Wind Resistant Design of Long Span Bridges

No.3

-- Wind Tunnel Tests --

Sungkyunkwan University

2012/9/27 Fall Term

Concurrent Prof. Hiroshi TANAKA

Introduction

- What is wind tunnel tests ?
- How to use them ?
- What is the benefit of them ?

Great Engineer of Suspension Bridges

But he did not consider aero dynamic forces which act on suspension bridges.
Therefore famous tragedy attacked him on10th November 1940

Leon Moisseiff (1872-1943)

Beginning of Wind Engineering

Tacoma Narrows Bridge 7th November 1940

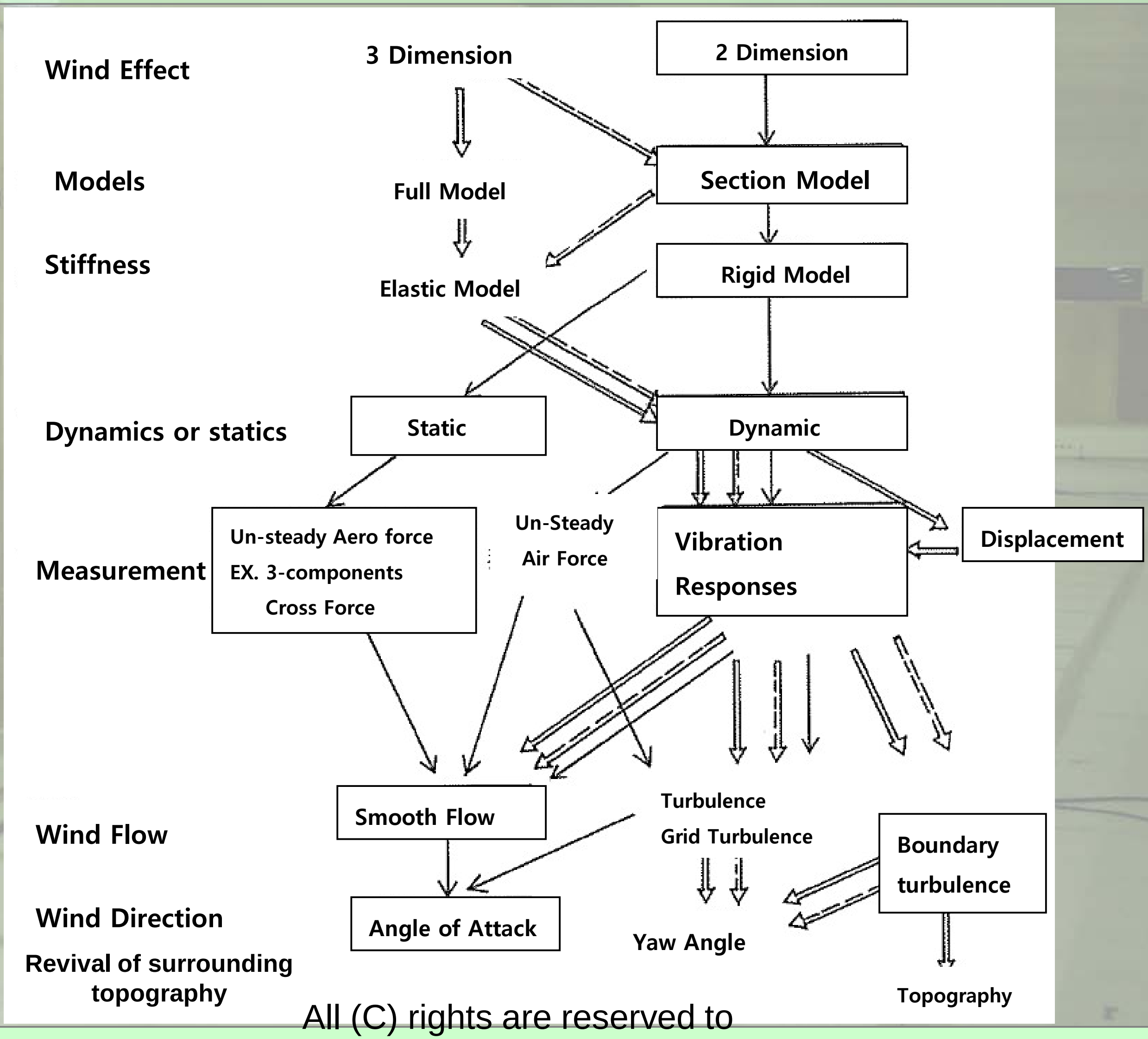
Various Kind of Wind Tunnel Tests

1） 2D Rigid Model Test
2） 3D Elastic Model Test
3） Static Coefficient Measurement
4） Unsteady Aerodynamic
5） Boundary Layer Test
6） Cable Vibration Test
7） etc.

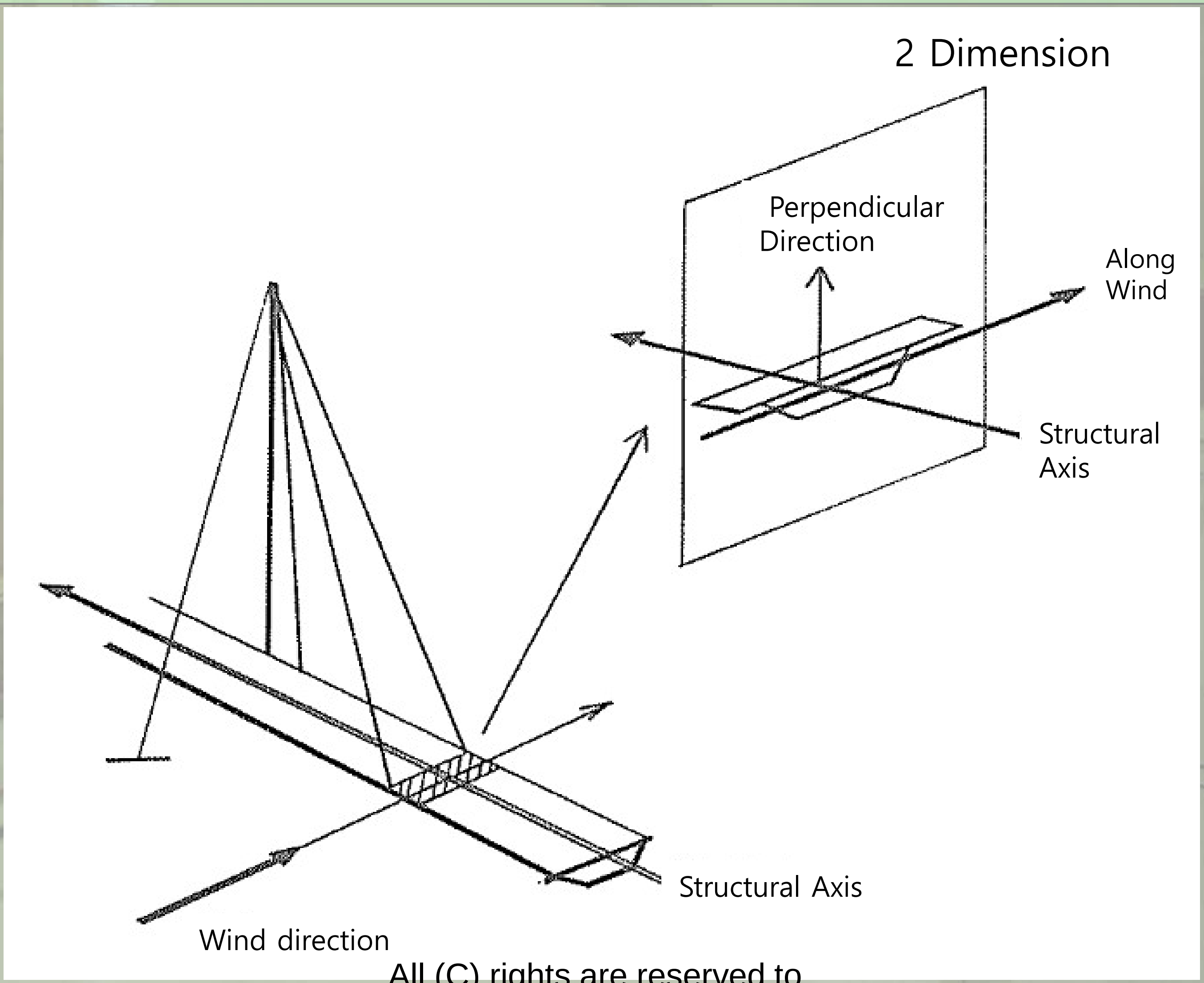
Theoretical classification of wind Tunnel Tests

- Response
  - Full Modeling of Bridge Prototype
    - Full Model Test
    - Tower Model in Erection
  - Partial Modeling of Prototype
    - Section Model Test
    - Tower Model in Completion
    - Taut Strip Model Test
- Aero-dynamic force
  - 3 Static-coefficient Measurement
  - Unsteady Force Measurement
- Wind characteristics
  - Topological Model Test(Measurement of Wind Velocity)

How to choose wind tunnel test?

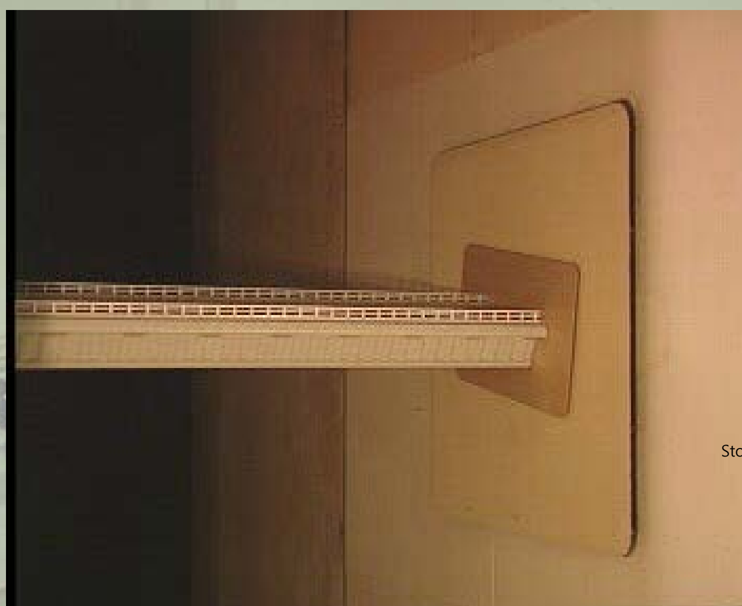


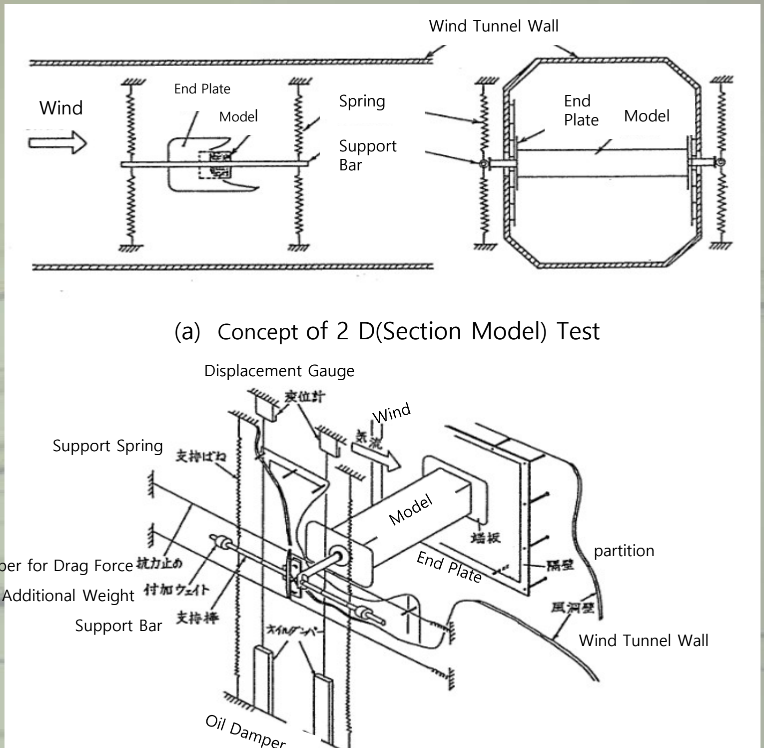
Concept of 2 D(Section) Model Test



Section Model Test

- [Section Model Test]





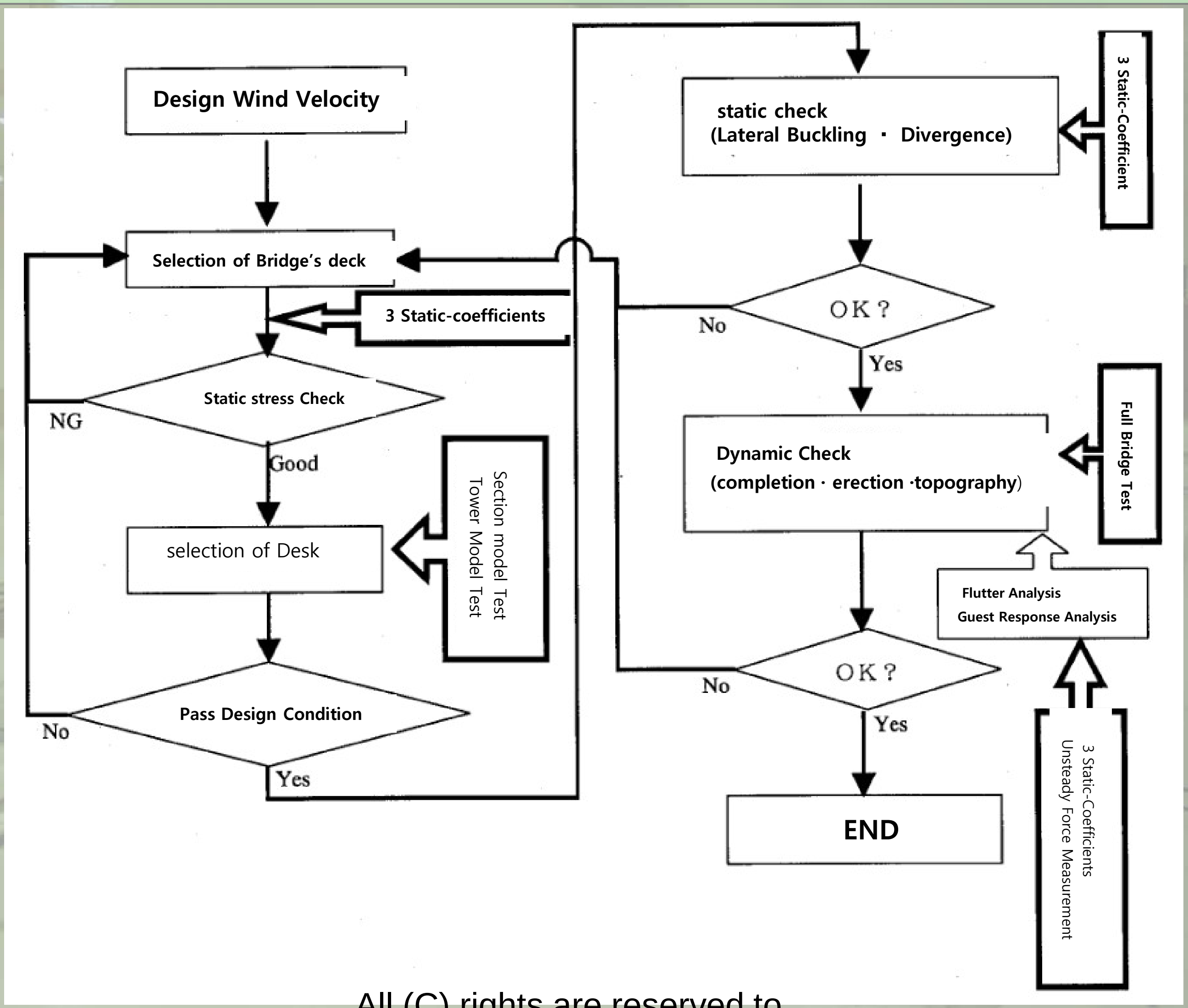
(a) Concept of 2 D(Section Model) Test

(b) Mechanism of 2 D Test

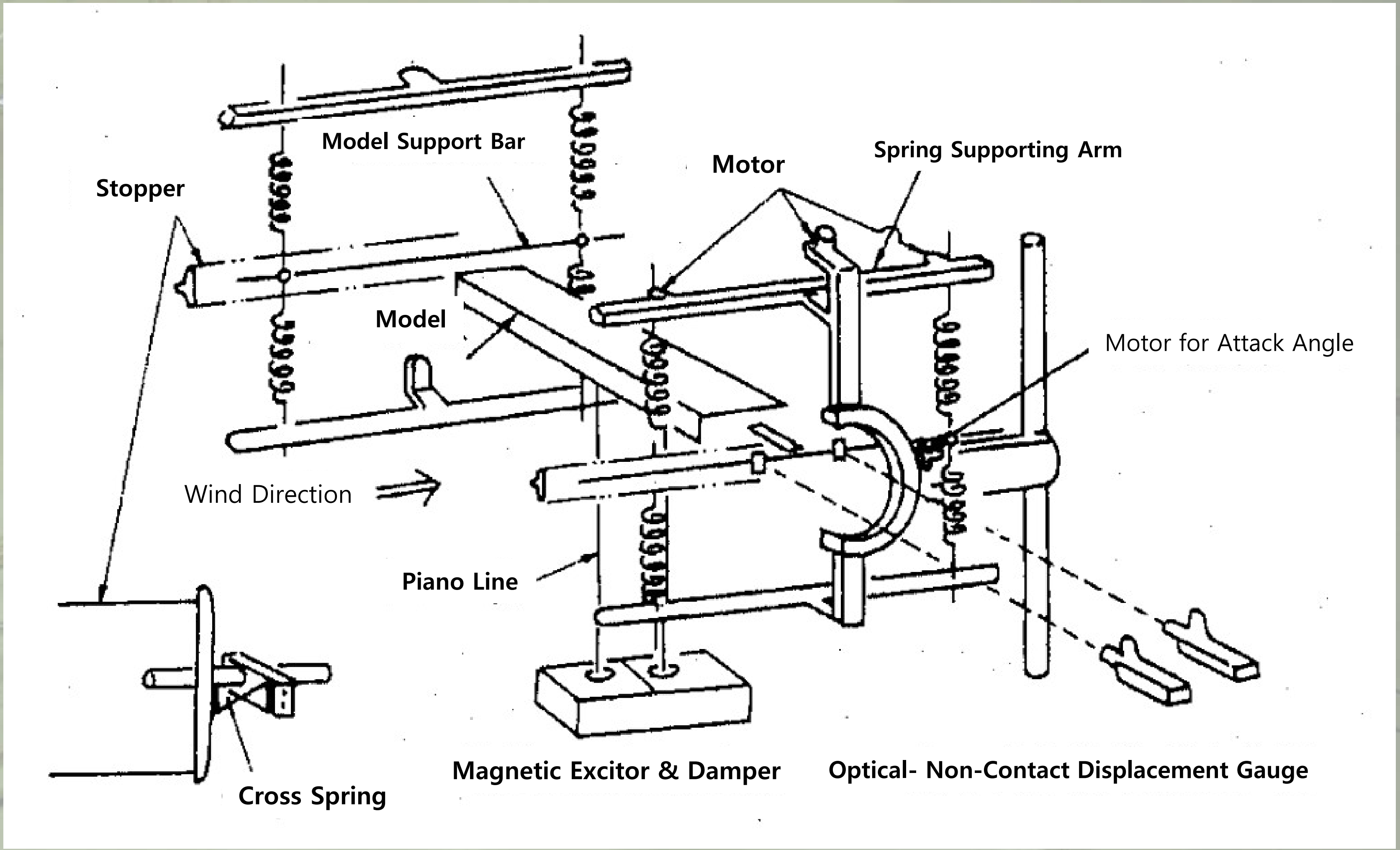
3 Dimensional Full Model Tests

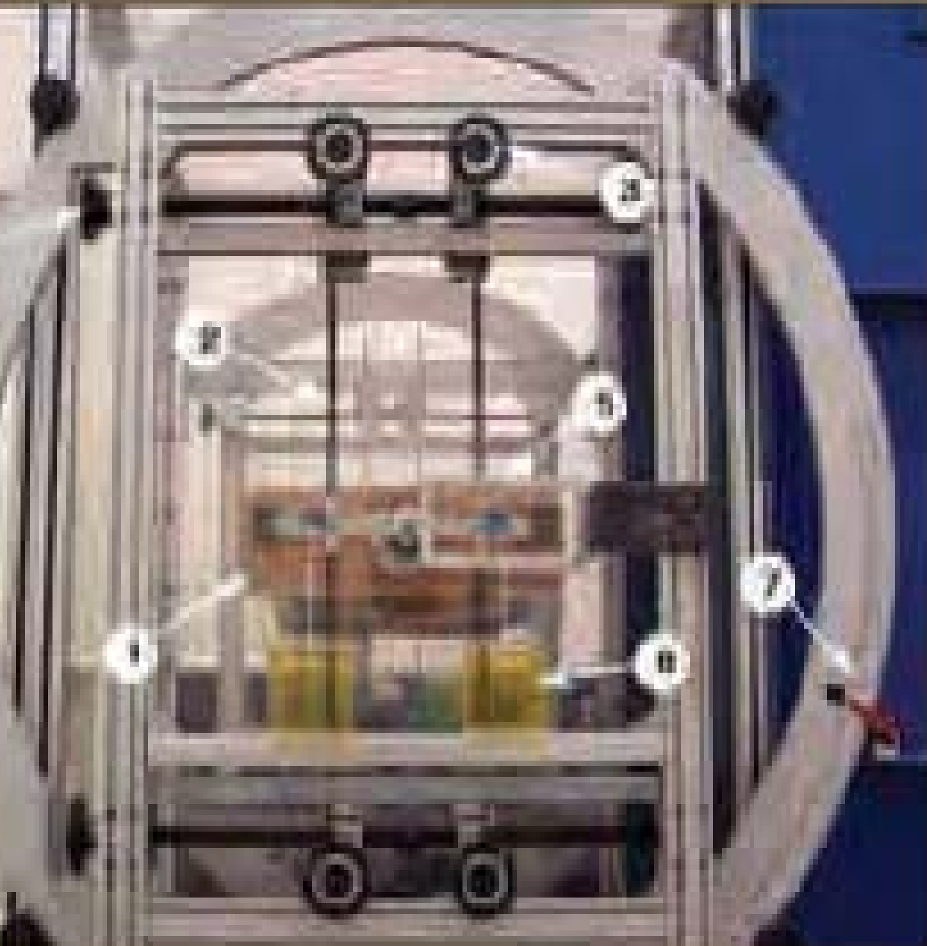
3-D Wind Tunnel of University Tokyo Model: Meiko Nishi Bridge

1. Wind Tunnel Simulation of Bridges



2 D(section) Model Test Devise





①단면모형

②Coil Spring

③스프링길이 조정장치

④스프링간격 조정장치

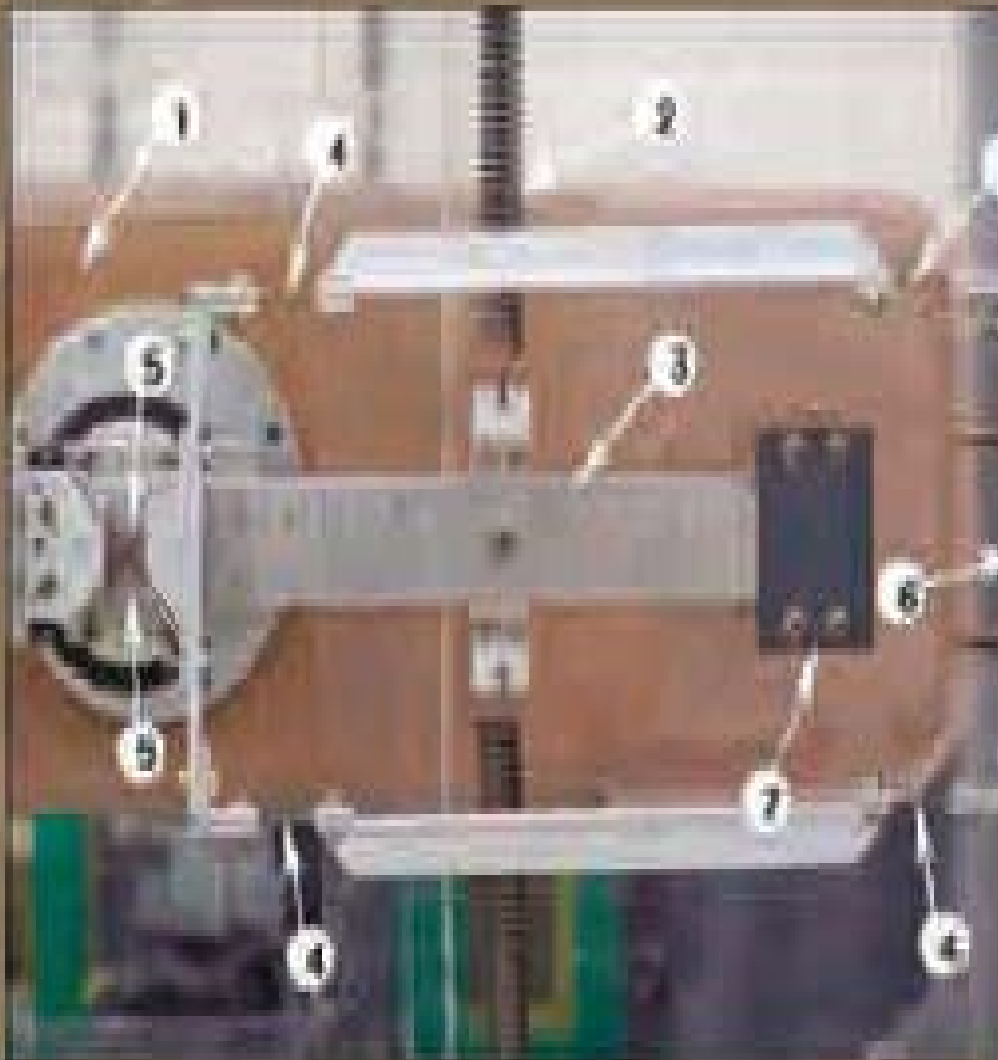
⑤연직 및 비틀림 자유도 시스템

⑥Oil Damper

⑦영각표시기

⑧영각구동장치

설비



①실험모형의 단판

②Coil Spring

③수평자

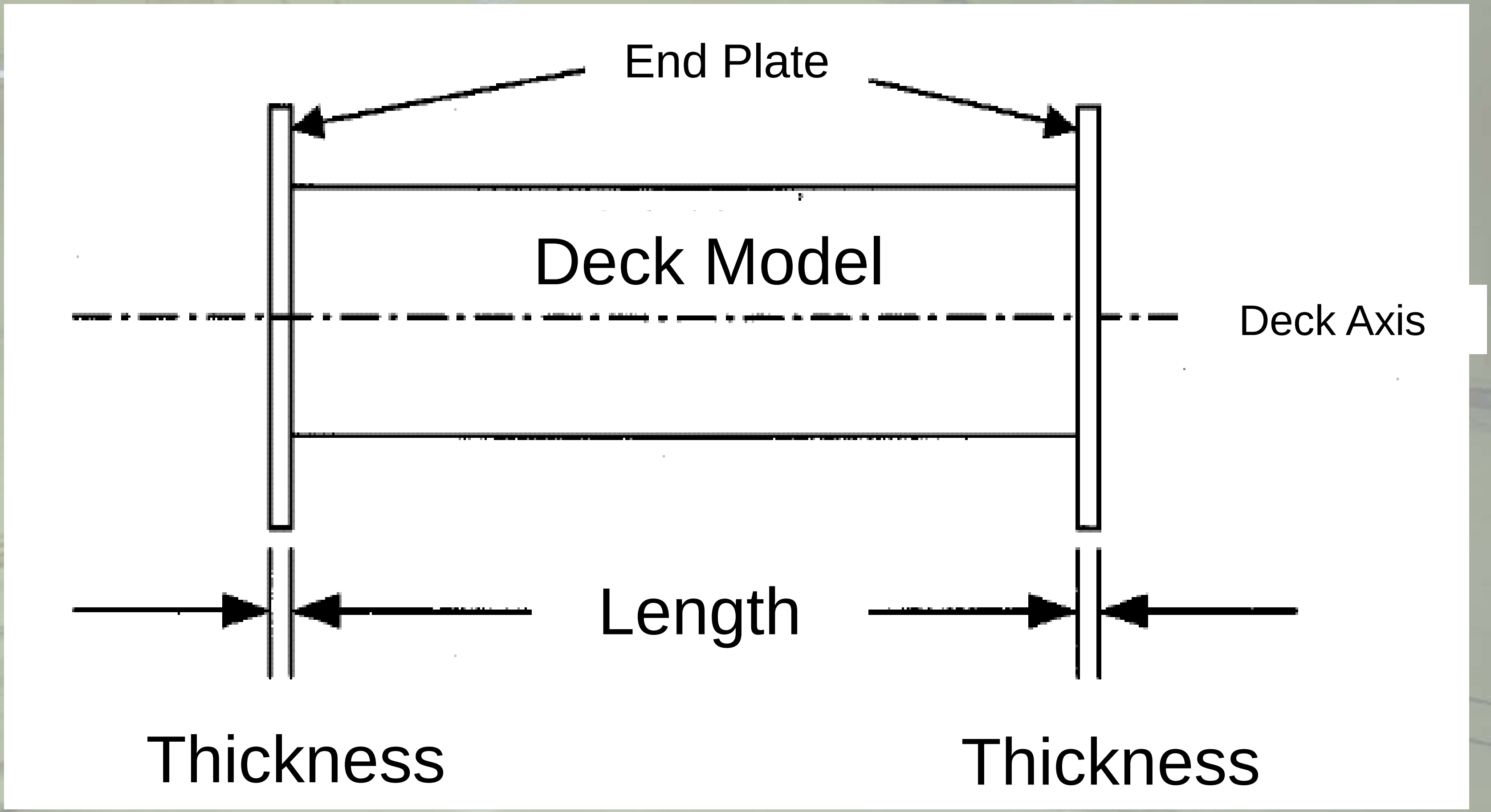
④연직자유도를 위한 판스프링

⑤비틀림자유도를 위한 판스프링

⑥기류방향 자유도 구속장치

⑦추가 질량

What is a section model？



2D (Section) Model Test

Grid Turbulent

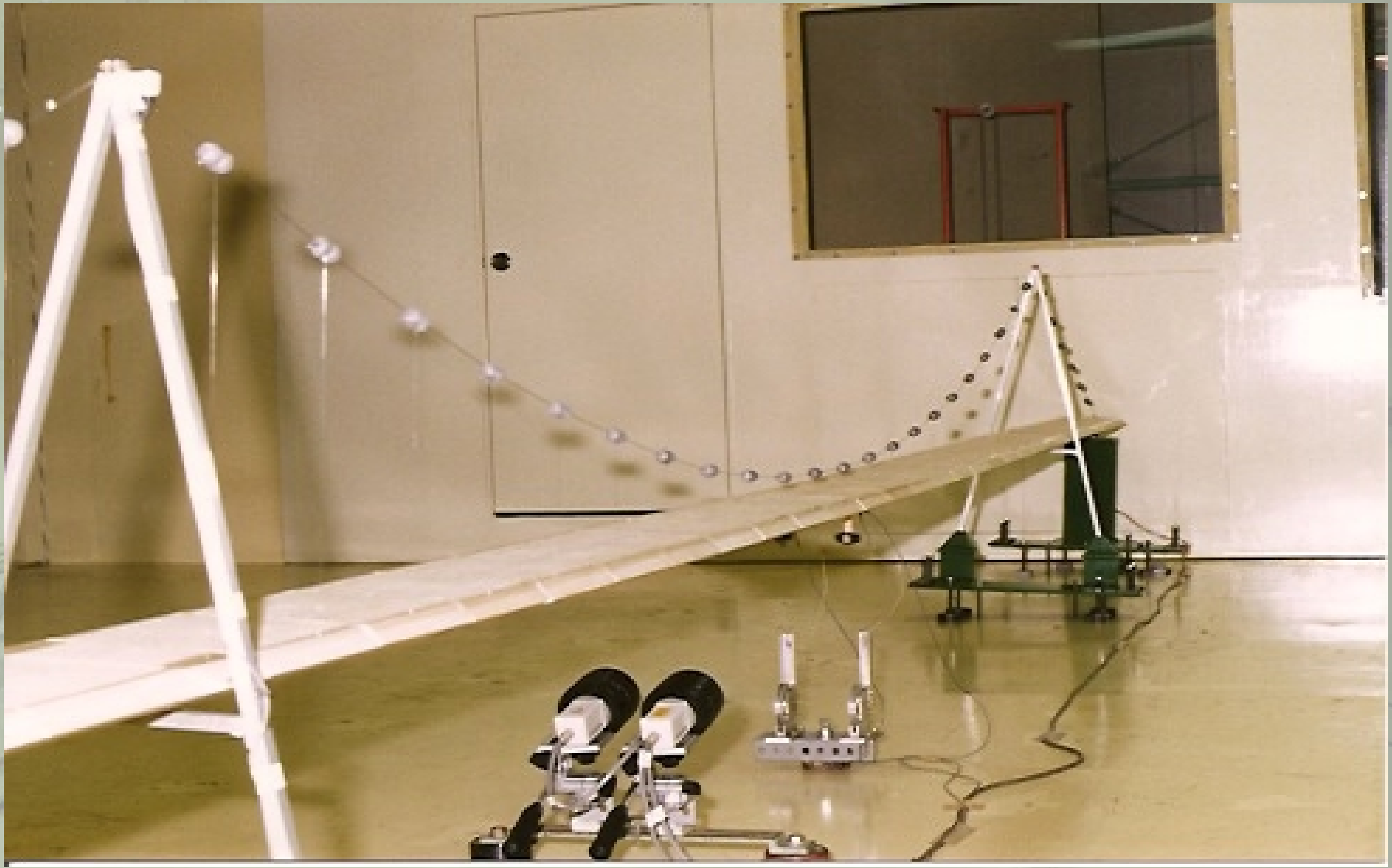
In Smooth Flow

In Turbulent Flow

3-D (Full) Model Test

Incheon Bridge

3D Full Model Test （by Dr.Tanaka）



Mono Cable Suspension Bridge

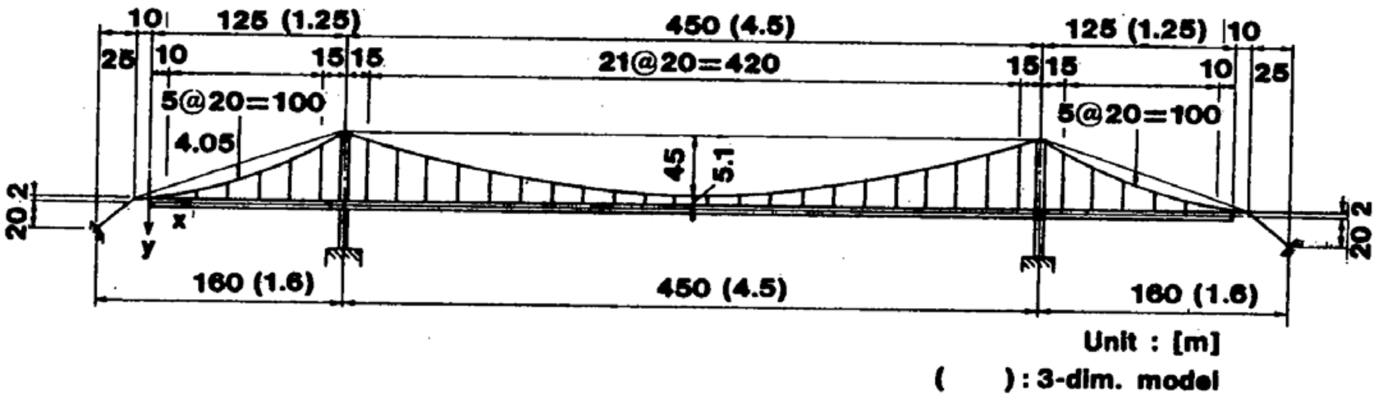


Fig.3.3.1 Mono-cable suspension bridge

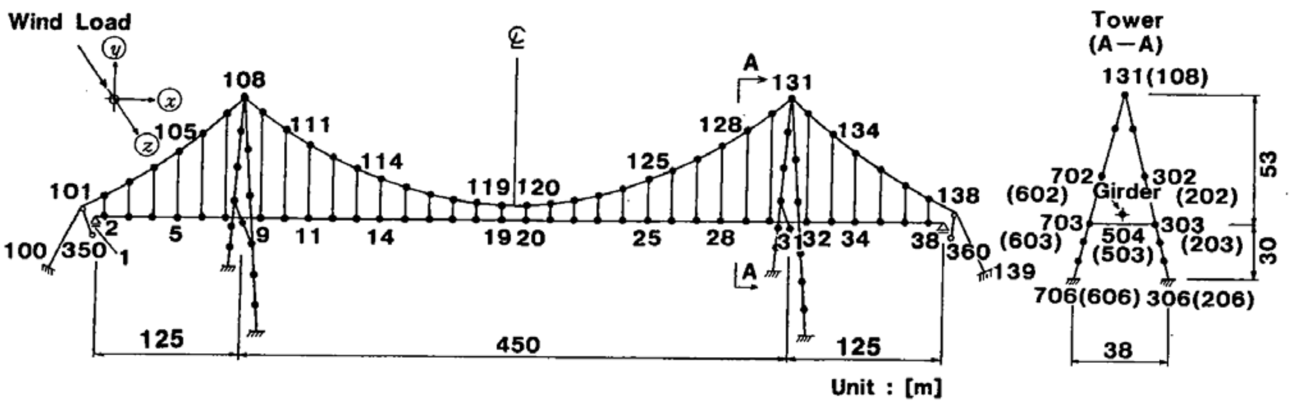


Fig.3.3.2 Analysis model of mono-cable suspension bridge

Ref. pp.39 from Dr. Hiroshi TANAKA Doctor Dissertation for Kyoto Univ. in 1993

Similarity Requirements

- Geometry Similarity
- Deck model tests require the following similarities

$$\frac{\Theta_\theta}{\rho B^4}\ ,\quad \frac{m_\eta}{\rho B^2}\ ,\quad \frac{V}{N_\theta B}\ ,\quad \frac{V}{N_\eta B}\ ,\quad \delta_\theta\ ,\quad \delta_\eta$$

Polar Inertia, Mass , Wind Velocity , Damping

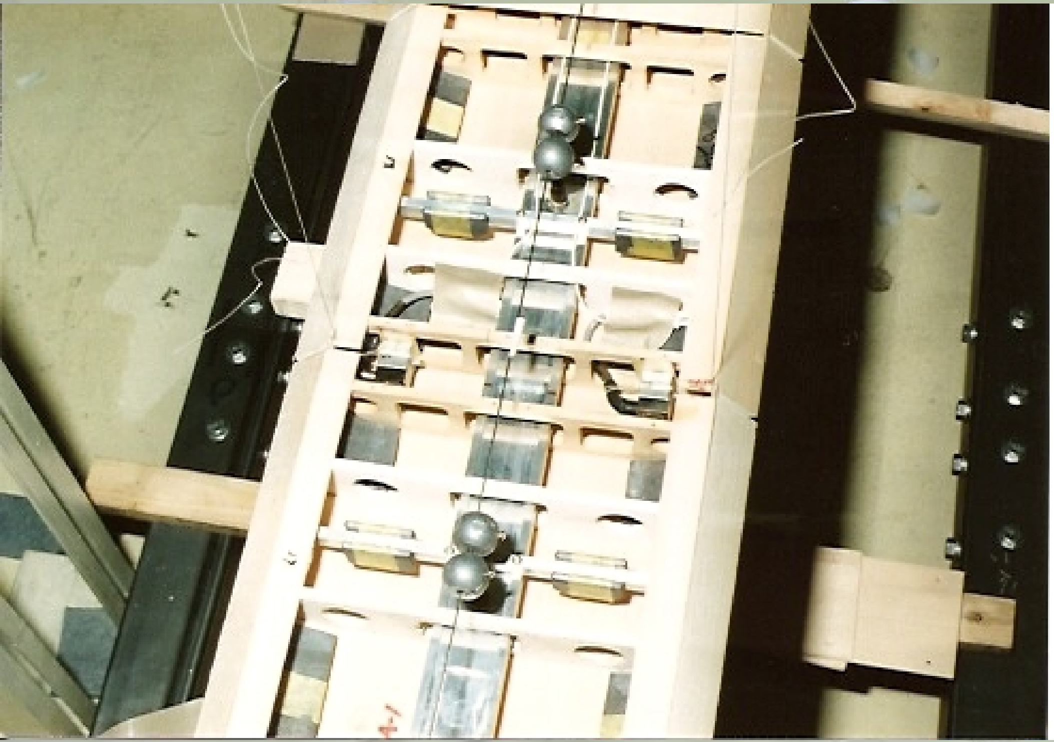
Table 3.: Three-dimensional model

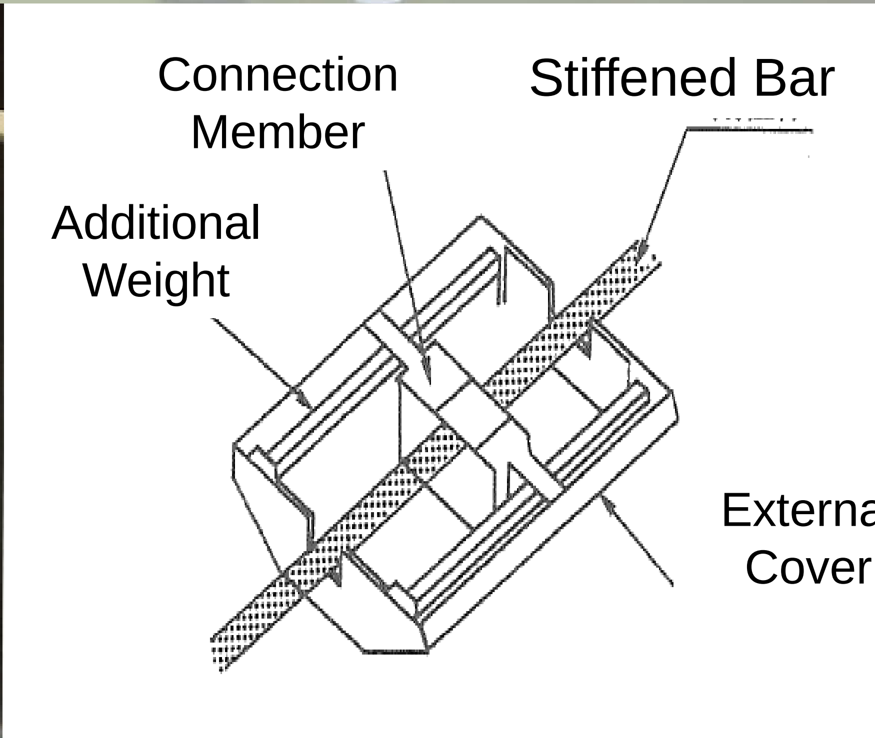
n = 100

Item	Prototype	Required Values		Model
Scale	1	1/n	1/100	1/100
Mass				
Cable	3.4 t/m	$1/n^2$	3.4 g/cm	3.4 g/cm
Girder	26.5 t/m	$1/n^2$	26.5 g/cm	26.5 g/cm
Tower	14.5 t/m	$1/n^2$	14.5 g/cm	4.8 g/cm
Mass Moment				
Girder	1060 tm^2/m	$1/n^4$	1060 $g{\cdot}cm^2/cm$	1060 $g{\cdot}cm^2/cm$
Stiffness				
Girder				
Vertical (EI_z)	$4.14 \times 10^7 tfm^2/Br$	$1/n^5$	4.14 $kgf{\cdot}m^2$	4.14 $kgf{\cdot}m^2$
Lateral (EI_y)	$55.1 \times 10^7 tfm^2/Br$	$1/n^5$	55.1 $kgf{\cdot}m^2$	85.9 $kgf{\cdot}m^2$
Torsion (GJ)	$1.67 \times 10^7 tfm^2/Br$	$1/n^5$	1.67 $kgf{\cdot}m^2$	1.67 $kgf{\cdot}m^2$
Cable (EA)	$0.82 \times 10^7 tf$	$1/n^3$	$8.2 \times 10^3 kgf/Br$	$5.7 \times 10^3 kgf/Br$
Frequency				
Vertical	0.2424 Hz	$\sqrt{n}$	2.424	2.53
Torsion	0.2999 Hz	$\sqrt{n}$	2.999	3.13
Freq. Ratio	1.237	1	1.237	1.237

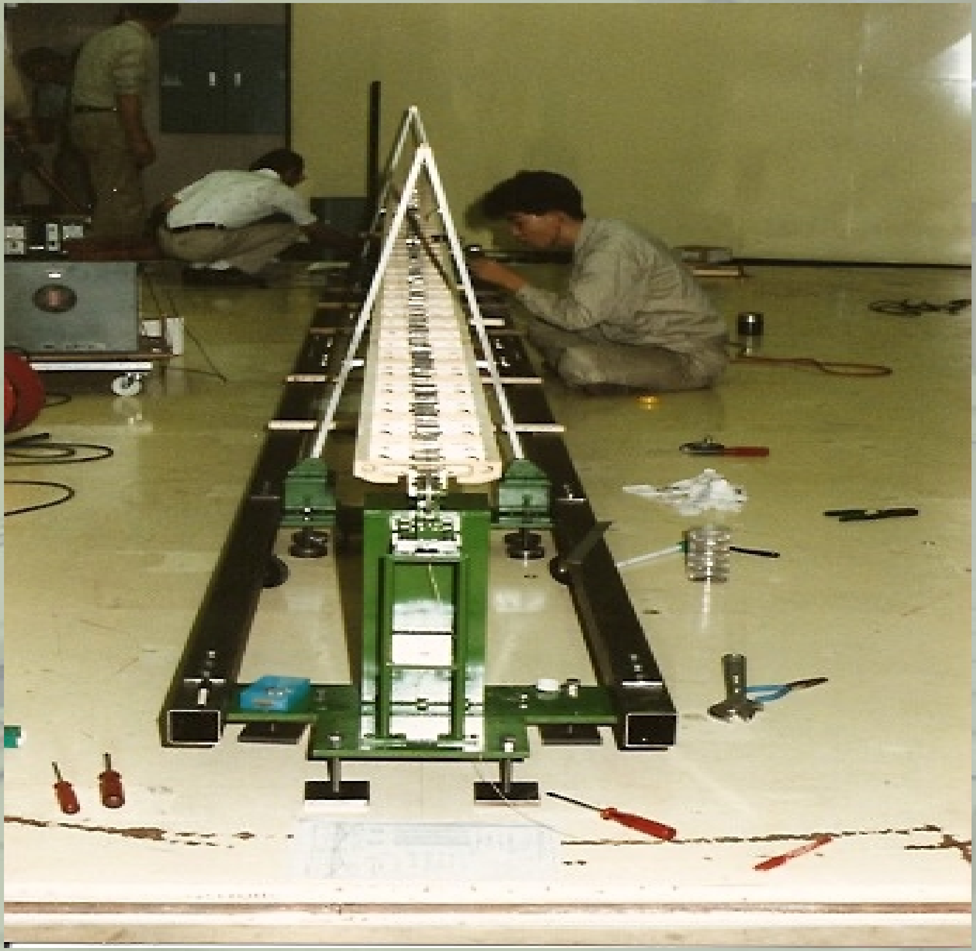
Ref. pp.45 from Dr. Hiroshi TANAKA Doctor Dissertation for Kyoto Univ. in 1993

Inside of 3D-Model



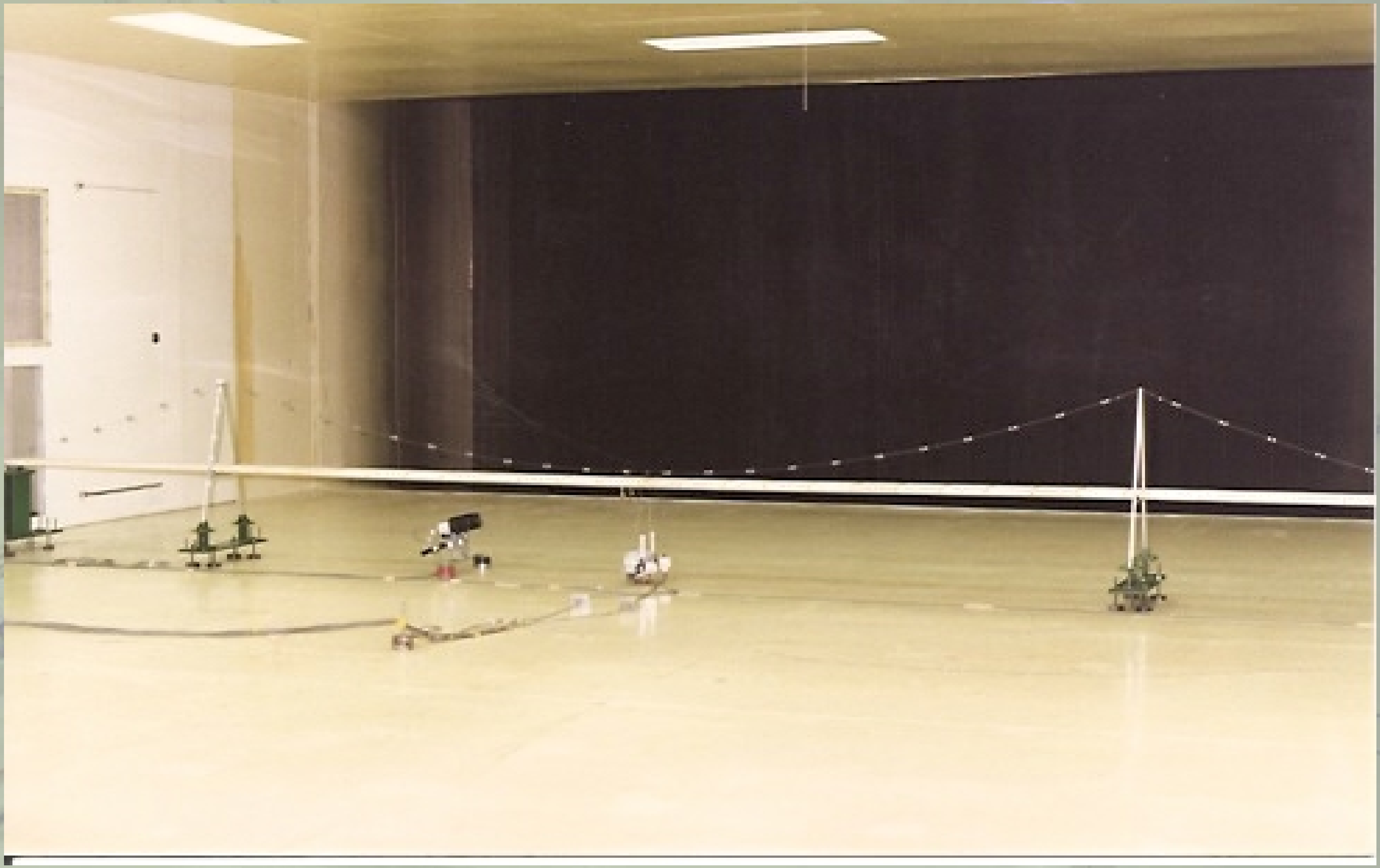


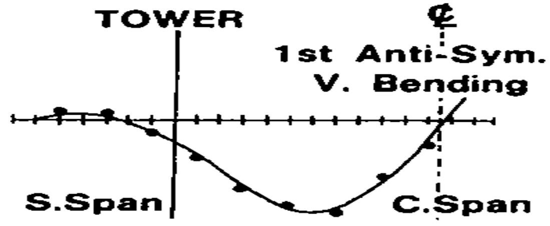
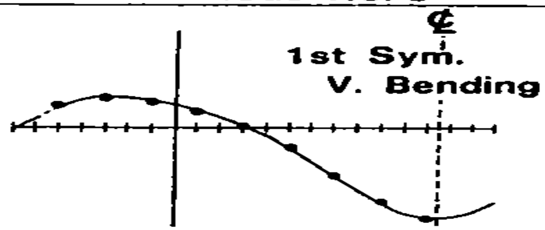
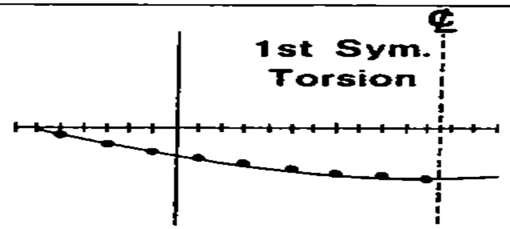
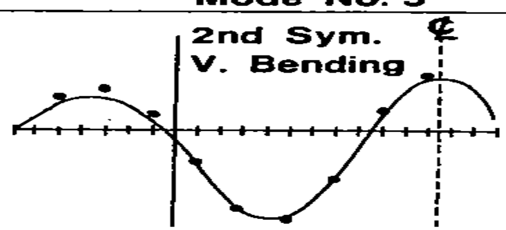
Full Model Assembling Work



Geometric Measurement

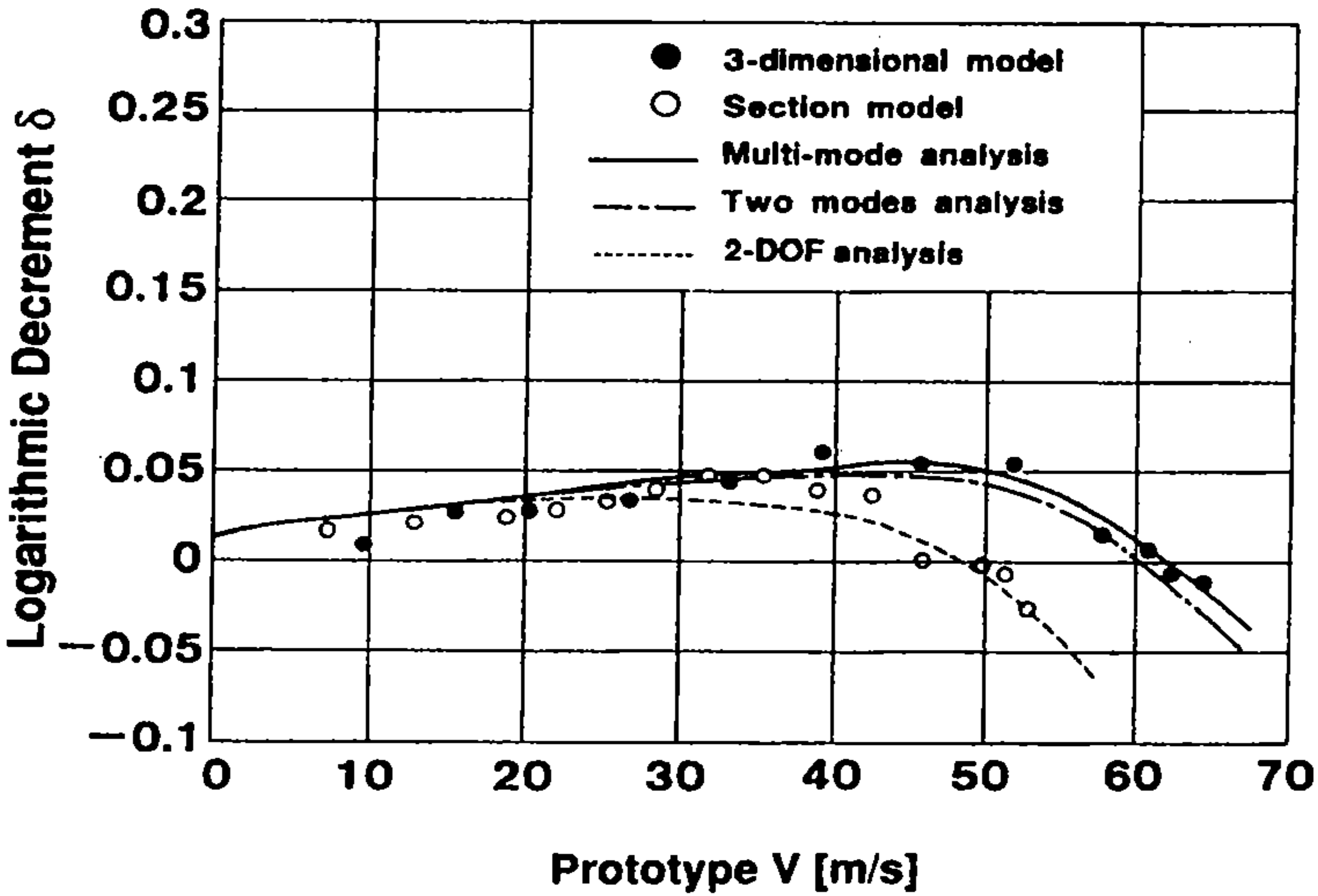
Completion of Full Model



Mode Shape —— Analysis ● Measured on Model	Analysis Prototype f_i [Hz]	Measured Model $\frac{f_i}{\sqrt{100}}$ [Hz]	Model Damping δ_i
 Mode No. 3	0.2219	0.225	0.079
 Mode No. 4	0.2424	0.253	0.014
 Mode No. 5	0.2999	0.313	0.012
 Mode No. 8	0.3745	0.371	0.014

(N.B.—— on other side span with sign change for Ant-Sym. Modes)

Ref. pp.50 from Dr. Hiroshi TANAKA Doctor Dissertation for Kyoto Univ. in 1993



(a) $\alpha = 0°$

Ref. pp.54 from Dr. Hiroshi TANAKA Doctor Dissertation for Kyoto Univ. in 1993

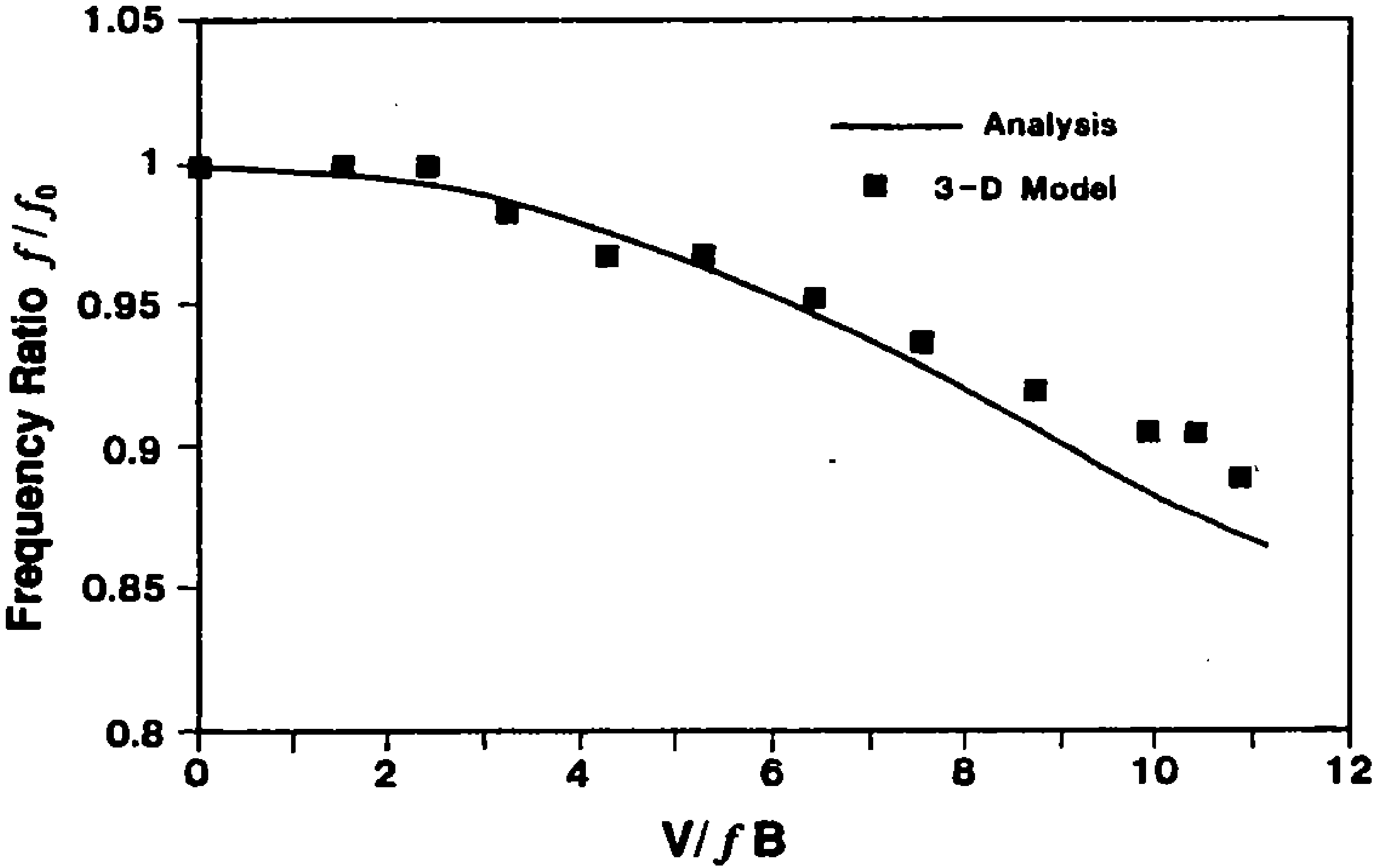


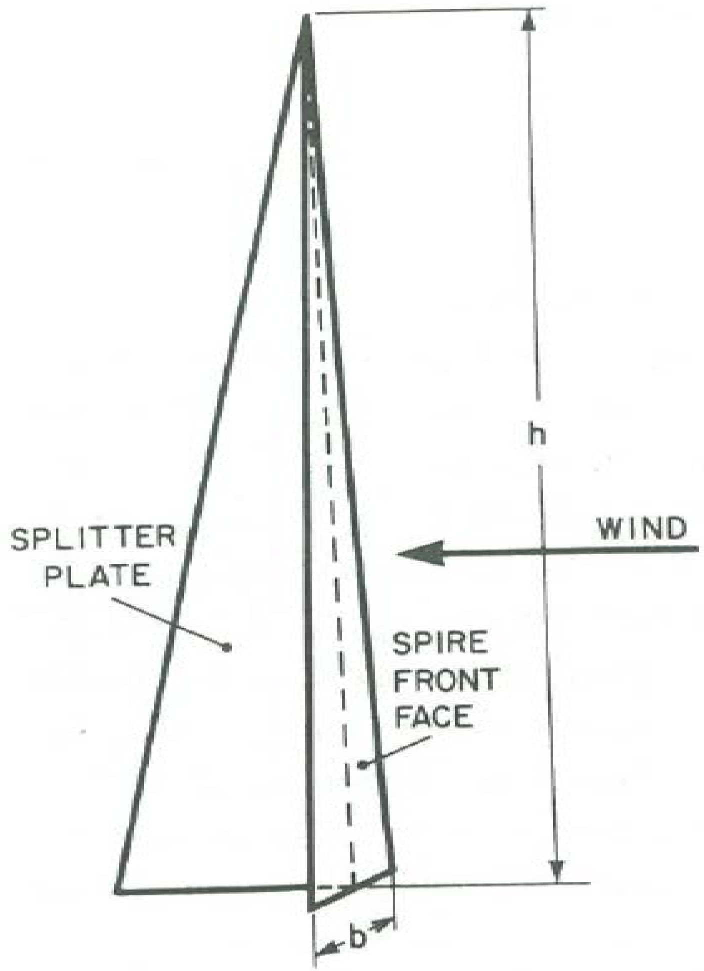
Fig.3.4.6 Frequency ratio f/f_0 of tapered box section ($\alpha = 0°$; 3-D model) and analysis

Ref. pp.56 from Dr. Hiroshi TANAKA Doctor Dissertation for Kyoto Univ. in 1993

3D Full Model Test with Water Tank

Wave Generator

3－D Turbulent Flow （Spire）



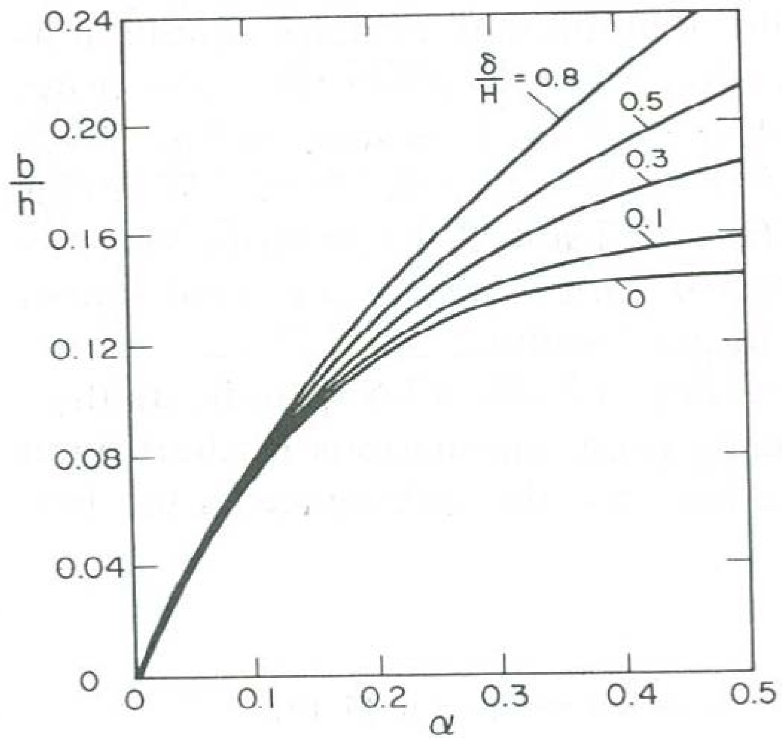
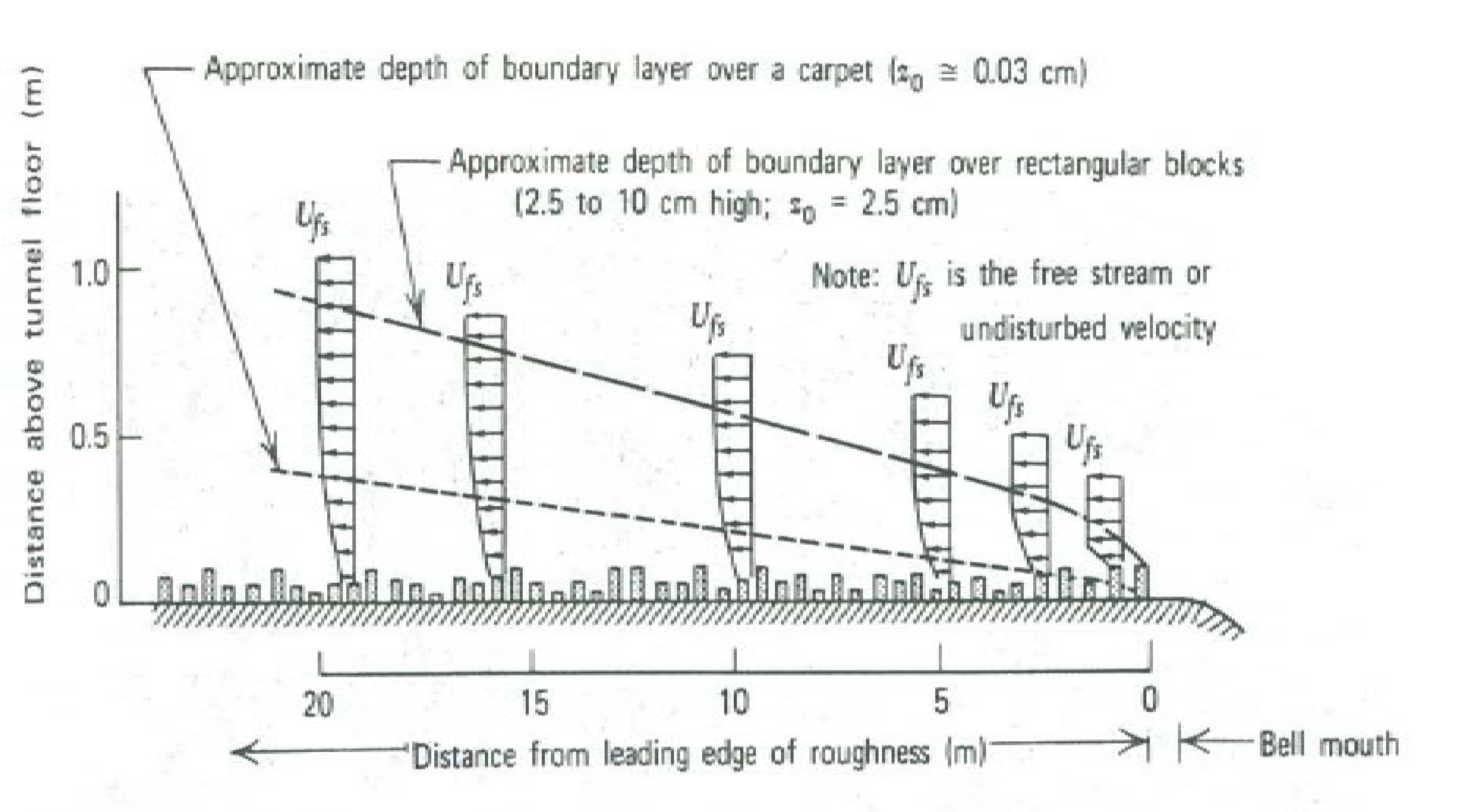


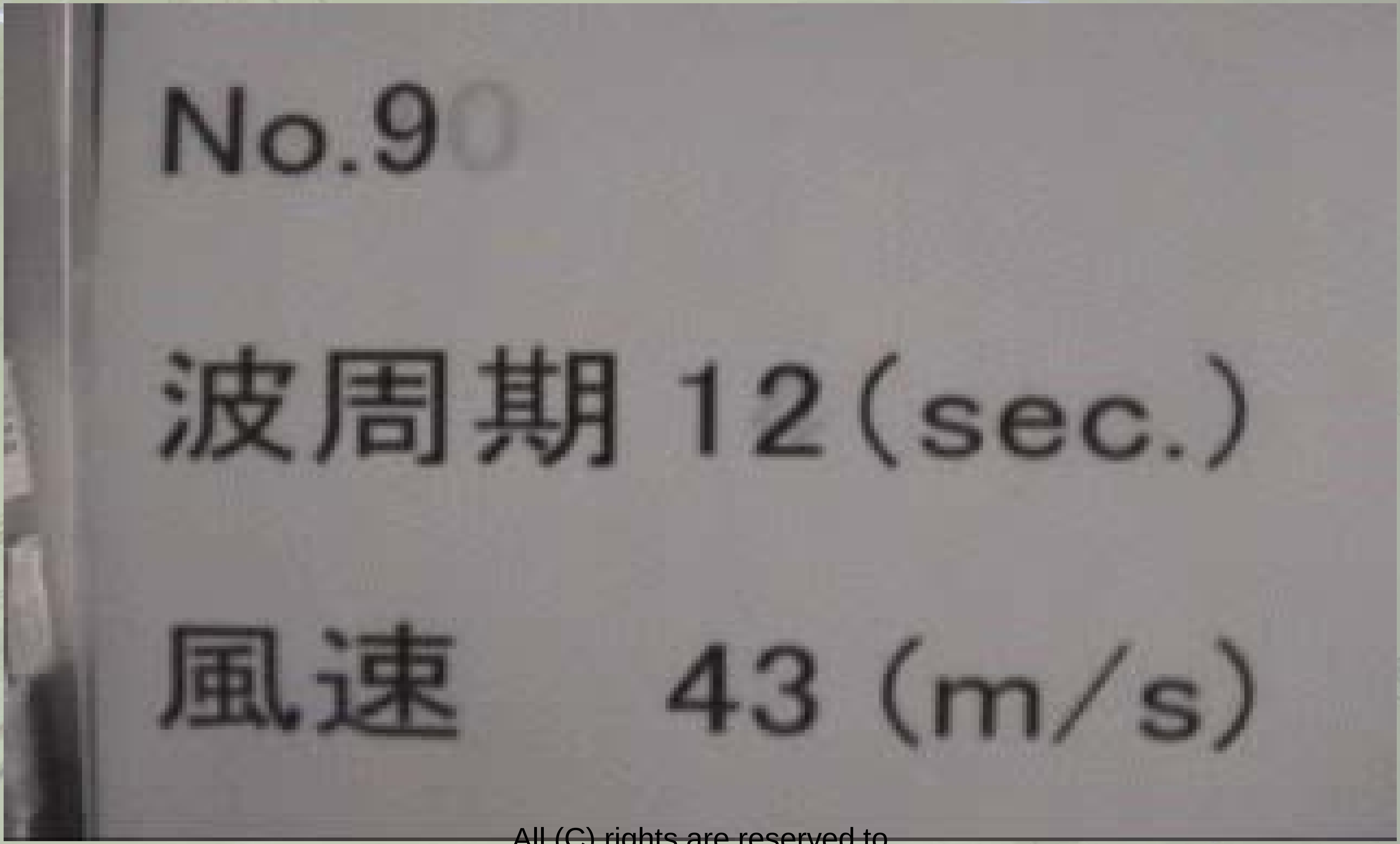
FIGURE 7.2.5. A proposed spire configuration. From H. P. A. H. Irwin, "The Design of Spires for Wind Simulation," *J. Wind Eng. Ind. Aerodyn.*, 7 (1981), 361–366.

3－D Turbulent Flow （Block）



Ref. PP.283 Simiu & Scanlan Wind Effects on Structures Third Edition

3D Test of Floating Bridge



Yume-Mai Floating Bridge

3D Tower Model Test（Erection）

Turbulent Flow

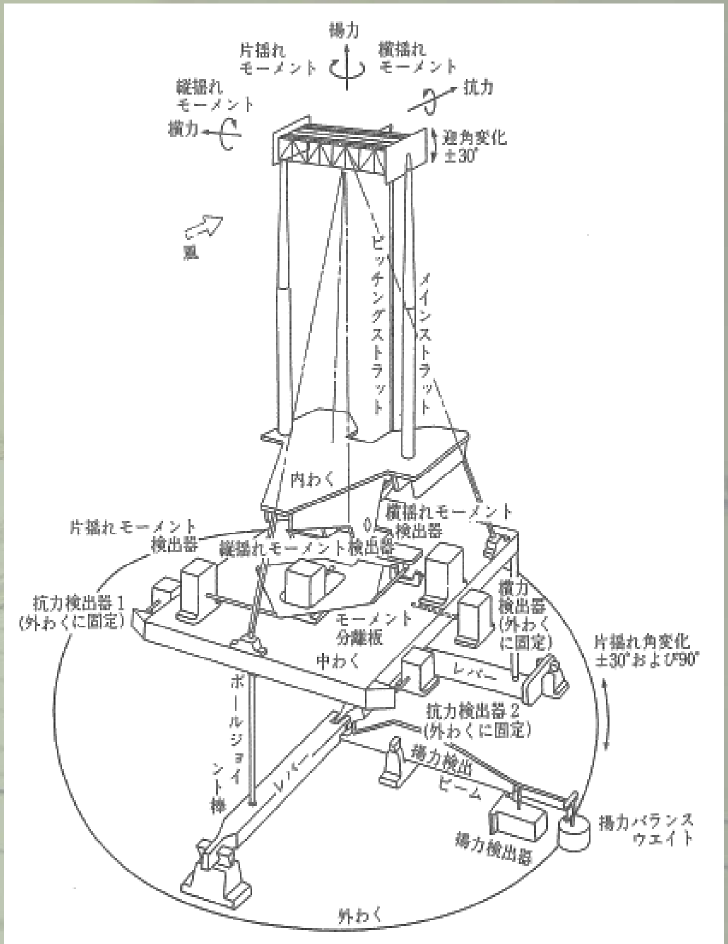
Static Aero-Coefficients

Definition is as follows:

$$C_D = P_D \Big/ \frac{1}{2}\rho V^2 A_n, \quad C_L = P_L \Big/ \frac{1}{2}\rho V^2 B, \quad C_M = M \Big/ \frac{1}{2}\rho V^2 B^2,$$

Measurement of P_D, P_L, M and V, ρ, A,B

3-Static-Coefficients Measurement (C_D,C_L,C_M)



図－10.4　六分力天秤の例

Example C_D C_L C_M

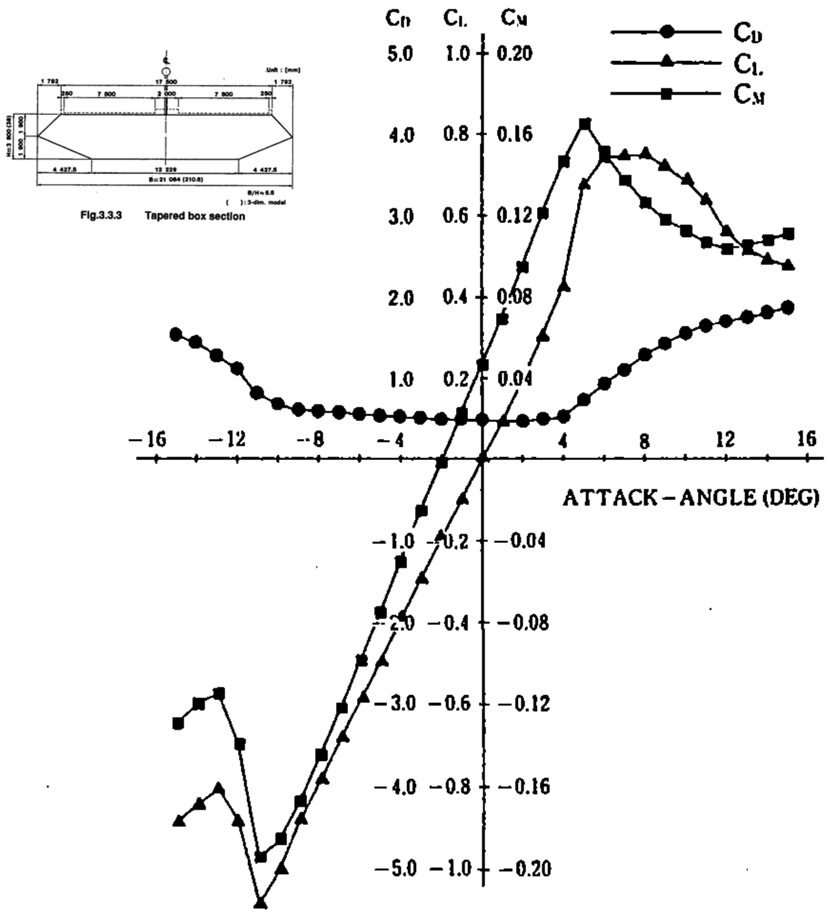


Fig.3.3.5 **Drag, lift and moment coefficients for tapered box section**

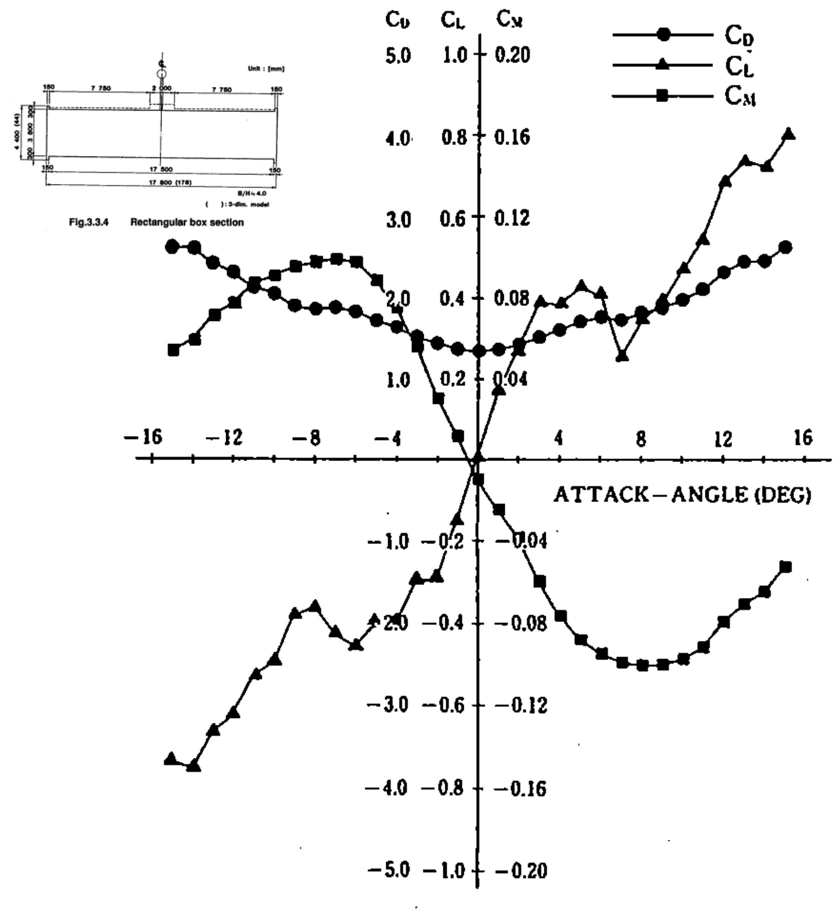


Fig.3.3.6 **Drag, lift and moment coefficients for rectangular box section**

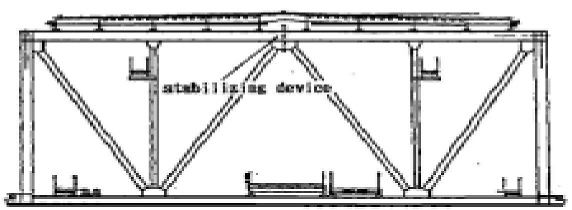
Tapered Box Section Rectangular Box Section

Example of Drag Force

Static forces:

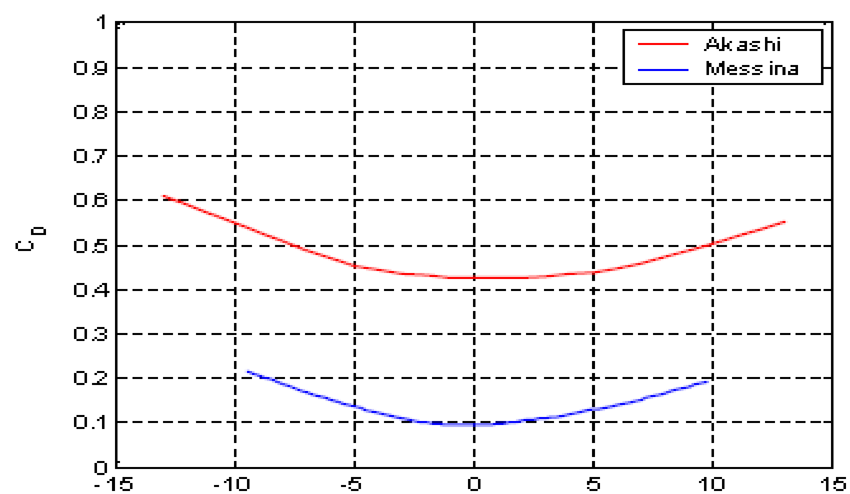
- Low C_D ⇒ wing profile

Akashi



Messina

$$F_D = \frac{1}{2}\rho V^2 B L C_D(\vartheta)$$



Static deformation under design wind speed:

Akashi: 60 m/s - 25 m

Messina: 62 m/s - 10 m

Rain-Wind Induced Vibration

Cable Vibration Phenomena

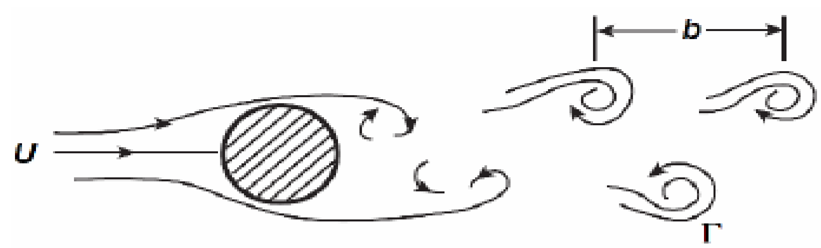
• Vortex-induced Vibration

Karman Vortex Trail

fs = SV/D ≒ 0.2V/D

High order mode、Low Wind velocity

$\delta = 0.01$ or more



• Wake Galloping (Wake-induced Flutter)

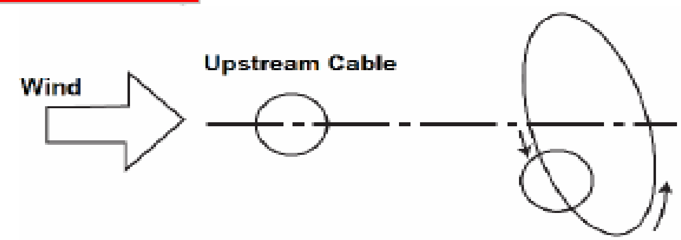
Spacing of Two Cables

Distance : 2<X/D<5 (10<X/D<20)

1st mode

Wind Velocity : V=25~50fnD

$\delta = 0.05$



• Rain Vibration

Water Rivulet (Rainfall) on Smooth Surface

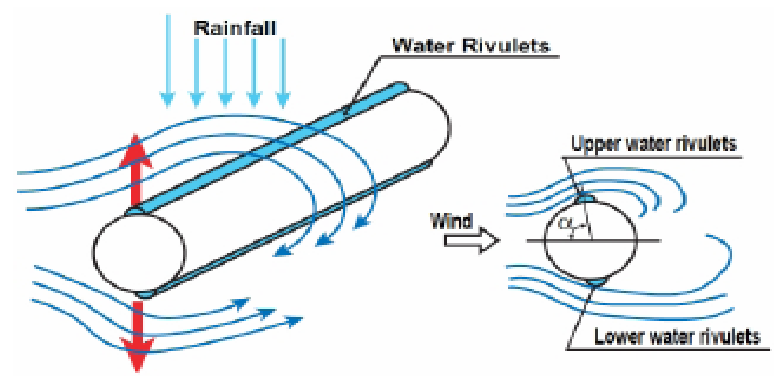
Lower order mode 1st~3rd mode

Frequency 1~3 Hz

Node length ≒50m

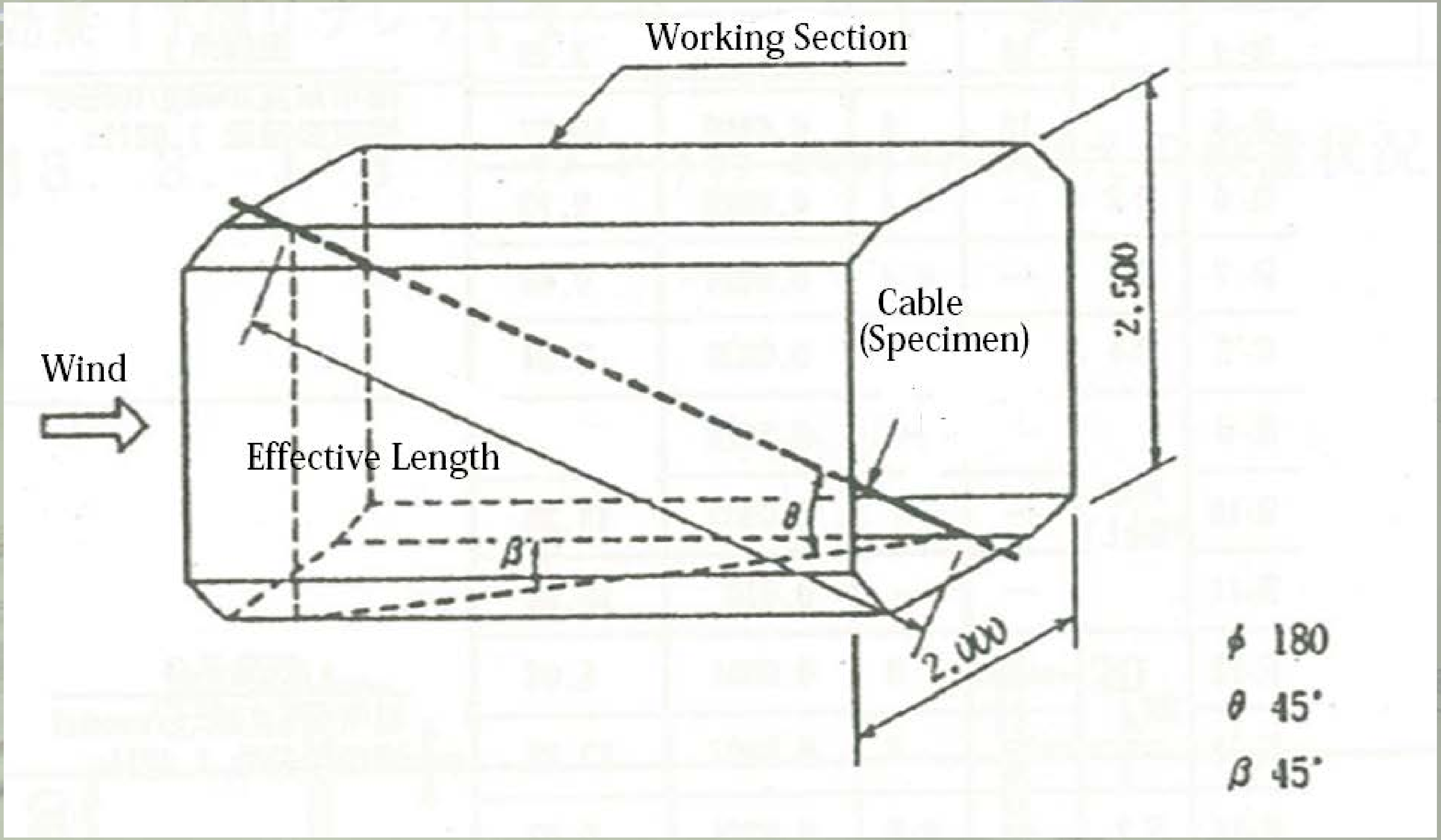
Wind Velocity : V=6~18m/sec with Rain

$\delta = 0.02 \sim 0.03$

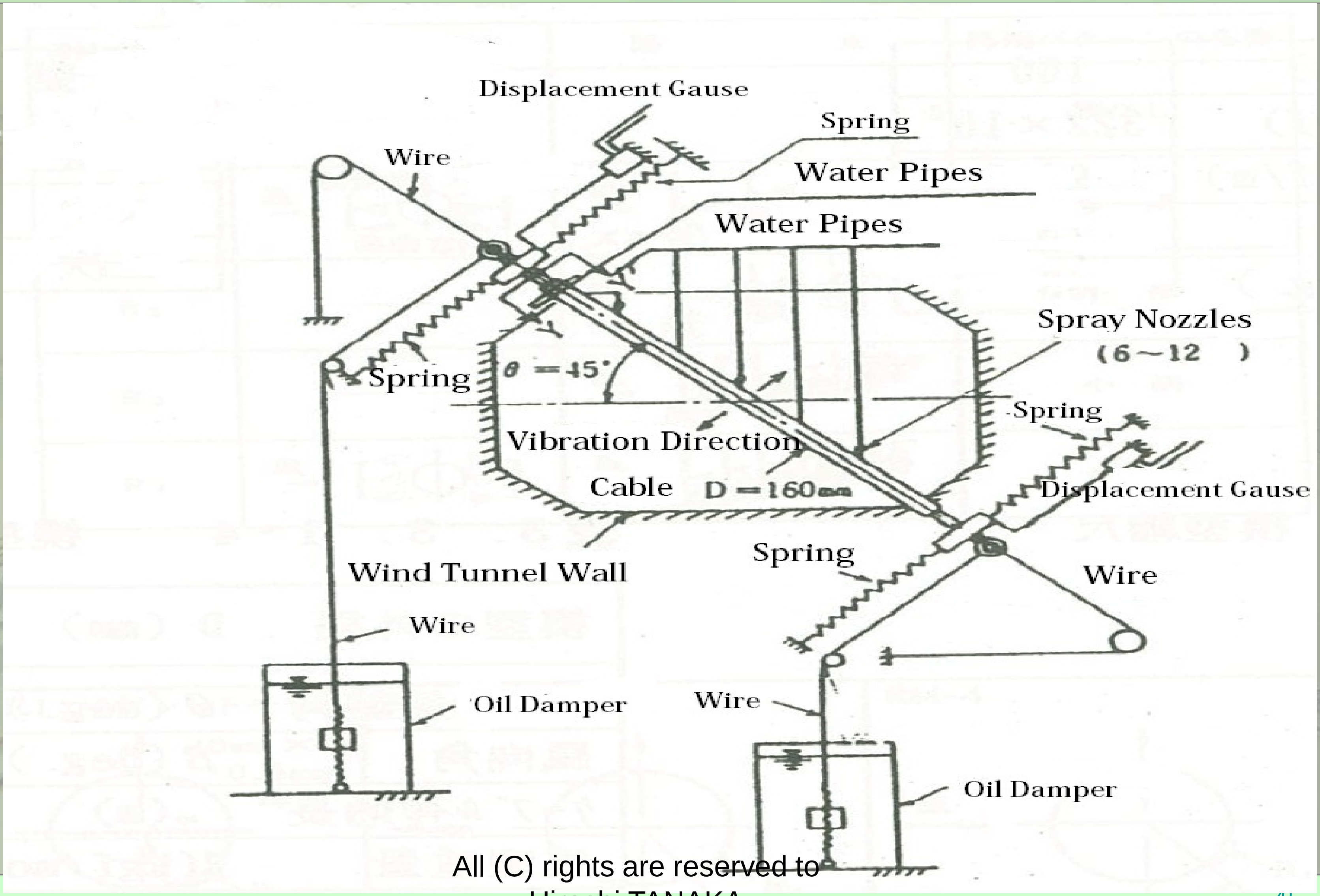


Wind Tunnel Devise

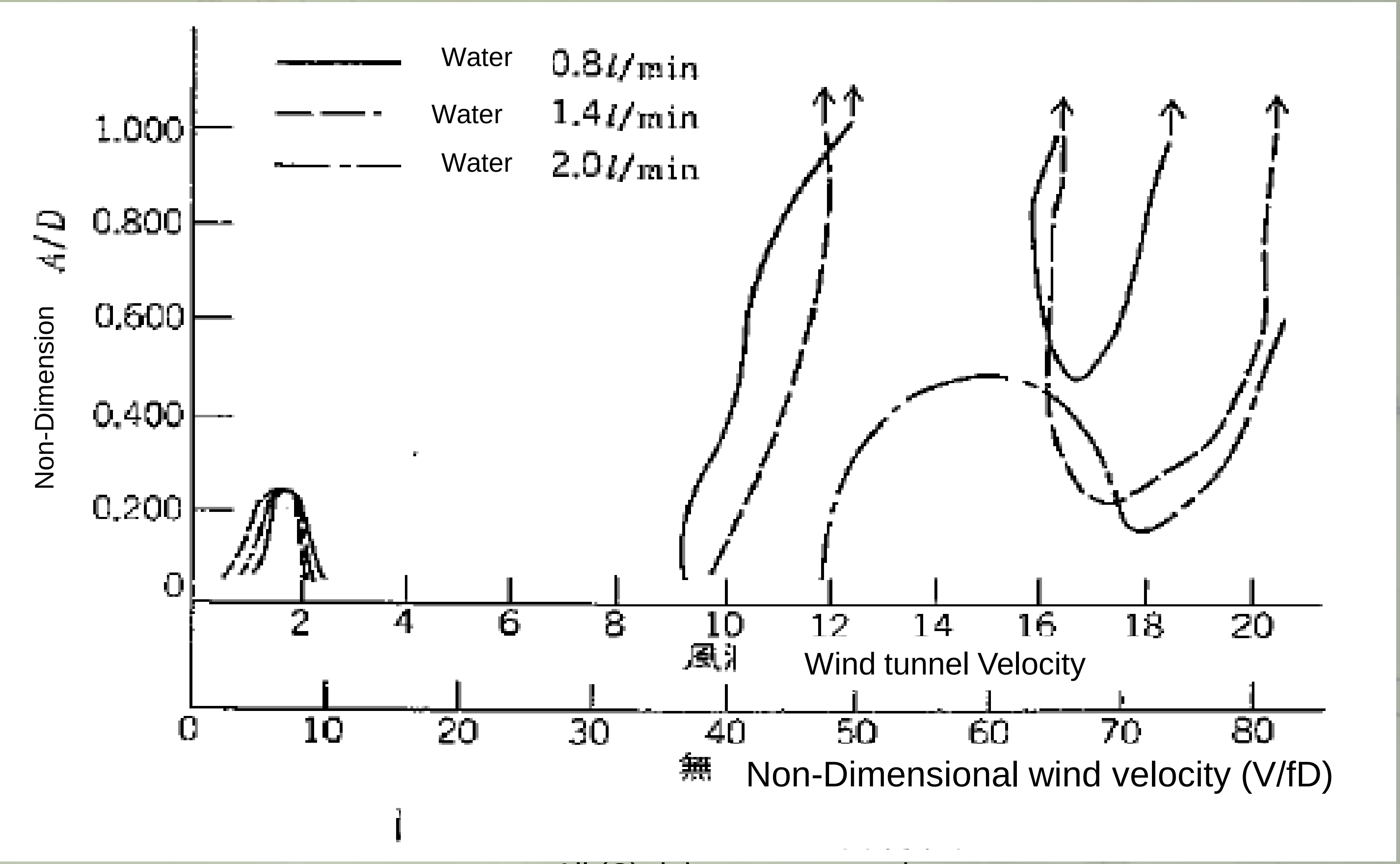
Test Setting(1)



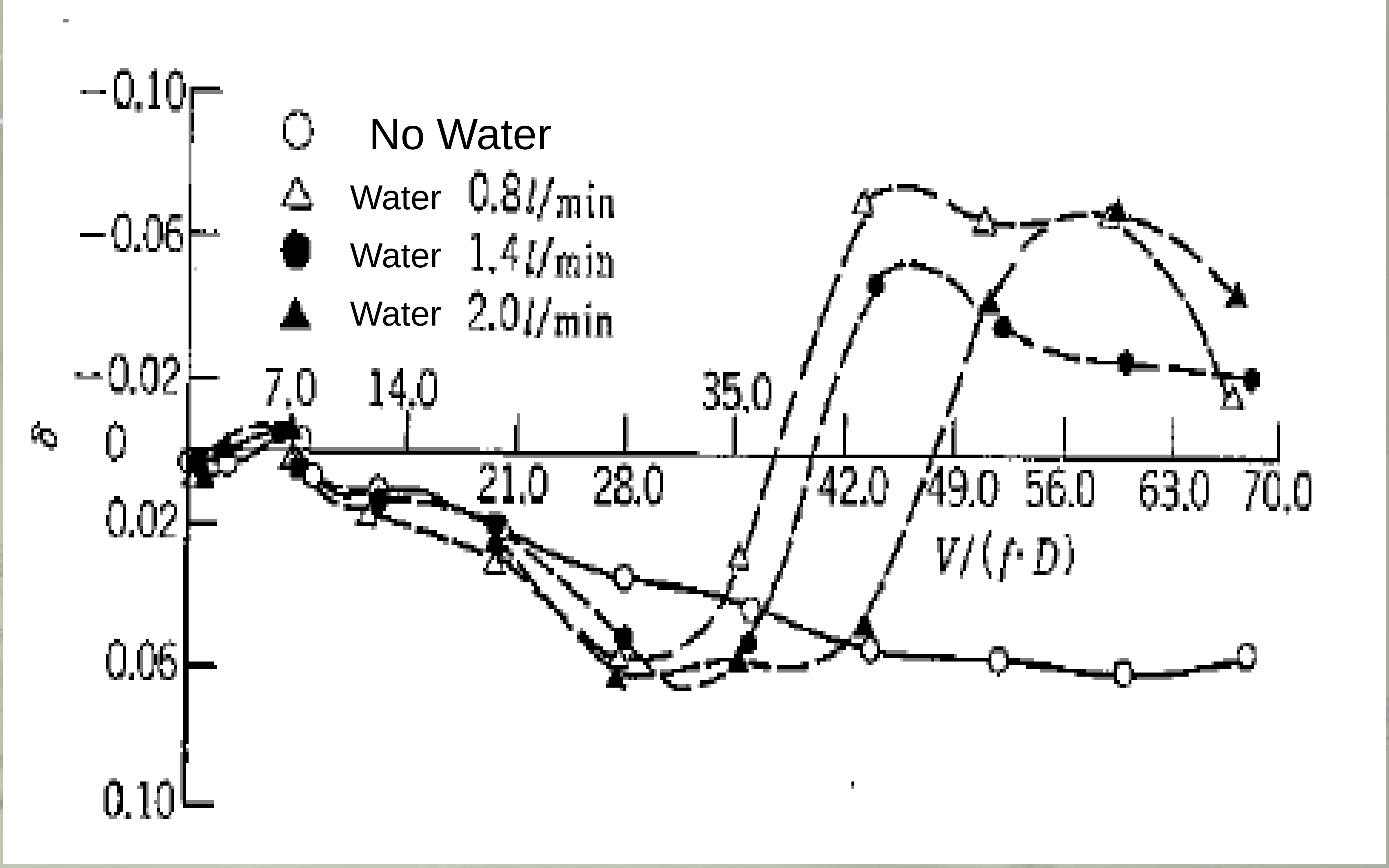
Test Setting(2)



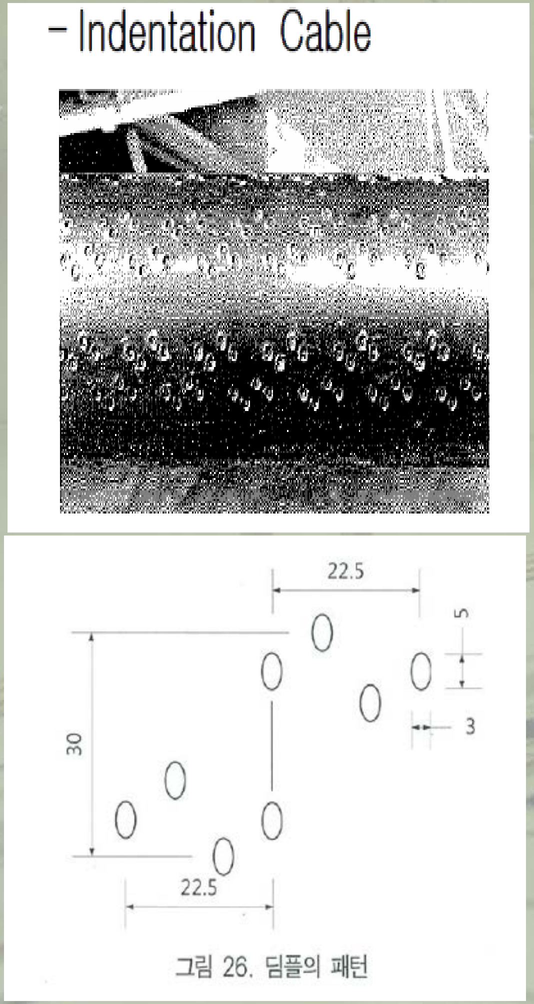
Water Quantity & Amplitude



$V/(f \cdot D) \sim \delta$



Cable Vibration Control



Incheon Bridge

Effectiveness of Dimple

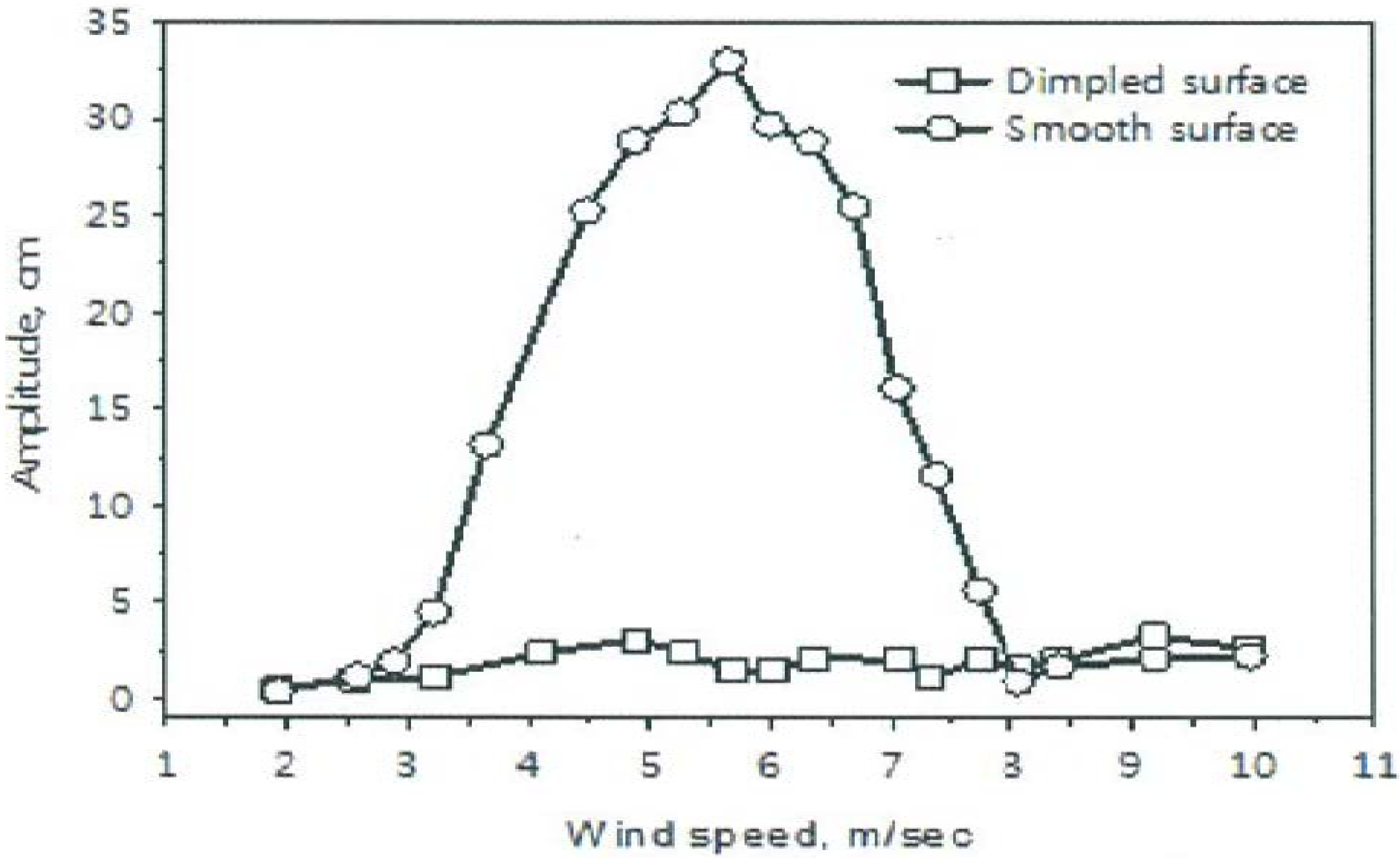


그림 25. 풍우진동에 대한 딤플의 효과(D=139mm, ξ=0.12%)

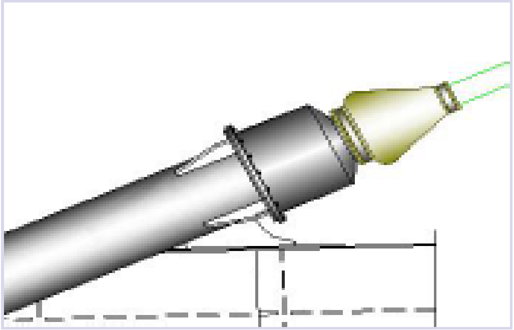
KTX Arch Bridge

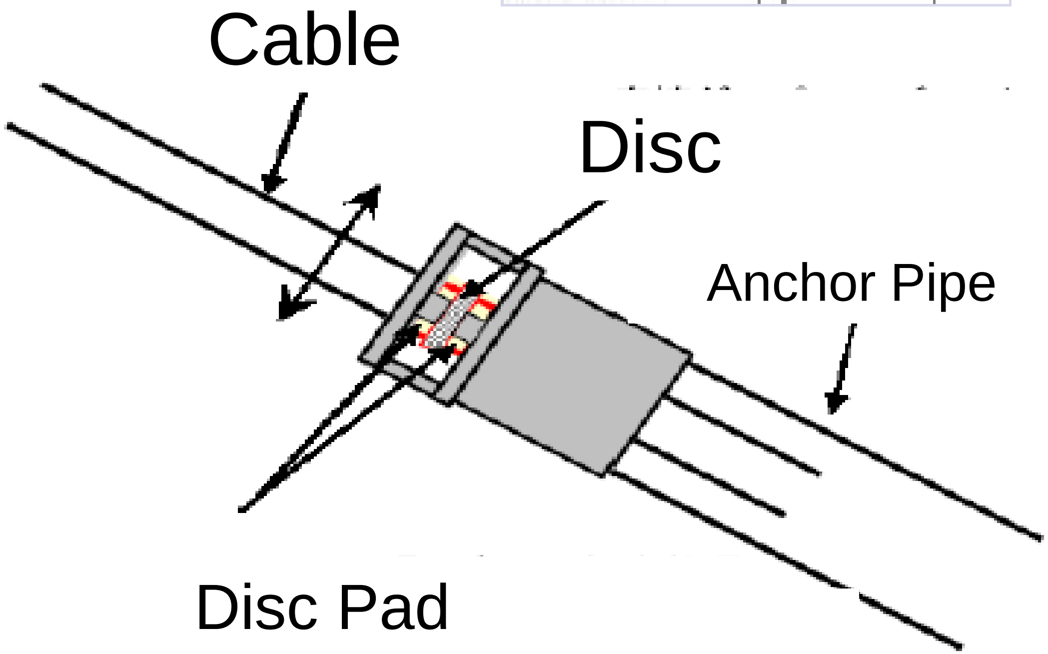
Helical Strakes by small cables

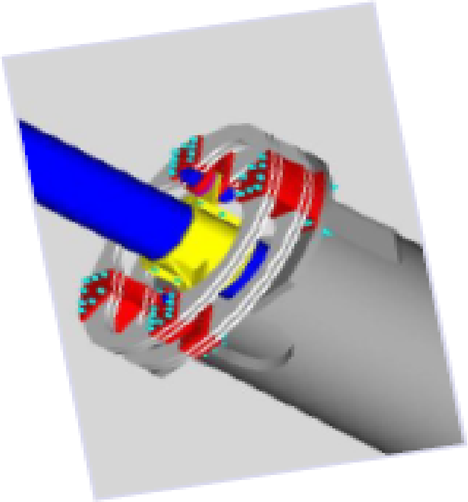
Nak-Dong Bridge

Disc Damper at Incheon Bridge

- Concept of Disc Damper







Disc Damper (Friction Damper)

Incheon Bridge Site

Strouhal Number

Definition of Strouhal Number(S_t)

$$S_t = f D / V \qquad (1.1)$$

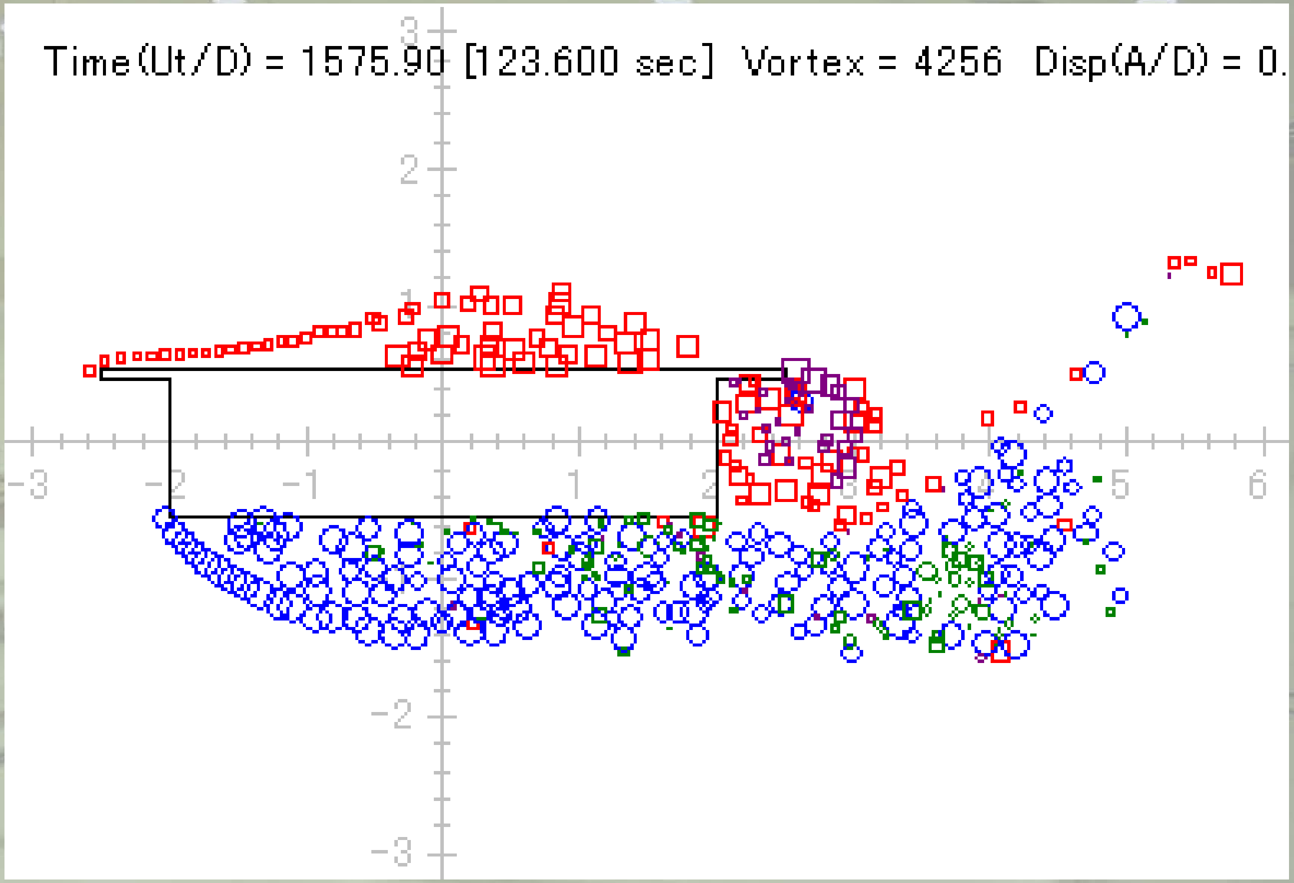
where, f : Vortex vibration frequency after body (Hz)

D : Referent height (m)

V : Wind Velocity (m/s)

Strouhal Number Measurement

f : Frequency of Vortex V: Wind Velocity

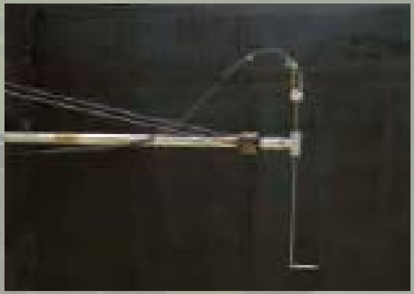


Damping

	Bending Vibration		Torsion Vibration	
	Log. Damping	Referent Amplitude (Taut Strip Model)	Log. Damping	Referent Amplitude (Taut Strip Model)
Truss Desk	0.03	1/200 Full Width of Deck	0.02	0.5° Degree at Reference point
Box deck	0.02		0.02	
Completion	0.02	1/500 of Tower Height	0.02	
Erection	0.01		0.01	

Setting Conditions of Wind Tunnel

a) Wind Distribution



Deviation of wind is within in ±1% .

b) Time Deviation of Wind Velocity

Intensity of turbulence should be within 1% .

c) Static Pressure Distribution

Static pressure distribution should be within 5% of dynamic pressure on the working section.

Model Condition（2） Scale

Scale of Model Should satisfy below.

Scale of Model

	Cord Length / Height of Working Section	Model Length / Cord Length	Blockade Rate
Closing Type	0.4 Below	2 以上	5% Below
Open Type	0.2 Below	3 以上	5% Below

Model Condition（1） Scale

- Scale is less than 1/ 100

- Small model is NG

- Details of prototype bridge must be reproduced especially for the experiment of vortex induced vibration and galloping.

3-Static Coefficients: C_D C_L C_M

a) Range of Attack Angle

Range: -15° ~ +15° at every 1°

b) Wind Velocity

10m/s and 20m/s

c) Preciseness

±0.1

Allowable Deviation of Wind Tunnel Tests

Wind tunnel test must be precise within the deviations below.

Table 1.1 Allowable Deviation

Items	Mass	Polar Moment	Frequency Ratio	Log. Damping
Allowable Value	± 2%	± 2%	± 5%	± 0.005

Method of Measurement（1）

a) Angle of Attack (Flutter ,Vortex Induced Vibration)

Deck Model Tests: Range is ±3°. Each 1°.

If the site seems to have more angle, we should change the range.

b) Range of Wind Velocity

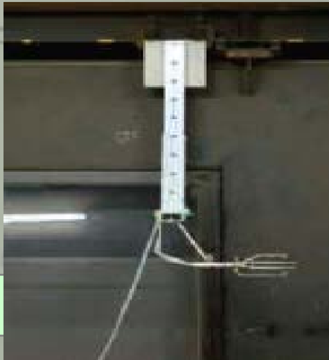
Deck Model Tests: Maximum is 1.2 x Design wind speed

c) Range of Amplitudes

Deck Model Tests: Torsion 0.5° ~ 5°、

Bending 1/200～1/20 of Model Length

These amplitudes must be clarified.



Method of Measurement（2）

d) Preciseness of measurement

Deck model tests must keep the following preciseness.

Table3.19 Preciseness of Measurement

Items	Torsion	Bending	
Preciseness	$\pm 0.05^\circ$	Model L	$\times 1/2000$

Format of test-results

- Torsion
  - Wind Velocity & Amplitude & Damping ($V \sim \theta \sim \delta$)
  - Wind Velocity & Damping ($V \sim \delta$)
  - Wind Velocity & Amplitude ($V \sim \theta$)
  - Flutter Critical Velocity Vs. Angle of Attack ($V_{cr} \sim \alpha$)

- Bending
  - Wind Velocity & Amplitude & Damping ($V \sim \eta \sim \delta$)
  - Wind Velocity & Damping ($V \sim \delta$)
  - Wind Velocity & Amplitude ($V \sim \eta$)

Turbulent Flow

How to make turbulent flow ??

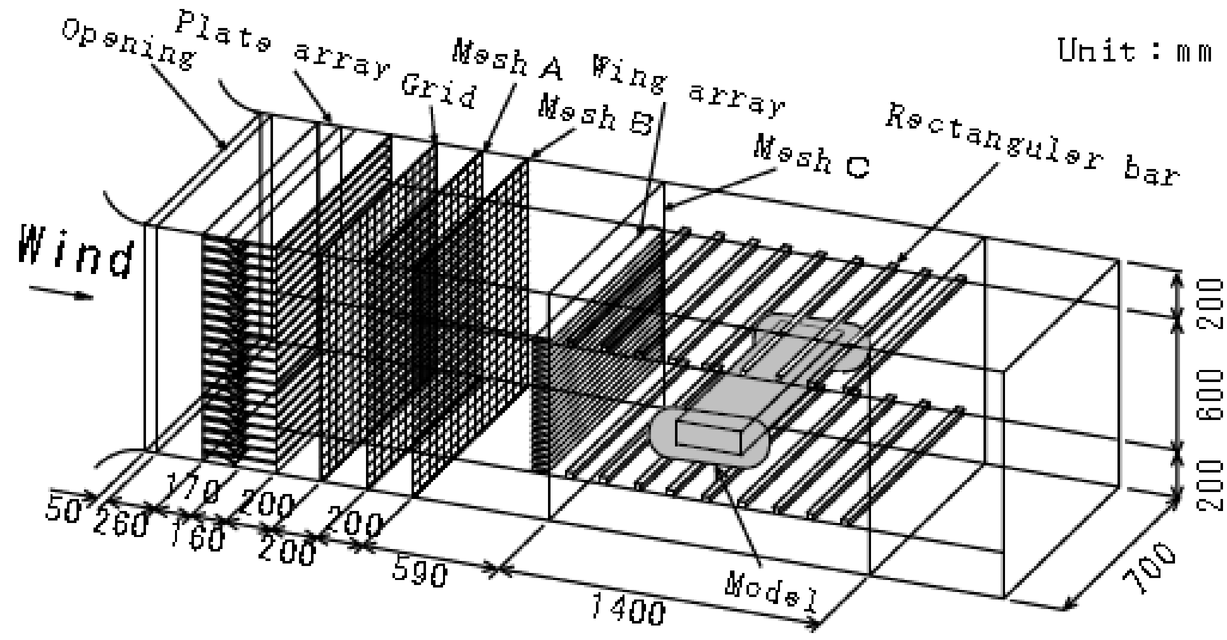


Fig.1 Turbulence generator in wind tunnel

Fig. Turbulence generator

Power Spectrum Simulation

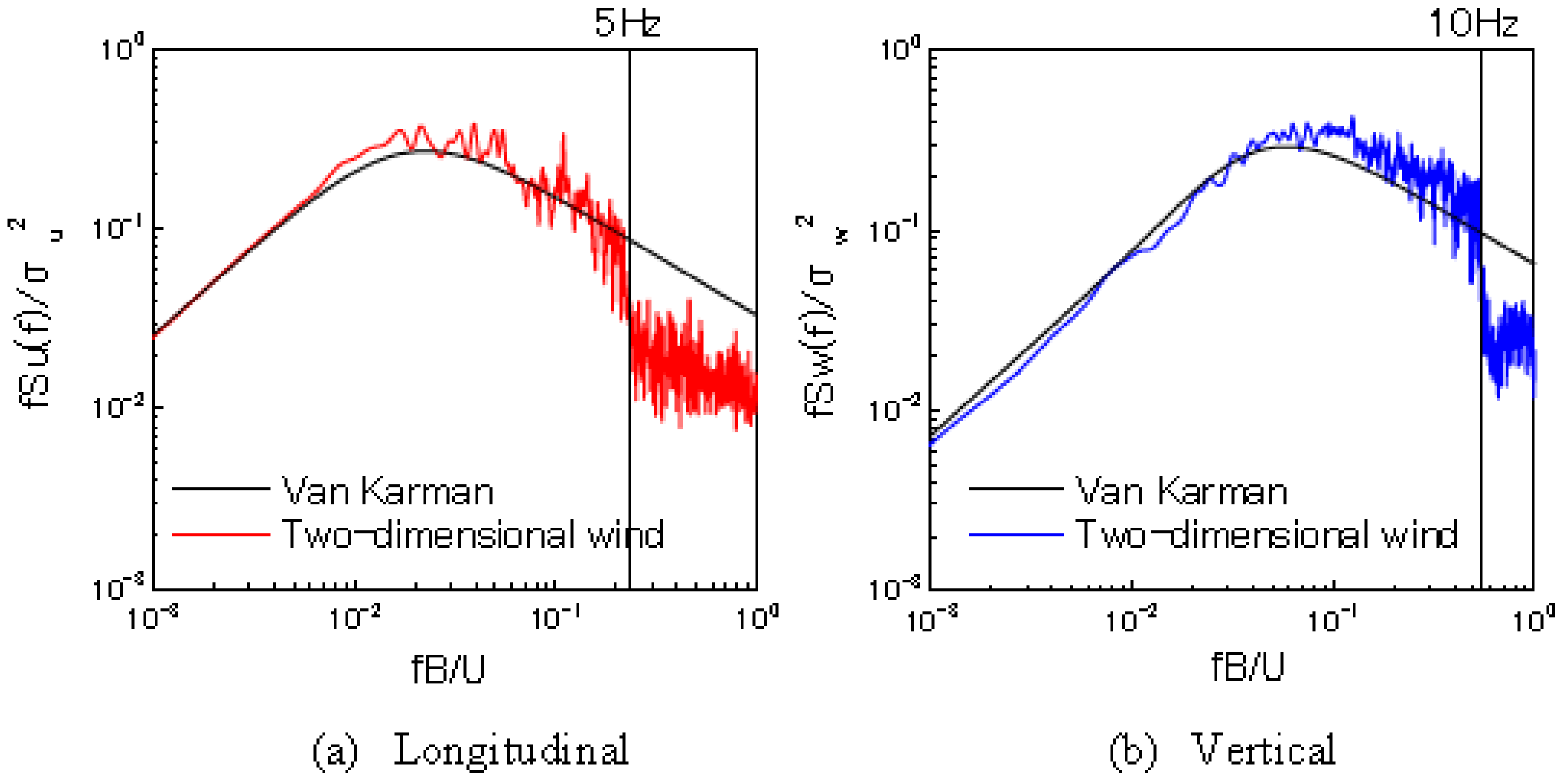
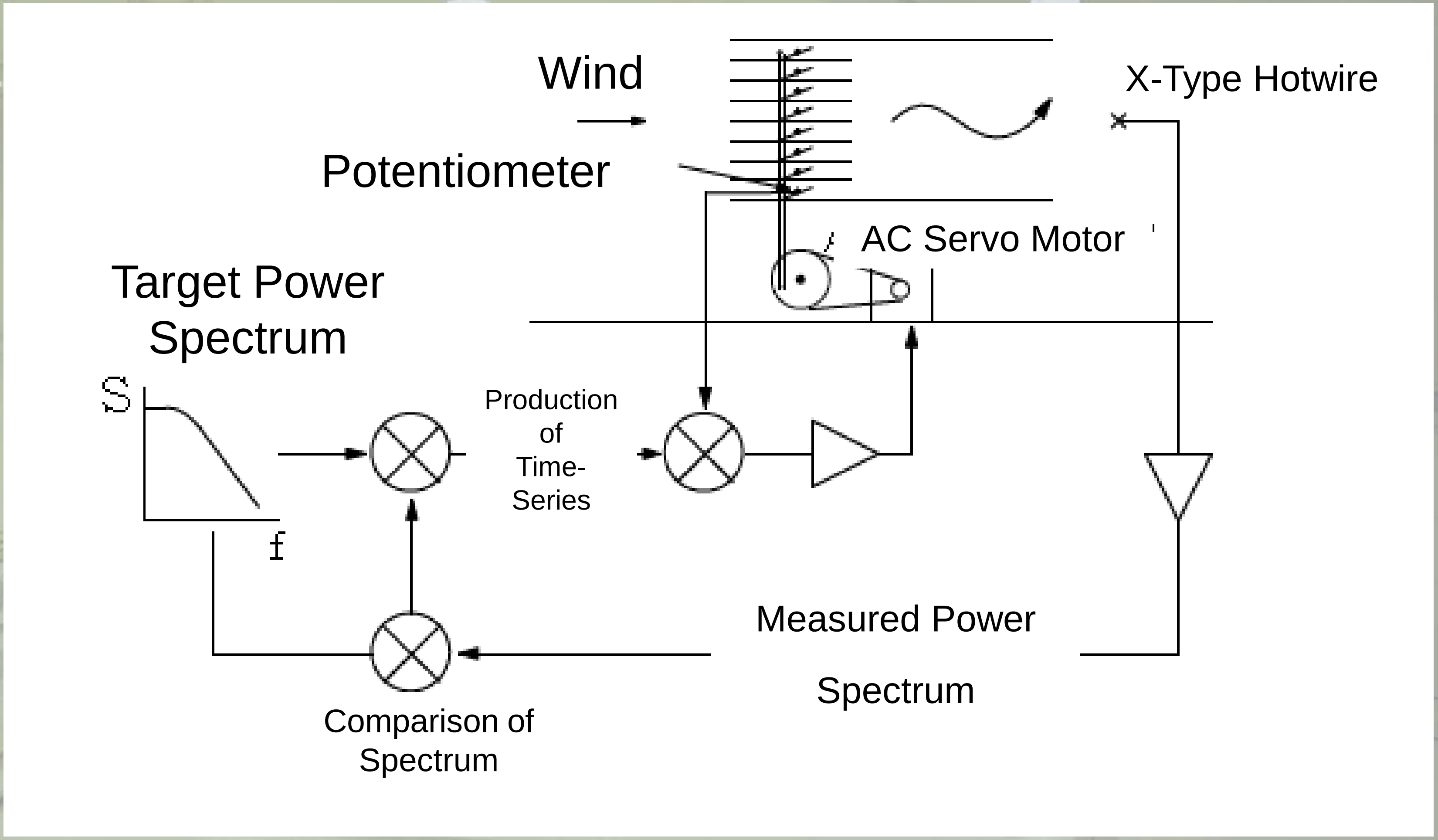


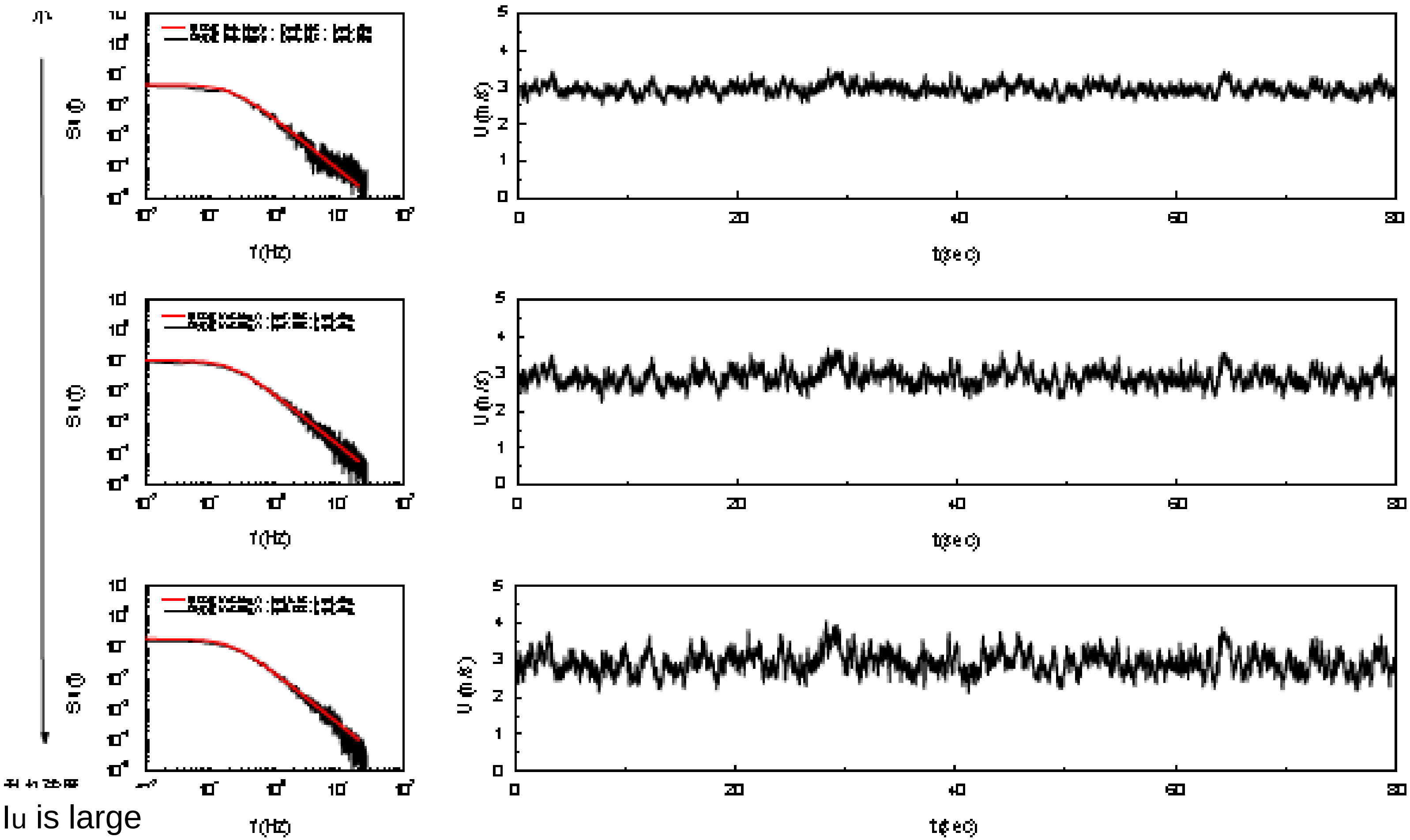
Fig.2 Power spectrum of generated wind

Turbulence Simulation System



Intensity of Turbulence (Iu) of Along Wind

Iu is small



Iu is large

図1 主流方向乱れ強度(Iu)のみを変化

Gust Generator

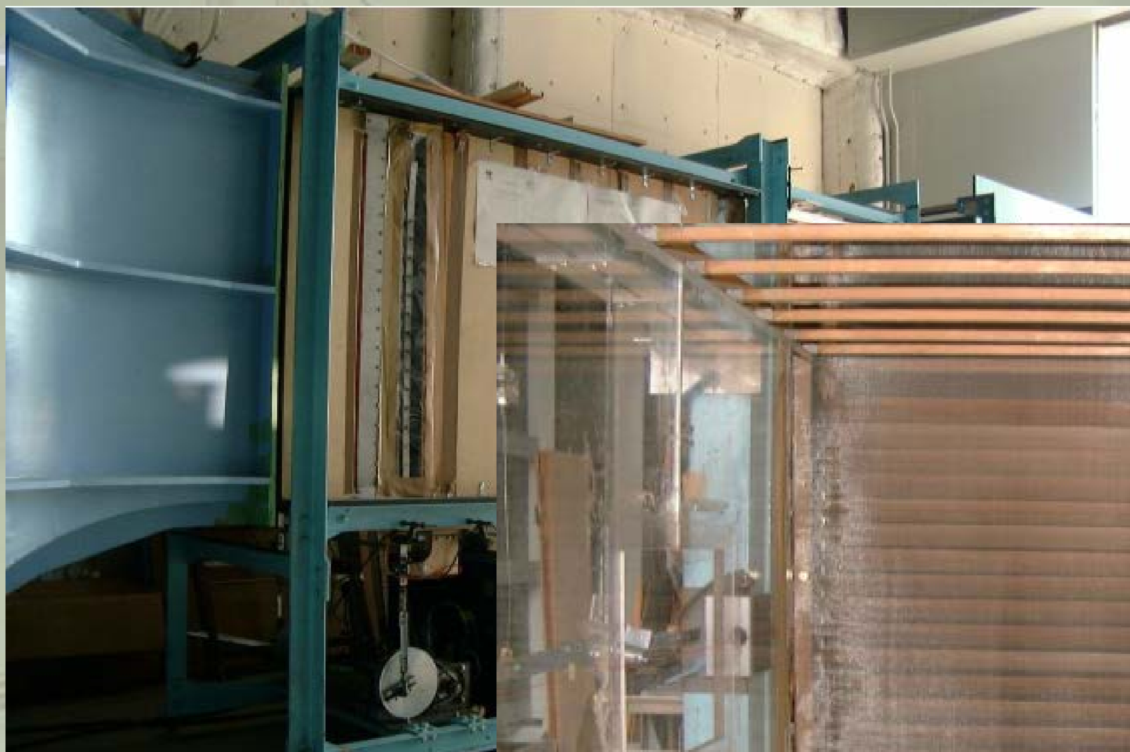
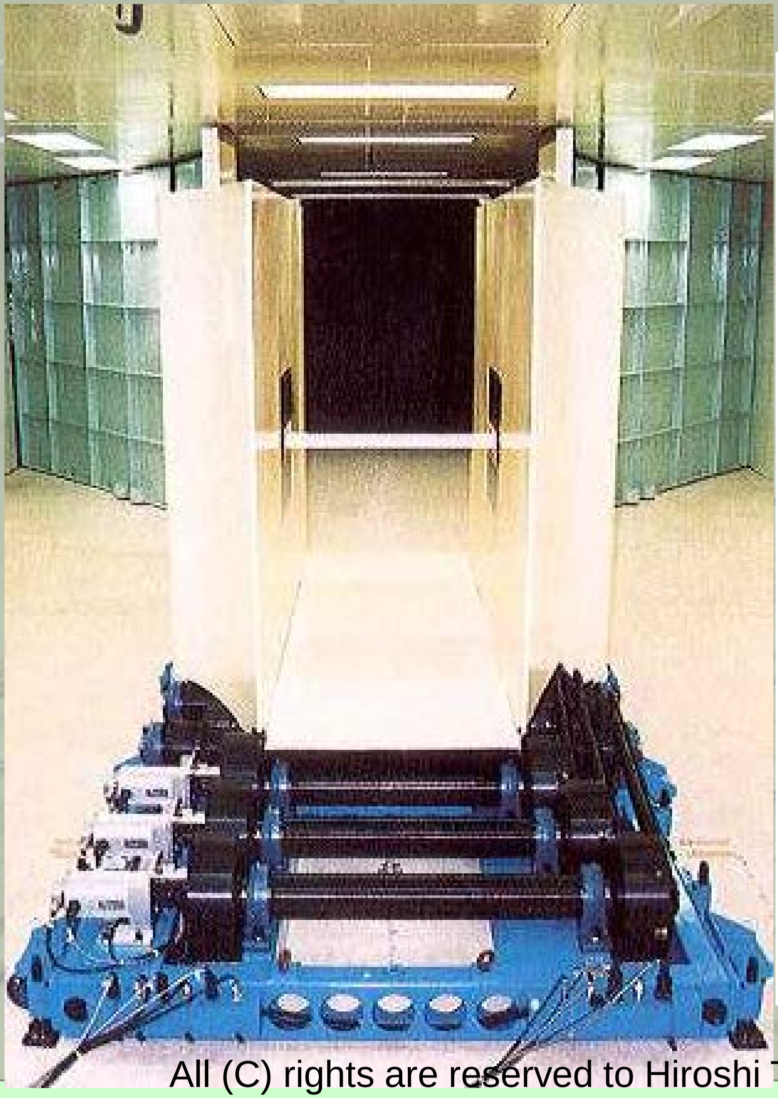


Plate Row

Wing Row

Servo Motor

Measurement of Flutter Derivatives



$$L_h = \frac{1}{2}\rho U^2 B\left[KH_1^*(K)\frac{\dot{h}}{U} + KH_2^*(K)\frac{B\dot{\alpha}}{U} + K^2 H_3^*(K)\alpha + K^2 H_4^*\frac{h}{B}\right]$$

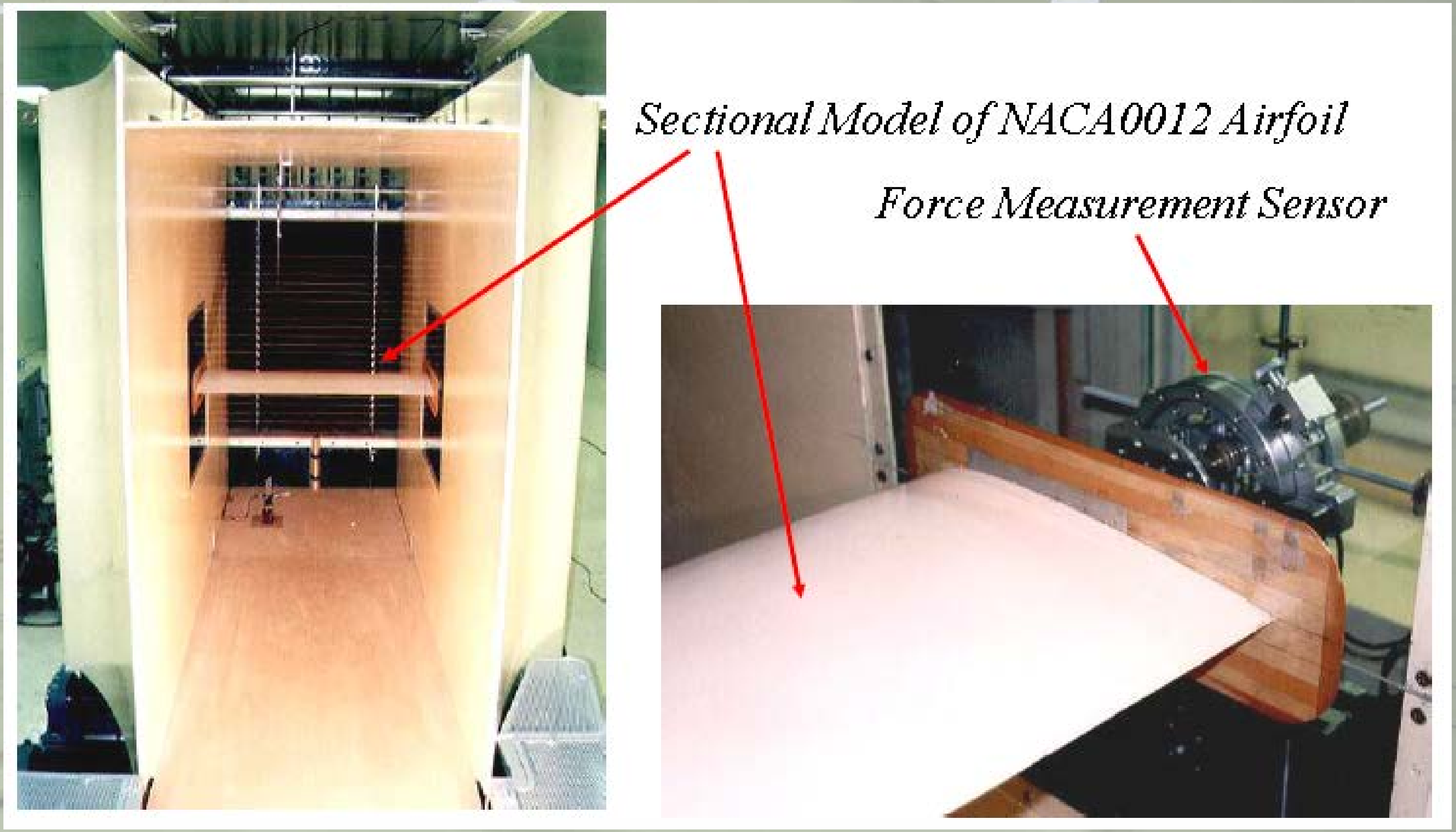
$$M_\alpha = \frac{1}{2}\rho U^2 B^2\left[KA_1^*(K)\frac{\dot{h}}{U} + KA_2^*(K)\frac{B\dot{\alpha}}{U} + K^2 A_3^*(K)\alpha + K^2 A_4^*\frac{h}{B}\right]$$

↓

Extraction of flutter derivatives
$H_1^* \sim H_4^*, A_1^* \sim A_4^*$

Forced Vibration Method

Forced Vibration Method



Flutter Equation

$$\ddot{X}_m(t) + 2h_m^s \cdot (\omega_m/\omega) \cdot \omega \cdot \dot{X}_m(t) + \omega_m^2 \cdot X_m(t) = \sum_n E_{mn} \cdot \omega \cdot \dot{X}_n(t) + \sum_n F_{mn} \cdot \omega^2 \cdot X_n(t) \quad (14)$$

$$E_{mn} = (\rho / 2M_m^*) \cdot \sum_i B_i \cdot \{\phi_{im}^{v}, \phi_{im}^{h}, \phi_{im}^{\theta}\}^T \cdot [H] \{\phi_{im}^{v}, \phi_{im}^{h}, \phi_{im}^{\theta}\} \cdot L_i$$

$$[H] = \begin{bmatrix} H_{1i}^{\ddagger}(K_i) \cdot B_i & H_{0i}^{\ddagger}(K_i) \cdot B_i & H_{2i}^{\ddagger}(K_i) \cdot B_i^2 \\ P_{0i}^{\ddagger}(K_i) \cdot A_i & P_{1i}^{\ddagger}(K_i) \cdot A_i & P_{2i}^{\ddagger}(K_i) \cdot A_i \cdot B_i \\ A_{1i}^{\ddagger}(K_i) \cdot B_i^2 & A_{0i}^{\ddagger}(K_i) \cdot B_i^2 & A_{2i}^{\ddagger}(K_i) \cdot B_i^3 \end{bmatrix} \quad (15)$$

$$F_{mn} = (\rho / 2M_m^*) \cdot \sum_i B_i \cdot \{\phi_{im}^{v}, \phi_{im}^{h}, \phi_{im}^{\theta}\}^T \cdot [\Omega] \{\phi_{im}^{v}, \phi_{im}^{h}, \phi_{im}^{\theta}\} \cdot L_i$$

$$[\Omega] = \begin{bmatrix} H_{4i}^{\ddagger}(K_i) \cdot B_i & H_{5i}^{\ddagger}(K_i) \cdot B_i & H_{3i}^{\ddagger}(K_i) \cdot B_i^2 \\ P_{4i}^{\ddagger}(K_i) \cdot A_i & P_{5i}^{\ddagger}(K_i) \cdot A_i & P_{3i}^{\ddagger}(K_i) \cdot A_i \cdot B_i \\ A_{4i}^{\ddagger}(K_i) \cdot B_i^2 & A_{5i}^{\ddagger}(K_i) \cdot B_i^2 & A_{3i}^{\ddagger}(K_i) \cdot B_i^3 \end{bmatrix} \quad (16)$$

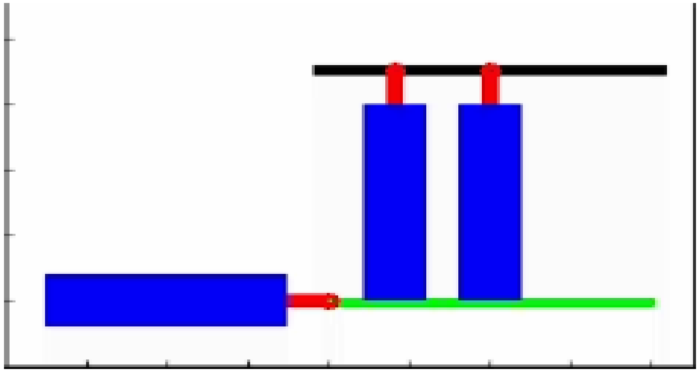
We can solve flutter equation using flutter derivatives.

Ref. H.Tanaka Flutter and Gust Response Analysis of the Messina Bridge –Benchmarking-

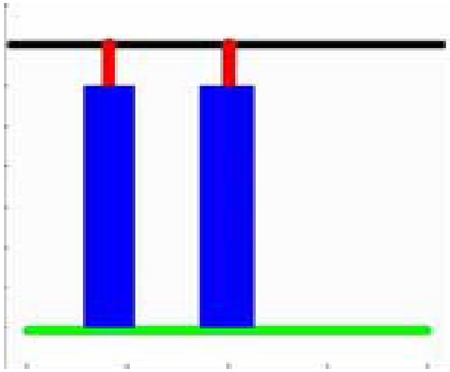
Experimental Set-up

- Static Coefficients
- Flutter Derivatives

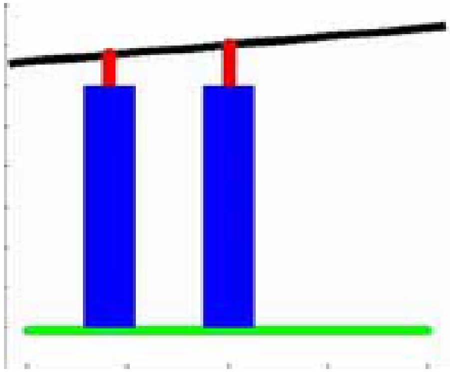
Forced motion:



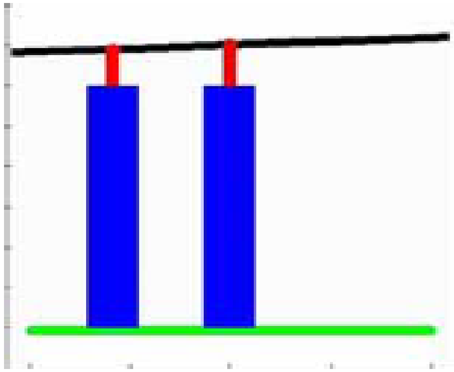
Horizontal



Vertical



Torsional



Vertical & Torsional

Thank You Very Much !!