Hybrid Simulation: Day 1 Review

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Hybrid Simulation

- Hybrid simulation is an experimentally based method for investigating the response of structure to dynamic excitation using a hybrid model
- A hybrid model is a an assemblage of one or more physical and one or more numerical, consistently scaled, substructures
- The equation of motion of a hybrid model under dynamic excitation is solved during a hybrid simulation test

Substructures

$$\begin{bmatrix} m_{pp} & m_{pc} \\ m_{cp} & m_{cc} \end{bmatrix} \begin{Bmatrix} \ddot{u}_p \\ \ddot{u}_c \end{Bmatrix} + \begin{bmatrix} c_{pp} & c_{pc} \\ c_{cp} & c_{cc} \end{bmatrix} \begin{Bmatrix} \dot{u}_p \\ \dot{u}_c \end{Bmatrix} + \begin{Bmatrix} R_p \\ R_c \end{Bmatrix} = -\begin{bmatrix} m_{pp} & m_{pc} \\ m_{cp} & m_{cc} \end{bmatrix} \begin{Bmatrix} \ddot{u}_{pg} \\ \ddot{u}_{cg} \end{Bmatrix}$$

- Hybrid models are, by definition made of substructures
- Restoring forces can be assembled
  - Proper transformations may be needed
- However, so can:
  - Damping forces from physical dampers
  - Inertia forces from the mass of the physical specimens

Similitude

Quantity (1)	Dimensions (2)	Procedure 1 (3)	Procedure 2 (4)
Length	L	(S)	(S)
Mass	M	(S^3)	S
Time	T	S	(1)
Stress	$ML^{-1}T^{-2}$	1	1
Velocity	LT^{-1}	1	S
Acceleration	LT^{-2}	$1/S$	S
Force	MLT^{-2}	(S^2)	(S^2)
Stiffness	MT^{-2}	S	S
Damping $(C = 2\xi\sqrt{KM})$	MT^{-1}	S^2	S
Natural frequency ω	T^{-1}	$1/S$	1

Note: Scale factor for quantity i; $S_i = i_p/i_m$; items in parentheses indicate specified factors.

- Kumar et.al.

Errors in Hybrid Simulation

- Dynamics of the prototype can be adequately represented by the discretized and substructured hybrid model
- Assembled equation of motion of the hybrid model can be accurately and reliably solved
- The experimental setup is properly design and is functioning reliably to enable precise application of target displacements and determination of the state of the physical substructures
- Numerical models of computer substructures are reliable and accurate enough

Integration Methods

- Enable step-wise solution of the equation of motion of the hybrid model:
  - Limitation of physcial models: no iterations
- Design of the hybrid model involves tradeoffs in choosing the integration method:
  - Explicit
  - Implicit
- The communication infrastructure and controller design at *nees@berkeley* are versatile enough to implement most of the integration algorithms invented to date:
  - Three-loop architecture with local estimators at each end of the communication link

OpenSees Framework

- Structure framework that is transparent and (easily) extensible and scaleable
- Enable separation of research domains:
  - EE research can do hybrid simulation using state-of-art
  - IT (and some EE) researchers can push the state-of-art forward
- OpenFRESCO:
  - Object-oriented, based on OpenSees
  - Integrates physical and computer elements into a common domain

Data Flow, Networks and Protocols

- Data flow in hybrid simulation needs a physical layer to live
- Types:
  - High sample rate/low latency (for hybrid simulation integration)
  - Low sample rate/some latency (streaming data to observers and researchers)
  - High sample rate/high latency (post-experiment analysis)
- A variety of hardware and protocols are used

Zipper Frame Test Example

- A real application of hybrid simulation
  - Evaluate the seismic response of the zipper frame structural system
  - Actual tests and use of data
  - Colaboraiton with NEES labs and non-NEES researchers
- OpenSees Navigator user interface
  - Uniform user interface for physcial and computer substructures
  - Examples

Your Own Example

- Treat the clevis hysteretic element as a source of non-linear behavior in your hybrid model
- Use similitude and geometric transformations to represent your sub-structure
- Choose an integration algorithm
- Try to estimate error limits
- Use OpenSees, OpenFRESCO and Navigator to implement

- I hope it will work!

Preview: Day 2

- Example: HS test 1
- OpenSees mini-workshop
- Example: HS test 2
- Hybrid simulation
  - Review and new directions
- *nees@berkeley* equipment site
  - Review of facilities
  - Doing a project here

Thank you!

Development and operation of the nees@berkeley equipment site is sponsored by NSF.

http://nees.berkeley.edu

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