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 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

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

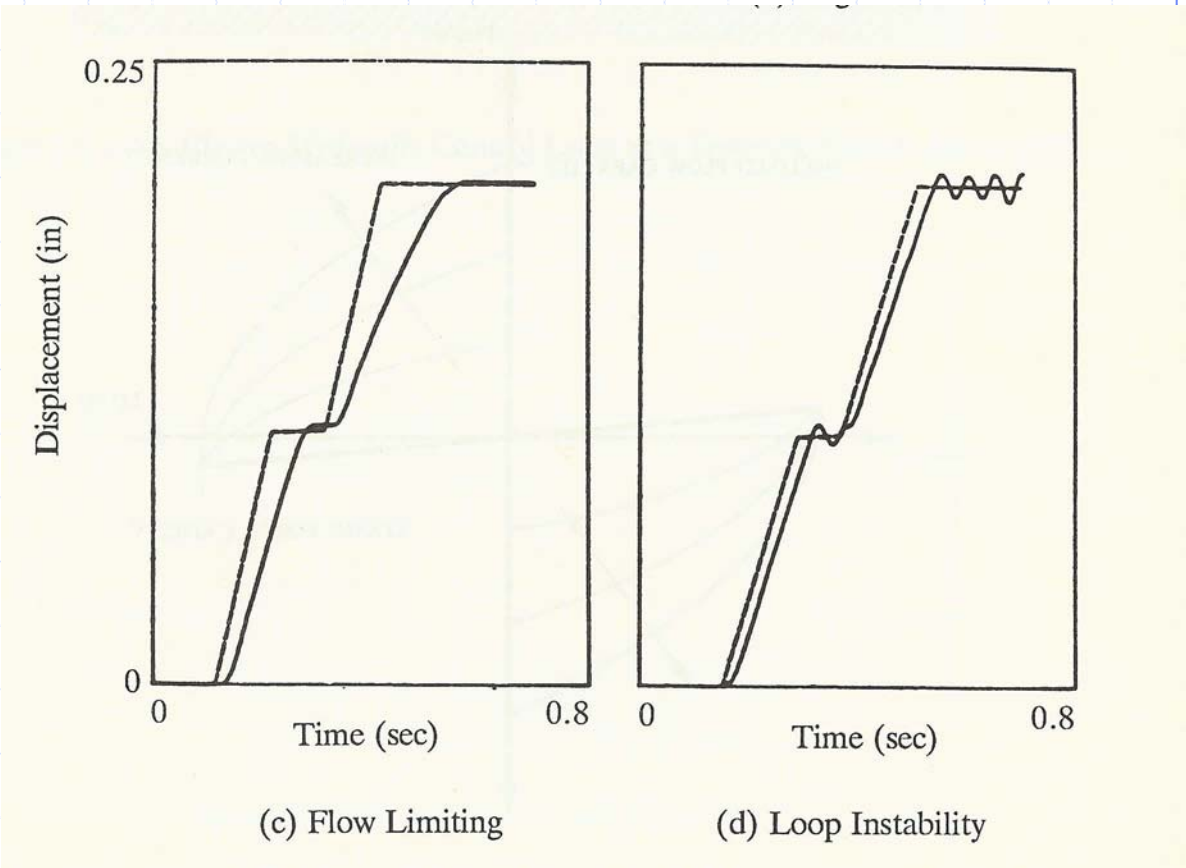
- Good numerical procedures may introduce:
  - Period elongation
  - Amplitude variation (decay or amplication)
  - Alteration of frequency content
  - Numerical damping (energy dissipation or generation):
    - This may be desirable!

Errors Inherent to Experiment Setup

- Two groups of errors, associated with:
  - Servo-hydraulic control loop
  - Measurements to determine state of physical substructures

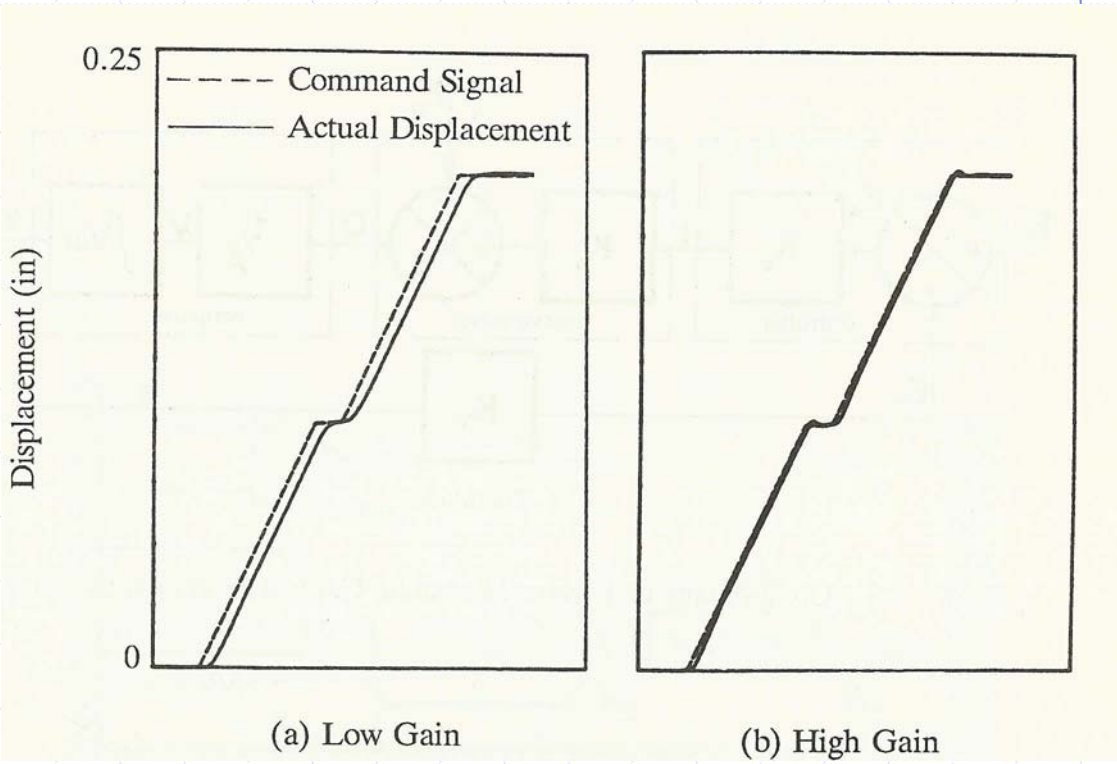
Control Loop Errors

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



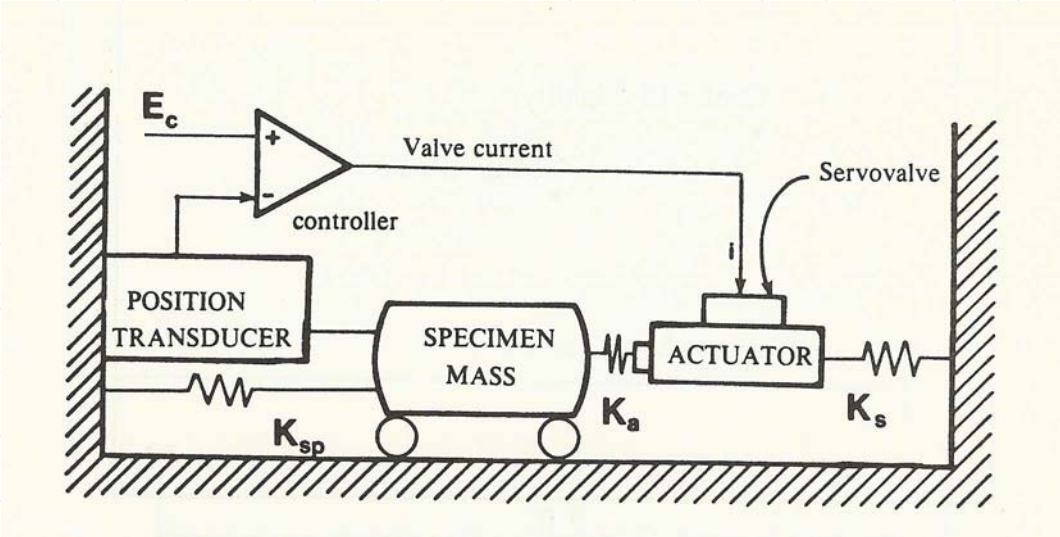
Control Loop Errors

- 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

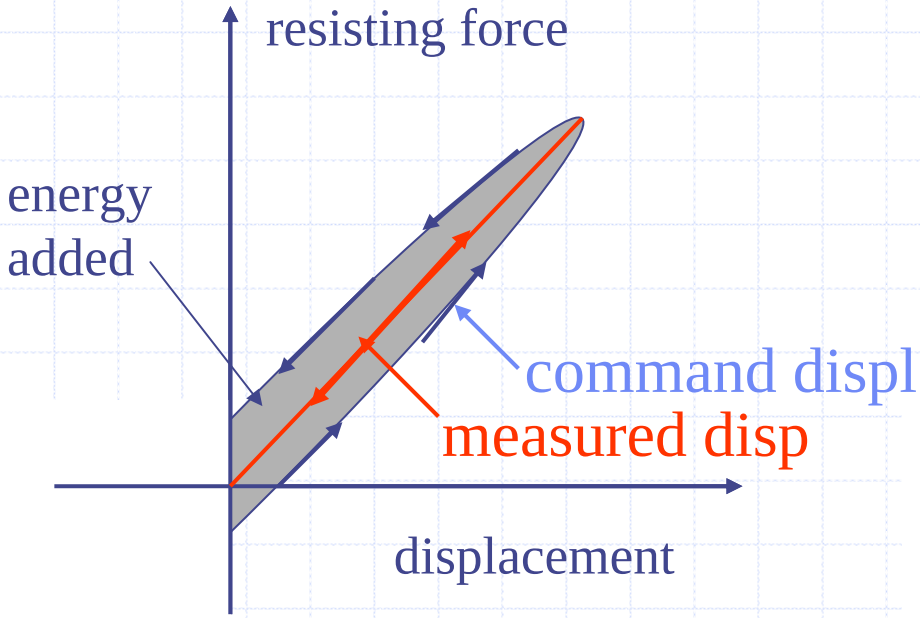
- Equation of motion:

$$Ma_i + Cv_i + r_i = f_i$$

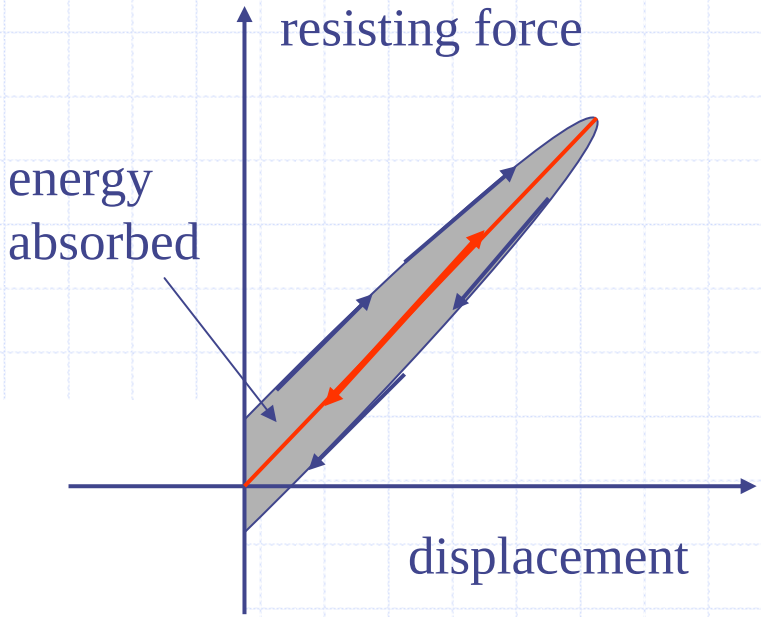
- Displacement errors:
  - Directly affect ability to evaluate the state of the structure
  - At interfaces to computer substructures, induce error in restoring forces
- Force errors:
  - Directly affect estimates of target displacement

Undershooting and Overshooting Displacements

Loading and unloading of linear-elastic element



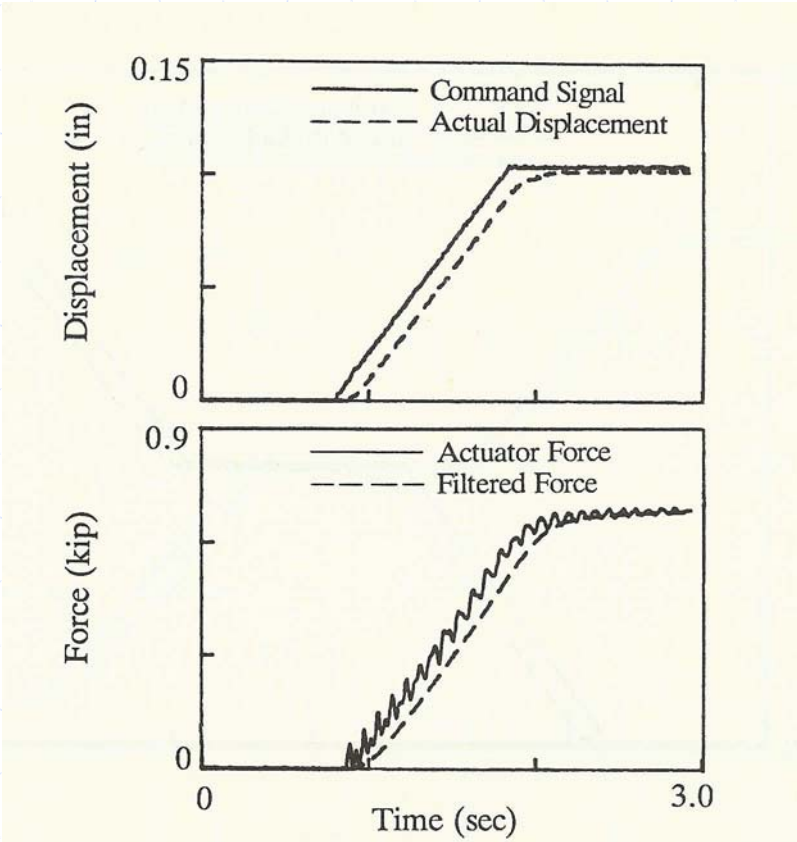
Undershooting (lag)



Overshooting

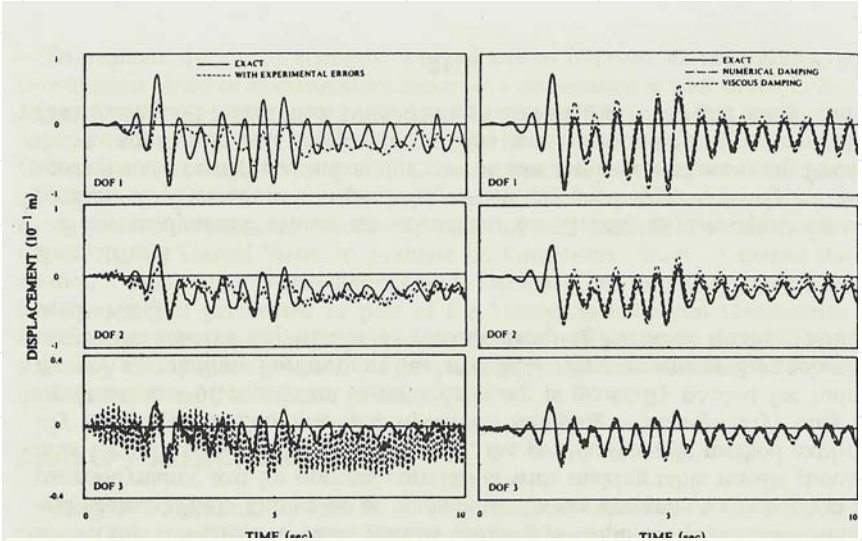
Actuator Lag and Force Noise

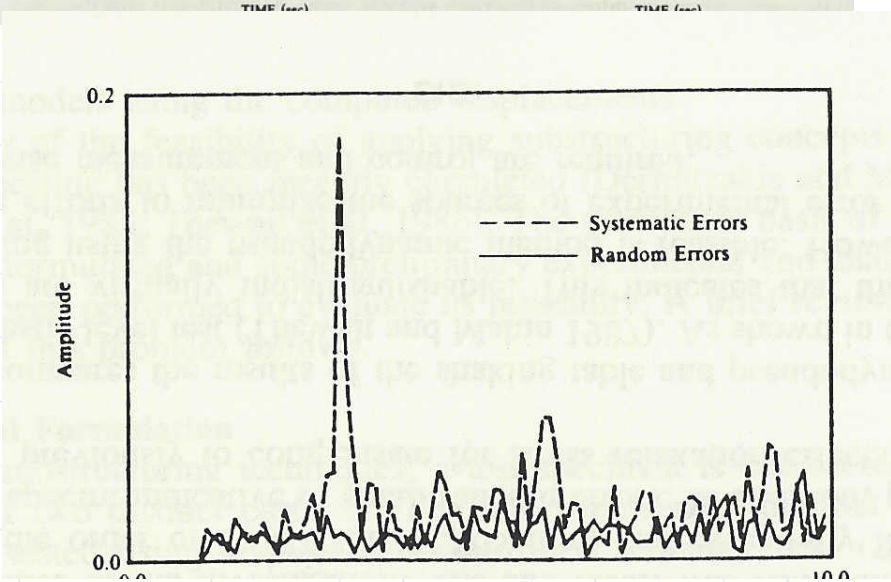
- Delay between command issue and completion of actuator movement:
  - In linear systems, equivalent to increase in viscous damping
- Noise in force reading:
  - Reduce repeatability and reliability
  - Filtering the force signal
  - Integrating momentum equations



Types of Error

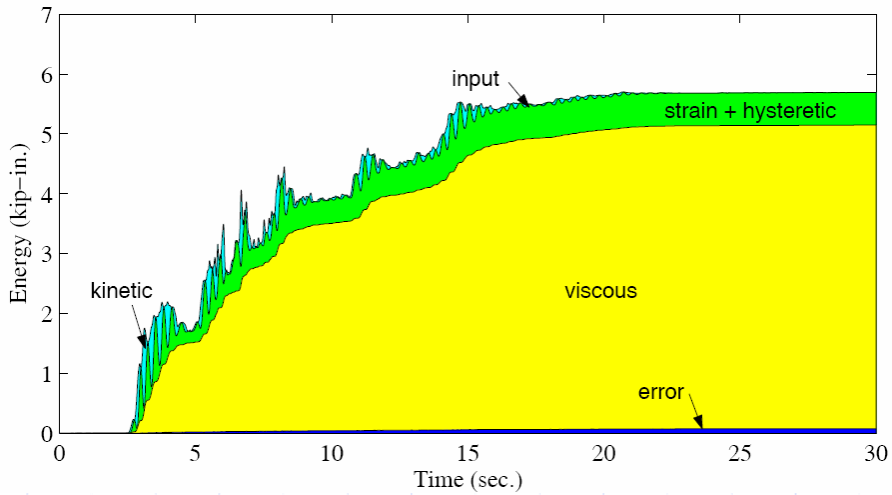
- Random error:
  - Does not have a significant effect on the test result
- Systematic error:
  - Significantly affects the test
- Detect using FFT and phase lag of error signal (command vs. applied)





Evaluation of Test Accuracy

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



$$E_i = \int r\,du \approx \frac{1}{2}(r_i + r_{i-1})^T (u_i - u_{i-1})$$

Evaluation of Test Accuracy During the Test

- Monitor error growth using available data:
  - Hybrid simulation error monitors:

$$HSEI^{S} = \frac{E^{error}}{E^{strain}} \qquad HSEI^{I} = \frac{E^{error}}{E^{input} + E^{strain}}$$

  - 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!

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