

Hybrid Simulation: Review

Bozidar Stojadinovic, Associate Professor

University of California, Berkeley



nees@berkeley

The George E. Brown, Jr. Network for Earthquake Engineering Simulation



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 physical 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
 - Collaboration with NEES labs and non-NEES researchers
- ◆ OpenSees Navigator user interface
 - Uniform user interface for physical 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, OpenFRESKO 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>

Contributions to this presentation from xxx are gratefully acknowledged.



nees@berkeley

The George E. Brown, Jr. Network for Earthquake Engineering Simulation

