REAL-TIME FORCE CONTROL FOR ADVANCING REAL-TIME HYBRID SIMULATION

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Why RTHS?

• Many of civil engineering materials are *rate-dependent* (e.g., steel, concrete, visco-elastic material, viscous material, etc.)

• Earthquake load is naturally *dynamic* ➔ real-time loading should be made to understand the true dynamic response of structures
Technical Barriers in RTHS

• Difficult to satisfy force boundary condition in **REAL-TIME** for *axially stiff members*

  ➢ A majority of civil infrastructures are axially stiff (columns, beams, walls, base isolators, etc.)
  
  ➢ Post-yield response is significantly affected by axial force ➔ important to satisfy axial force boundary condition accurately

  ➢ The lack of knowledge for real-time force control significantly restricts the implementation of RTHS for axially stiff structures
Large-Scale Slow Dynamic Tests
which are challenging to be conducted in real-time

Full-scale slow hybrid simulation for an SMRF beam-column connection

Newly Developed Real-Time Force Control

- **D-ATS Force Control Method**: Combination of the ATS compensator with the added compliance method

Experimental Test Setup to Validate the D-ATS method

Nonlinear SDOF steel mass block system with MR damper

Steel mass block ($m=73$kg)

Compliance spring ($k_c=53.5$ kN/m)

25kN actuator

MR damper

Reaction frame

25kN load cell

Unidirectional bearing guide

Spring for steel block ($k_s=85$ kN/m)

Steel mass block

Accelerometer

LVDT
Sine Sweep Testing

Frequency response (force)

Frequency response (displacement)

\[ f_n = 5.4 \text{Hz} \]
Earthquake Load Application (1994 Northridge EQ)

- Force-disp. relationship
- Amplitude ratio of measured force to target force
- Sync. subspace plot
  - NRMS error = 4.3%

Analysis results:
- Force-disp. relationship: Amplitude ratio of measured force to target force
  - $f_n = 5.4\text{Hz}$
Large-Scale Force Application Using FLF

For large-scale force application, a flexible loading frame (FLF) can be used as an added compliance spring.
Large-Scale Force Application Using FLF

An RC column test setup in the Hybrid Structural Testing Center (HYSTEC) at Myongji University with FLF (force capacity=180kN)
Cyclic Displacement Test for RC Column with FLF

**Input Horizontal Cyclic Displacement History**

Maximum velocity = 250mm/s

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**Applied Axial Load for Fast Cyclic Test** (real-time test)

*Target axial load = 144kN*

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**Applied Axial Load for Slow Cyclic Test** (100 times slower than real-time test)

*Target axial load = 144kN*
Damage Pattern: Slow Vs Fast Cyclic Tests

About **15% strength reduction** was observed due to the concentrated damage pattern at **fast loading rate**.
Multi-Axis Real-Time Hybrid Simulation

Two-span bridge subjected to both *horizontal* and *vertical* ground motions*

Modeling of horizontal motion

(SDOF system)

Modeling of vertical motion

* Vertical reaction force at the bridge pier is the target axial force for the RC pier during RTHS

Multi-Axis Ream-Time Hybrid Simulation

Satisfactory actuator control performance was achieved.

Lateral displacement

Axial force

Overview

Close-up view
Concluding Remarks

• New force control method (D-ATS method) can effectively resolve:
  ➢ Natural velocity feedback effect
  ➢ Real-time force application to nonlinear structures
  ➢ Satisfying axial force boundary condition for axially stiff members

• With this new force control method, critical dynamic response of structures can be effectively investigated by conducting large-scale RTHS, EFT, and fast cyclic loading tests.
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