

Hybrid Simulation: Errors and Accuracy

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Assumptions Behind 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 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 amplification)
 - Alteration of frequency content
 - Numerical damping (energy dissipation or generation):
 - ◆ This may be desirable!

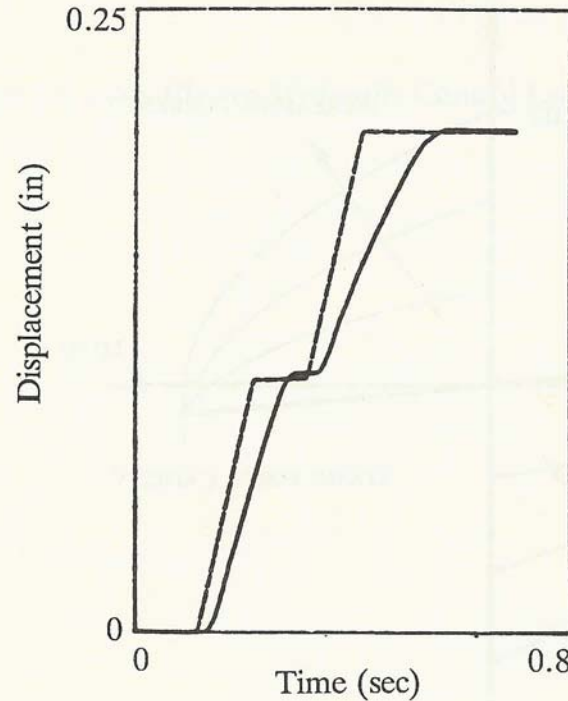
Errors Inherent to Experiment Setup

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

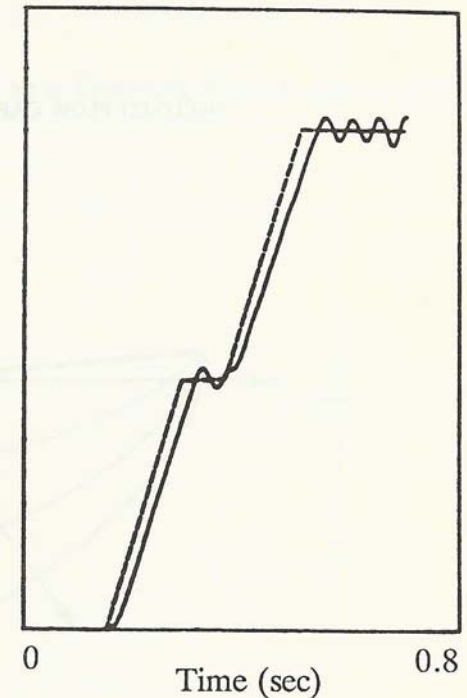
Control Loop Errors

◆ Actuator dynamics:

- Oil-column frequency
- Servo-valve properties
- Hydraulic power supply properties



(c) Flow Limiting

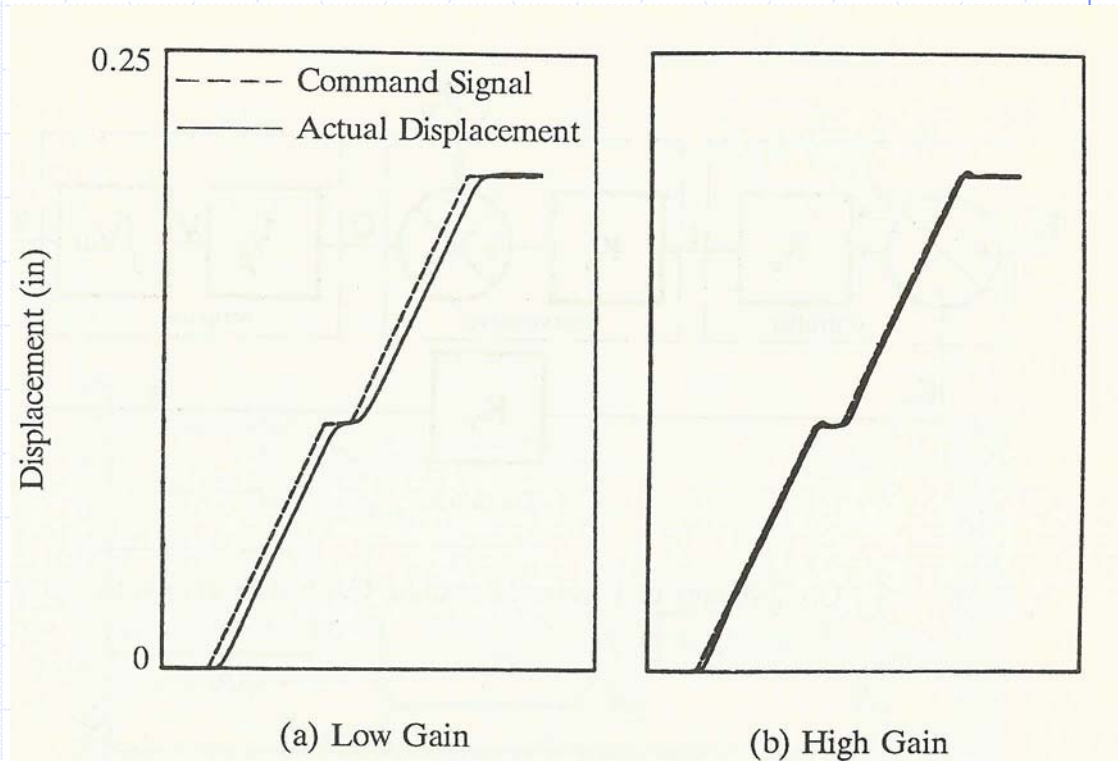


(d) Loop Instability

Control Loop Errors

◆ Control-loop dynamics:

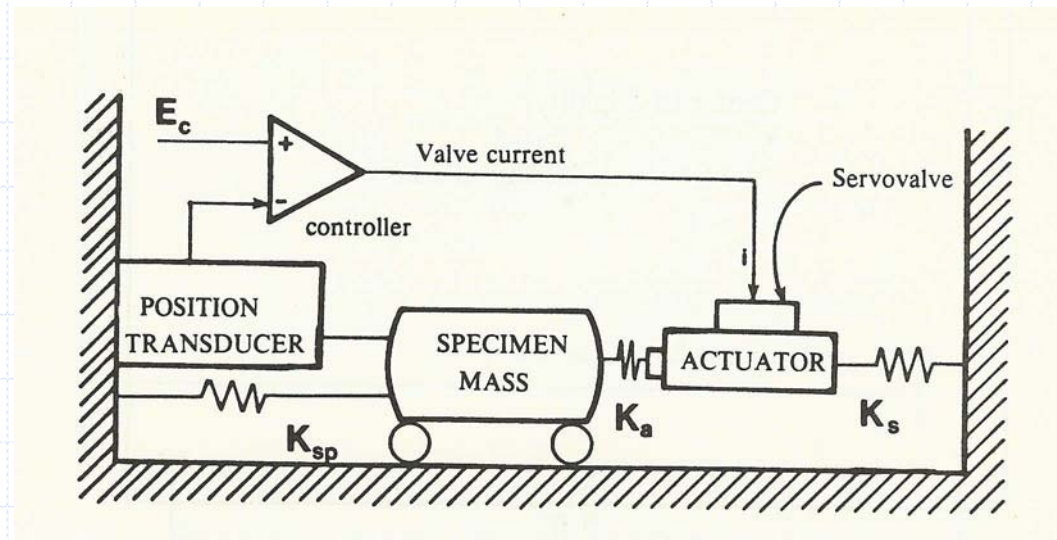
- Command tracking
- Lag
- Overshoot
- Settling time



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:

$$Ma_i + Cv_i + r_i = f_i$$

◆ Displacement errors:

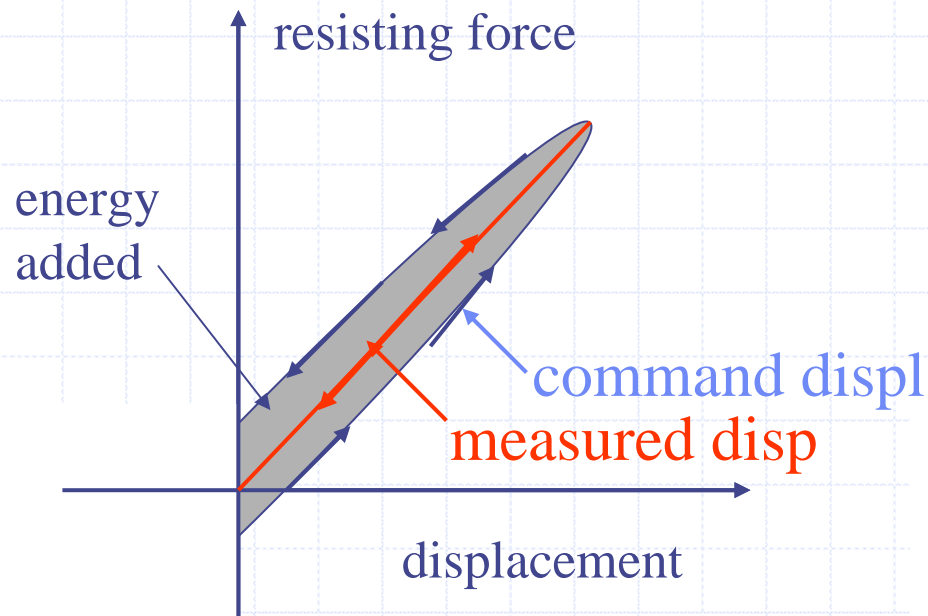
- Directly affect ability to evaluate the state of the structure
- At interfaces to computer substructures, induce error in restoring forces

◆ Force errors:

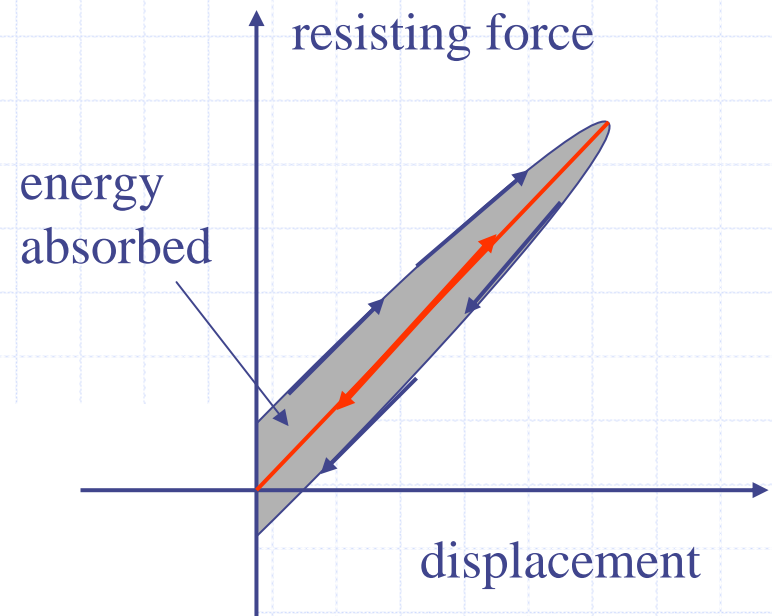
- Directly affect estimates of target displacement

Undershooting and Overshooting Displacements

Loading and unloading of linear-elastic element



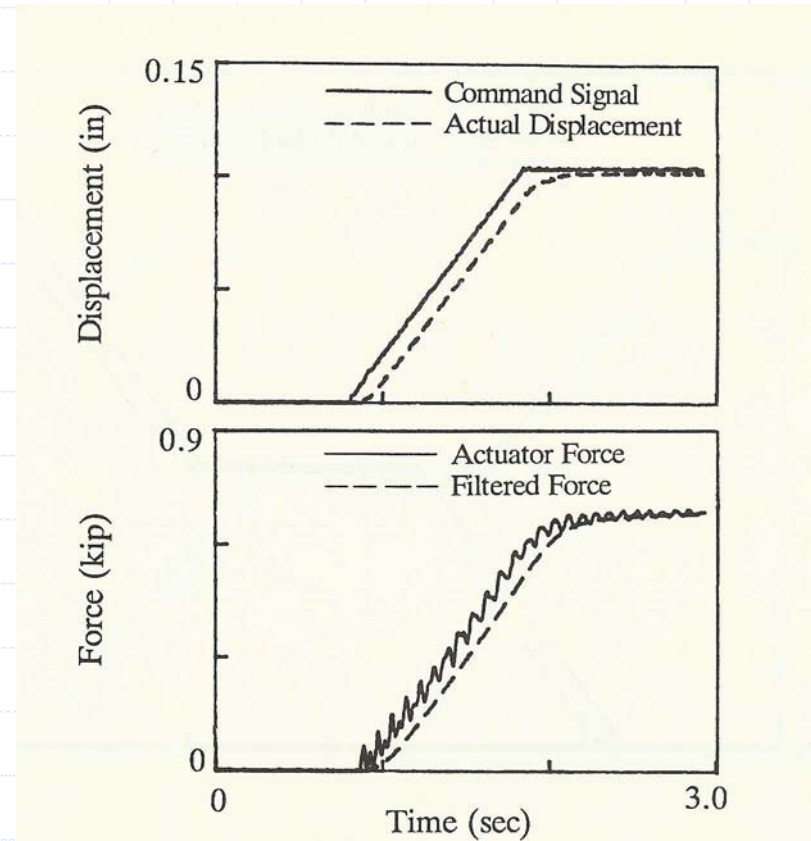
Undershooting (lag)



Overshooting

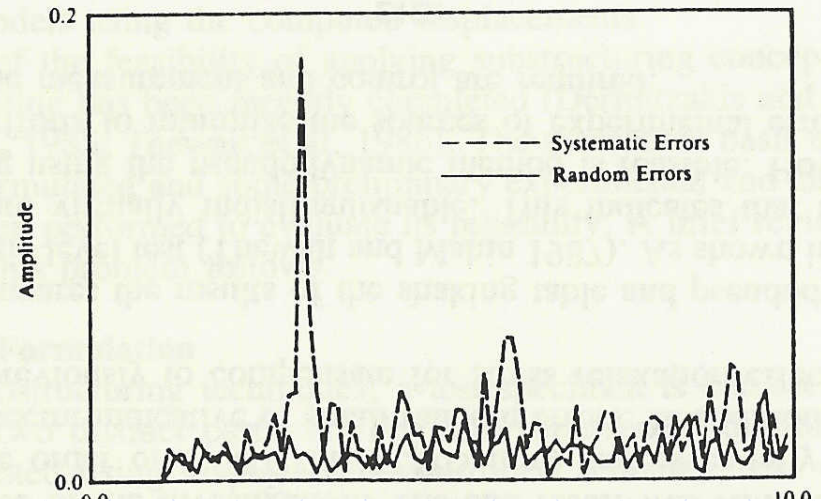
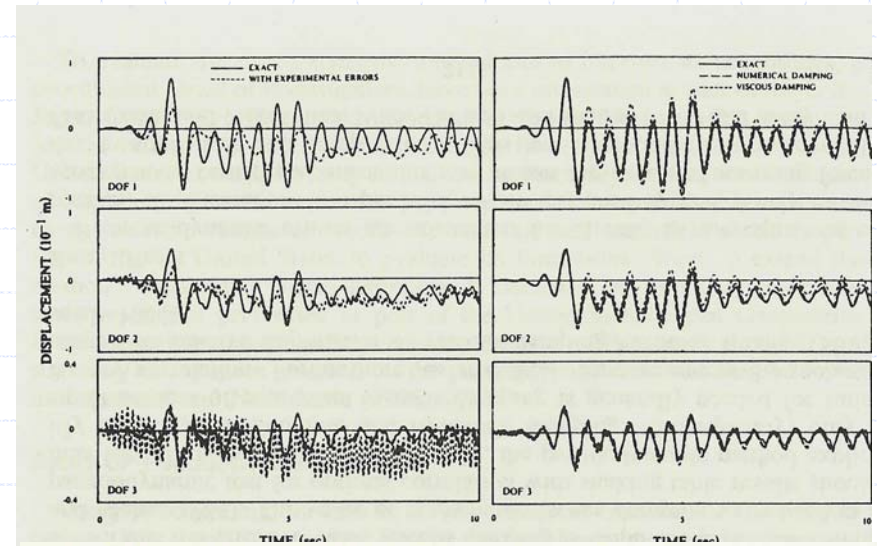
Actuator Lag and Force Noise

- ◆ 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

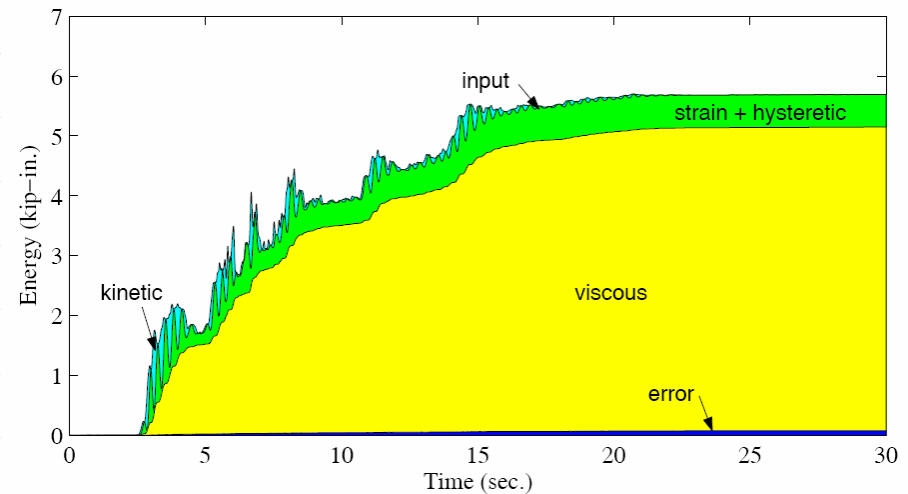
- ◆ Random error:
 - Does not have a significant effect on the test result
- ◆ Systematic error:
 - Significantly affects the test
- ◆ Detect using FFT and phase lag of error signal (command vs. applied)



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:

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

- 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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