Hybrid Simulation: Errors and Accuracy

Bozidar Stojadinovic, Associate Professor

University of California, Berkeley
Inherent Limitations of Hybrid Simulation

- Dynamics of the prototype can be adequately represented by the discretized and sub-structured hybrid model.
- Assembled equation of motion of the hybrid model can be accurately and reliably solved.
- The experimental setup is properly designed 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.
Errors due to Structural Modeling

 Structural idealization
  - Discretization:
    - Stiffness and strength distribution
    - Mass distribution
  - DOF condensation (or neglect)
  - Accuracy and reliability of numerical models

 Modeling of damping and damping effects
  - Adequacy of viscous damping model

 Strain rate effects:
  - Material loaded quickly appear stronger than when loaded slowly
Errors due to Numerical Integration

- Numerical methods may be unstable in the face of round-off error.
- Numerical integration procedures may require data (tangent stiffness) that is not readily available, or is ill-conditioned.
- Explicit methods are conditionally stable: they may require a short time-step for integration.
Errors due to Numerical Integration

Good numerical procedures may introduce:

- Period elongation
- Amplitude variation (decay or amplification)
- Alteration of frequency content
- Numerical damping (energy dissipation or generation):
  - This may be desirable!
Errors Inherent to Experiment Setup

Two groups of errors, associated with:

- Servo-hydraulic control loop
- Measurements to determine state of physical substructures
Control Loop Errors

- Actuator dynamics:
  - Oil-column frequency
  - Servo-valve properties
  - Hydraulic power supply properties

(c) Flow Limiting  (d) Loop Instability
Control Loop Errors

Control-loop dynamics:

- Command tracking
- Lag
- Overshoot
- Settling time
Control Loop Error

Specimen/Test Setup interaction:
- Large specimen mass is difficult to move
- Stiff specimens wrt. stiffness of actuators and reaction points
- Restoring force or velocity approaching actuator capacity
Measurement Errors

- Errors in instruments that measure displacement and force:
  - Calibration
  - Friction or slop in attachments
  - Electronic noise
- A/D and D/A conversion
- Sampling and filtering
Effects of Errors

Equation of motion:

\[ M a_i + C v_i + r_i = f_i \]

Displacement errors:
- Directly affect ability to evaluate the state of the structure
- At interfaces to computer substructures, induce error in restoring forces

Force errors:
- Directly affect estimates of target displacement
Undershooting and Overshooting Displacements

Loading and unloading of linear-elastic element

- Undershooting (lag)
  - Energy added
  - Command displacement
  - Measured displacement

- Overshooting
  - Energy absorbed

Displacement vs. resisting force
Actuator Lag and Force Noise

- **Delay between command issue and completion of actuator movement:**
  - In linear systems, equivalent to increase in viscous damping

- **Noise in force reading:**
  - Reduce repeatability and reliability
  - Filtering the force signal
  - Integrating momentum equations
Types of Error

- **Random error:**
  - Does not have a significant effect on the test result

- **Systematic error:**
  - Significantly affects the test

- Detect using FFT and phase lag of error signal
  (command vs. applied)
Evaluation of Test Accuracy

- Magnitude of error may be used to evaluate accuracy of a hybrid simulation:
  - Error signal
  - Cumulative error increment
  - Energy errors

\[ E_i = \int rdu \approx \frac{1}{2} (r_i + r_{i-1})^T (u_i - u_{i-1}) \]
Evaluation of Test Accuracy During the Test

- Monitor error growth using available data:

  - Hybrid simulation error monitors:

    \[
    HSEI^S = \frac{E^{\text{error}}}{E^{\text{strain}}} \quad HSEI^I = \frac{E^{\text{error}}}{E^{\text{input}} + E^{\text{strain}}}
    \]

  - Good correlation to conventional error measures
  - Able to estimate if test is going badly
  - Still specimen-dependent
Meaning of Test Accuracy

- What do we mean by accuracy?
- A hybrid simulation is one instantiation of structural response to random input:
  - It is just one of many points in a data cloud: thus, statistical means may be used to evaluate accuracy of a test
- Use of a hybrid simulation as a benchmark test may be questioned
- This is an open problem
Thank you!

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

http://nees.berkeley.edu

Contributions to this presentation from Prof. Gilberto Mosqueda and Dr. Chris Thewalt are gratefully acknowledged.