983)



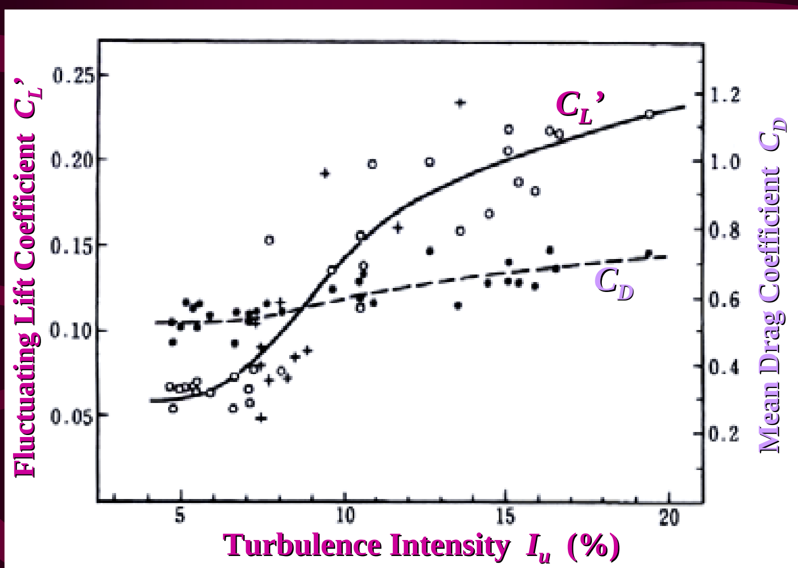
Strouhal number of 3D cylinder and prisms
(Turbulent Flow, Vickery 1968)



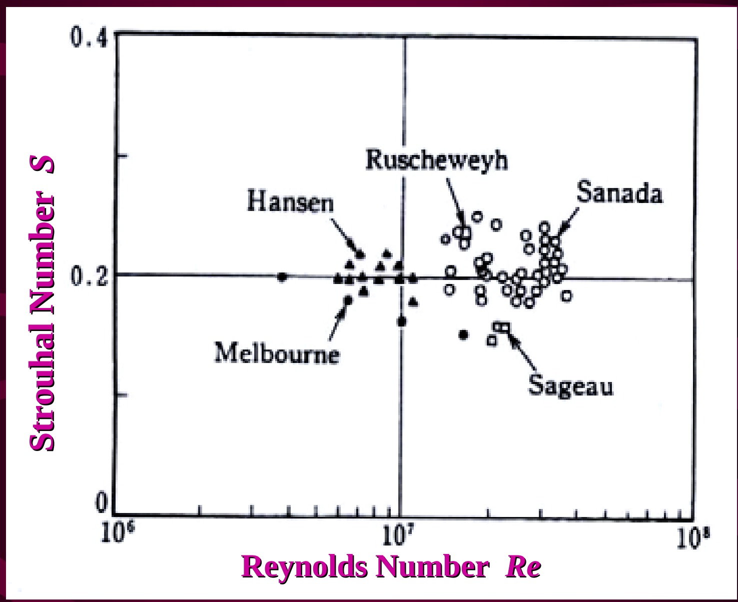
Fluctuating lift coefficient of circular cylinder
(2D, Smooth Flow, Schewe 1983)



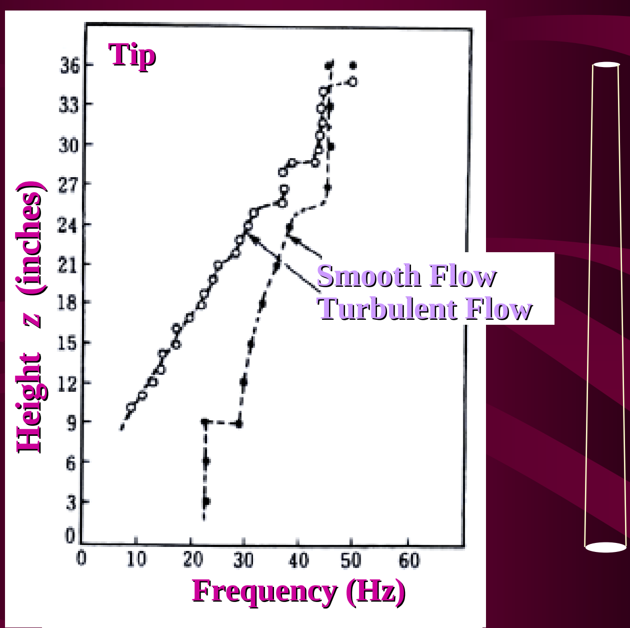
Power spectra of fluctuating lift forces of 3D circular cylinder (Turbulent Flow, Vickery 1968)



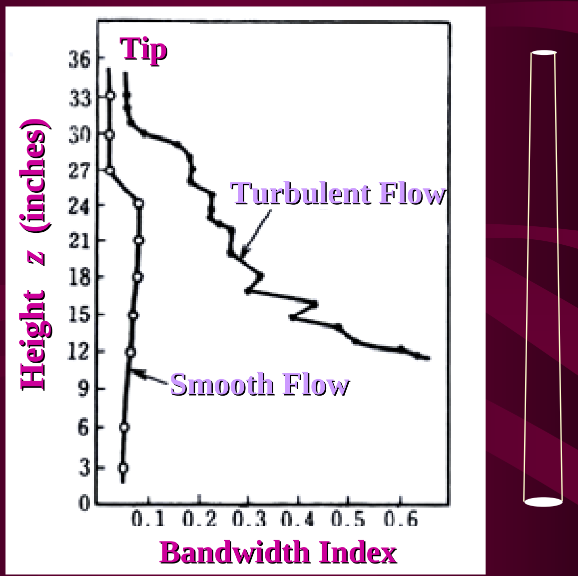
Fluctuating lift coefficient and mean drag coefficient of a 200m high circular chimney (Full-scale, Local wind forces at 0.7*H*, Vickery 1988)



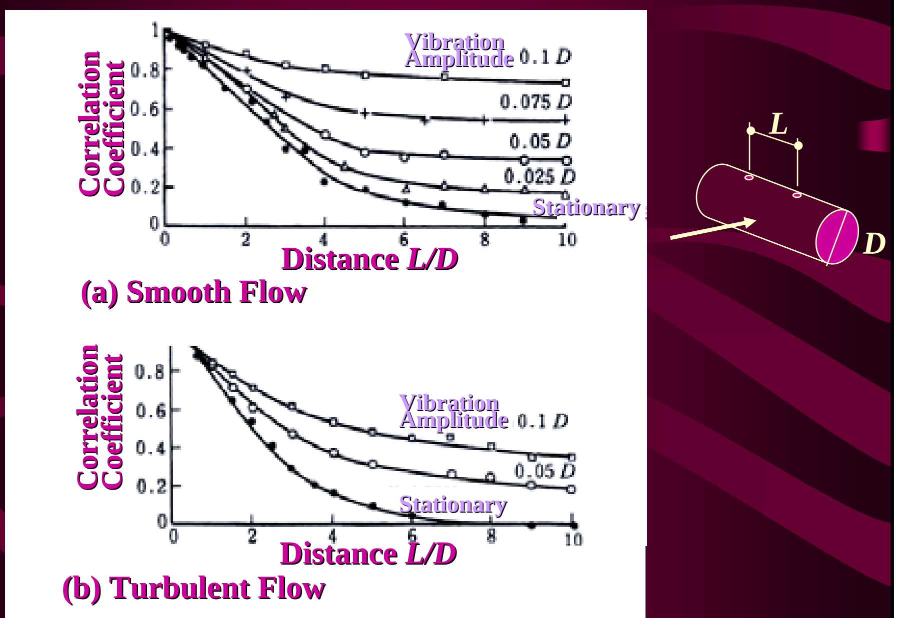
Strouhal number of chimneys (Full-scale)



Vortex-shedding frequency
(3D tapered chimney model, Vickery & Clark 1972)



Bandwidth index of power spectral peak of fluctuating lift force of a chimney model (Vickery & Clark 1972)

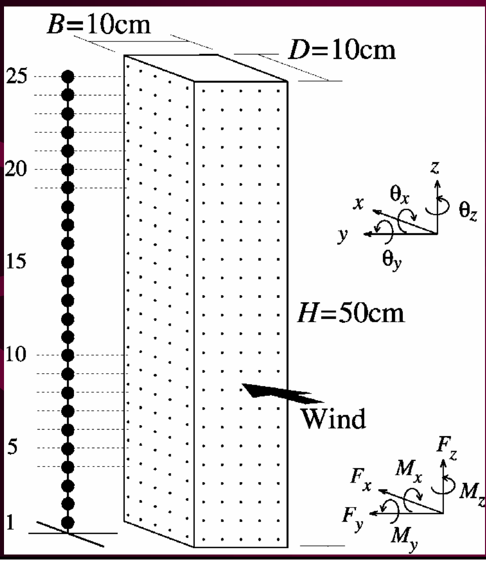


Correlation of pressures acting on a circular cylinder ($\theta = 90°$) (2D, Novak & Tanaka 1975)

Design Wind Loads

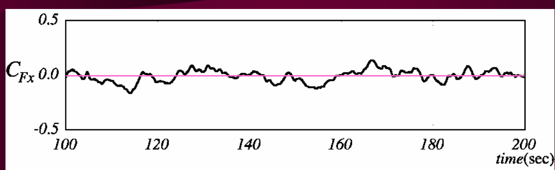
Wind Load Effects

Pressure Measurement Model and Analytical Lumped Mass Model

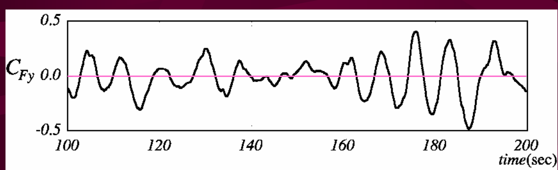


- **Length Scale = 1/400**
- **Mean Wind Speed Profile α = 1/6**
- **500 Pressure Taps**
- **Δt = 0.00128 sec**
- ***T* = 42 sec (32,768 samples)**
- **3DOF × 25 masses = 75DOF**

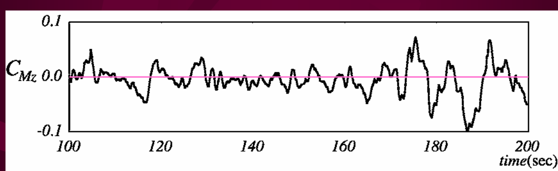
Generalized Wind Force Coefficients



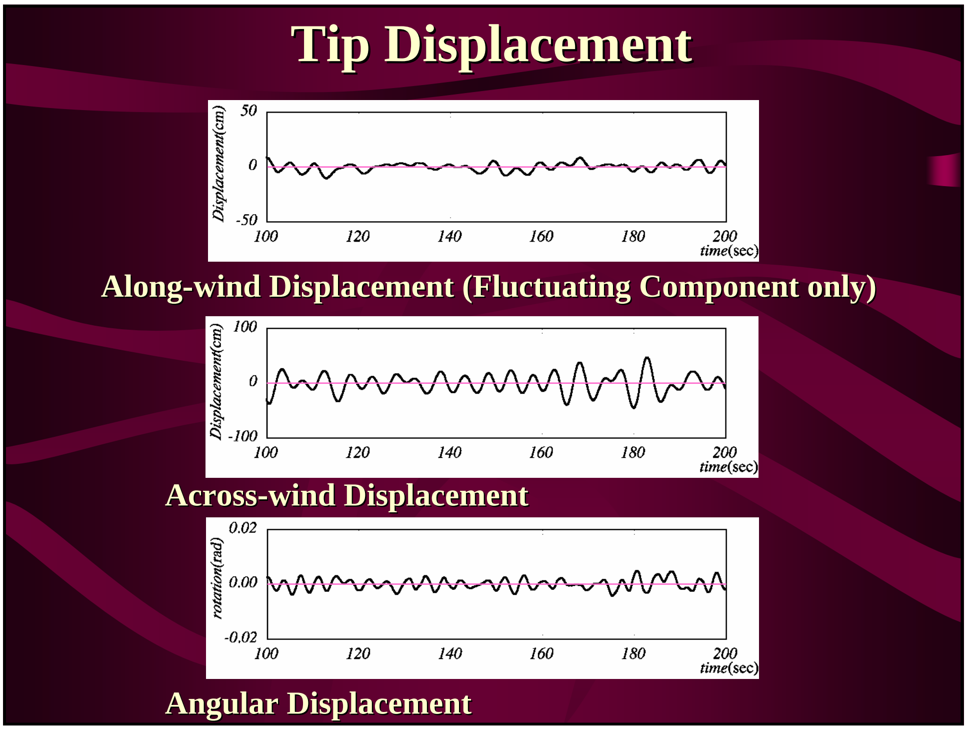
Along-wind Force (Fluctuating Component only)



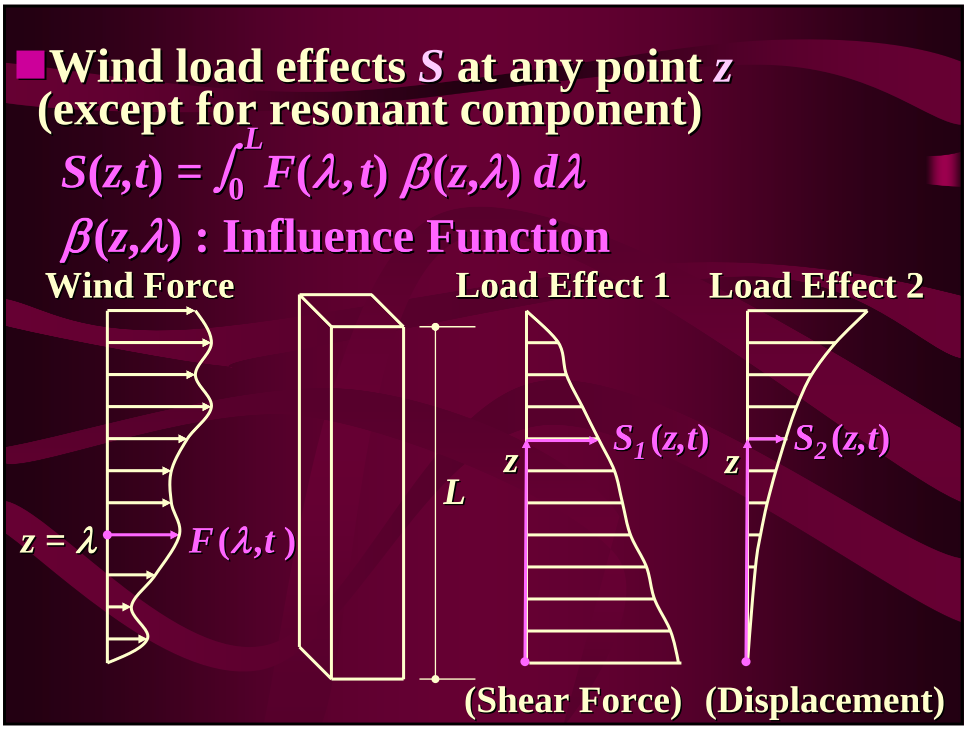
Across-wind Force



Torsional Moment

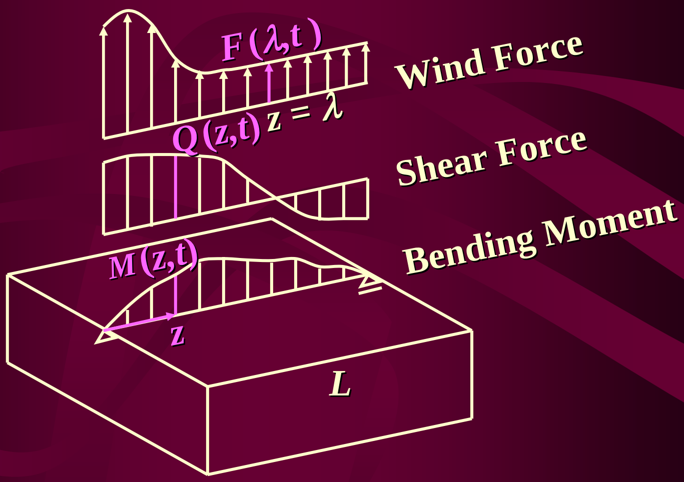


Tip Displacement
Displacement(cm)
50
0
-50
100
120
140
160
180
200
time(sec)
Along-wind Displacement (Fluctuating Component only)
Displacement(cm)
100
0
-100
100
120
140
160
180
200
time(sec)
Across-wind Displacement
rotation(rad)
0.02
0.00
-0.02
100
120
140
160
180
200
time(sec)
Angular Displacement



Wind load effects S at any point z
(except for resonant component)
$S(z,t) = \int_0^L F(\lambda,t)\ \beta(z,\lambda)\ d\lambda$
$\beta(z,\lambda)$: Influence Function
Wind Force
Load Effect 1
Load Effect 2
$z = \lambda$
$F(\lambda,t)$
L
z
$S_1(z,t)$
z
$S_2(z,t)$
(Shear Force)
(Displacement)

Wind forces and wind load effects on roof beams



$$S(z,t) = \int_0^L F(\lambda,t)\beta(z,\lambda)\, d\lambda$$

- **Influence function**

- Bending moment at *z* of a roof beam

$$\beta(z,\lambda) = \left(1 - \frac{z}{L}\right)\lambda, \quad 0 < \lambda \le z$$

$$\beta(z,\lambda) = \left(1 - \frac{\lambda}{L}\right)z, \quad z < \lambda \le L$$

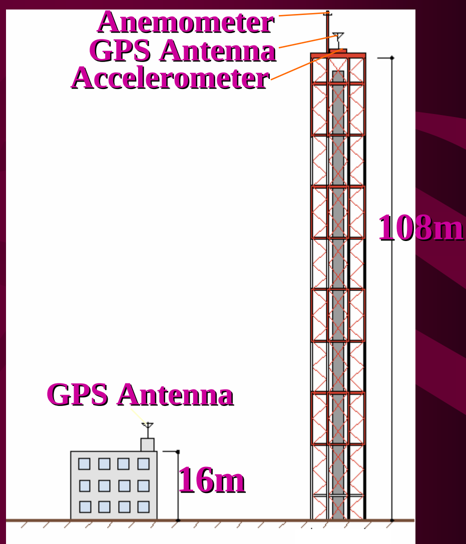
- Shear force at *z* of a roof beam

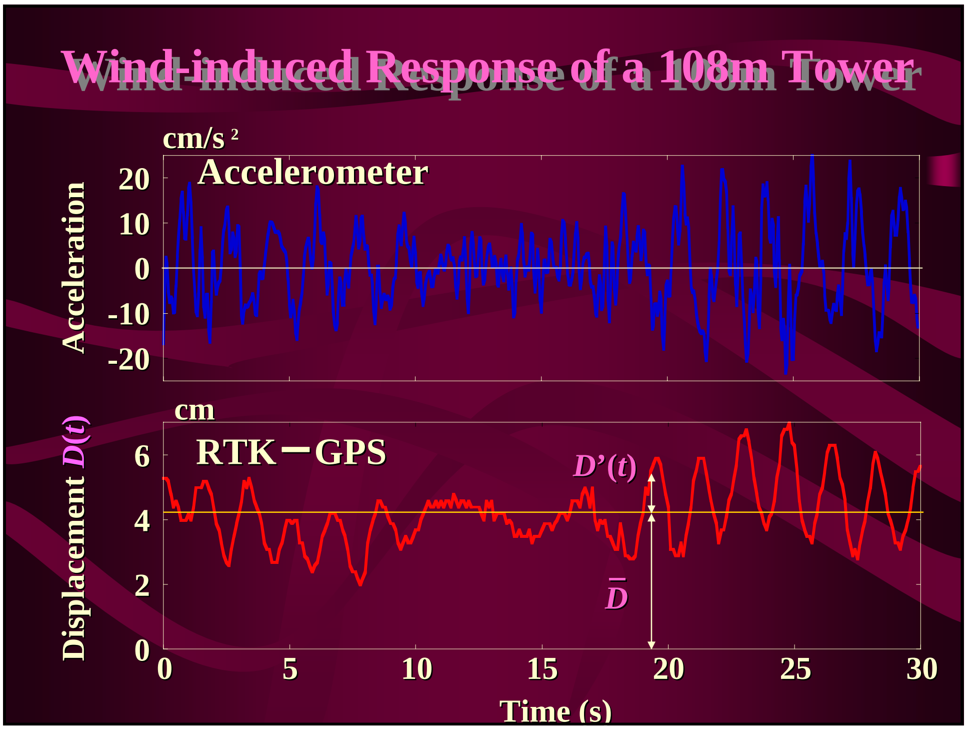
$$\beta(z,\lambda) = -\frac{\lambda}{L}, \quad 0 < \lambda \le z$$

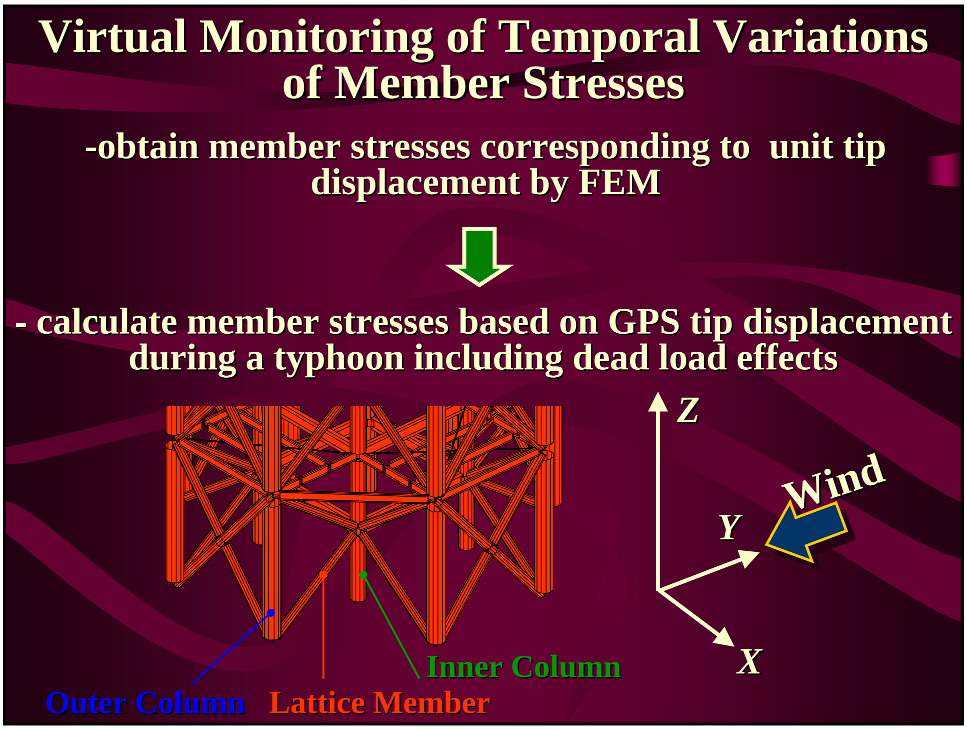
$$\beta(z,\lambda) = 1 - \frac{\lambda}{L}, \quad z < \lambda \le L$$

Static Wind Load, Dynamic wind Load and Quasi-static Wind Load

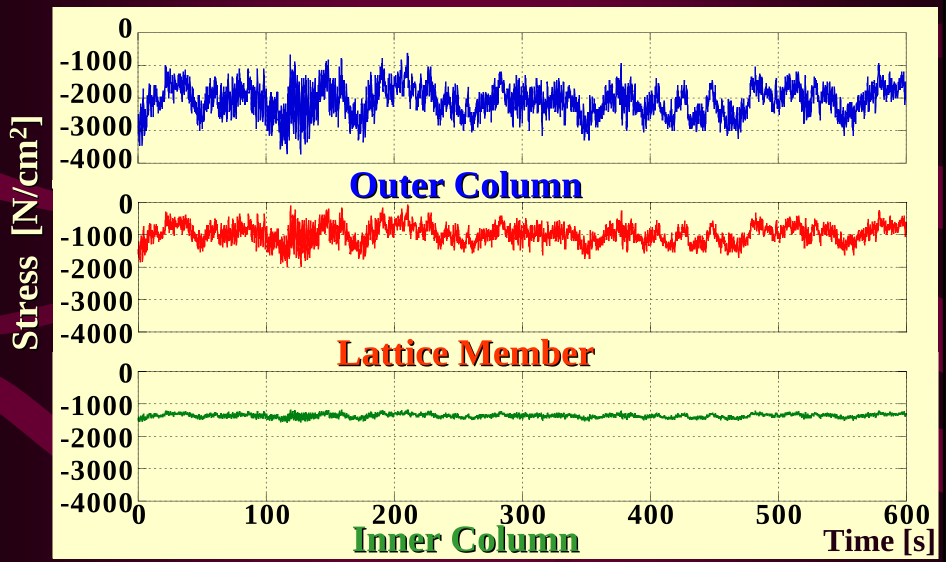
GPS Monitoring




Wind-induced Response of a 108m Tower
cm/s ²
Accelerometer
Acceleration
20
10
0
-10
-20
cm
RTK－GPS
D'(t)
D̄
Displacement D(t)
6
4
2
0
0
5
10
15
20
25
30
Time (s)


Virtual Monitoring of Temporal Variations of Member Stresses
-obtain member stresses corresponding to unit tip displacement by FEM
- calculate member stresses based on GPS tip displacement during a typhoon including dead load effects
Z
Y
X
Wind
Inner Column
Outer Column
Lattice Member

Temporal variations of member stresses during a typhoon due to GPS monitoring and FEM analysis



■Mean Component of Wind Force $\bar{F}$

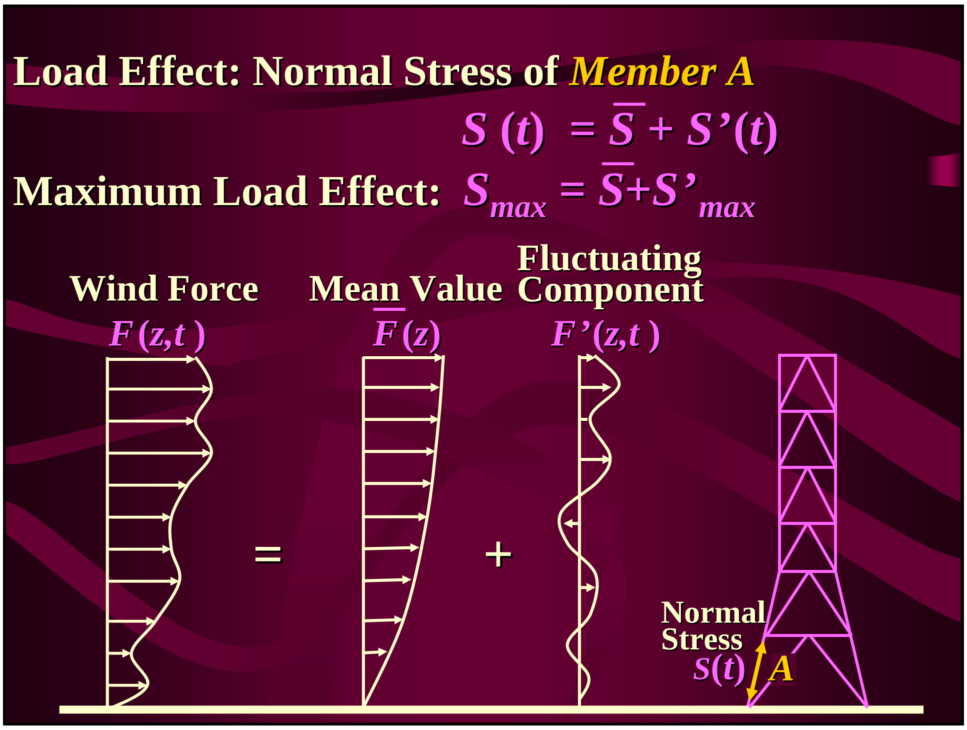
→ Static Wind Load (due to mean wind speed)

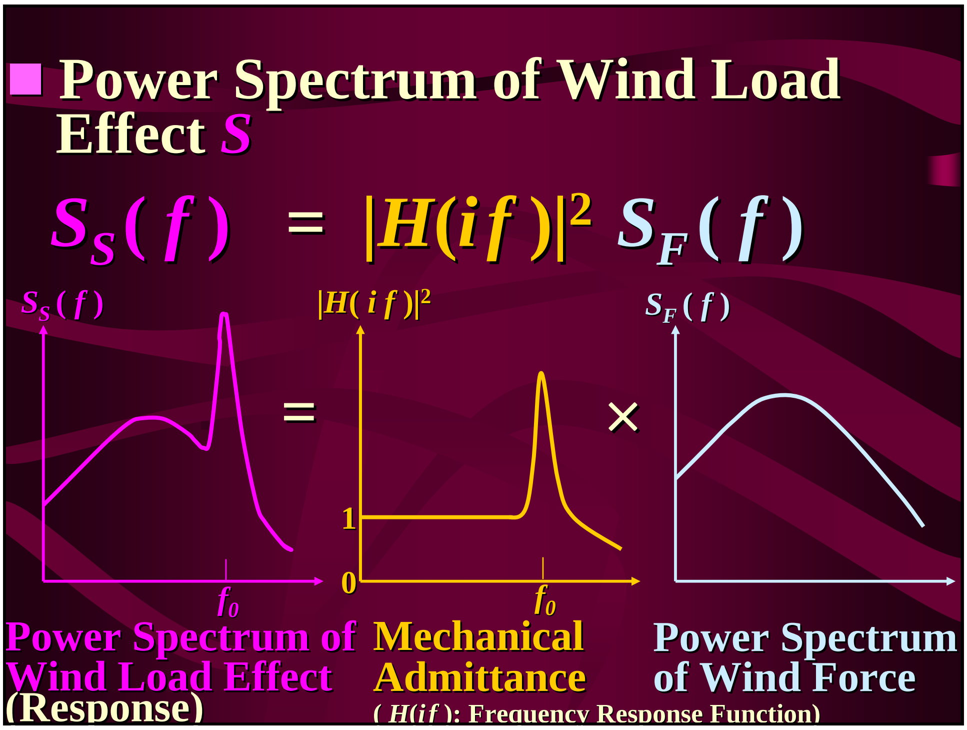
→ Mean Wind Load Effects $\bar{S}$

■Fluctuating Component of Wind Force $F'(t)$

→ Dynamic Wind Load

→ Fluctuating Wind Load Effects $S'(t)$


Load Effect: Normal Stress of Member A
S (t) = S̄ + S'(t)
Maximum Load Effect: S_max = S̄+S'_max
Wind Force
F (z,t)
Mean Value
F̄ (z)
Fluctuating Component
F'(z,t)
=
+
Normal Stress
S(t)
A

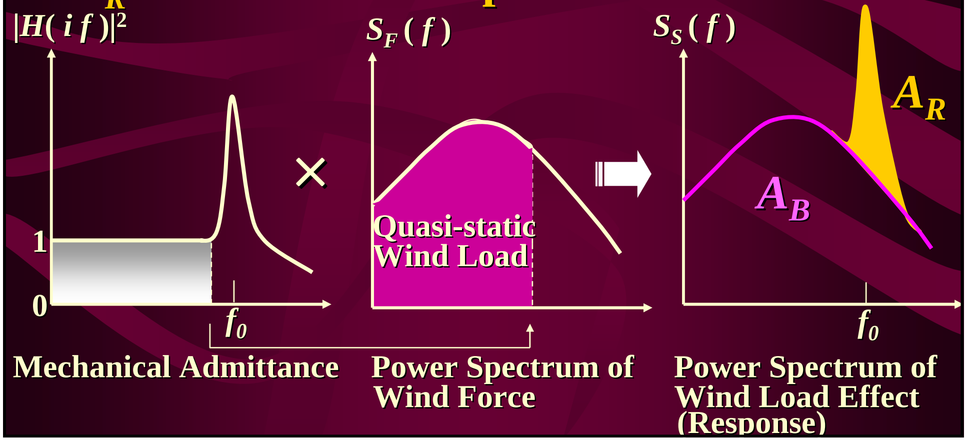

Power Spectrum of Wind Load Effect S
S_S(f) = |H(if)|² S_F(f)
S_S (f)
|H(i f)|²
S_F (f)
=
×
1
0
f₀
f₀
Power Spectrum of Wind Load Effect (Response)
Mechanical Admittance
(H(if): Frequency Response Function)
Power Spectrum of Wind Force

■Variance of wind load effect S:

$$\sigma_S^2 = \int_0^{\infty} S_S(f)\,df = A_B + A_R$$ (Spectrum: One-sided)

A_B : Background (Quasi-static) component

A_R : Resonance component



■Maximum Load Effect $S_{max} = \bar{S} + S'_{max}$

$$\bar{S} = \frac{\bar{F}}{K}$$

Peak Factor

$$S'_{max} = g_S\,\sigma_S = g_S\sqrt{A_B + A_R}$$

■Gust Response Factor : G_S

$$G_S = \frac{S_{max}}{\bar{S}} = \frac{\bar{S} + S'_{max}}{\bar{S}} = 1 + \frac{S'_{max}}{\bar{S}}$$

■Equivalent Static Wind Load Causing Maximum Load Effect S_{max} : F_{ES}

$$F_{ES} \equiv G_S\,\bar{F}$$

$$\left(\frac{F_{ES}}{K} = G_S\frac{\bar{F}}{K} = G_S\,\bar{S} = S_{max} \right)$$

S.O. Rice (1945), Cartwright & Longuet-Higgins (1956)

Peak Factor : g_S

$$g_S \approx \sqrt{2\ln \nu T} + \frac{0.5772}{\sqrt{2\ln \nu T}}$$

0.5772 ← Euler's Constant

T : Sample length ← e.g. 10min

ν : Average number of peaks for unit time

$$\nu = \frac{1}{2\pi}\left\{\frac{\int_0^\infty (2\pi f)^4 S_S(f)df}{\int_0^\infty (2\pi f)^2 S_S(f)df}\right\}^{1/2}$$

$$\approx \frac{1}{2\pi}\left\{\frac{\int_0^\infty (2\pi f)^2 S_S(f)df}{\int_0^\infty S_S(f)df}\right\}^{1/2} \approx f_0\sqrt{\frac{A_R}{A_B+A_R}} \approx f_0$$

(Narrow-band Process)

f_0 : Fundamental Natural Frequency

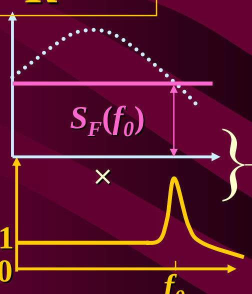
Variance of wind load effect S:

$$\sigma_S^2 = \int_0^\infty S_S(f)df = A_B + A_R$$

$$\approx \frac{1}{K^2}\int_0^\infty S_F(f)df + \frac{\pi}{4\zeta}\frac{f_0 S_F(f_0)}{K^2}$$

$$= \frac{\sigma_F^2}{K^2}\left\{1 + \frac{\pi}{4\zeta}\frac{f_0 S_F(f_0)}{\sigma_F^2}\right\}$$

Response due to a white noise input $S_F(f_0)$



Acceleration Response:

$$\sigma_{\ddot{x}}^2 = (2\pi f_0)^4 A_R$$

$$= \frac{\pi}{4\zeta}\frac{f_0 S_F(f_0)}{M^2}$$

K : Building Stiffness

ζ : Damping Ratio

M : Building Mass

- Equivalent Static Wind Load : F_{ES}

$$F_{ES} \equiv G_S \bar{F}$$

$= \textit{Gust Response Factor} \times \textit{Static Wind Load}$

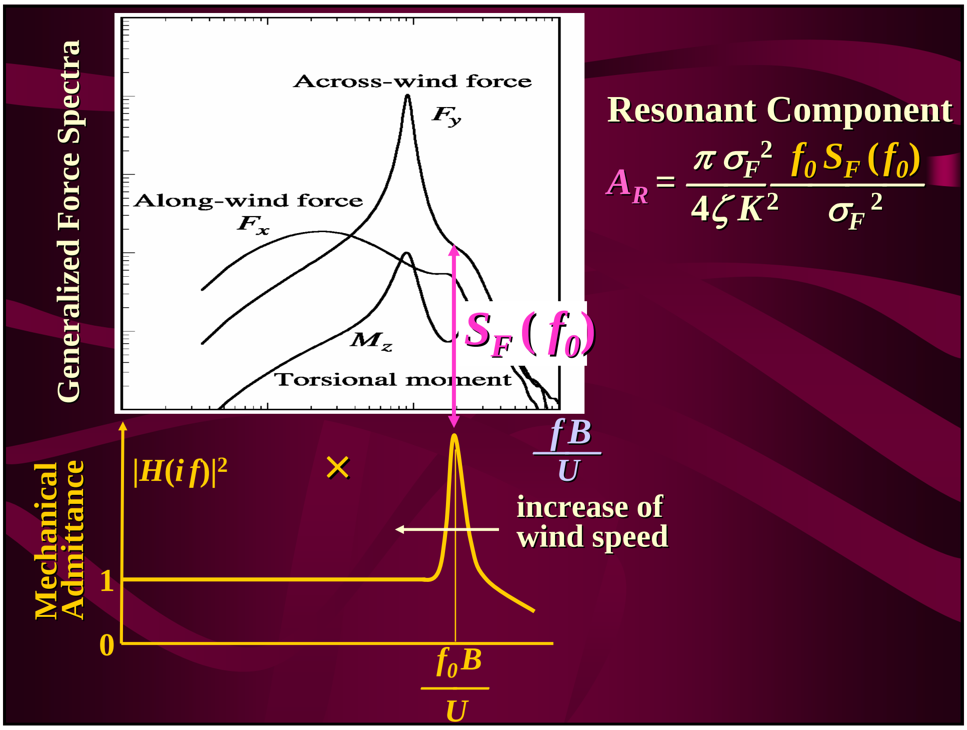
$$G_S = 1 + \frac{g_S \sqrt{A_B + A_R}}{\bar{S}}$$

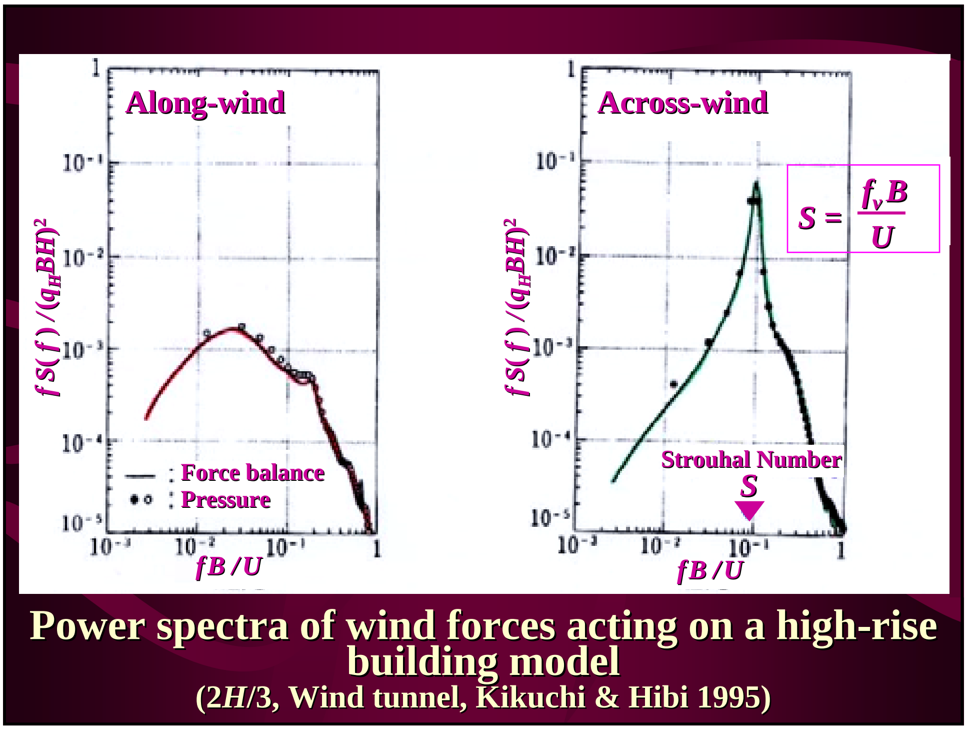
g_S : Peak Factor
A_B: Quasi-static Component
A_R: Resonant Component

Variation of Responses with Mean Wind Speed

Example !!

- Acceleration Responses
  - Along-wind : $\ddot{X}_{MAX} \propto U^{2.5}$
  - Across-wind: $\ddot{Y}_{MAX} \propto U^{3.7}$
- Displacement Responses
  - Along-wind : $X_{MAX} \propto U^{2.1}$
    (Mean component $\propto U^2$)
  - Across-wind: $Y_{MAX} \propto U^{3.1}$


Generalized Force Spectra
Across-wind force
F_y
Along-wind force
F_x
M_z
Torsional moment
$S_F(f_0)$
Resonant Component
$A_R = \frac{\pi \sigma_F^2}{4\zeta K^2} \frac{f_0 S_F(f_0)}{\sigma_F^2}$
$\frac{fB}{U}$
Mechanical Admitance
$|H(if)|^2$
×
increase of wind speed
1
0
$\frac{f_0 B}{U}$


Along-wind
Across-wind
$fS(f)/(q_H BH)^2$
: Force balance
: Pressure
$S = \frac{f_v B}{U}$
Strouhal Number
S
fB/U
Power spectra of wind forces acting on a high-rise building model
(2H/3, Wind tunnel, Kikuchi & Hibi 1995)