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Design of experimental apparatus for real-time wind-tunnel hybrid simulation of bridge decks

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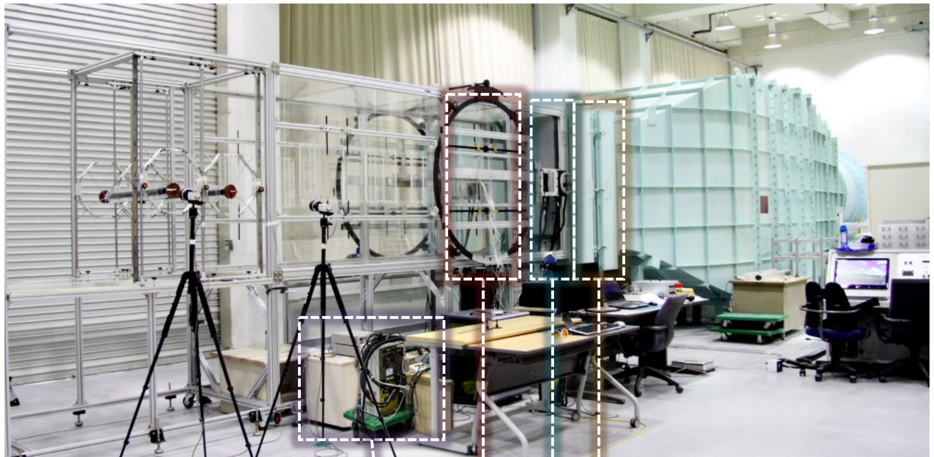
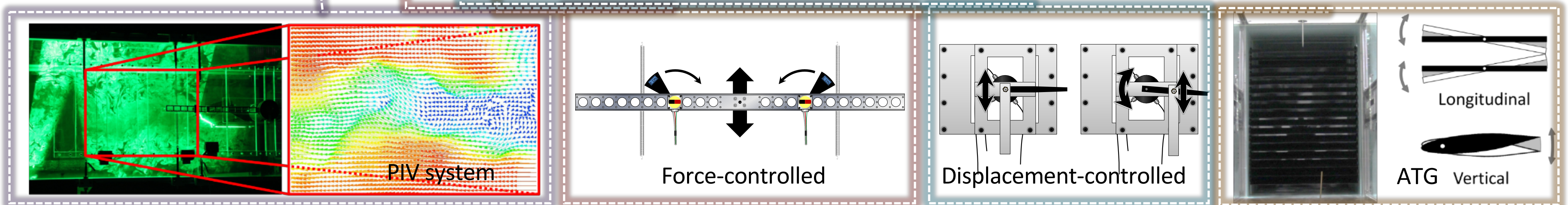
- Editor-in-Chief, KSCE Journal of Civil Engineering (Springer Indexed in SCIE)

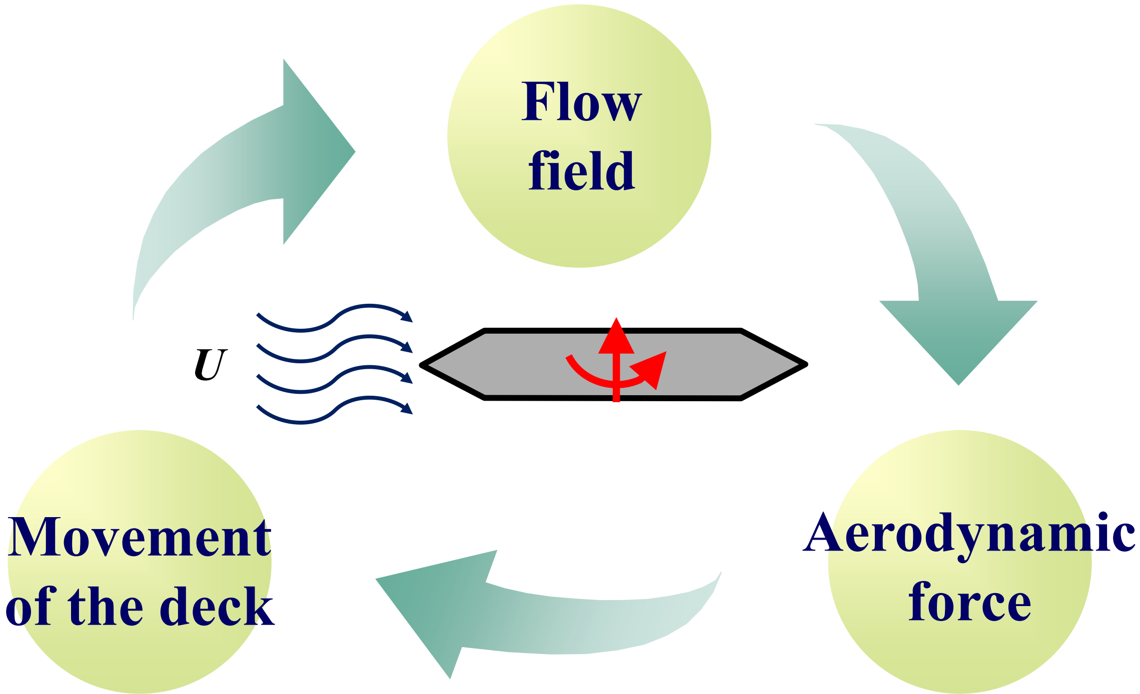
Le Cachalot Wind Tunnel
Seoul National University



- Wind resistance design for 20+ cable-supported bridges
- Wind tunnel facilities
  - Wind tunnel (Test section : W(1.0 m) × H(1.5 m) × L(4.0 m), Maximum wind velocity : 23 m/s)
  - Force-controlled steady-state exciter
  - Displacement-controlled harmonic exciter
  - Active turbulence generator(ATG)
  - PIV system

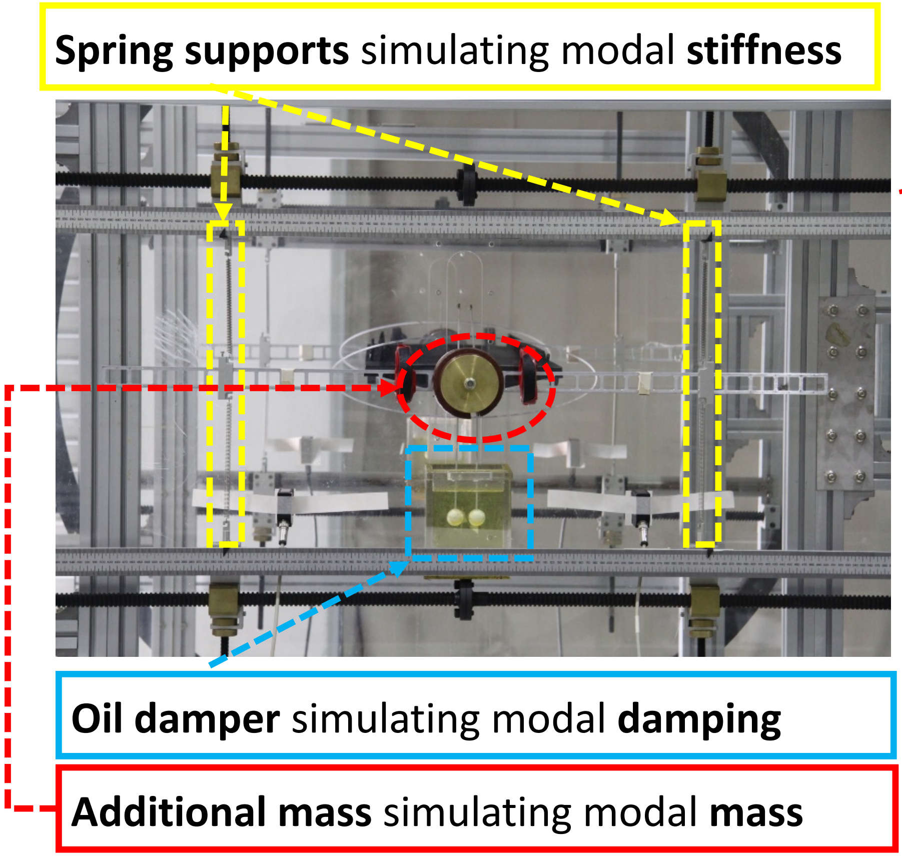


Flow-structure interaction: Aeroelastic phenomena

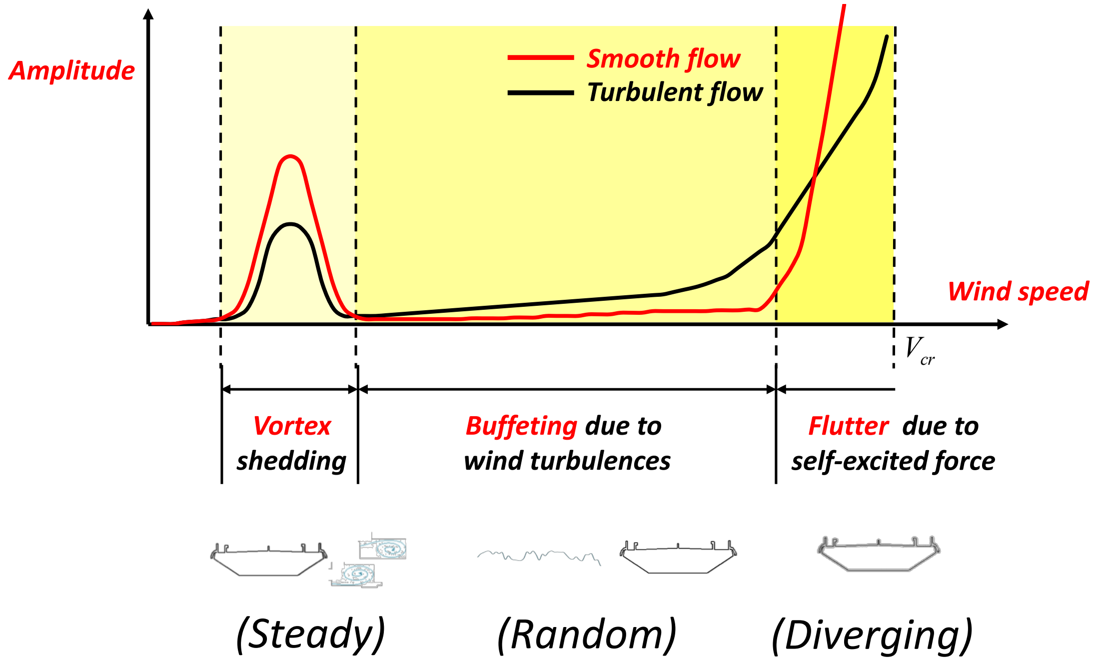


- The effect of the wind load acting on the bridge deck is related to the **buffeting force (aerodynamic) caused by the fluctuation** of the air current, the **self-excited force (aeroelastic) due to the deck motion**, and the **vortex-induced force generated from the separation of the flow field** around decks.
- **Limitations in measuring motion-dependent aeroelastic force components in spring-supported wind tunnel test**

Spring-supported motional test for flutter instability and VIV (smooth)



2-DOF setting for coupled motion between only two targeting modes (heaving & torsion)



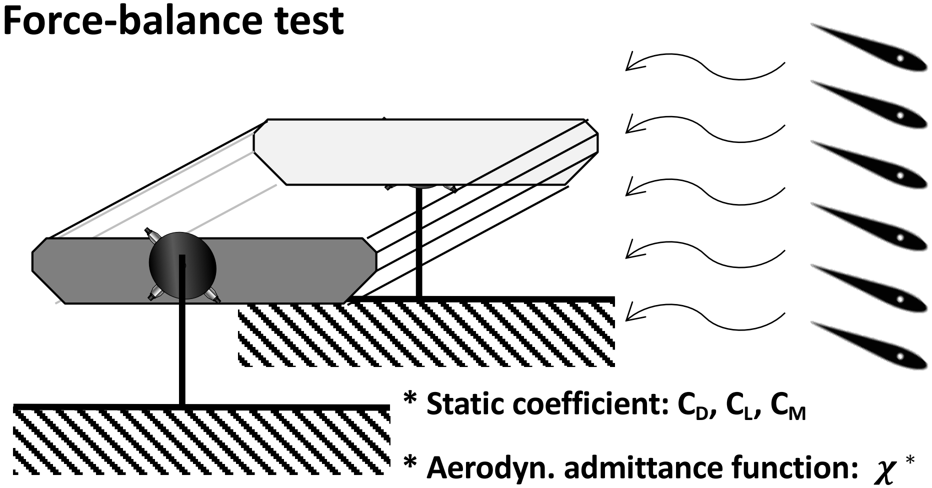
- **Physical limitations**

- **Time-consuming setup** for the dynamic system with trial-and-error approach
- **Unidentified wind loads**
- Aeroelastic motions by **only two modes** (e.g., a dominant torsional mode with coupled heaving mode)

Two-phase approach for multi-mode aerodynamic motion (turbulent)

Aerodynamic coefficients from wind tunnel tests

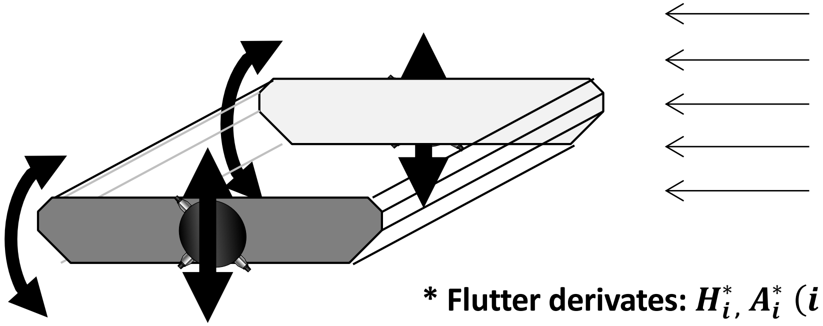
Force-balance test



* Static coefficient: C_D, C_L, C_M

* Aerodyn. admittance function: χ^*

Prescribed motion test



* Flutter derivates: H_i^*, A_i^* $(i = 1, \cdots 6)$

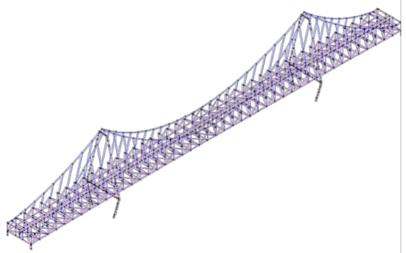
(Scanlan and Tomko, 1971)

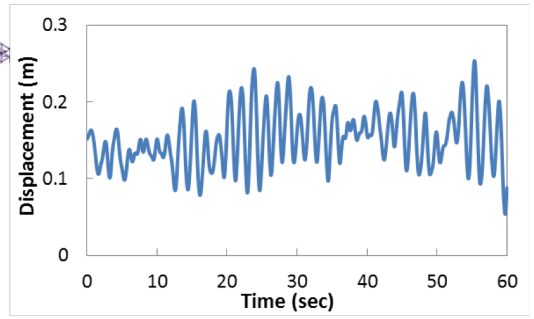
Multi-mode buffeting analysis

$$\begin{bmatrix}F_D\\F_L\\F_M\end{bmatrix} = F_{static} + F_{Buffet} + F_{self-excited}$$

$$= \frac{\rho U^2 B}{2}\begin{bmatrix}C_D\\C_L\\BC_M\end{bmatrix} + \frac{\rho U B}{2}\begin{bmatrix}\chi^*_{D_u} & \chi^*_{D_w}\\ \chi^*_{L_u} & \chi^*_{L_w}\\ \chi^*_{M_u} & \chi^*_{M_w}\end{bmatrix}\begin{bmatrix}u\\w\end{bmatrix}$$

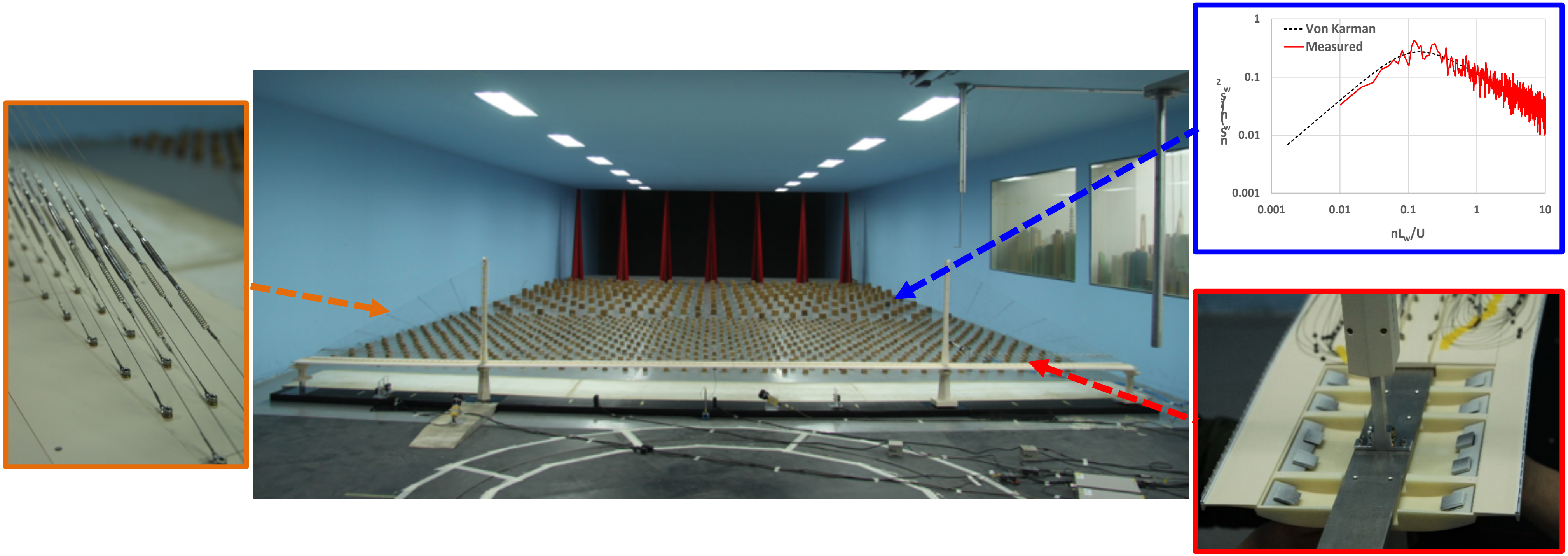
$$+ \frac{\rho U B}{2}\begin{bmatrix}P_1^* & P_5^* & P_2^*\\ H_5^* & H_1^* & H_2^*\\ A_5^* & A_1^* & A_2^*\end{bmatrix}\begin{bmatrix}\dot{p}\\ \dot{h}\\ \dot{\alpha}\end{bmatrix} + \frac{\rho U^2 B}{2}\begin{bmatrix}P_4^* & P_6^* & P_3^*\\ H_6^* & H_4^* & H_3^*\\ A_6^* & A_4^* & A_3^*\end{bmatrix}\begin{bmatrix}p\\ h\\ \alpha\end{bmatrix}$$





- **Physical limitations**
  - The system identification **procedure for flutter derivatives was not substantially updated** for last 50 years.
  - **Multi-mode buffeting response** cannot be estimated in section model tests.

Aeroelastic full-bridge models with multi-modes (turbulent, smooth)



- **Multi-modes** can be considered.
- Not enough but **practically acceptable** turbulence in terms of **length scale** can be generated.
- Wind loads on **cables and pylons** are also reflected.

➢ **Physical limitations**

- **Limited number of modes** can be practically realized.
- **High laboring work for design of frame model, high manufacturing costs, and long-period of preparation**

Collaboration between SNU & U of T

SEOUL NATIONAL UNIVERSITY

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Wind-tunnel testing experience

- Aerodynamic design of stable deck section
- wind-tunnel testing based on similitude law
- System identification for aeroelastic parameters

Aerodyn. & aeroelastic analysis

- Feasibility study of RTHS by a theoretical simulation
- Capacity evaluation of dynamic actuator

RTHS in wind tunnel

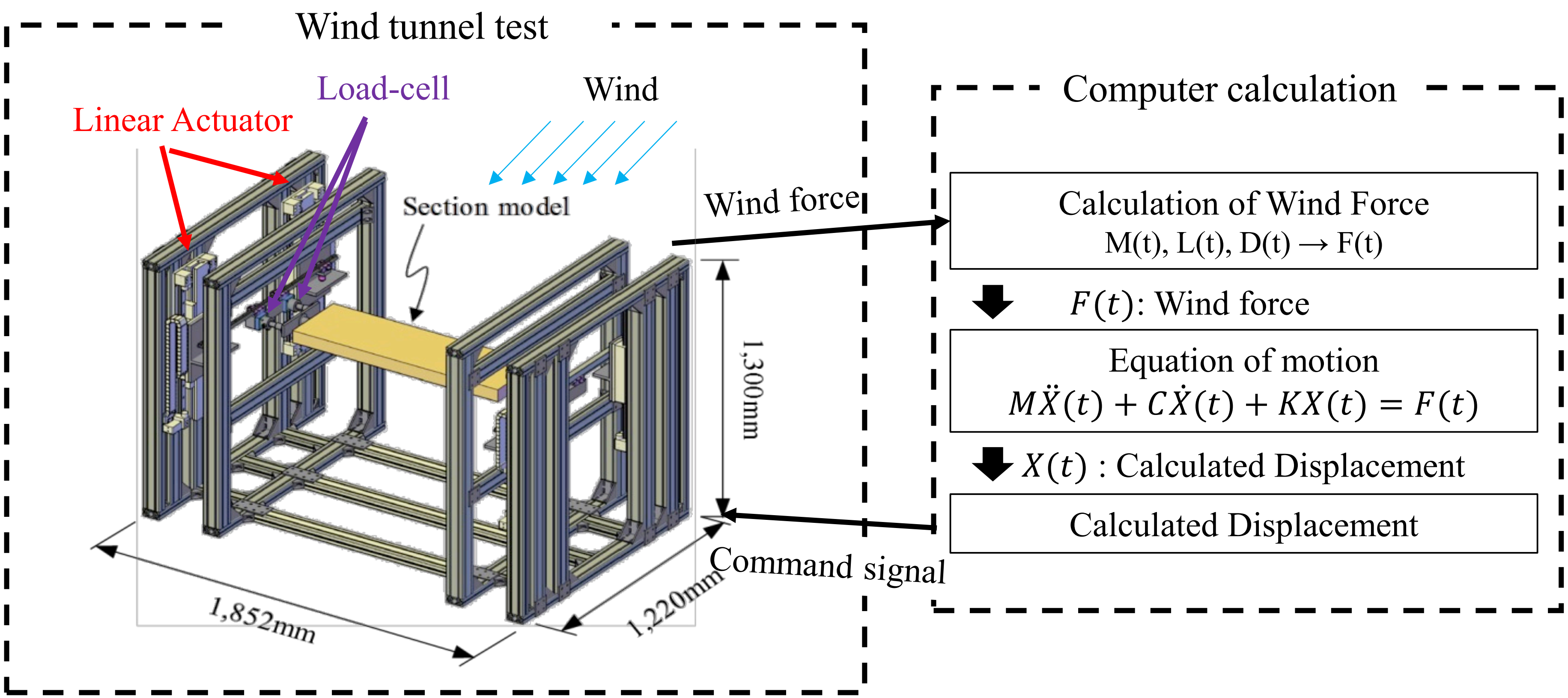
Hybrid Sim. in EQ & fire

- PsD hybrid simulation of structures subjected to earthquake
- RTHS for structures subjected to fire
- Frequency-dependent SSI analysis in time-domain

Motor-control design

- Design of linear motor and DAQ systems for 2D motion
- Time-delay compensation for linear motors for RTHS

Proposed RTHS for section-model tests



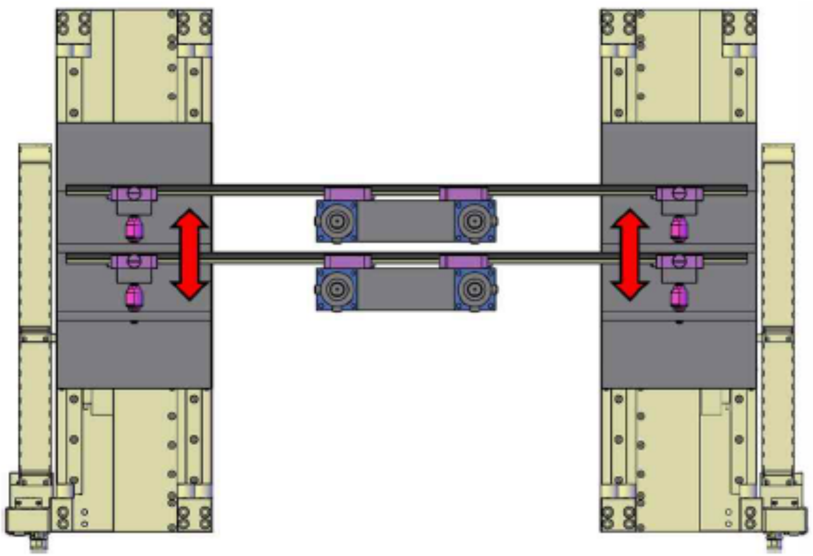
- **Expected benefits** of RTHS

- **Convenient setup** of modal parameters. **Just input** in cyber system.
- Wind force and dynamic motions are **simultaneously measured**.
- Do not require assumptions in simulating wind-structure interaction (**ideal** for aeroelastic phenomena)
- Potentially applicable to **multi-mode simulation in section model tests (i.e., buffeting response)** when large-scale turbulence is generated by active turbulence generator.

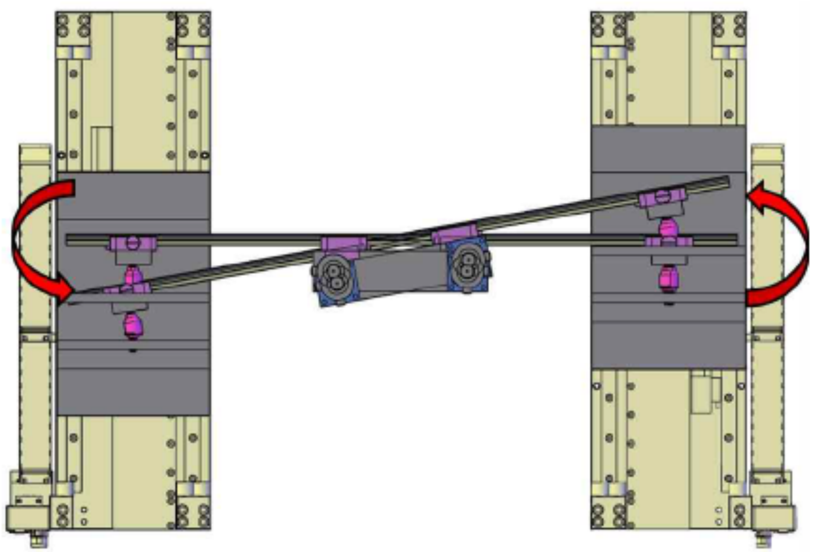
Design of physical parts

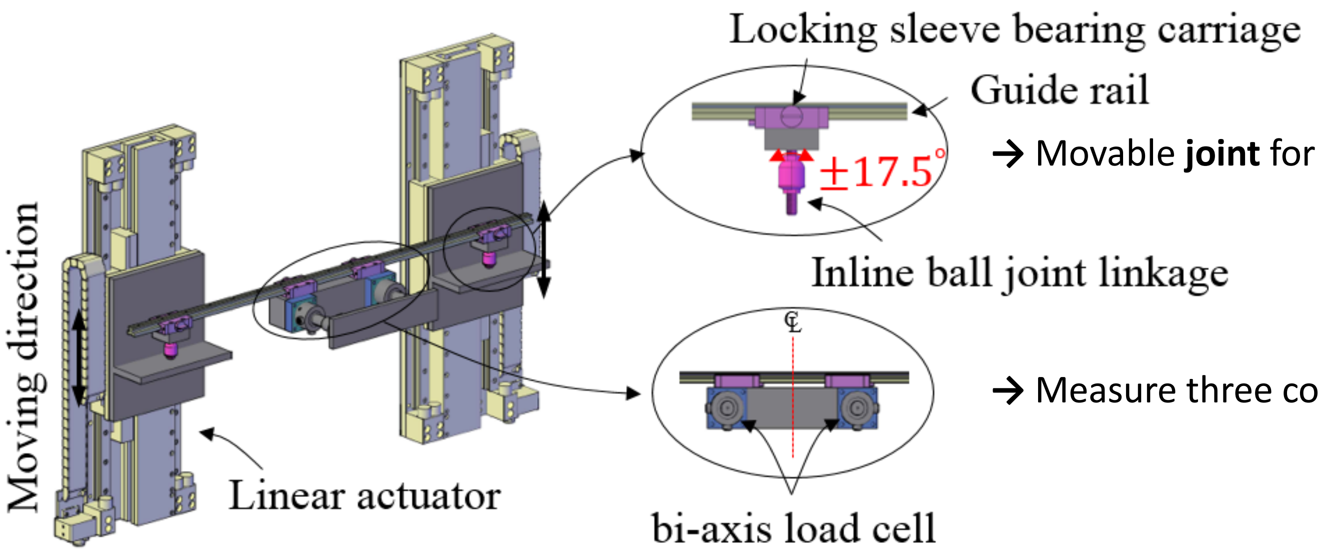
- Simulation of 2-D motions with four linear actuators

Vertical motion



Torsional motion





→ Movable **joint** for rotation

→ Measure three components of wind force

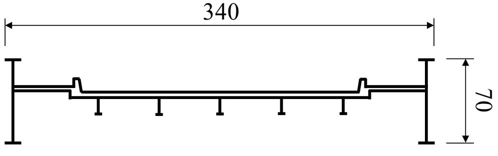
Design of physical parts

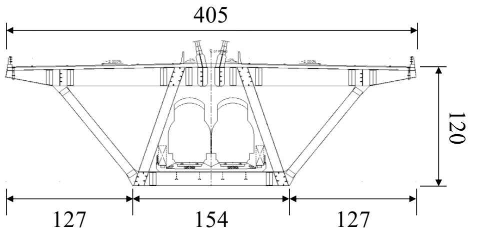
➢ Required capacities of motors and load cells

Examined bridges

Length scale: 1/100-1/35

(Unit: mm)





<Tacoma narrow bridge>

- **Flutter-susceptible** section

<A designed cabled-stayed bridge>

- **Significant vibrations** at high wind speed

Selection of motor and load cell capacity

	Maximum value
Vertical Displacement (mm)	14.7
Torsional Displacement (radian)	555.4
Lift force (N)	446.9
Moment (N·m)	77.4

Safety margin of 2 was taken into account.

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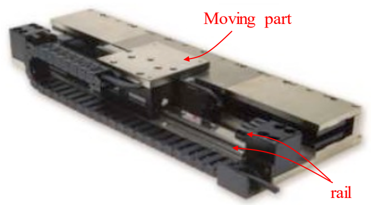
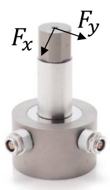
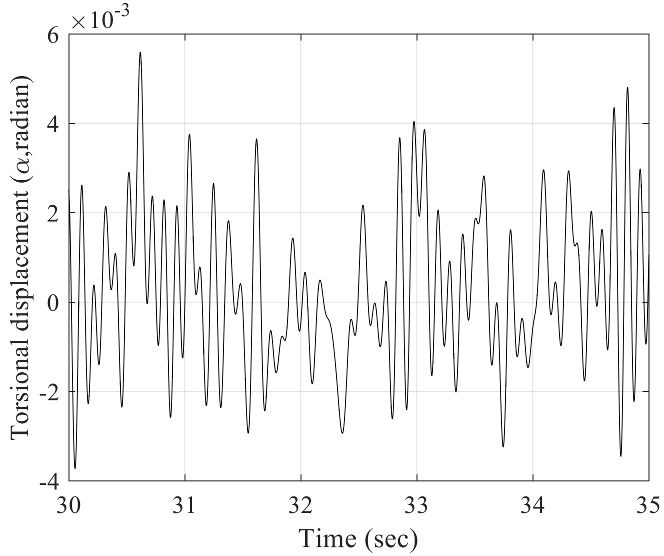


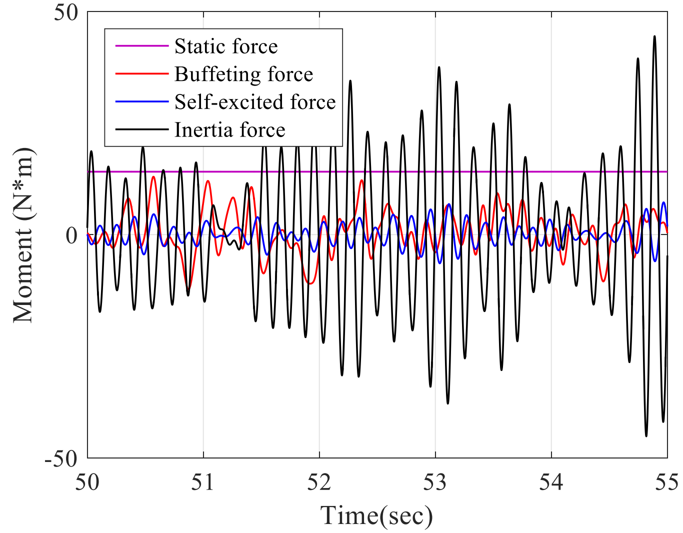


MBA400

Time-domain buffeting analysis

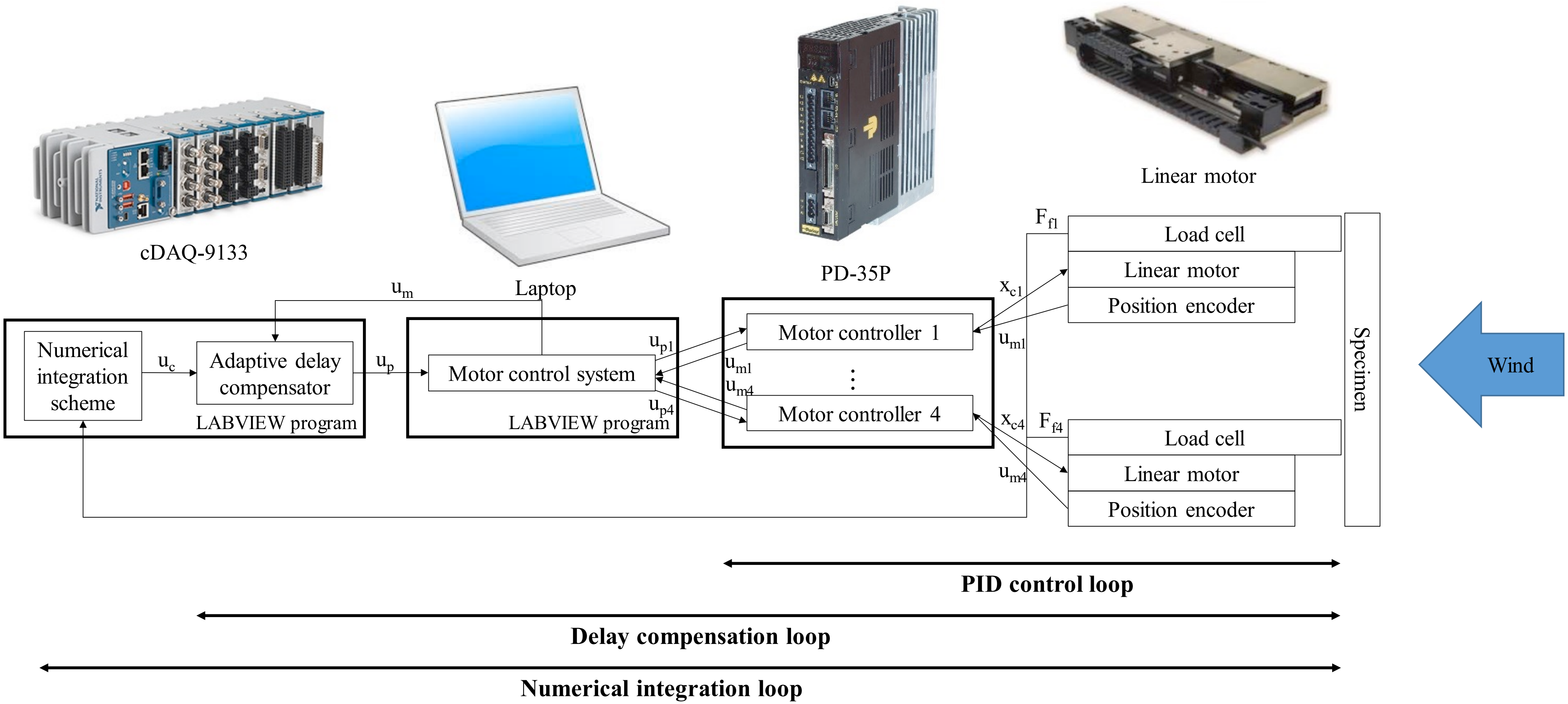


Maximum displacement



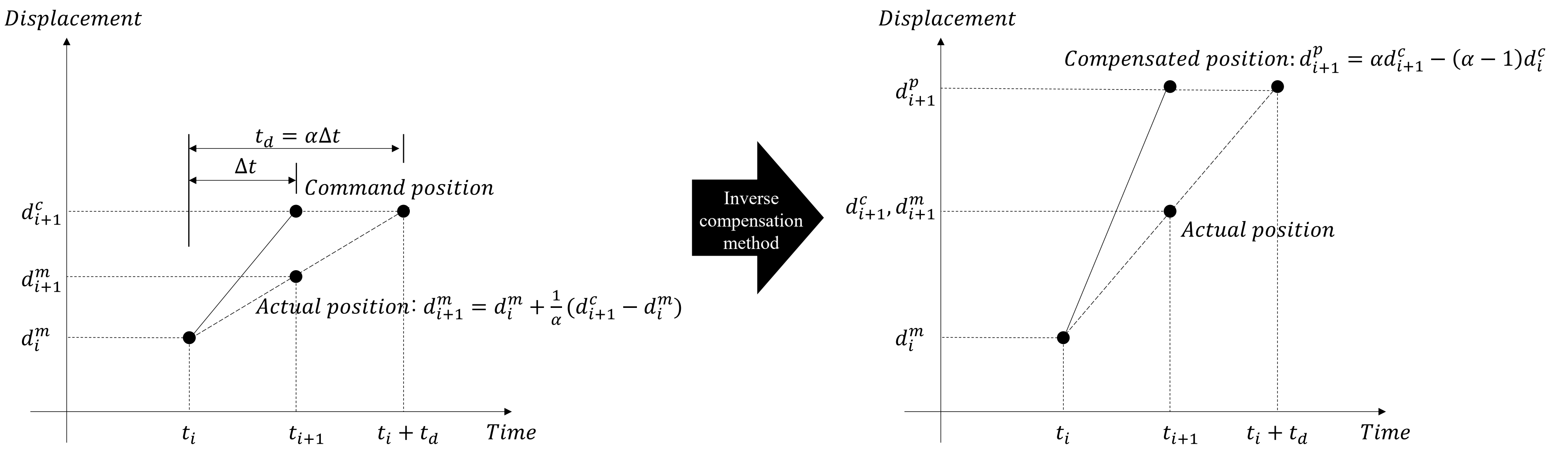
Maximum moment

Design of control parts



Design of control parts

- **Time-delay compensation**
  - Inverse compensation (Chen and Ricles, 2009)
  - Adaptive inverse compensation (Chen and Ricles, 2010)
  - Improved adaptive inverse compensation (Chen et al., 2012)

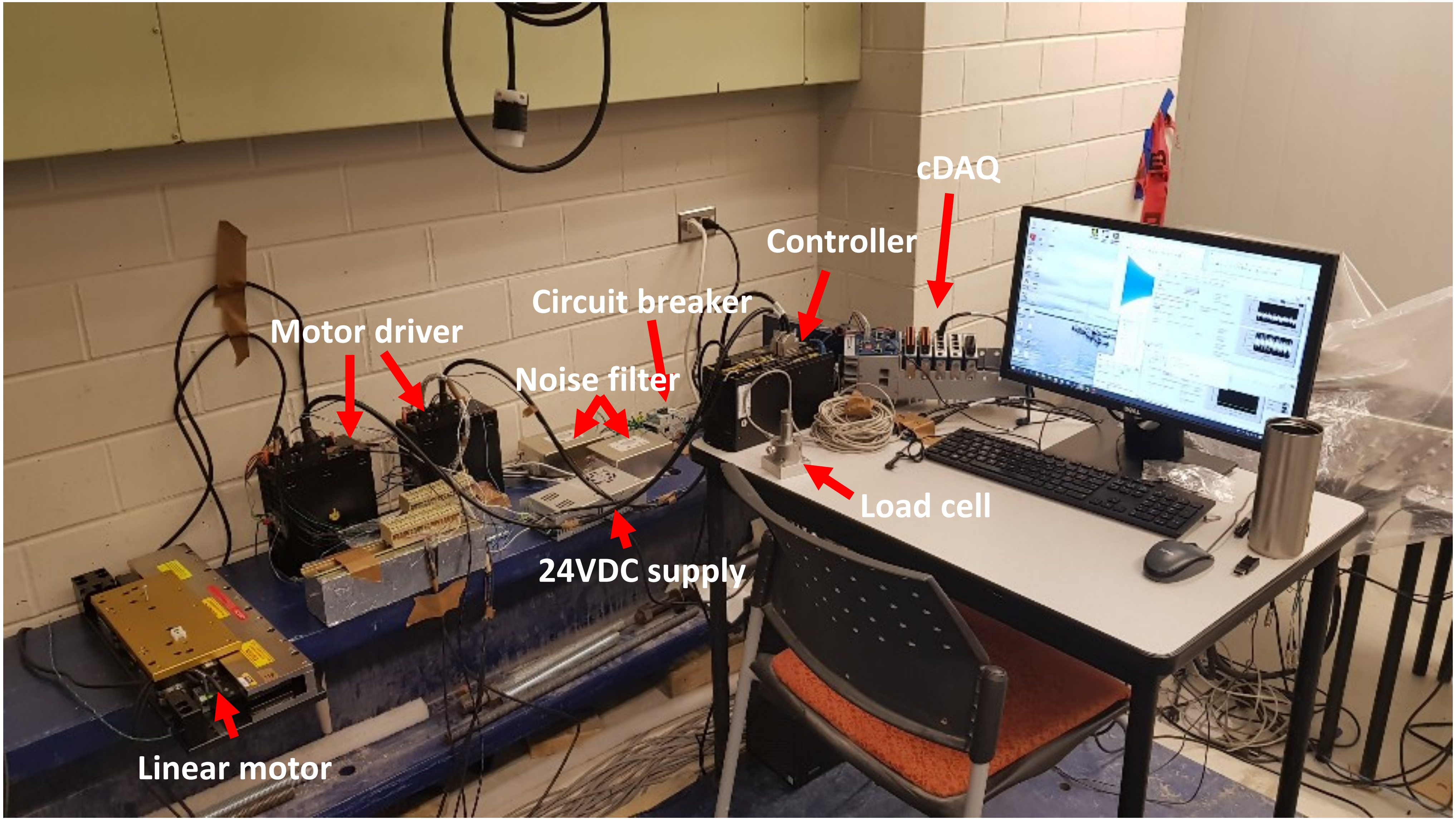


Chen, C., and Ricles, J. M. (2009). Analysis of actuator delay compensation methods for real-time testing. *Engineering Structures*, *31*(11), 2643-2655.

Chen, C., and Ricles, J. M. (2010). Tracking error-based servohydraulic actuator adaptive compensation for real-time hybrid simulation. *Journal of Structural E ngineering*, *136*(4), 432-440.

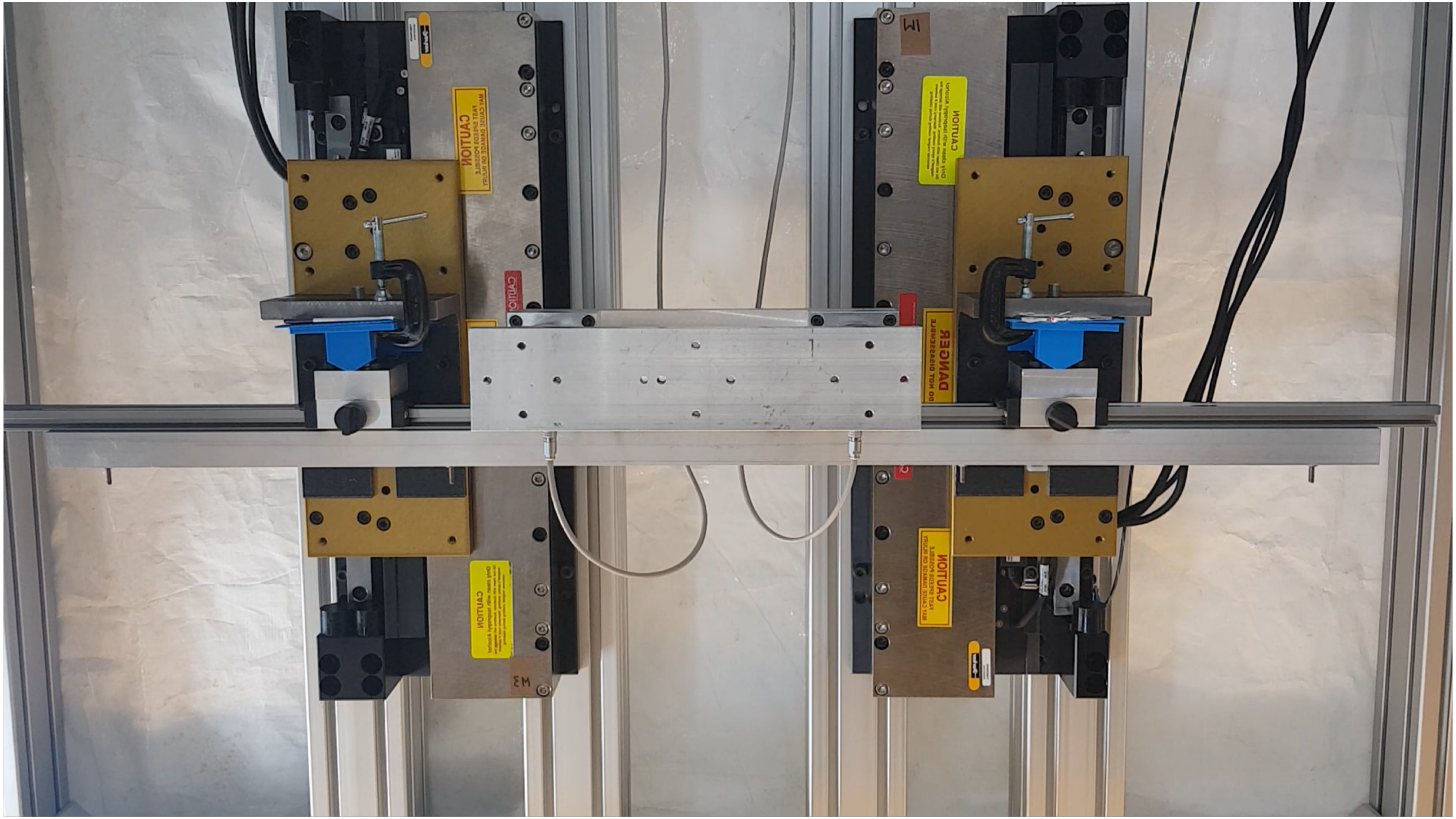
Chen, C., Ricles, J. M., and Guo, T. (2012). Improved adaptive inverse compensation technique for real-time hybrid simulation. *Journal of Engineering Mecha nics*, *138*(12), 1432-1446.

Preliminary tests for controlling parts



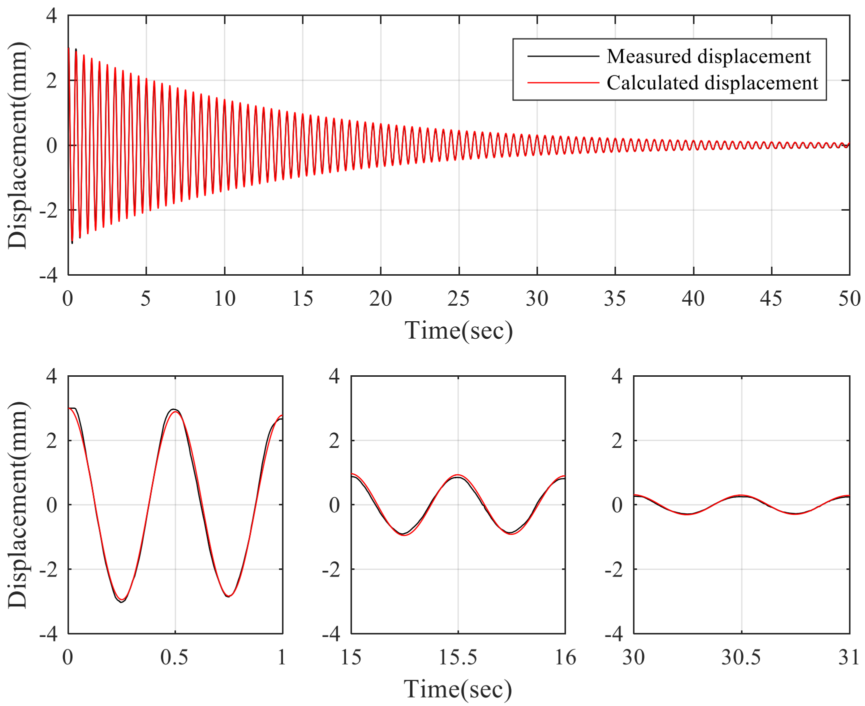
Simulation of free vibration response subjected to initial displacement

- Initial displacement: **h_0=3mm, α_0=0.3 degree**
- Inputted modal parameters: **m_h= 50kg, m_α= 1kg·m^2, f_h= 2Hz, f_α= 3Hz, ζ_h= ζ_α = 0.6%**

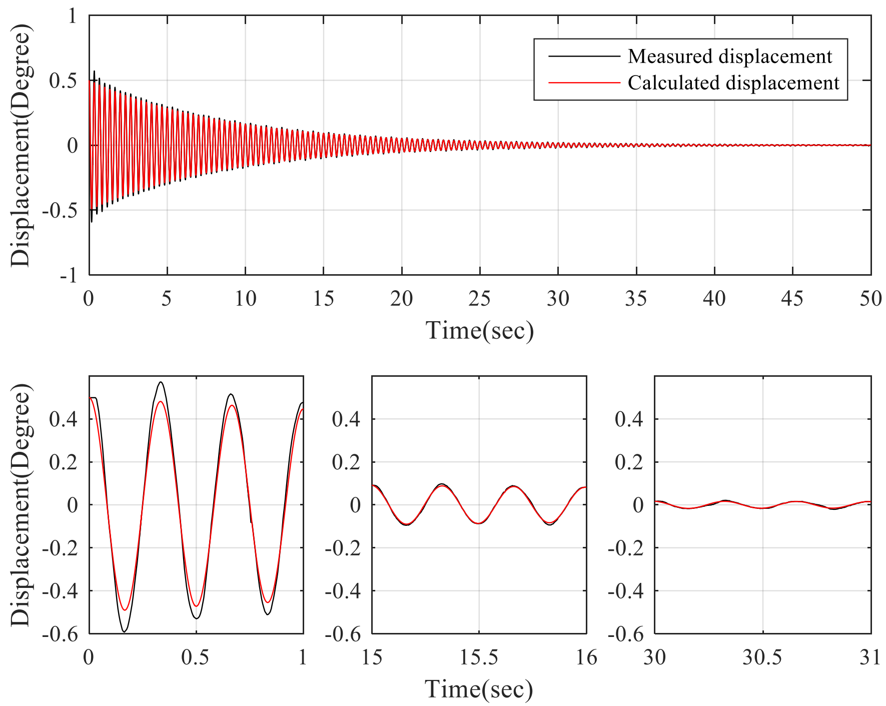


Coincidence between measured RTHS response and theoretical solution

- Initial displacement: **h_0=3mm, α_0=0.3 degree**
- Inputted modal parameters: **m_h= 50kg, m_α= 1kg·m^2, f_h= 2Hz, f_α= 3Hz, ζ_h= ζ_α = 0.6%**



Vertical displacement



Torsional displacement

Concluding remarks and further studies

- **Feasibility of RTHS control was demonstrated** with the developed apparatus.
- **The linear motors were designed** for covering the practical range of wind-induce forces for the scaled section model.
- **The potential advantage of the proposed RTHS technology includes**
  - Elimination of conventional **time-consuming setup**
  - **Simultaneous measurement** of wind **forces** and dynamic **motions**
  - **Rigorous simulation** of aeroelastic **wind-structure interaction**
  - Potential **multi-mode buffeting simulation** in section model tests with ATG
- Further study will be continued to the applicable level to the actual bridge projects.