Lecture 7

Wind Tunnel Tests and Full-scale Measurements

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Wind Tunnel Tests

- Satisfaction of necessary and possible dynamic, kinetic and geometric similarity laws
- Confirmation of test repeatability
- Appropriate calibration of transducers etc.

Wind Tunnel Testing Manuals

e.g. Building Center of Japan (1994)
American Society of Civil Engineers (1999)
Wind Tunnel Flows

- Simulated Flow
  - cannot reproduce exact characteristics
- Building Model
  - cannot have exactly the same geometrical shape
- Similarity Laws
  - cannot be exactly satisfied

Similarity Laws
Geometrical Similarity

- Building Dimensions
  \[ H/L, D/L, B/L \]
- Topography, Surrounding Buildings, Obstacles
  \[ R/L \]
- Turbulence Scale
  \[ L_{ux}/L \]
- Boundary Layer Height, Roughness Length
  \[ Z_o/L, z_d/L \]
**Similarity Laws**

**Kinetic Similarity (Approaching Flow)**

- Mean Wind Speed Profile
  \[ \frac{U(z)}{U(z_{ref})} \]
- Turbulence Intensity
  \[ \frac{I_u(z)}{I_u(z_{ref})}, \quad I_u(z_{ref}) \]
- Power Spectral Density
  \[ \frac{fS_u(f)}{\sigma_u^2} \]

**Similarity Laws**

**Dynamic Similarity**

- Reynolds Number
  \[ \frac{UL}{\nu} \]
- Damping Ratio
  \[ \zeta \]
- Reduced Frequency
  \[ fL/U, \quad \frac{fU}{f_0L} \]
- Mass Ratio
  \[ \frac{\rho_s}{\rho} \]
- Elastic Parameters
  \[ \frac{E_{eq}}{\rho U^2} \quad (E_{eq} = \frac{EI}{B^4} \text{ Bending Stress}, \quad \frac{EA}{B^2} \text{ Normal Stress}, \quad \frac{Eh}{B} \text{ Membrane Stress}) \]
- Initial Strain
  \[ \frac{N_0}{EA} \text{ (Membrane Structure)} \]
- Acoustic Stiffness, Acoustic Damping
  \[ \pi L^4 \rho \sigma_a^2 / N_0 V_0, \quad \xi_a \text{ (Membrane Structure)} \]
- Internal Pressure Ratio
  \[ p_i/q \text{ (Membrane Structure)} \]
- Froude Number
  \[ \frac{U}{\sqrt{gB}} \text{ (Membrane Structure)} \]
**Nomenclature**

- $A$: Sectional area, $B$: Building width, $C_a$: Sonic velocity,
- $D$: Building depth, $E$: Elastic modulus, $E_{eq}$: Equivalent elastic parameter, $f$: Frequency, $f_0$: Natural frequency,
- $g$: Gravity acceleration, $H$: Building height,
- $I$: Geometrical moment of inertia, $I_\alpha(z)$: Turbulence intensity at height $z$, $L$: Representative building length,
- $L_{ux}$: Turbulence scale, $N_0$: Initial stress, $p_i$: Internal pressure, $q$: Reference velocity pressure,
- $R$: Representative length of topography, $S_\alpha(f)$: Power spectra of wind speed, $U$: Reference mean wind speed,
- $U(z)$: Mean wind speed at height $z$, $V_o$: Volume of internal space, $Z_c$: Gradient height, $z_o$: Roughness length,
- $z_{ref}$: Reference height, $\nu$: Dynamic viscosity, $\rho$: Air density, $\rho_S$: Building density, $\sigma_u$: Standard deviation of wind speed, $\zeta$: Damping ratio, $\zeta_a$: Acoustic damping ratio

**Important Points**

- Reynolds Number Effects
  - Curved Surfaces
  - Surface Roughness
  - Pressurized Wind Tunnel
- Blockage Effects
  - $A_M/A_W < 5\%$ (at least 10\%)
  (\(A_M\): Projected area of models including surrounding \(A_W\): Sectional area of wind tunnel)
- Wall Constraint Effects
- Modeling of Surrounding Areas
- Reference Pressure etc.
Length Scale & Temporal Scale

\[ L = UT \rightarrow \lambda_L = \lambda_U \lambda_T \]

- \[ \lambda_L = \frac{L_{\text{model}}}{L_{\text{full-scale}}} \]
  (length scale)
- \[ \lambda_U = \frac{U_{\text{model}}}{U_{\text{full-scale}}} \]
  (velocity scale)
- \[ \lambda_T = \frac{T_{\text{model}}}{T_{\text{full-scale}}} = \lambda_L \frac{\lambda_L}{\lambda_U} = \frac{1}{300} \frac{1}{3} = 1/100 \]
  (temporal scale)

Wind Tunnel Tests

- Wind Pressure
- Wind Force
- Wind-induced Response
- Wind Speed
  - Topographic Effects
  - Pedestrian Level Winds
- Dispersion Around Buildings
- Air pollution
- Ventilation etc.
Wind Tunnel Tests for Wind Resistant Design of Buildings

- High-Frequency Force Balance
  - Dynamic/Static Forces
- Multi-Channel Pressure Measuring System
  - Mean/FluctuatingPressures
- Elastic Model
  - Dynamic/Static Responses

Modeling of Surrounding Buildings

Wind Engineering Institute
High-Frequency Force Balance

Wind Engineering Institute

High-Frequency Force Balance

Rigid Light-weight Model
Model Base
Strain-Gauge
Rotational Center

(BCJ Designer’s guide to wind tunnel tests)
High-Frequency Force Balance

- Higher $f_0$ is desired.
- Light weight model

Elastic Models

Rocking Model  2D Model  Lumped-mass Model  Full-elastic Model

(BCJ Designer’s guide to wind tunnel tests)
Elastic Model (Rocking Type)

(BCJ Designer’s guide to wind tunnel tests)
Elastic Model (Lumped-Mass)

(Courtesy of Shimizu Corp.)

Full-Elastic Model

-Epoxy resin with iron powder

Coincidence of Mass Ratio $\rho_S/\rho$
Multi-channel Pressure Model

Compensation of Tubing Effects
Pressure Measurement

Wind Pressure \( p_t = P_t - P_S \)

Field Measurements and Validity of Wind Tunnel Testing
Eiffel Tower drawn by G.A. Eiffel (Davenport, 1975)

Meteorological Instruments at Top of Eiffel Tower

(Gavenport, 1975)
Field Measurements

- Essentially random and non-stationary
- Rare phenomena
  --- have to be continued for a long period
- Various constraints on instrumentation for measurements

Quality of data is not always satisfactory!

Low-rise Buildings
- Aylesbury comparative experiment
- Texas Tech Building
Texas Tech Building

Comparison of TTU full-scale data with wind tunnel data (Rofail, 1995)
Approaching Wind Azimuth $\theta$

Comparison between 1:50 model data and 1:100 model data by Windtech (Rofail, 1995)

High-rise Buildings

- Nakano Denden Building
  External Pressures
  Wind-induced Responses

- Nagasaki Huis Ten Bosch Domtoren
  Wind-induced Responses

- Setagaya Business Square
  External/Internal Pressures
Comparison between full-scale and wind tunnel model responses, Fujimoto et al., 1980
Comparison of full-scale and wind tunnel model responses during Typhoon 9121

Setagaya Business Square

Kato et al., 1996
Comparison of full-scale and wind tunnel model-scale pressure coefficients (Kurita et al., 1996)

Correlation between full-scale and model-scale mean pressure coefficients (Kato et al., 1996)
Temporal variations of mean internal pressures
(Full-scale, Kato et al., 1996)

Setagaya Business Square

Variation of mean internal pressures with reference velocity pressure (Full-scale, Kato et al., 1996)
### Pedestrian Level Winds

- Speed-up around corners, Down-wash effects, Venturi effects, etc.
- Adverse reaction of the public to new buildings that have unpleasant wind conditions
- **A municipal bylaw of Tokyo:** Wind tunnel tests and field measurements of wind speed around the building before and after construction are required for buildings higher than 100m.

![Graph showing comparison between full-scale and model-scale mean wind speeds (BCJ, 1984)]

*Shinjuku New Metropolitan area*  
*Tsukishima area*  
*Comparison between full-scale and model-scale mean wind speeds (BCJ, 1984)*