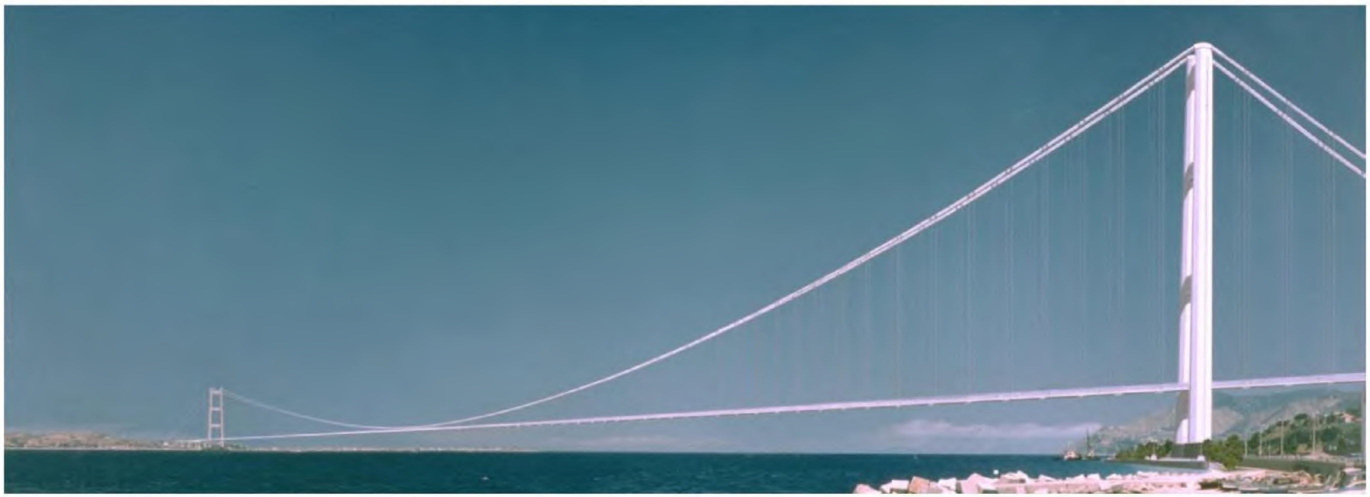
Flutter and Gust Response Analyses of the Messina Strait Bridge - Benchmark Study -

SAMSUNG C&T H. Tanaka
NTI Inc. A. Hatanaka
SAMSUNG C&T J.H.Yang

Contents

the Messina Straits Bridge



Sicily

Southern Mainland Italy

Longest span	3300m (Akashi-Kaikyo 1991m)
Tower height	382.6m (Akashi-Kaikyo 298.3m)
Deck width	60.4m (Akashi-Kaikyo 35.5m)
Cable diameter	4×1.24m (Akashi-Kaikyo 2×1.12m)
Design wind speed	75m/s (Akashi-Kaikyo 80m/s)

Reference from J. Ramsden, Proc. of Bridge Engineering 2 Conference 2009.

Deck Section

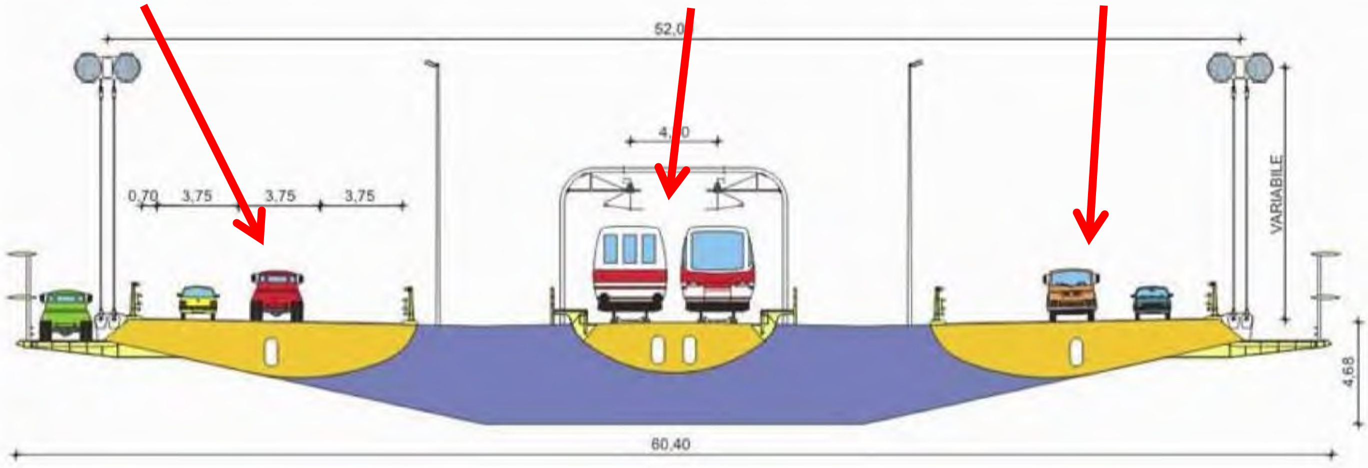
Deck weight 18.1 t/m

Cable weight 37 t/m

Total weight 55.1t/m

Chord	Material	Total weight	N. Boxes	Road lane	N. Tracks
60 m	Steel	66500 t	3	6 + 2	2

Roadway Box Girder Railway Box Girder Roadway Box Girder



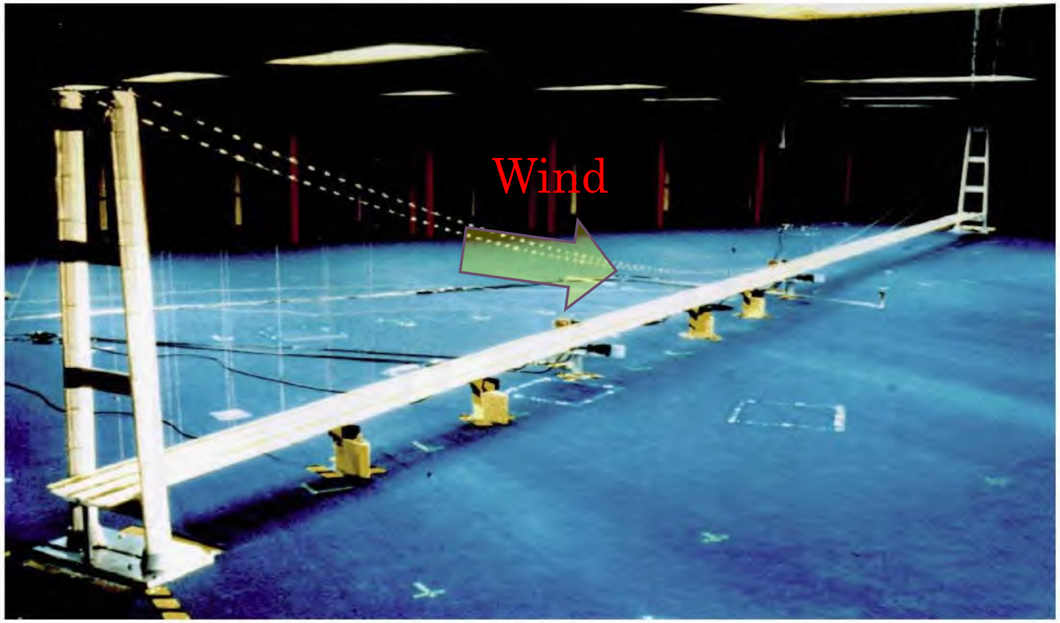
Reference from G. Diana : Messina Bridge Project – Technical Challenges -, 2006

What is the benchmark study?

- The aerodynamic study (wind tunnel test and analysis) of the Messina Straits Bridge has been carried out by Prof. Diana's research group of Politecnico di Milano, Italy.
- The structural and aerodynamic data has been disclosed on the Internet.
- We can be compared with their flutter & gust response analyses and experimental results.
- In this analysis, we use the aerodynamic analysis codes developed by Dr.Yamamura and Dr.Tanaka.

Full Aeroelastic Model Test in Boundary Layer Turbulent Flow

Full aeroelastic model: DMI (1992)



Reference from G. Diana : Messina Bridge Project – Technical Challenges -, 2006

Outline of Flutter Analysis

- The flutter analysis is the **3-dimensional (3D) flutter analysis** of multi-degree of freedom system with a 3-dimensional frame model (**Mult-Mode Flutter Analysis**).

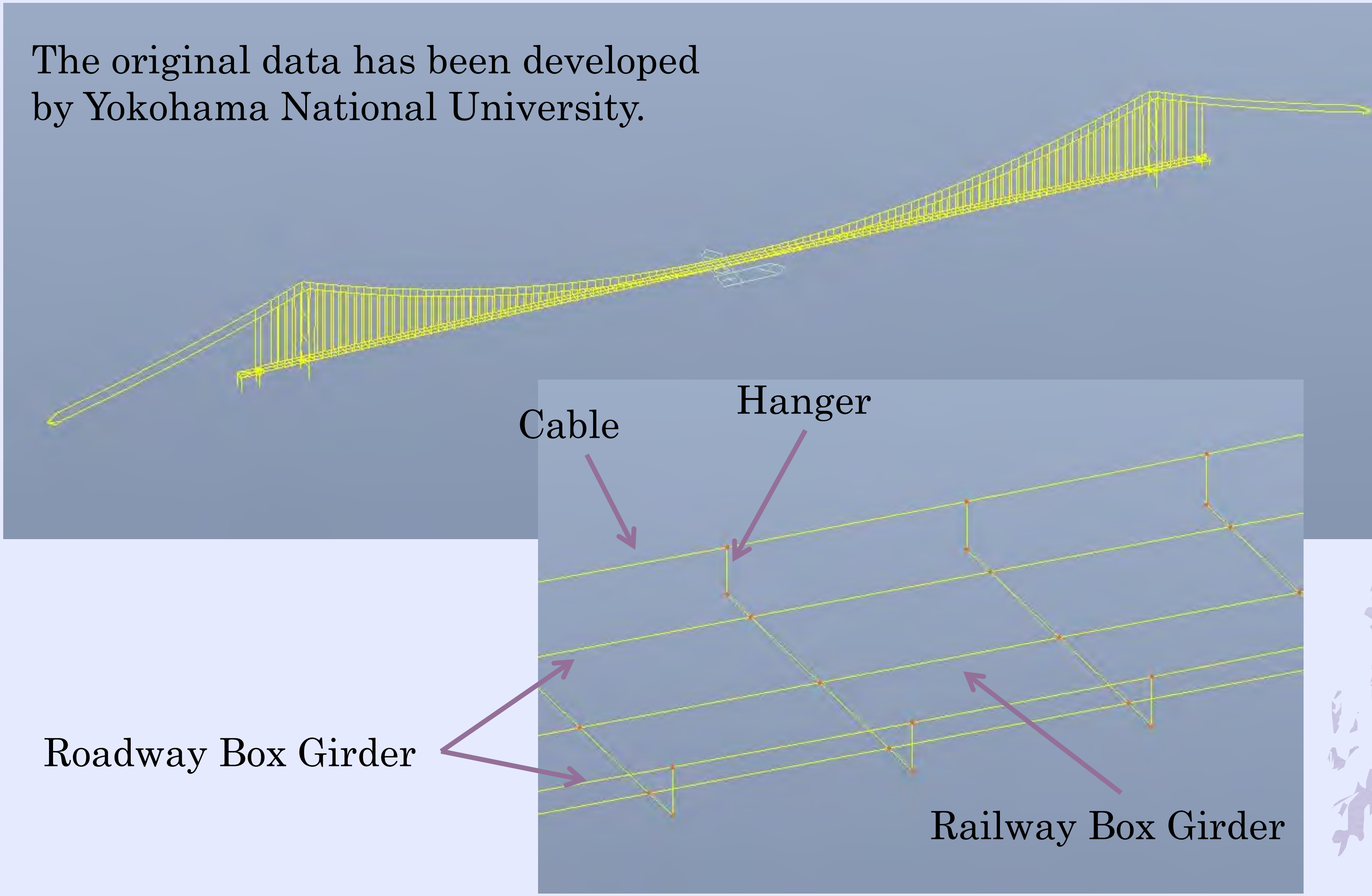
- Self-excited forces are formulated using **Scanlan's conventions** (flutter derivatives: P^*_i, H^*_i, A^*_i).

- **The benchmark data (experimental data)** of the flutter derivatives for **lift** and **moment forces** are used. The flutter derivatives for **drag force** are calculated by **quasi steady theory**.

- The flutter analysis is carried out using **modal analysis approach**. The lowest two or three bending modes and the lowest torsional mode are selected as **the key modes of coupling flutter modes**.

- The structural damping in air flow is calculated by **complex Eigen value analysis**. From the structural damping , **the flutter onset velocity** are identified.

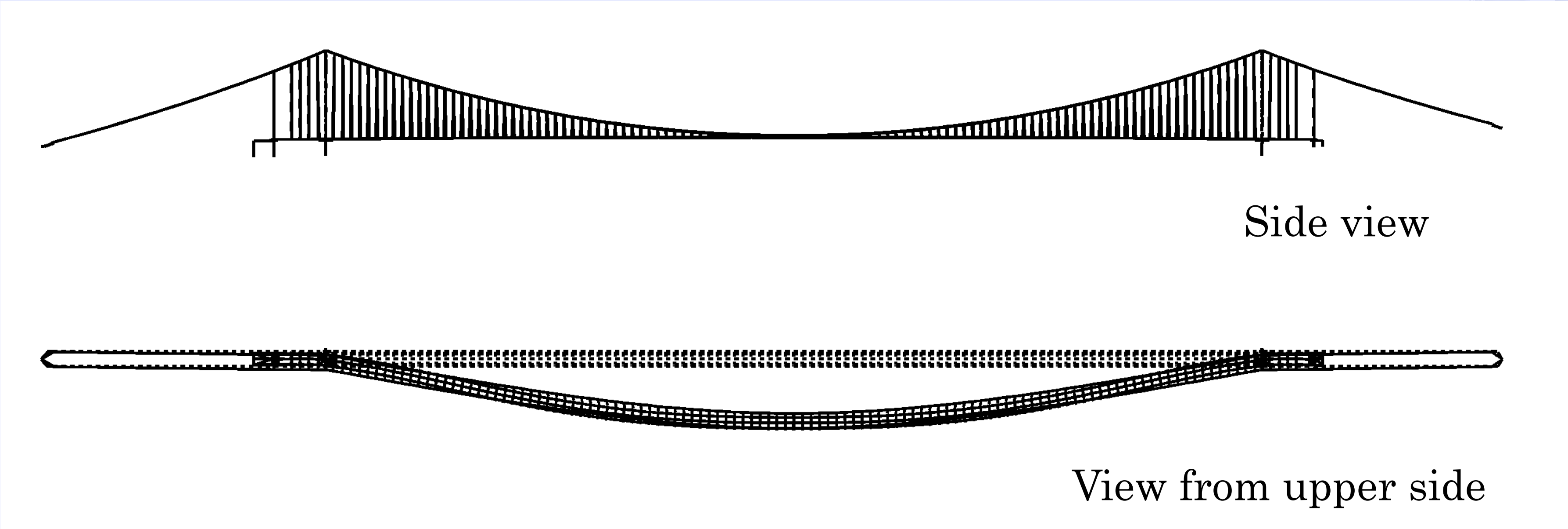
FEM Model (Beam Element)



Natural Frequency Analysis

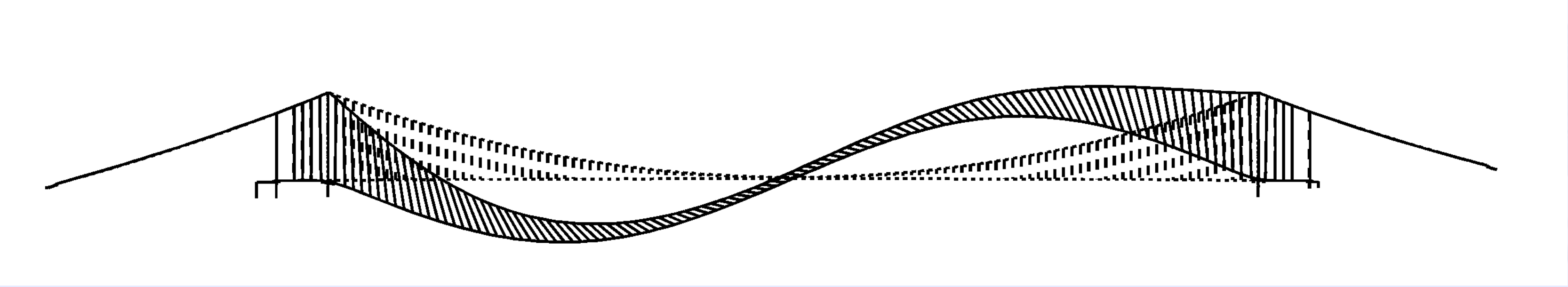
Mode No. of NTI Model	Natural Freq.(Hz)			Equivalent Mass (t/m or t^2/m)	Mode description
	NTI	YNU AM1[2)]	Prof. Diana's group[3)]		
1	**0.031**	**0.031**	**0.033**	**52.6**	**Sym. and horizontal**
2	**0.059**	**0.059**	**0.059**	**33.8**	**Asym. and horizontal**
3	**0.063**	**0.064**	**0.061**	**60.2**	**Asym. and vertical**
4	**0.078**	**0.078**	**0.080**	**57.0**	**Sym. and vertical**
5	0.084			—	—
6	**0.090**	**0.076**	**0.081**	**32,421**	**Asym. and torsional**
7	0.091			—	—
8	0.096			—	—
9	0.098			—	—
10	**0.101**	**0.093**	**0.097**	**31,203**	**Sym. and torsional**

Vibration Mode
- 1st mode of sway motion -

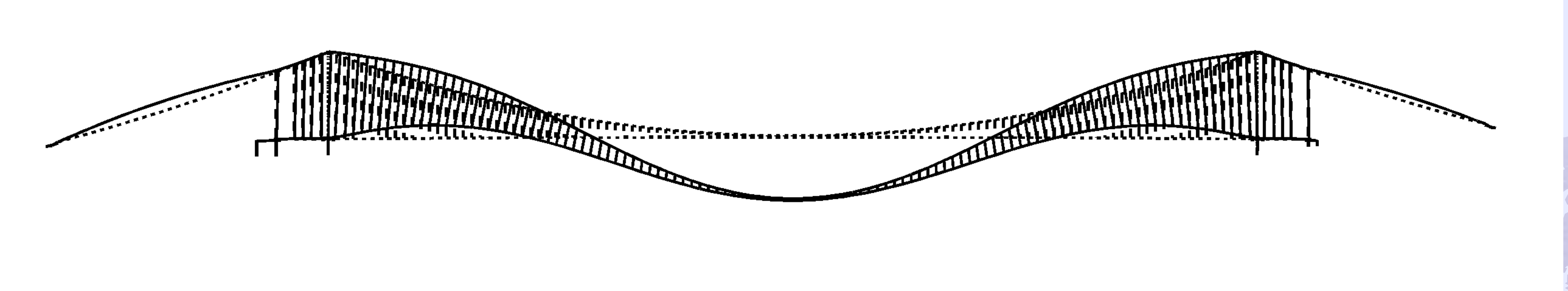


$f = 0.031\text{Hz}$, $T = 32.2\text{sec}$, $M_{eq} = 52.6\text{t/m}$

Vibration Mode
- 1st & 2nd modes of bending motion -



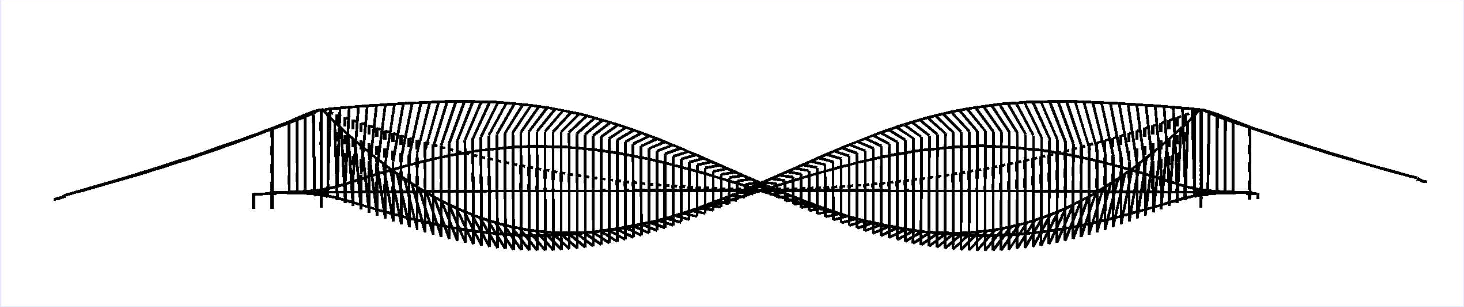
1st bending mode has asymmetric mode shape.
$f = 0.063Hz$, $T = 15.8sec$, $M_{eq} = 60.3t/m$



2nd bending mode has symmetric mode shape.
$f = 0.078Hz$, $T = 12.8sec$, $M_{eq} = 57.0t/m$

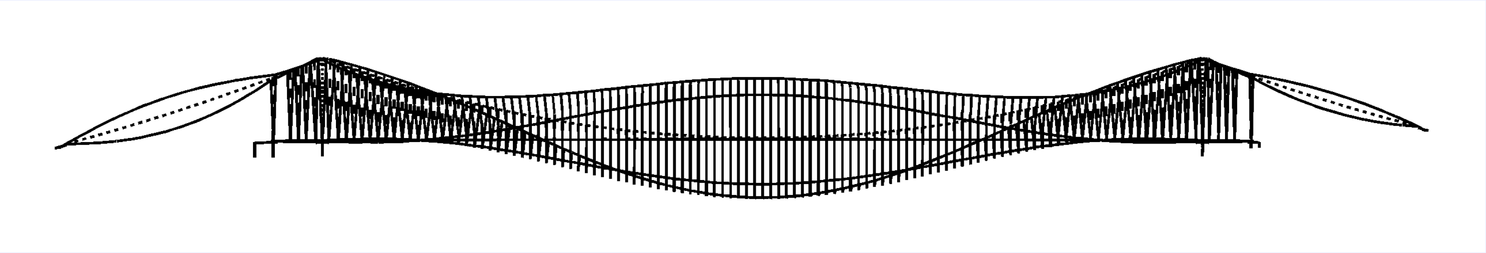
Vibration Mode

- 1^{st} & 2^{nd} modes of torsional motion -



1^{st} torsional mode has asymmetric mode shape.

$f = 0.090$Hz, $T = 11.2$sec, $I_{eq} = 32.421 tm^2/m$



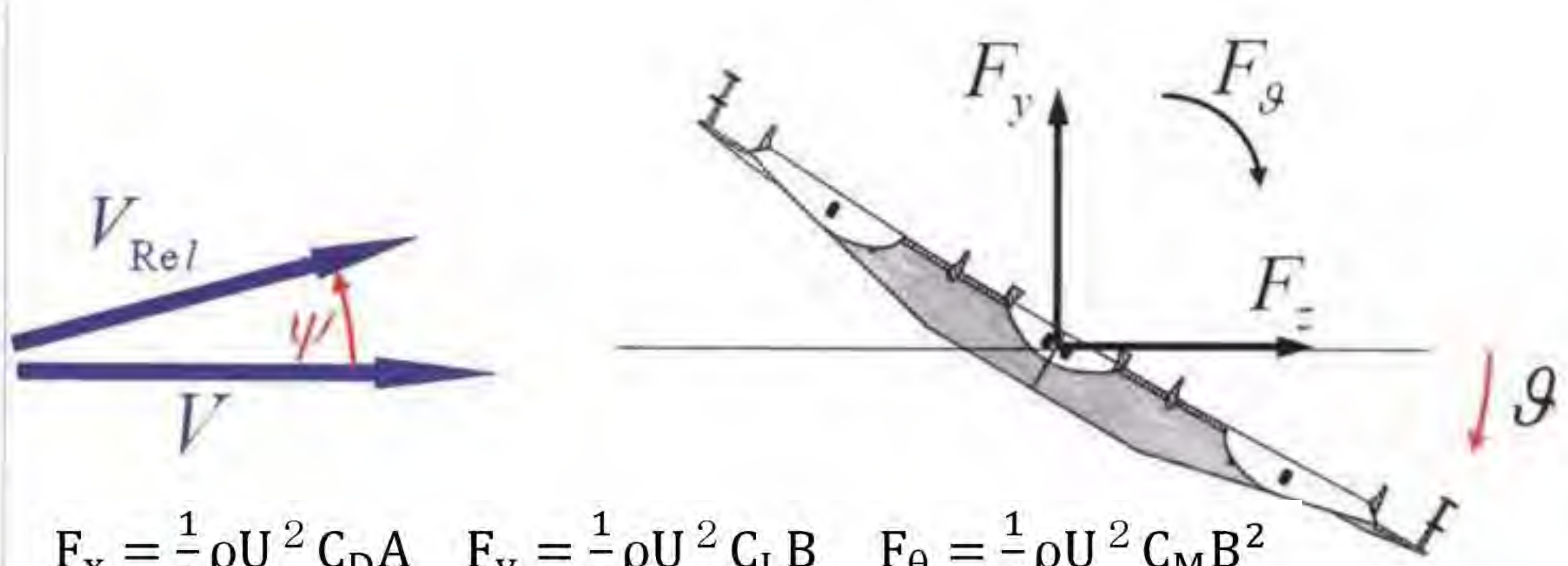
1^{st} torsional mode has symmetric mode shape.

$f = 0.101$Hz, $T = 9.9$sec, $I_{eq} = 32.203 tm^2/m$

Some comments on Vibration Characteristics

- The vibration characteristics (natural freq. & vibration mode) is consistent with the results of Prof. Diana's research group.
- The 1st bending and torsional modes have asymmetrical mode shape.
- The predictive flutter mode will be asymmetrical mode. Therefore, in flutter analysis, <u>the asymmetrical mode may be selected as the key vibration mode of coupled flutter.</u>

Static Aerodynamic Force Coefficients - Sign Convention -

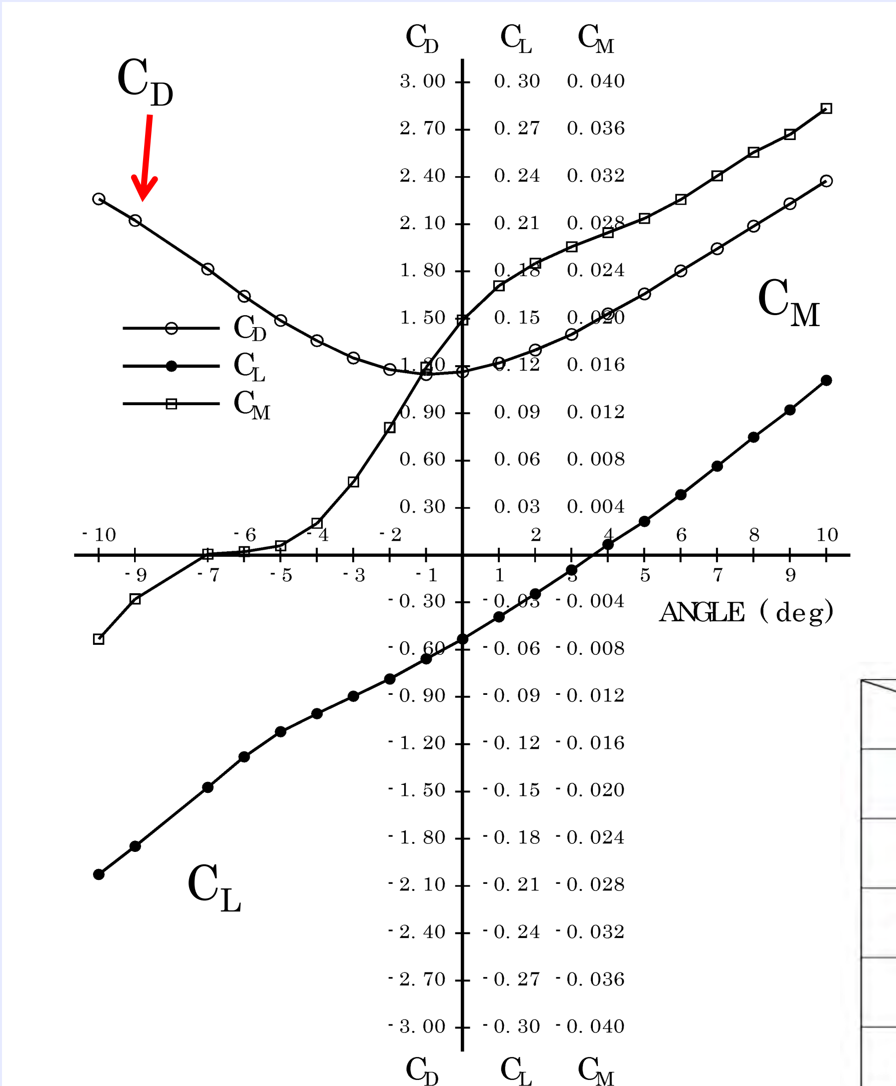


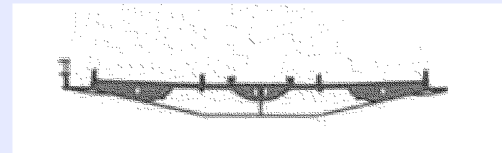
$$F_x = \frac{1}{2}\rho U^2 C_D A \quad F_y = \frac{1}{2}\rho U^2 C_L B \quad F_\theta = \frac{1}{2}\rho U^2 C_M B^2$$

F_i : aerodynamic force per unit length
U: mean wind velocity, ρ : Air density
A : projection area per unit length (m^2/m)
B : bridge deck width (m)
C_i (i = D, L, M) : static aerodynamic force coefficient
(D : Drag, L : Lift, M : Moment)

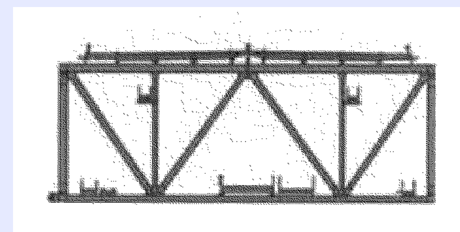
Reference from G. Diana : Messina Bridge Project – Technical Challenges -, 2006

Static Aerodynamic Force Coefficients - Measured Data -





Messina Straits Bridge



Akashi-Kaikyo Bridge

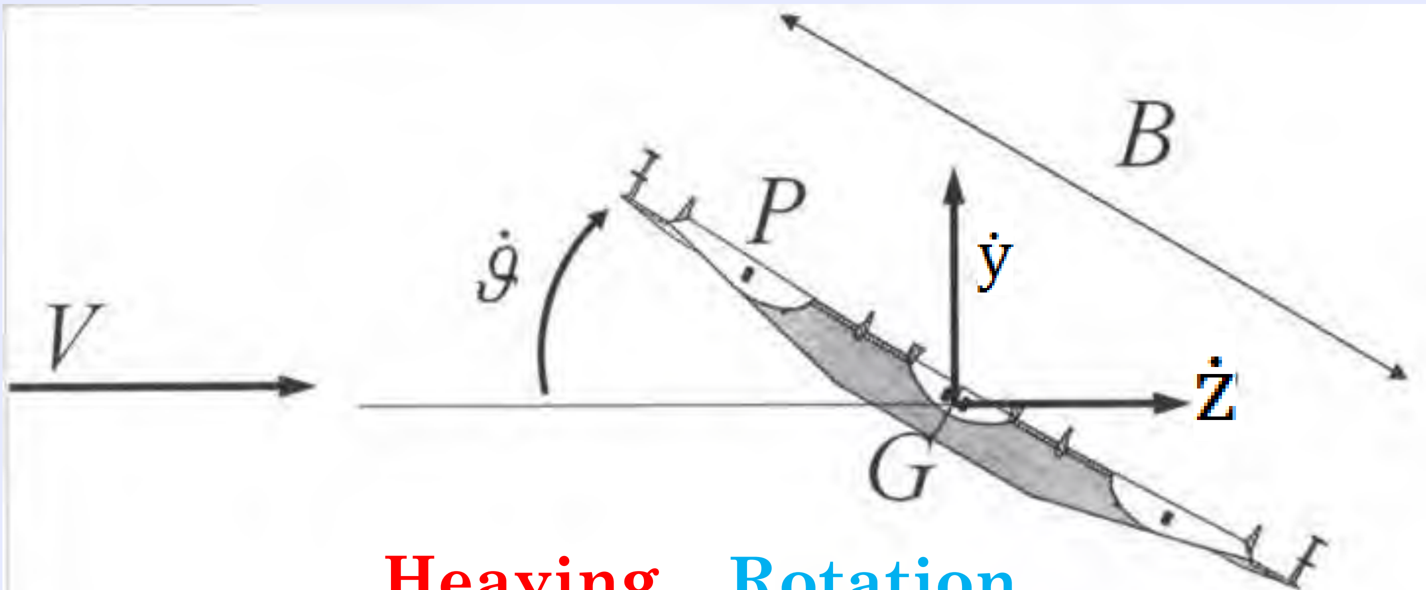
	Messina	Akashi-Kaikyo
C_D	1.164	1.993
C_L	-0.053	0.0080
$dC_L/d\alpha$	0.765	1.446
C_M	0.020	-0.0046
$dC_M/d\alpha$	0.198	0.337

Static Horizontal Deflection due to Wind of Full Aeroelastic Model at U_p = 60m/s

Maximum Deflection at Center Span
Messina Straits Bridge : around**10m**, Akashi Kaikyo Bridge : about **30m**

Reference from G. Diana : Messina Bridge Project – Technical Challenges -, 2006

Flutter Derivatives of deck girder - Motion Induced Aerodynamic Force -



Heaving **Rotation**

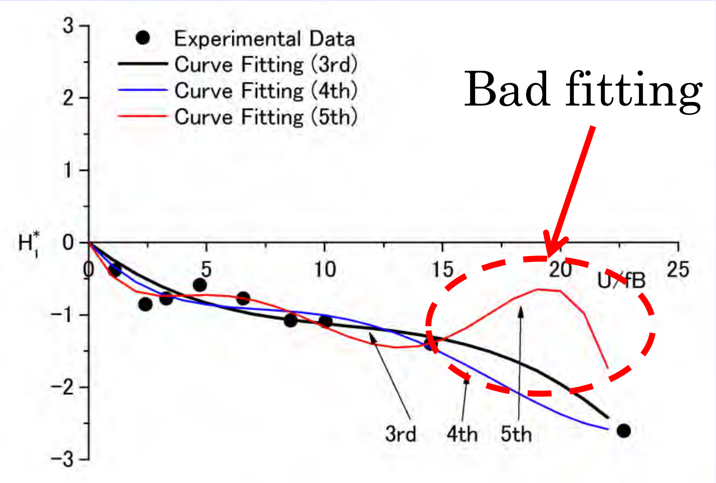
$$F_y = pBL\frac{1}{V^{*2}}\left\{\left(H_4^* + iH_1^*\right)\frac{y}{B} + \left(H_3^* + iH_2^*\right)\vartheta\right\},$$

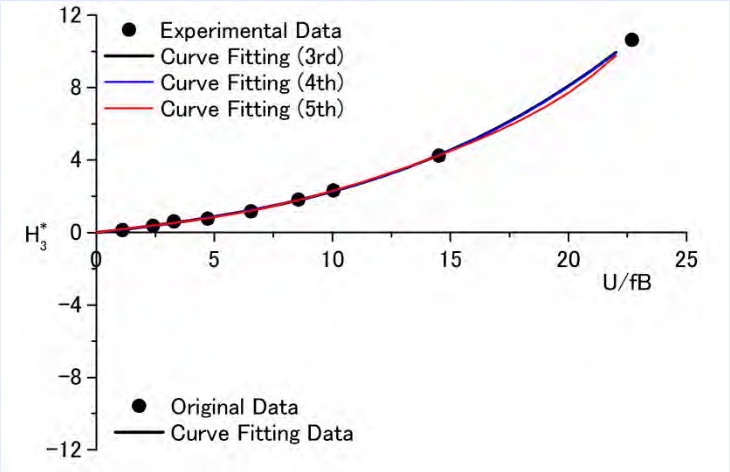
$$V^* = U/fB$$

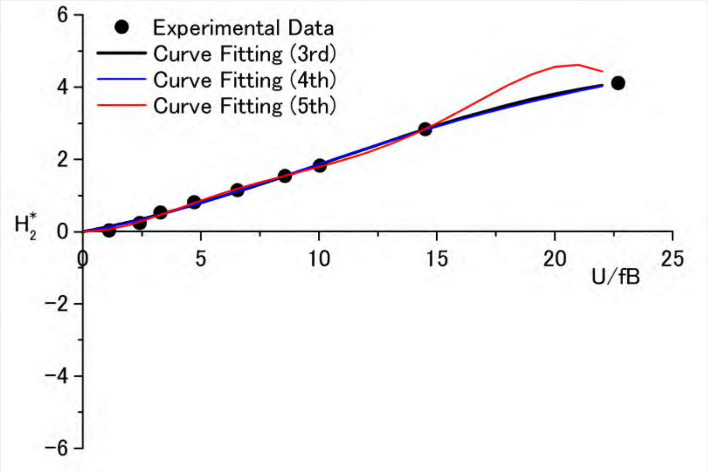
$$F_\vartheta = pB^2L\frac{1}{V^{*2}}\left\{\left(A_4^* + iA_1^*\right)\frac{y}{B} + \left(A_3^* + iA_2^*\right)\vartheta\right\},$$

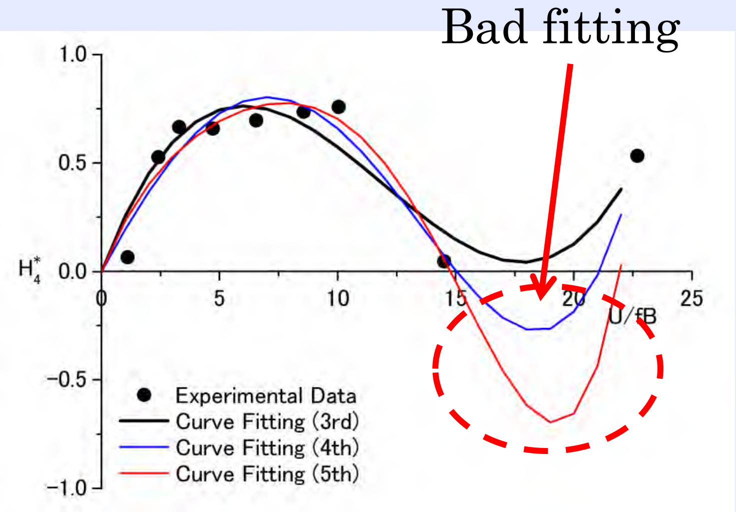
Reference from G. Diana : Messina Bridge Project – Technical Challenges -, 2006

Flutter Derivatives(H_i^*) for Lift Force

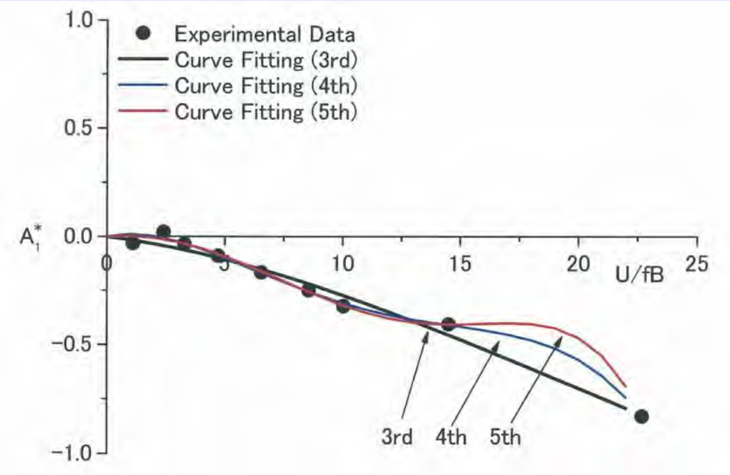


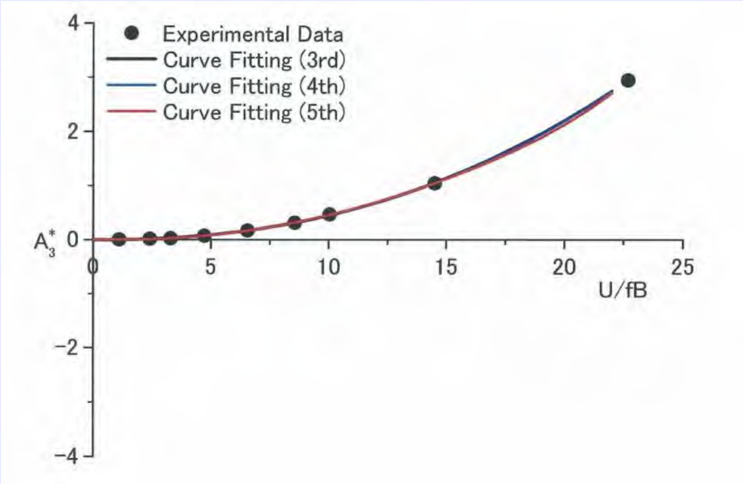


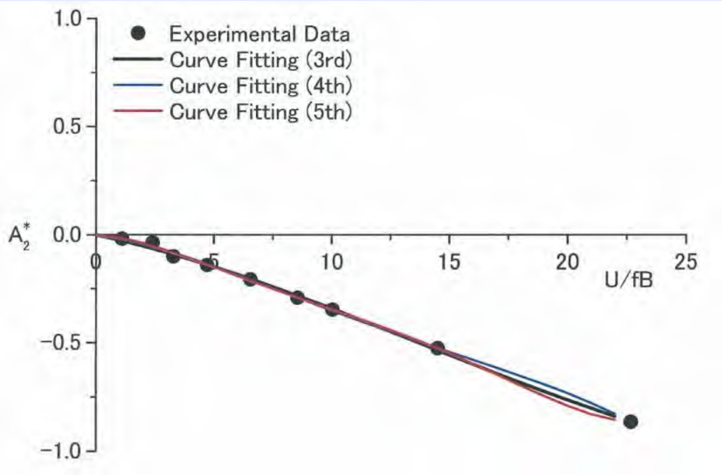


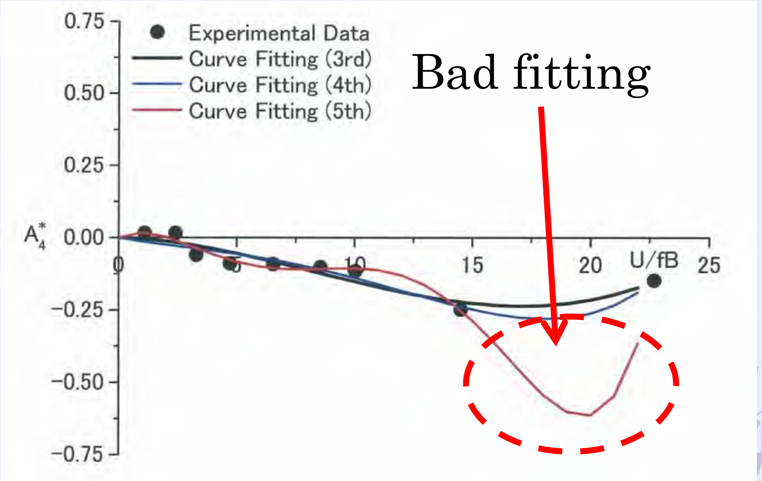


Flutter Derivatives(A_i*) for moment force







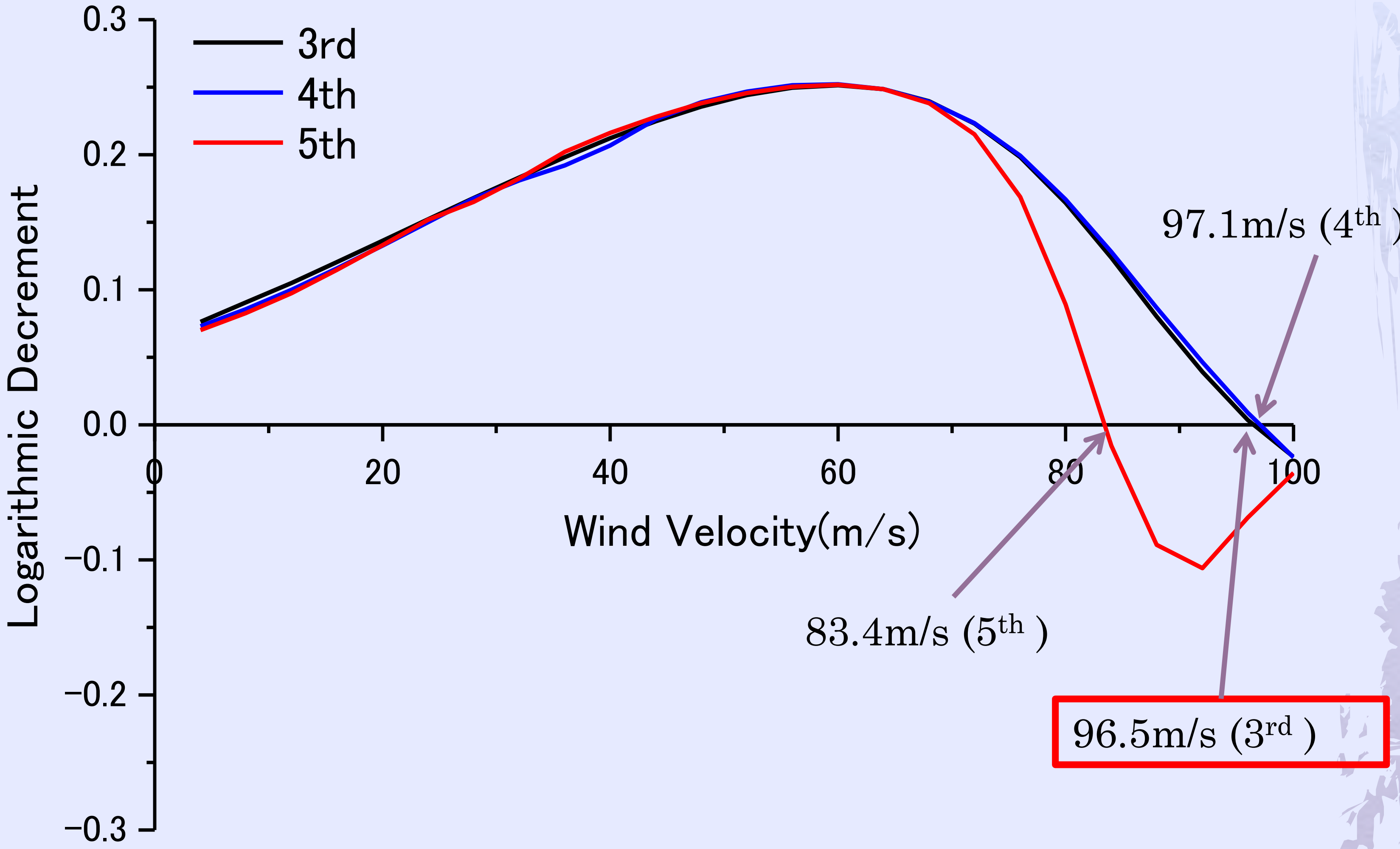


Comparison of fitting curves for flutter derivatives by 2D flutter analysis
- Vibration Characteristics of 2D Rigid Model-

Notation		Unit	Value
B	Bridge Deck Width	m	60
A	Projection Area per Unit Length	m	4.68
f_h	Natural Frequency of Vertical Motion	Hz	0.0634
f_θ	Natural Frequency of Torsional Motion	Hz	0.0895
m	Mass per Unit length	t/m	60.2
I	Inertia Mass per Unit Length	tm^2/m	3242
δ_h	Structural Damping of Vertical Motion	—	0.0628 (h = 1%)
δ_θ	Structural Damping of Torsional Motion		

Comparison of fitting curves for flutter derivatives by 2D flutter analysis

- V - δ Curve -



Flutter Derivatives for 3D Flutter Analysis

		Motion					
		Sway		Vertical		Rotational	
		Vel.	Disp.	Vel.	Disp.	Vel.	Disp.
Force	Drag	$Q(P_1^*)$	–	$Q(P_0^*)$	–	$Q(P_3^*)$	–
	Lift	$Q(H_0^*)$	–	$M(H_1^*)$	$M(H_4^*)$	$M(H_2^*)$	$M(H_3^*)$
	Moment	$Q(H_0^*)$	–	$M(A_1^*)$	$M(A_4^*)$	$M(A_2^*)$	$M(A_3^*)$

$$P^*_{0i} = -(dC_D / d\alpha) / K_i = -C'_{Di} / K_i$$

$$P^*_{1i} = -2C_{Di} / K_i, \quad P^*_{2i} \fallingdotseq 0$$ [3]

$$P^*_{3i} = (dC_{Di} / d\alpha) / K_i^2 = C'_{Di} / K_i^2$$

$$H^*_{0i} \fallingdotseq -2C_{Li} / K_i, \quad A^*_{0i} = -2C_{Mi} / K_i$$

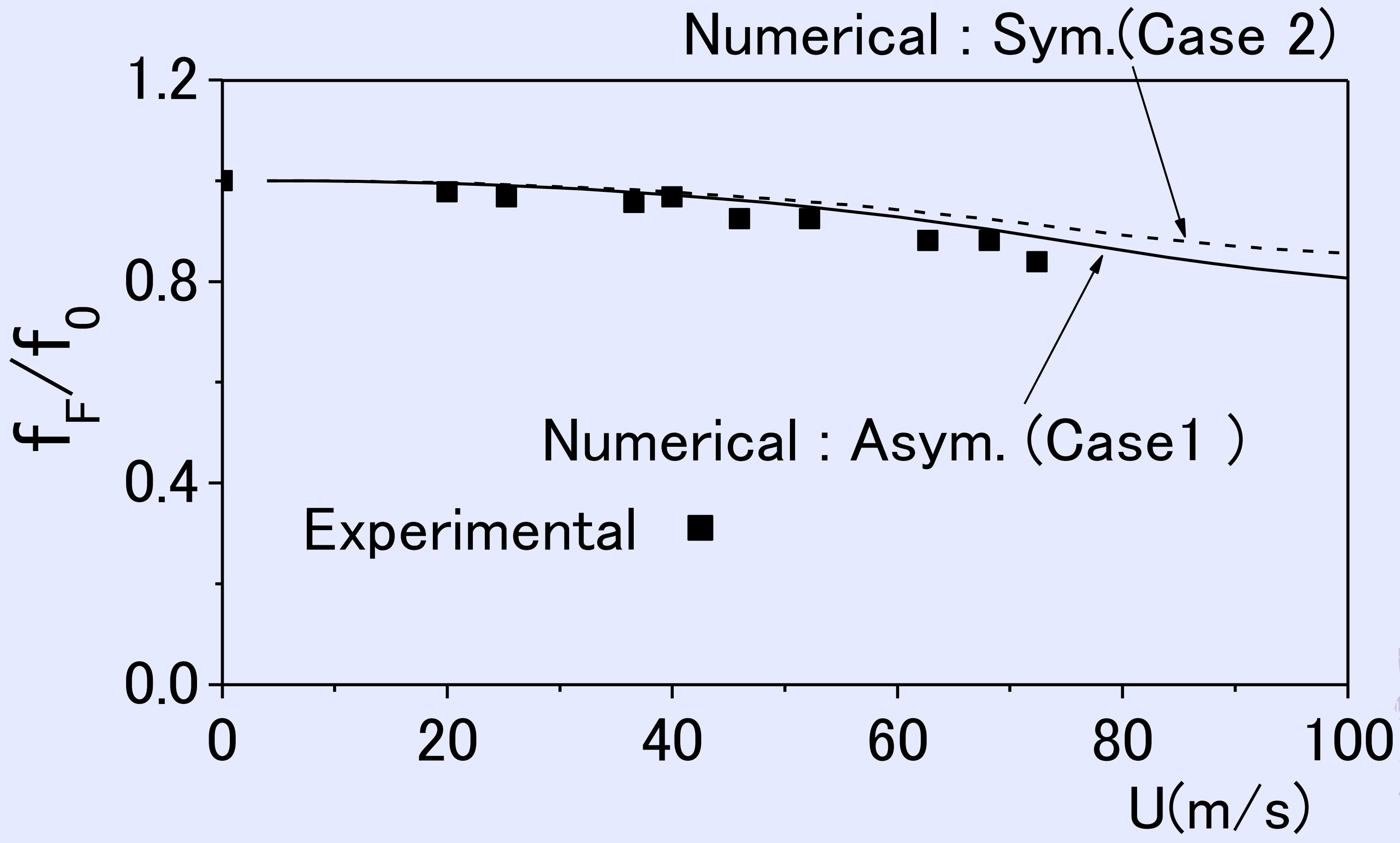
Measured values
as the benchmark data

Calculated values by
quasi steady theory

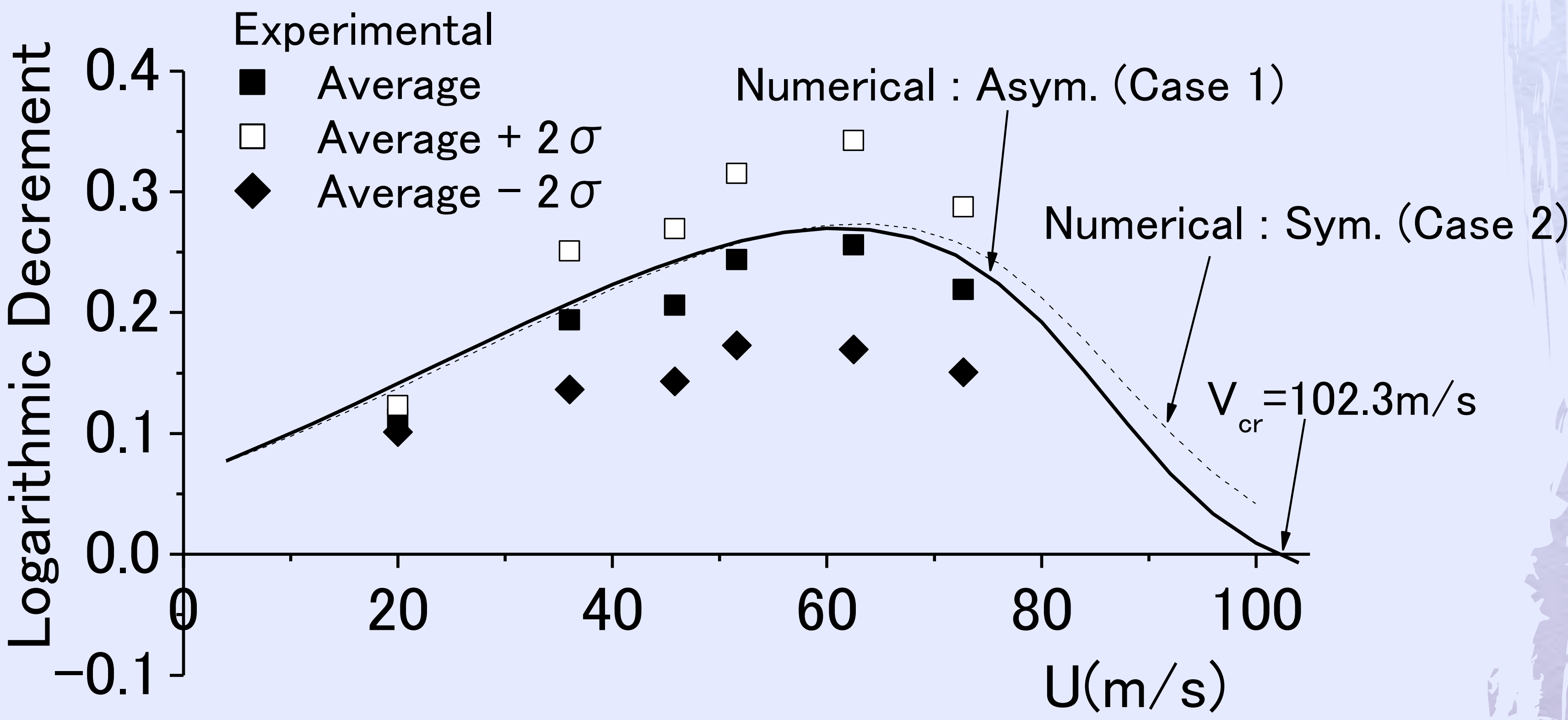
Input Data of 3D Flutter Analysis

Static Aerodynamic Force	① Bridge Deck：Experimental data at α=0deg. ② Cable：$C_D = 0.7$ ③ Hanger Cable：No consideration ④ Tower：$C_D = 1.8$
Flutter Derivatives	① Bridge Deck Measured data for benchmark Calculated data by quasi steady theory ② Cable H_1^* was calculated by quasi steady theory.
Structural Damping	① Sway motion $\delta = 0.0251$ (h = 0.4%) ② Vertical and rotational motions $\delta = 0.0628$ (h = 1%) (*) Measured values of aeroelastic model
Air Density	0.12 ($kg \cdot s^2/m^4$)

Results of 3D Flutter Analysis - Mode Frequency Curve -

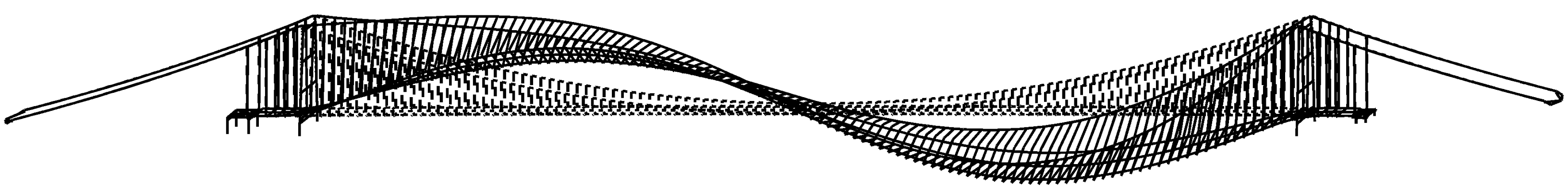


Results of 3D Flutter Analysis - Structural Damping Curve -



Results of 3D Flutter Analysis
- Flutter Mode Shapes -

Wind Velocity = 104m/s

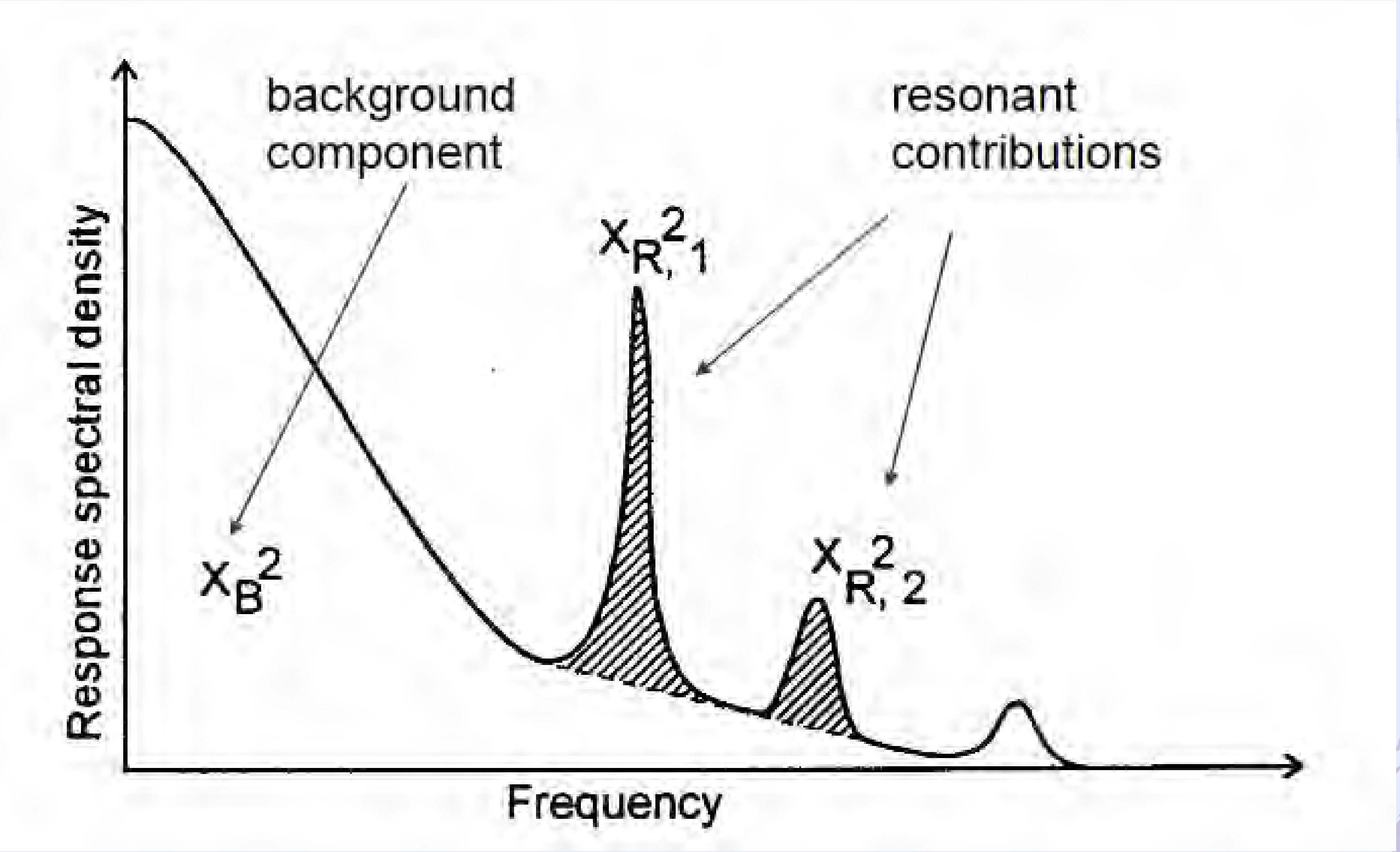


Frequency = 0.072Hz,   Log. decrement = -0.00705

Outline of Gust Response Analysis

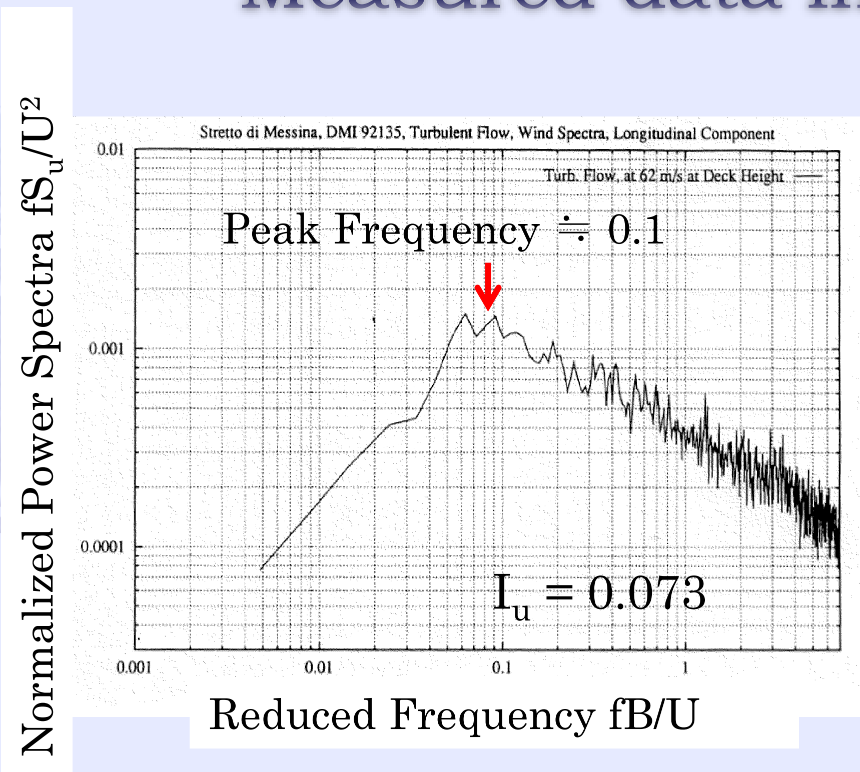
- The gust response analysis is the **3-dimensional gust response analysis** of multi-degree of freedom system with 3-dimensional frame model.
- Buffeting forces of drag, lift and moment are formulated as **quasi-steady aerodynamic forces** with horizontal and vertical fluctuating wind velocities.
- The power spectral density functions of real buffeting force is also considered by **aerodynamic admittance functions**.
- Based on random vibration theory, **the integration of the power spectral density function of gust responses** gives variance of the gust response in the n-th mode as **resonant response**.
- In addition to resonance response, the quasi steady response (**back ground response**) is also calculated.
- **The root mean square response for the 50 modal responses** is composed by summation of variance of all modes.
- **The maximum expected responses** are calculated by multiplying the root mean square responses by **gust peak factor** defined by Davenport.

Gust Response
- Resonant & Background Responses -

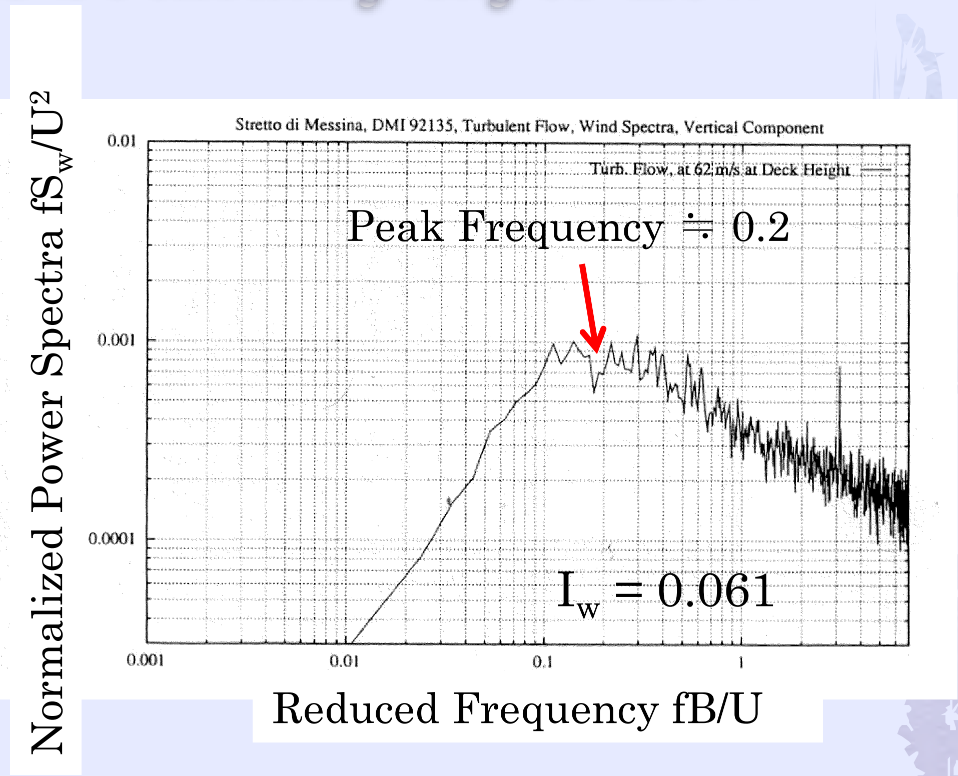


Reference from J.D.Holmes : Along Wind Response

Power Spectra of Wind Gust at Deck Height
- Measured data in boundary layer flow -

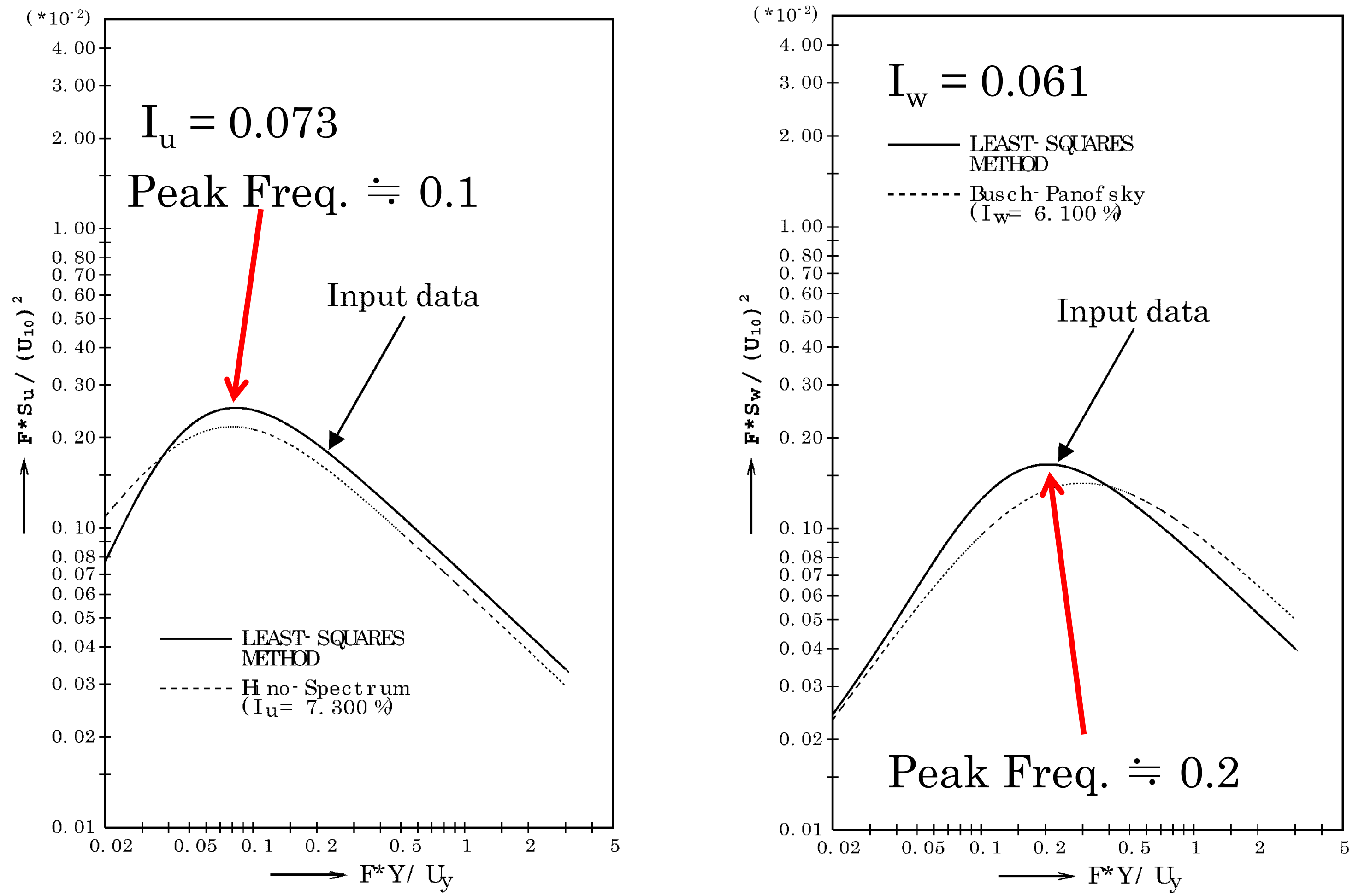


(a) Horizontal Comp.



(b) Vertical Comp.

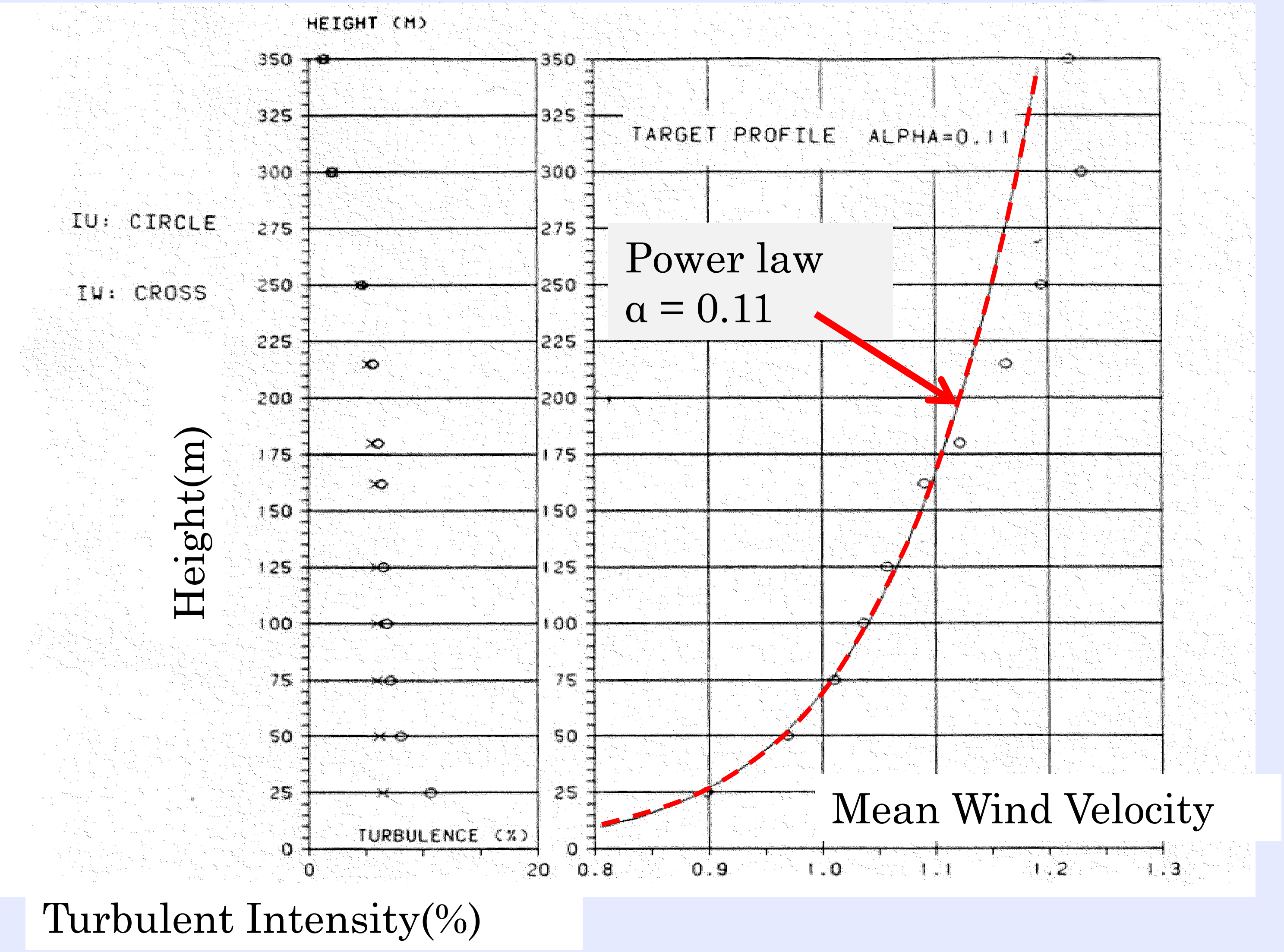
Power Spectra of Wind Gust at Deck Height
- Input data for gust response analysis-



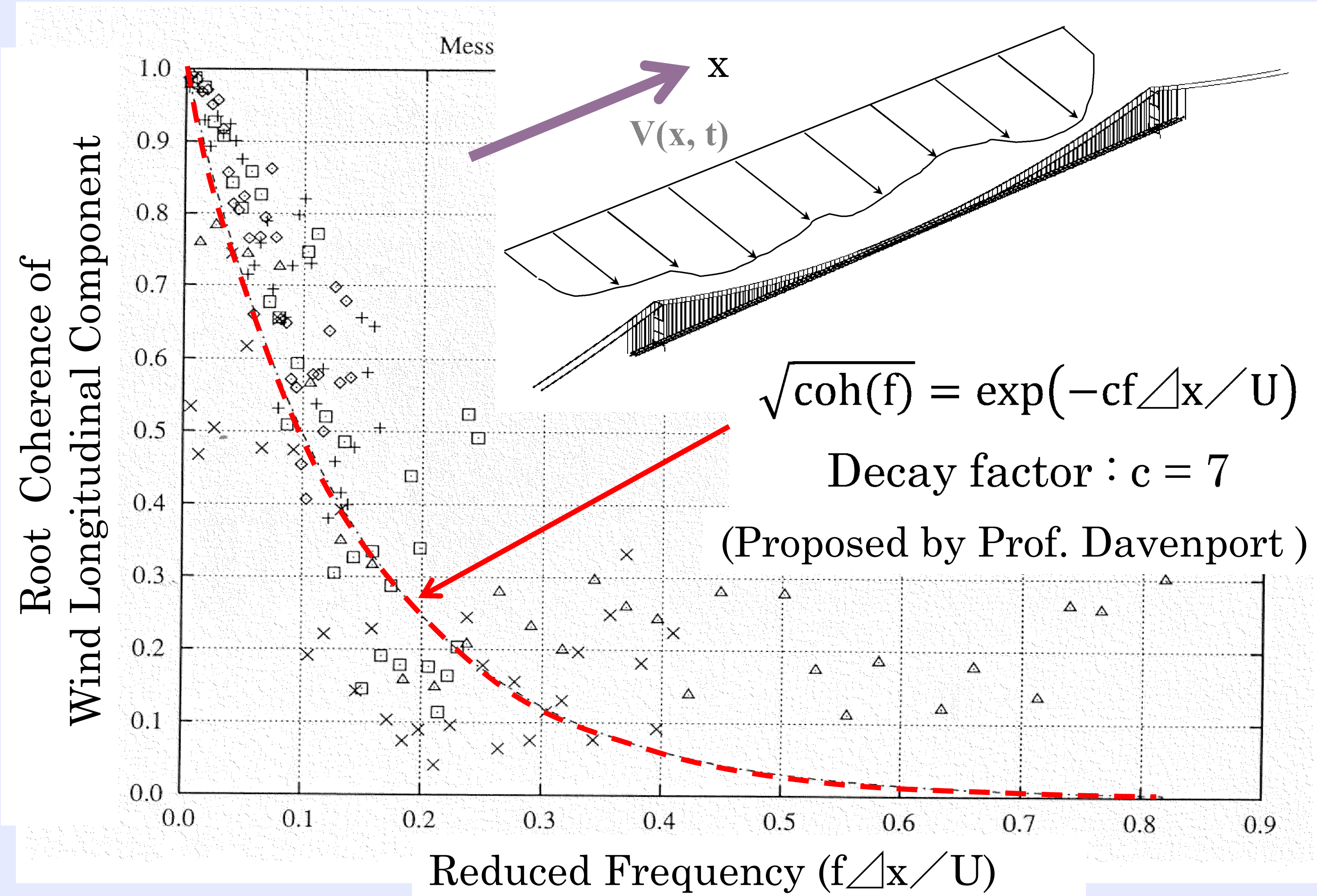
(a) Horizontal Component

(b) Vertical Component

Vertical Profile of wind velocity and turbulent intensity



Spatial Correlation of Horizontal Wind Gust



$$\sqrt{coh(f)} = \exp(-cf\triangle x / U)$$

Decay factor：c = 7

(Proposed by Prof. Davenport)

Input Data of 3D Gust Response Analysis

Aerodynamic Admittance	Drag : Davenport Formula Lift and Moment : Sears Function
Spatial Correlation	Davenport Formula (Decay Factor : k = 7)
Wind Power Spectra	The fitted wind power spectra to the measured wind power spectra in boundary layer turbulent flow
Wind Power	Power law of vertical profile α= 0.11
Peak Factor	Davenport Formula (T = 600sec)

(*) Input data of static and dynamic aerodynamic force, structural damping and air density are equal to the data of flutter analysis.

Results of Gust Response Analysis

		NTI(①)	Diana(②)	Exp.　(③)
Lateral(m)	Mean	9.91(1.00)	9.49(0.96)	8.36(0.84)
	RMS	1.81(1.00)	—	0.28(0.15)
Vertical (1/2)(m)	RMS	0.44(1.00)	—	0.26(0.59)
Vertical (1/4)(m)	RMS	0.50(1.00)	0.43(0.86)	0.29(0.58)
Rotational (deg.)	Mean	0.64(1.00)	0.52(0.81)	0.40(0.63)
	RMS	0.29(1.00)	0.26(0.90)	0.17(0.59)

Refinement of Gust Response Analysis

- For refinement of horizontal gust response

  → Recalculation of spatial correlation of horizontal wind gust

  → Modification of Davenport formula
- For refinement of vertical and rotational gust response

  → Use of the aerodynamic admittance function measured by Prof. Diana

Spatial Correlation of Horizontal Wind Gust
- for good fitting to experimental data -

①Davenport Formula

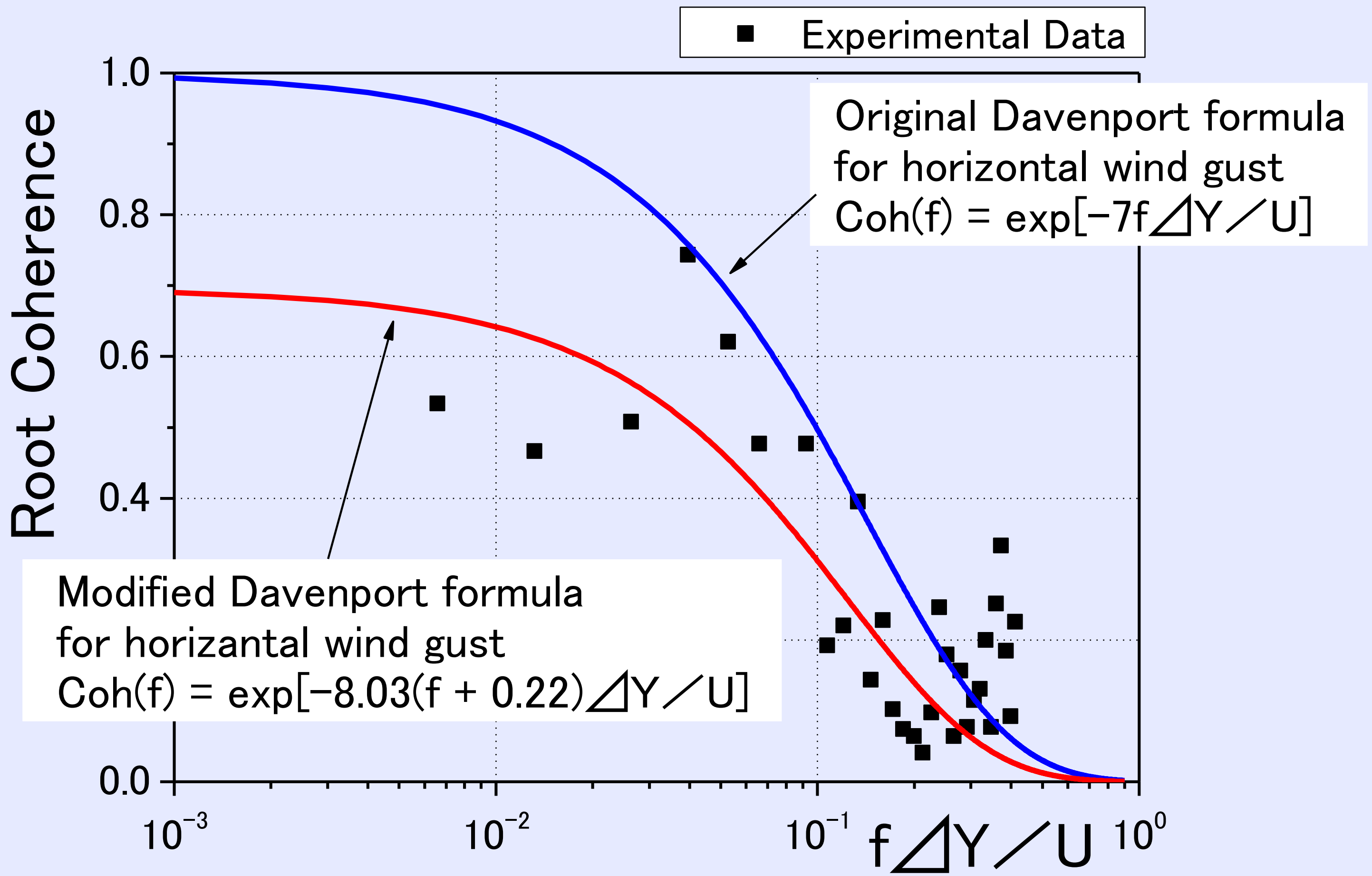
$$\sqrt{coh(f)} = \exp(-cf\triangle x/U)$$

② Modified Davenport Formula

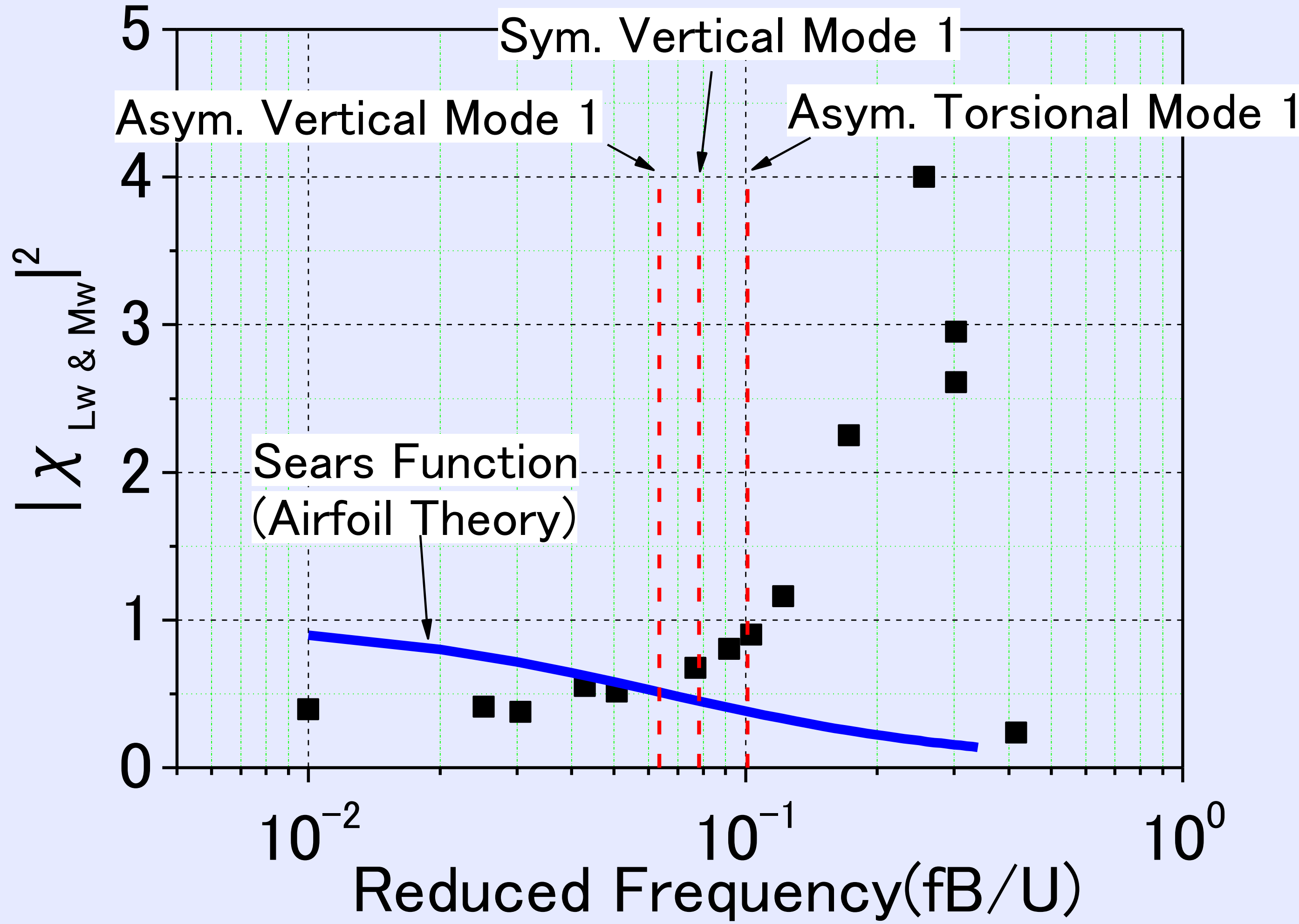
$$\sqrt{coh(f)} = \exp[-c(f+f_0)\triangle x/U]$$

f_0 is identified as the fitting parameter to the experimental data.

Refinement of spatial correlation of horizontal wind gust



Use of the measured aerodynamic admittance function for lift and moment forces



Results of Gust Response Analysis

		NTI(①)	Diana(②)	Exp.（③）
Lateral(m)	Mean	9.91(1.00)	9.49(**0.96**)	8.36(**0.84**)
	RMS	0.55(1.00)	—	0.28(**0.51**)
Vertical (1/2)(m)	RMS	0.20(1.00)	—	0.26(**1.27**)
Vertical (1/4)(m)	RMS	0.21(1.00)	0.43(**0.86**)	0.29(**1.39**)
Rotational (deg.)	Mean	0.64(1.00)	0.52(**0.81**)	0.40(**0.63**)
	RMS	0.19(1.00)	0.26(**0.90**)	0.17(**0.89**)

Conclusions
- Natural Frequency Analysis -

- The natural frequency in this analysis agreed to the original results by Prof. Diana’s research group within the about 10% error.
- The lowest modes of bending and torsional motions have asymmetric mode shapes.

Conclusions
- Flutter Analysis -

- The flutter onset velocity of 3D frame model was 102m/s.
- The analysis results on flutter frequency and logarithmic damping agree well to the experimental results. The flutter mode had asymmetrical mode shape.

Conclusions
- Gust Response Analysis -

- The analysis results agreed well to the numerical results by Prof. Diana's research group. However, the analysis results were smaller than the experimental RMS responses.
- Especially, the analysis result of sway motion was very smaller than the experimental RMS responses.
- The large errors on the RMS response of sway motion were thought to be due to the estimation errors of spatial correlation.

Continued on the following page

Conclusions
- Gust Response Analysis -

- For the refinement of gust response analysis, Davenport formula was modified to fit the experimental data of spatial correlation.
- The experimental data of the aerodynamic admittance functions for lift and moment forces was used.
- The RMS response of sway motion is better than the previous analysis.
- The RMS response of torsional motion agrees well to the experimental response. However, the RMS responses of bending motion were smaller than the experimental responses.