Real-Time Aerodynamics Hybrid Simulation: A Novel Wind-Tunnel Model for Flexible Bridges

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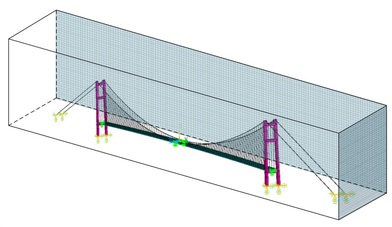
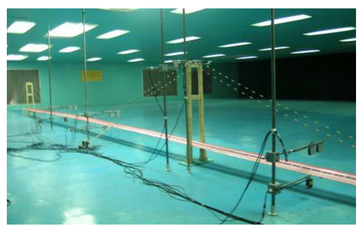
Introduction

Wind-bridge interaction
Fluid-Structure Interaction (FSI)



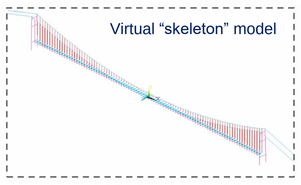
3D FSI simulation
Not available at High Re

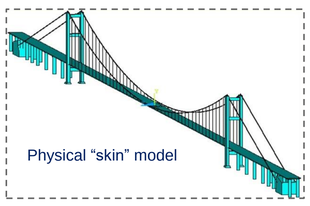


Full-bridge model test
Inaccuracy in simulating structural dynamic properties

Real-Time Aerodynamics Hybrid Simulation (RTAHS)

Concept of RTAHS





"Skeleton" of the full-bridge model, characterizing the dynamic properties, is numerically simulated in the computer.

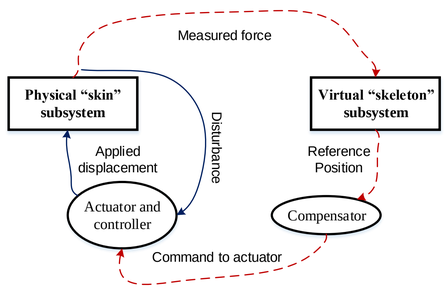
Actuators operate in displacement control

"Skin" of the full-bridge model, characterizing aerodynamic properties, is physically modeled in the wind tunnel

Aero. force

Displacement

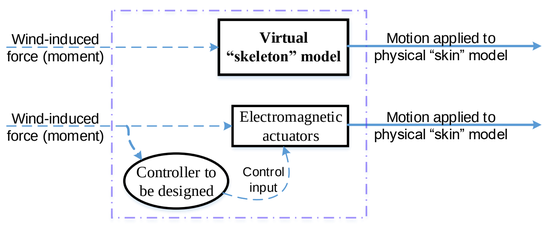
A novel control design



Conventional configuration of RTAHS

VS

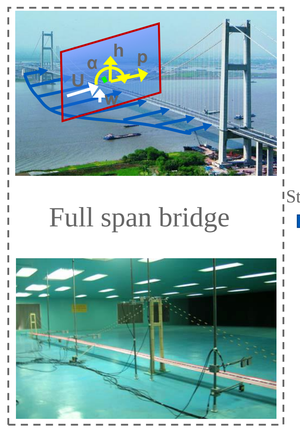
A novel control design



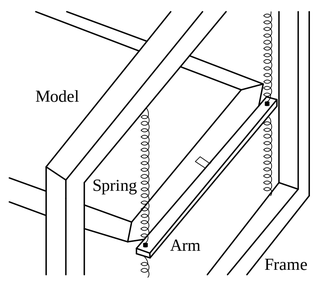
The conventional control design depends on one's understanding of the physical "skin" model

The novel design decouples the controller design from the physical "skin" model

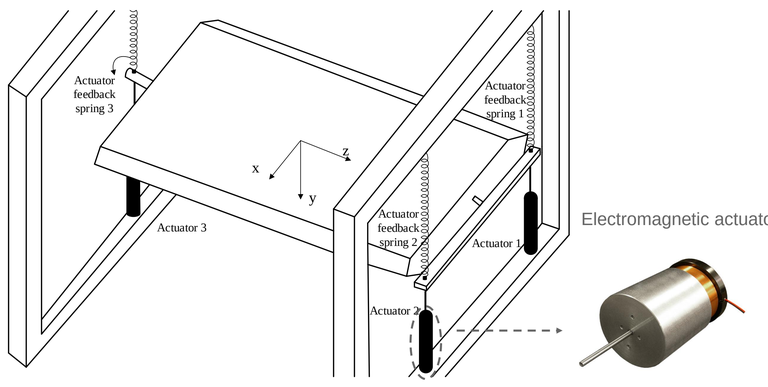
Formulation of RTAHS



Setup of RTAHS in wind tunnel

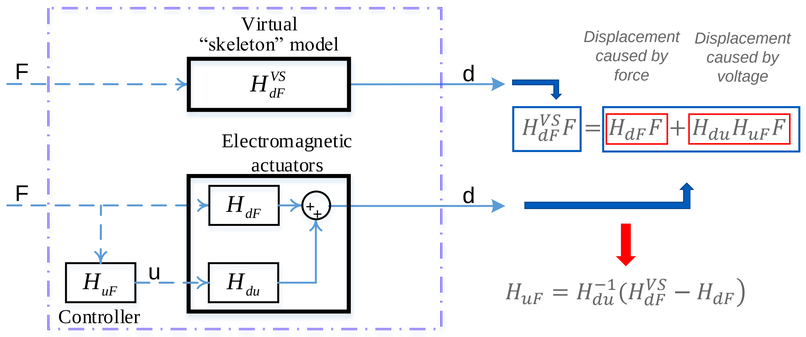


Setup of conventional sectional model test.



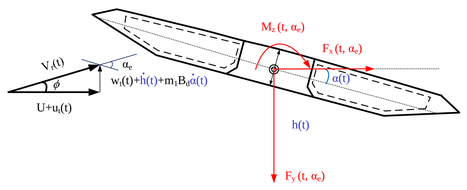
Setup of RTAHS in the wind tunnel.

Controller design



$$H_{dF}^{VS}F = H_{dF}F + H_{du}H_{uF}F$$

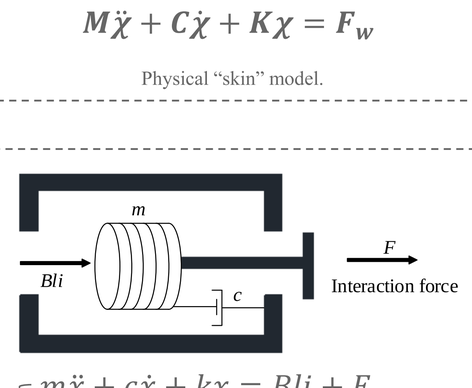
$$H_{uF} = H_{du}^{-1}(H_{dF}^{VS} - H_{dF})$$



$$M\ddot{\chi} + C\dot{\chi} + K\chi = F_w$$

Physical "skin" model.

$$H_{dF}^{VS}$$



$$\begin{cases} m\ddot{x} + c\dot{x} + kx = Bli + F \\ u - Bl\dot{x} = L\dfrac{di}{dt} + Ri \end{cases}$$

Linear electromagnetic actuator model.

$$H_{du} \quad H_{dF}$$

Designed controller $H_{uF} = H_{du}^{-1}(H_{dF}^{VS} - H_{dF})$

Numeric example

Parameters of a bridge sectional model

Parameter	Sectional model	Real bridge deck	Scale ratio
Length	1 m	65 m	1:65
Width	0.6308 m	41 m	1:65
Mass per unit length	7.6142 kg/m	32170 kg/m	$1:65^2$
Moment of inertia per unit length	0.4912 kg·m	8768902 kg·m	$1:65^4$
Vertical frequency	2.641 Hz	0.195 Hz	65:4.8
Torsional frequency	7.191 Hz	0.531 Hz	65:4.8
Wind speed	12.5 m/s	60 m/s	1:4.8
Damping ratio	0.005	0.005	1:1

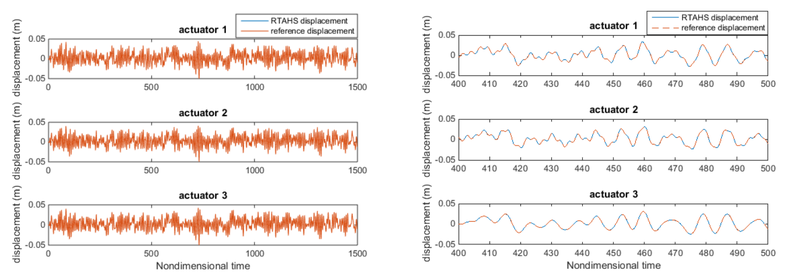
Parameters of a linear electromagnetic actuator

Parameter	Value
Damping in the voltage mode	25 N·s/m
Coil inductance	0.0021 H
Coil resistance	3 Ω
Force to current ratio	22.2 N/A
Mass of the coil	0.71 kg
Stiffness of the spring	5000 N/m

Linear physical "skin" model

$$F_y^{lin} = -\frac{1}{2}\rho U^2 B_d\{[C_L] + [F_{L_b}] + [-F_{L_{se}}]\}\Big|_{\alpha_s}$$

$$M_z^{lin} = \frac{1}{2}\rho U^2 B_d^2\{[C_M] + [M_b] + [M_{se}]\}\Big|_{\alpha_s}$$



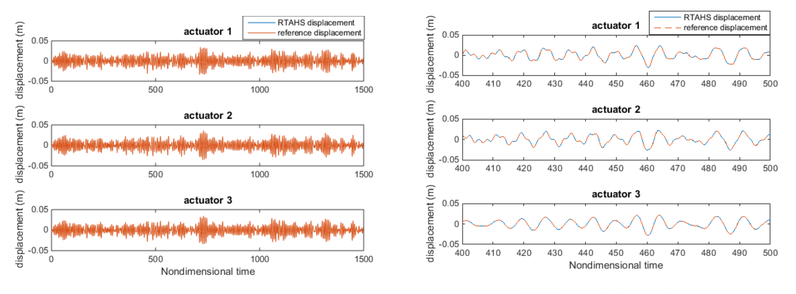
(a) Complete simulation results (b) Zoomed-in version

Comparison between linear RTAHS and reference displacements.

Nonlinear physical "skin" model

$$F_y^{non} = -\frac{1}{2}\rho B\left\{V_r^{l\,2}\{C_L(\alpha_e^l)\cos(\phi^l) + C_D(\alpha_e^l)\sin(\phi^l)\} + U^2\{[C_L] + [F_{L_b}] + [-F_{L_{se}}]\}\Big|_{\alpha_e^l}\right\}$$

$$M_z^{non} = \frac{1}{2}\rho B^2\left\{V_r^{l\,2}\{C_M(\alpha_e^l)\} + U^2\{[C_M] + [M_b] + [M_{se}]\}|_{\alpha_e^l}\right\}$$



(a) Complete simulation results (b) Zoomed-in version

Comparison between nonlinear RTAHS and reference displacements.

References

1. Wu, T., and Kareem, A., 2013. Bridge aerodynamics and aeroelasticity: A comparison of modeling schemes. Journal of Fluids and Structures, 43, 347-370.

2. Stefanaki, A., 2017. A Simple Strategy for Dynamic Substructuring and its Application to Soil-Foundation-Structure Interaction. Doctoral dissertation, State University of New York at Buffalo.

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