A Unified View of Hybrid Simulation Algorithms

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Background

Hybrid Simulation Development at UB NEES Site
- Control Systems Approach

CU NEES Site
- Numerical Analysis Approach

Unified View
Outline

- What is hybrid simulation?
- Challenges in implementing a hybrid simulation system
- Types of hybrid simulation
- Hybrid simulation algorithms – architecture and equivalence
- Force-based substructuring
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Multi-story Building

Rest of the structure is undamaged – does not have to be physically built in the laboratory.

Most damage happens here – need better understanding by experimentation.

Earthquake
Interact during the experiment to mimic testing the whole building.
Real-time Hybrid Simulation

- When the physical subsystem has
  - Rate-dependent behavior
  - Inertia effects
- The simulation needs to be carried out in real-time
- Focus of rest of the presentation
Hybrid Simulation is useful for qualification/proof-of-concept testing when the interaction of a component with its surroundings needs to be accurately represented.

For Discovery
- Develop or calibrate Material/system models
  - Hybrid simulation *not very useful* for this purpose
  - Some kind of computation-in-the-loop with geometric reasoning about state-space may be possible

For Qualification
- Examine the performance of a component in its host environment
- Proof of concept tests
- *Interaction* with surroundings may significantly modify input
- Hybrid simulation is useful
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Feedback interaction in reality

External Input (Eg. Ground Motion)

Substructure 1

Computational

Substructure 2

Physical

Boundary Condition

Work Conjugate

Boundary Condition
In hybrid simulation however ...

**NEW DYNAMICS**

- **Substructure 1**
  - Computational
  - External Input (Eg. Ground Motion)
  - Boundary Condition

- **Substructure 2**
  - Physical

- **Sensor**

- **Actuator / Transfer Device**
  - Natural Physical Feedback
  - Actuator Feedback

- **Work Conjugate Boundary Condition**
Challenges

- These additional dynamics create significant problems.
- When the structure to be simulated is lightly damped, almost always renders the system unstable.
- Need to develop control algorithms to make hybrid simulation possible.
- Causality → Design of such algorithms requires knowledge about physical substructure (predictive model, implicit integration etc.) → This is a conflict → Robustness of algorithm with respect to modeling of the physical substructure.
- A numerical algorithm need not be causal, a hybrid simulation algorithm does.
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Hybrid Simulation

Pseudo-dynamic

- External Input (E.g. Ground Motion)
- Substructure 1: Computational
- Substructure 2: Physical
- Boundary Condition
- Work Conjugate Boundary Condition

 Has no inertia effects of interest

- Born from the displacement-based finite element – one of the elements is now physical!
- Algorithms also reflect this
- If in addition, there are no frequency-dependent behavior is the physical substructure – can be done as slowly as we want to

Dynamic

- External Input (E.g. Ground Motion)
- Substructure 1: Computational
- Substructure 2: Physical
- Boundary Condition
- Work Conjugate Boundary Condition

 Has significant inertia effects

- More practical applications necessitate this form of hybrid simulation
- My research is in this area
Hybrid Simulation

Pseudo-dynamic

- Real-time
- Slow

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NEES Sites

Dynamic

Hybrid simulation with
Shaking Tables

My research interest
Outline

- What is hybrid simulation?
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Recall

Motivation: Want end of actuator to look like Substructure 1
Introduce a controller

- **External Input**
- **Substructure 1** (Computational)
  - Takes the same input as Substructure 1
  - Boundary Condition
- **Controller**
  - Tries to do the same thing as Substructure 1
- **Substructure 2** (Physical)
  - Work Conjugate
  - Boundary Condition
- **Actuator / Transfer Device**
  - Natural Physical Feedback
  - Actuator Feedback
Model Matching Control

- Controller designed so that ⬤ does the same thing as ⬤
- Part implemented in the computer
Another Paramterization

Internal Model Control - IMC

Part implemented in the computer
Example

\[ \frac{1}{ms^2 + cs} \]

[k] 

[p] 

[\sum] 

[\text{External Excitation}]

[\text{Interface Force}]

[\text{Actuator}]

[\text{Physical Substructure}]

[\text{Stiffness} \ K]

[\text{Actuator Model}]

[\text{Modeling Error}]
Time Discretization – Example 1

Numerical Integration

Use Newmark

Discretize at same sampling rate (ex: 1 ms)

Semi-implicit Operator Split Method
Time Discretization – Example 2

Use Newmark

Discretize at **slower** sampling rate (ex: 10 ms)

Discretize at **faster** sampling rate (ex: 10 ms)

**Fully implicit method** (ex: Shing et al.)
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Force-based Substructuring

External Input
(Eg. Ground Motion)

Substructure 1
Computational

Imposed Boundary Condition
= Displacement
= Force

Work Conjugate of
Imposed Boundary Condition
= Force

Substructure 2
Physical

WHY?
Need for force-based substructuring - I

- Shake Table
- Laminar Soil Box
- Foundation
- Structural Actuator
- Focus of interest
- Well understood
Need for force-based substructuring - I

- Distributed mass
- Foundation
- Laminar Soil Box
- Shake Table
- Structural Actuator
- Response Feedback
- Has to operate in Force Control

Acceleration input: Table introduces inertia forces

Inertia forces in the Shake Table are introduced by the Table itself.
The three interface DOF are stiffly coupled – poor conditioning and more sensitivity to actuator dynamics.

One of the vertical actuators could be in force control.

Dynamic force control is an interesting problem by itself.
Force control – challenging problem

- Hydraulic actuator fitted with flow-regulating servo-valve
  - Inherently a velocity source
  - Designed to be mechanically stiff for good position control
  - Friction, stick-slip, breakaway forces on seals, backlash cause force noise
  - Stiff oil columns make force control very sensitive to control parameters often leading to instability
For force control, we need a flexible interface
Arrangement for force control

Target Force → 1 / $K_{LC}$ → Command Signal → Actuator in Displacement Control → Measured Force

Structure

Series Spring, $K_{LC}$

Compensator

Structure Displacement
Explanation of force control scheme

Target Force = \( F \)

Displacement command = \( F / k_{spring} \)

+ Structure Displacement
Small-scale test setup

- Load Cell
- Series Spring
- Structure Disp.
- Transducer
- Actuator
- Structure Disp. Transducer
Actuator displacement control

- Tuned very well in displacement control
- Standard PIDF controller

- Time-delay = 5.6 ms

![Graph showing magnitude and phase versus frequency](image)
Time-delay effect on force transfer function

Need predictive capability in compensator
Smith predictor

Smith Predictive Compensator

\[ \frac{1}{K_{LC}} + \sum \text{Corrective Displacement} + \sum \text{Predictive Displacement} + \sum \text{Model of Structure-Spring System} \]

\[ T = e^{-st} \]

\[ K_{LC} + \sum \text{Series Spring} \]

\[ \frac{1}{ms^2 + cs + k} \]

Structure
Force transfer function with predictive compensation

![Graph showing force transfer function with and without compensation. The graph plots magnitude against frequency with a clear distinction between the two conditions.](image-url)
Conclusions

- Hybrid simulation – online combination of computation and physical experimentation
- Real-time hybrid simulation – when physical subsystem had rate-dependent behavior or inertia effects
- Challenge – *added dynamics and feedback paths* created by the transfer system/actuator applying that applied interface conditions between the two substructures.
- Control systems approach and numerical analysis approach shown to be equivalent
- Numerical analysis (finite element) approach for simulation development, control systems approach for stability and robust stability and performance analysis