be certain.

MTS®

HYBRID SIMULATION COMBINED WITH FATIGUE TESTING METHOD

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MTS Systems Co.

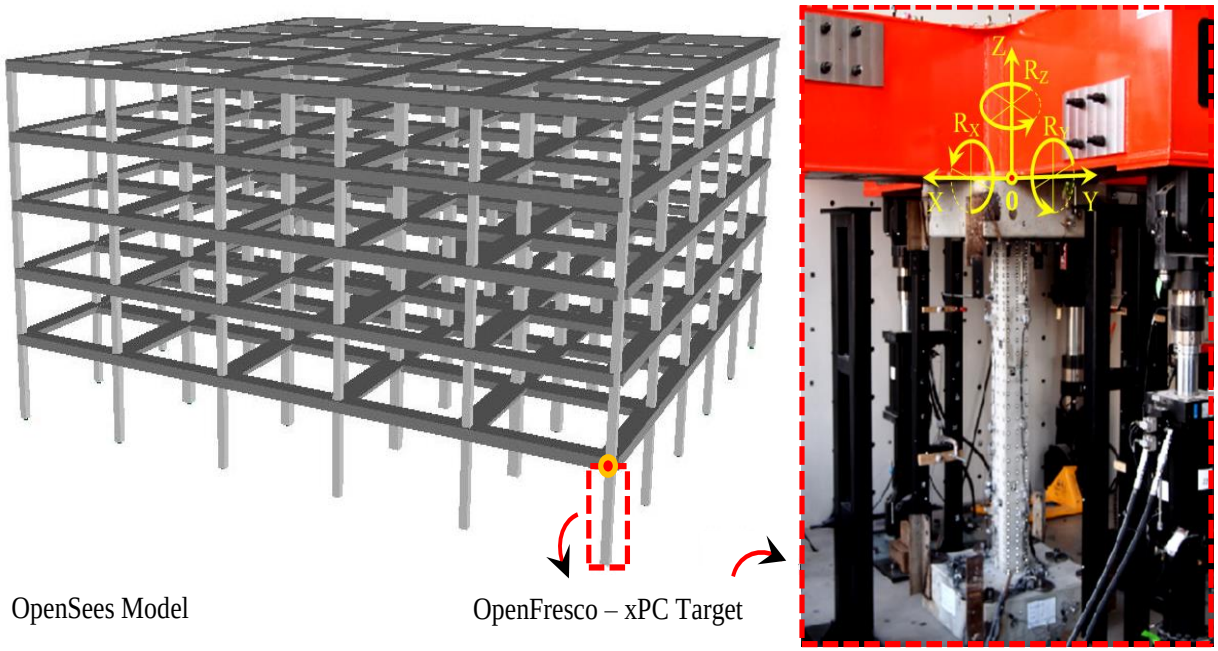
Contents

- Introduction of hybrid simulation
- Hybrid simulation with ANSYS
- Hybrid simulation with reduced order models
- Hybrid simulation coupled with fatigue testing
- Conclusions

Introduction of Hybrid Simulation

Hybrid Simulation

- Test only a portion of a structure. Model rest of the structure.
- MTS works closely with multiple universities, such as UC Berkeley, to develop hybrid simulation methodology.
- MTS has provided quasi static, real-time, and soft real-time hybrid simulation solutions to more than 100 customers.



OpenSees Model

OpenFresco – xPC Target

Courtesy of Swinburne University

Hybrid Simulation Example – Wind Energy

Engineering Structures 126 (2016) 417–431

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Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Performance evaluation of full-scale tuned liquid dampers (TLDs) for vibration control of large wind turbines using real-time hybrid testing

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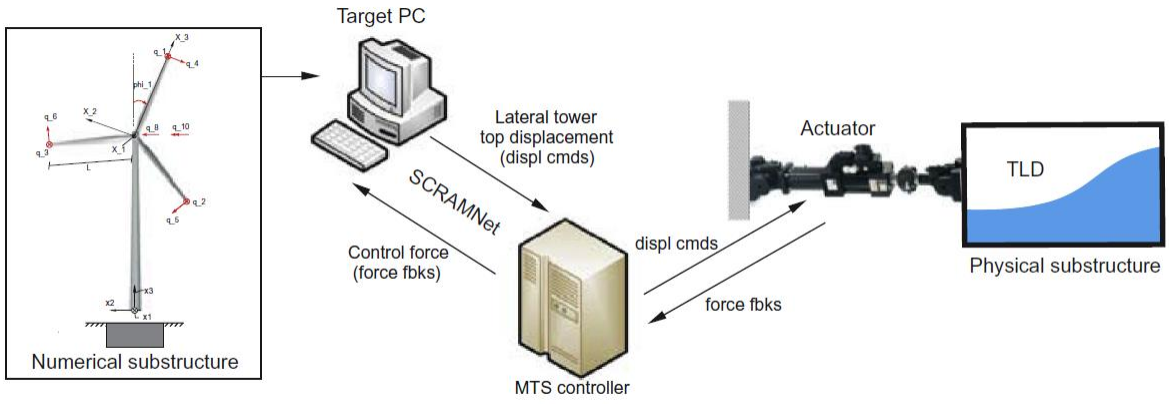

Fig. 2. Conceptual view of the RTHT for the TLD-wind turbine system.

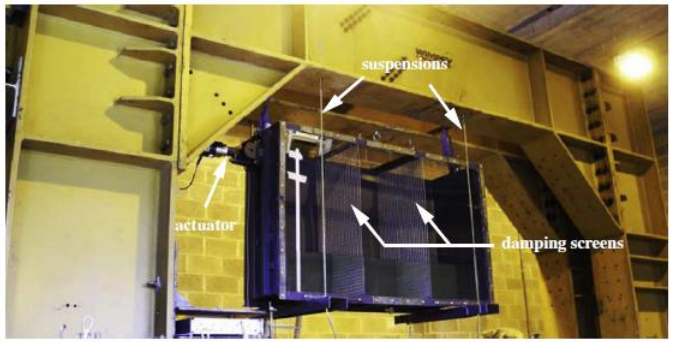

Fig. 5. Test setup and the physical substructure (the TLD).

Research carried out using MTS real-time hybrid simulation system at Trinity College Dublin, Ireland.

Hybrid Simulation Example – Wind Energy

Proceedings of the 35th International Conference on Ocean, Offshore and Arctic Engineering
OMAE2016
June 19-24, 2016, Busan, Korea

OMAE2016-54435

REAL-TIME HYBRID MODEL TESTING OF A BRACELESS SEMI-SUBMERSIBLE WIND TURBINE. PART I: THE HYBRID APPROACH

Thomas Sauder (MARINTEK/AMOS), Valentin Chabaud (NTNU), Maxime Thys (MARINTEK), Erin E. Bachynski (MARINTEK), Lars Ove Sæther (MARINTEK)
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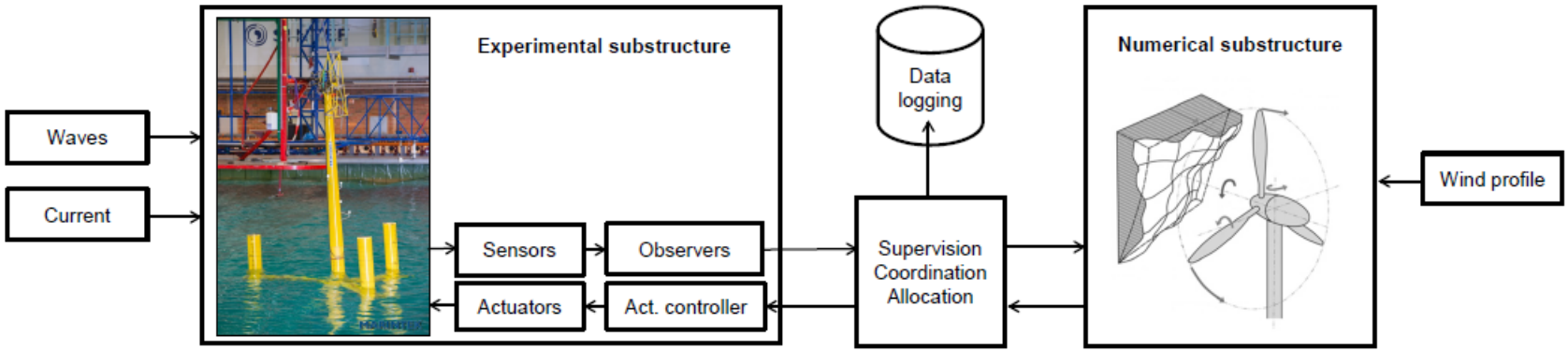
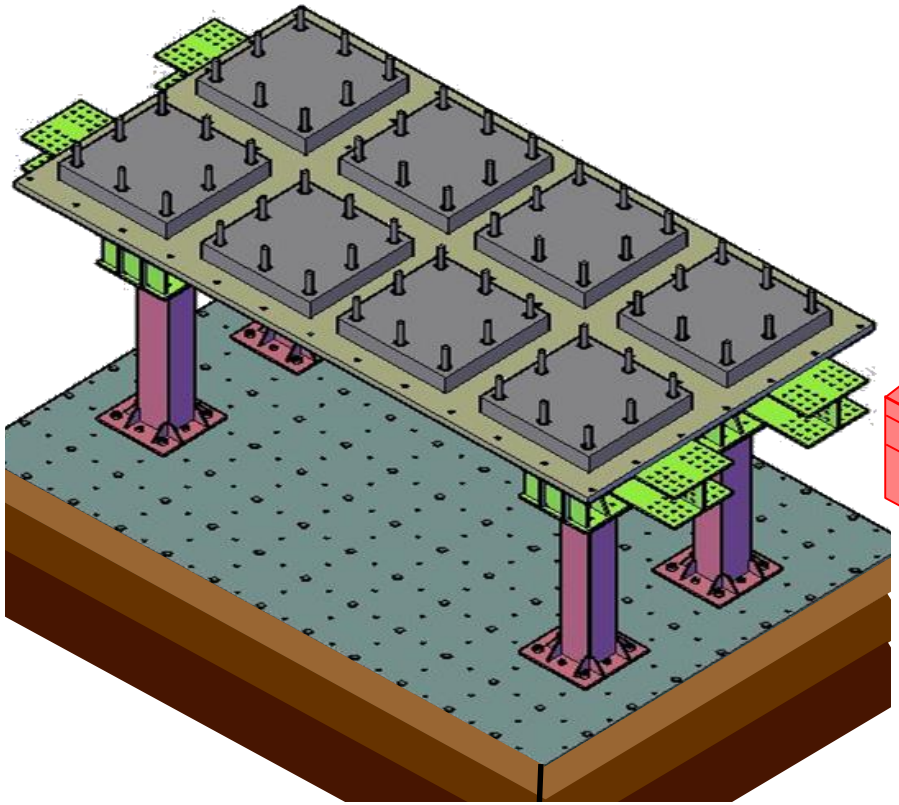
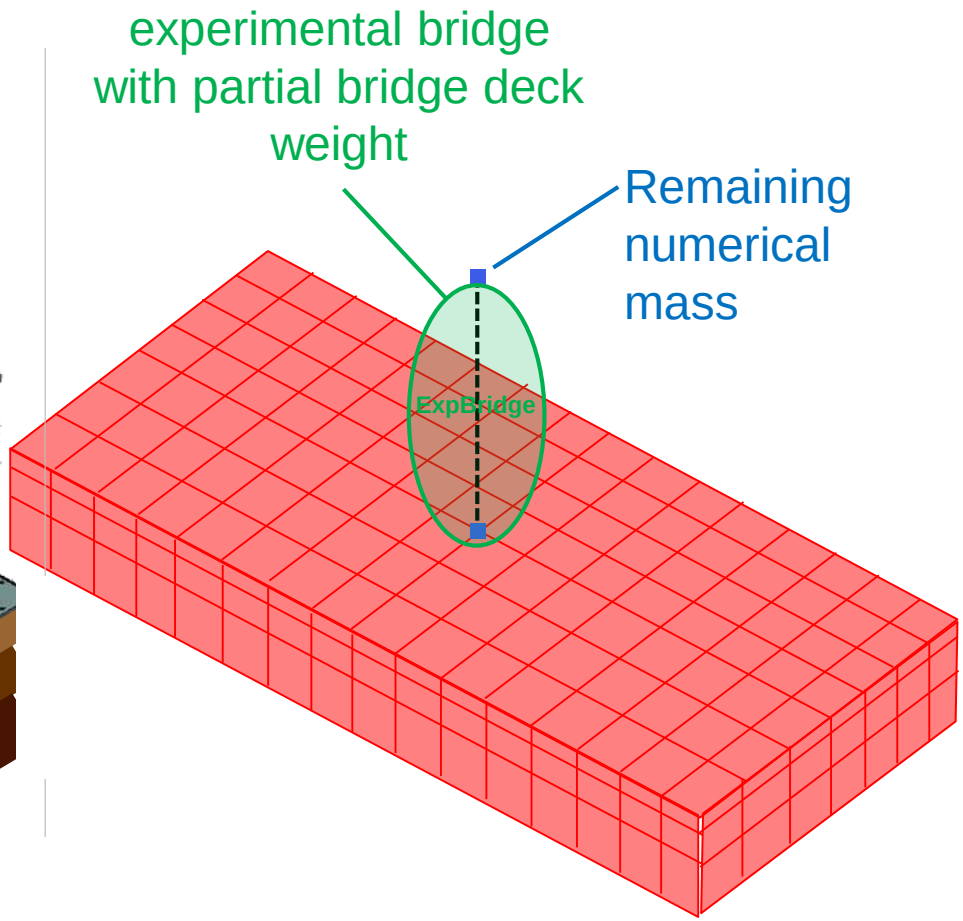


Real-Time HS with Single Table and Loading Actuator

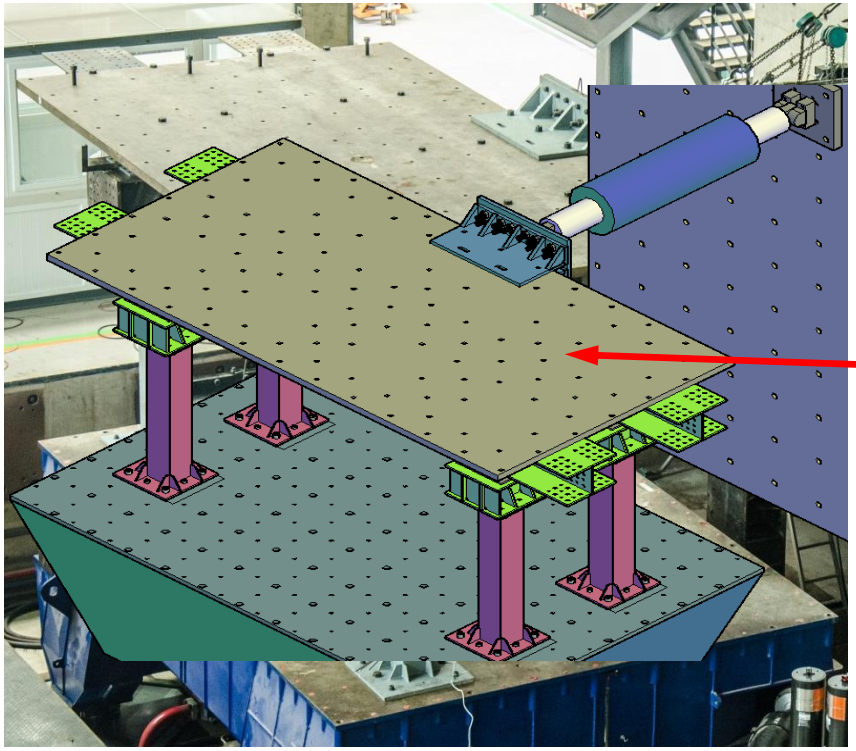


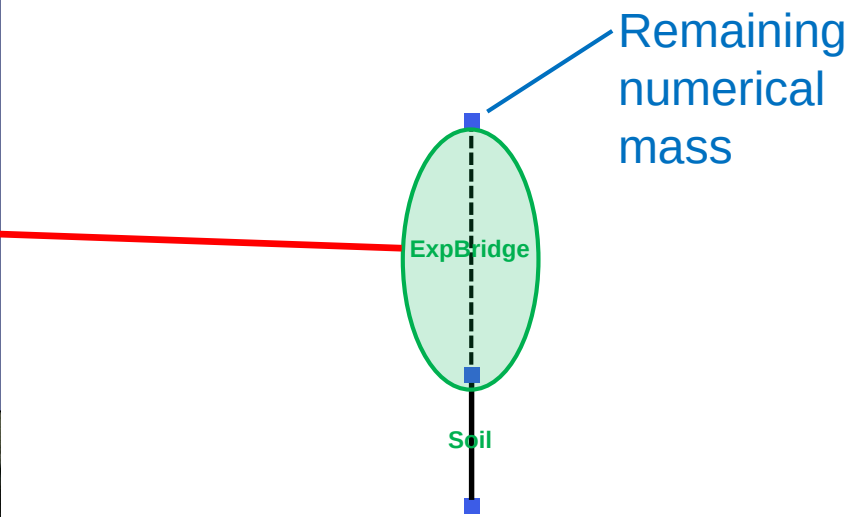
Actual Bridge Configuration
(with foundation + soil)



Simplified Hybrid OpenSees
Model of Bridge

Real-Time HS with Single Table and Loading Actuator





Physical Test Specimen (columns + isolators + partial-weight bridge deck)

Simplified Hybrid OpenSees Model of Bridge (Stage 2)

Quasi Static Hybrid Simulation

Simulation PC

Structural Model

OpenFresco
& CSI

Test PC

Servo-control Program

Servo-controller

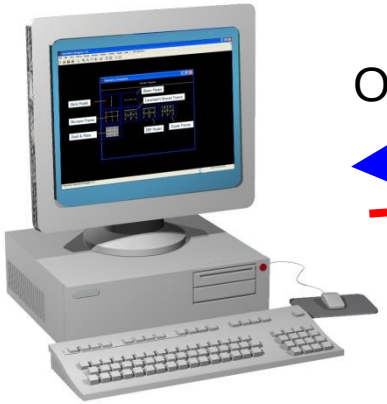
Real-time Test Control

Test Rig

Real Time Flow Chart

MTS Soft Real-Time Hybrid Simulation Solution

OpenSees
Matlab
Simulink
Abaqus



OpenFresco

Target PC

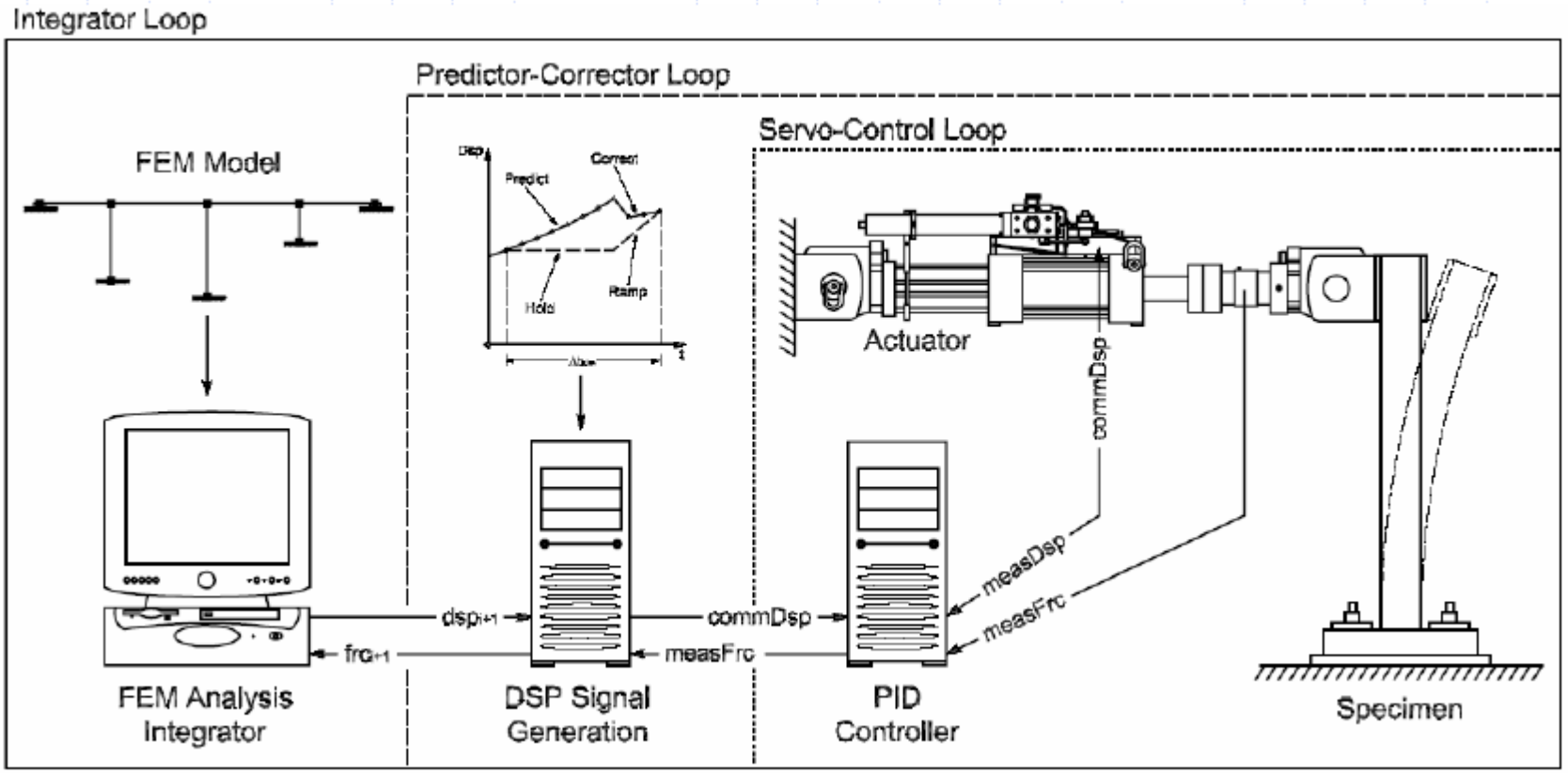
Target PC with
Predictor-Corrector

Scramnet
Interface

Flextest Controller

Test Rig

Three Tier Structure of Soft Real-Time Approach



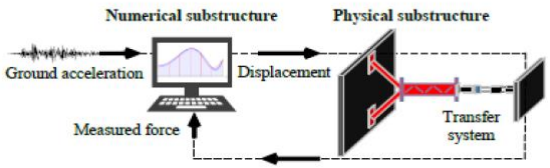
- Allow simulation steps to be much larger than the close loop steps. Therefore, Model can be much more complicated.
- Models run in Windows OS. No need to compile the model to C++ code and run at a real-time machine.

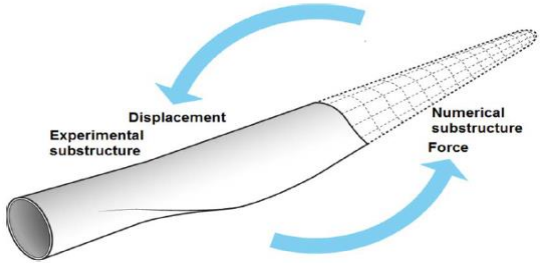
Hybrid Simulation with ANSYS

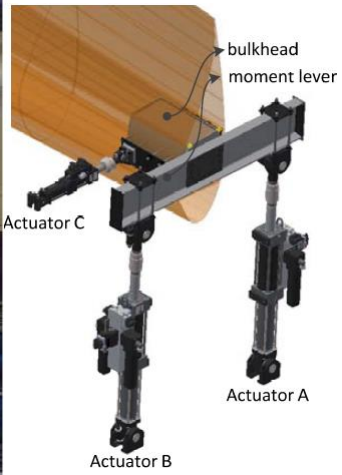
Hybrid Simulation with ANSYS

- ANSYS is widely used in many areas. Hybrid simulation with ANSYS can help spreading hybrid sim in other industries.
- There have been several requests to do hybrid simulation with ANSYS.

ANSYS







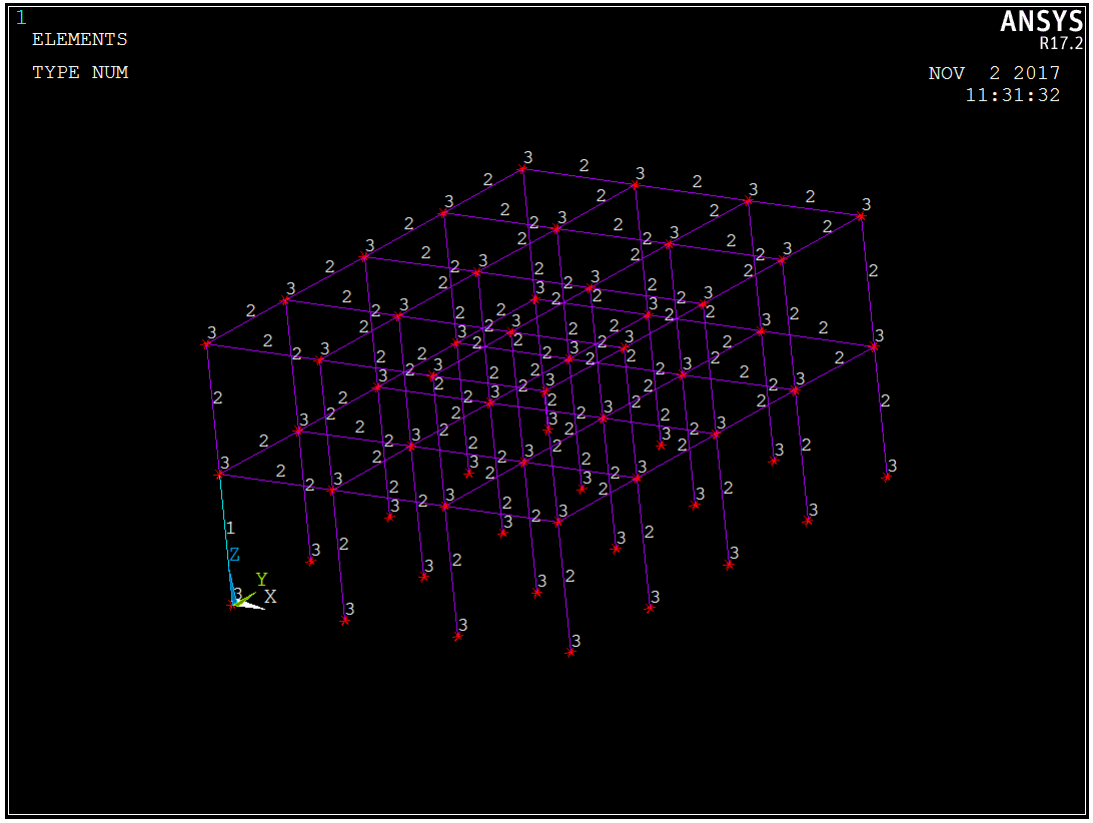
ANSYS is the desired finite element analysis software for DTU blade hybrid simulation.

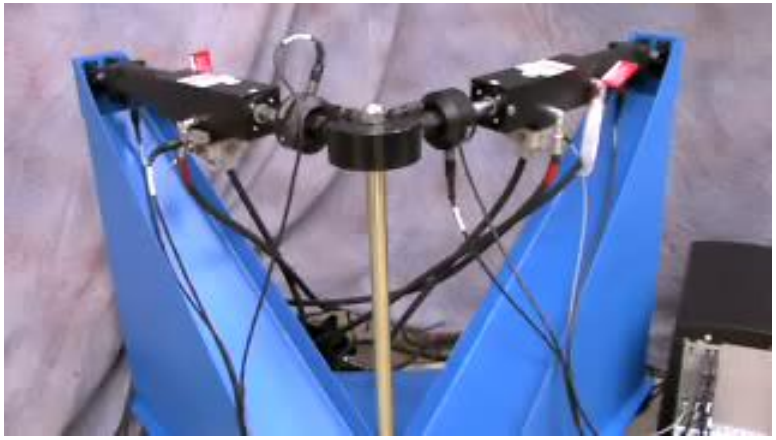
Generic Client Element for ANSYS

- User-defined element in ANSYS
- Generic Client Element is an interface to OpenFresco
- Has arbitrary number of nodes and degrees of freedom
- Uses TCP sockets for communication
- Makes use of Experimental Elements already in OpenFresco
- Generic Client Element is programmed once for a specific FESoftware

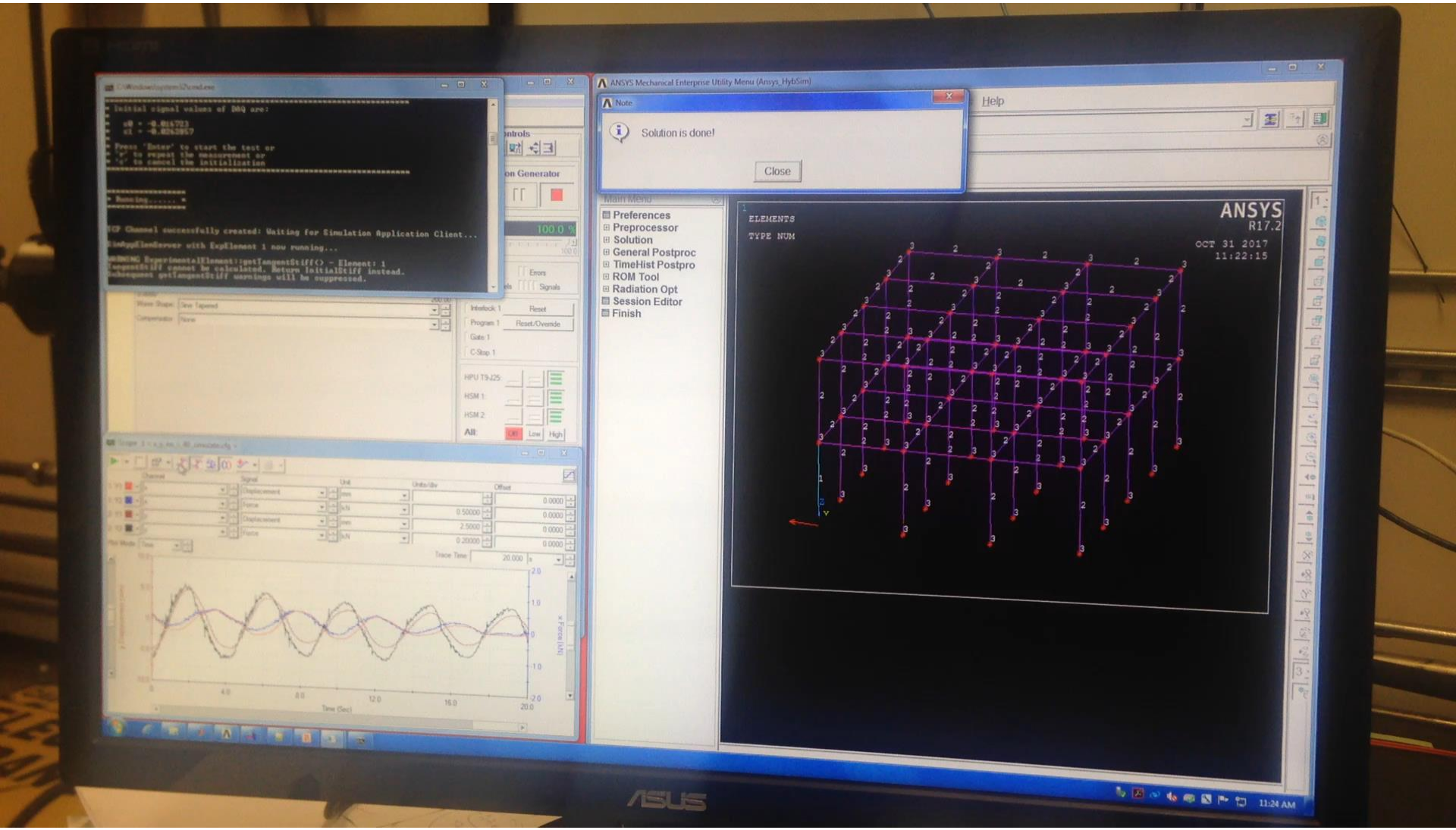
```
c ...   send trial response to experimental site
c
        sData(1) = 3
        do 5, j = 1,4
          sData(1+j) = hsv(i,2+j)
    5   continue
c
        dataTypeSize = sizeDouble
        nleft        = sizeSendData
        call senddata(socketID, dataTypeSize, sData, nleft, stat)
```

Ansys Hybrid Simulation Demo Example





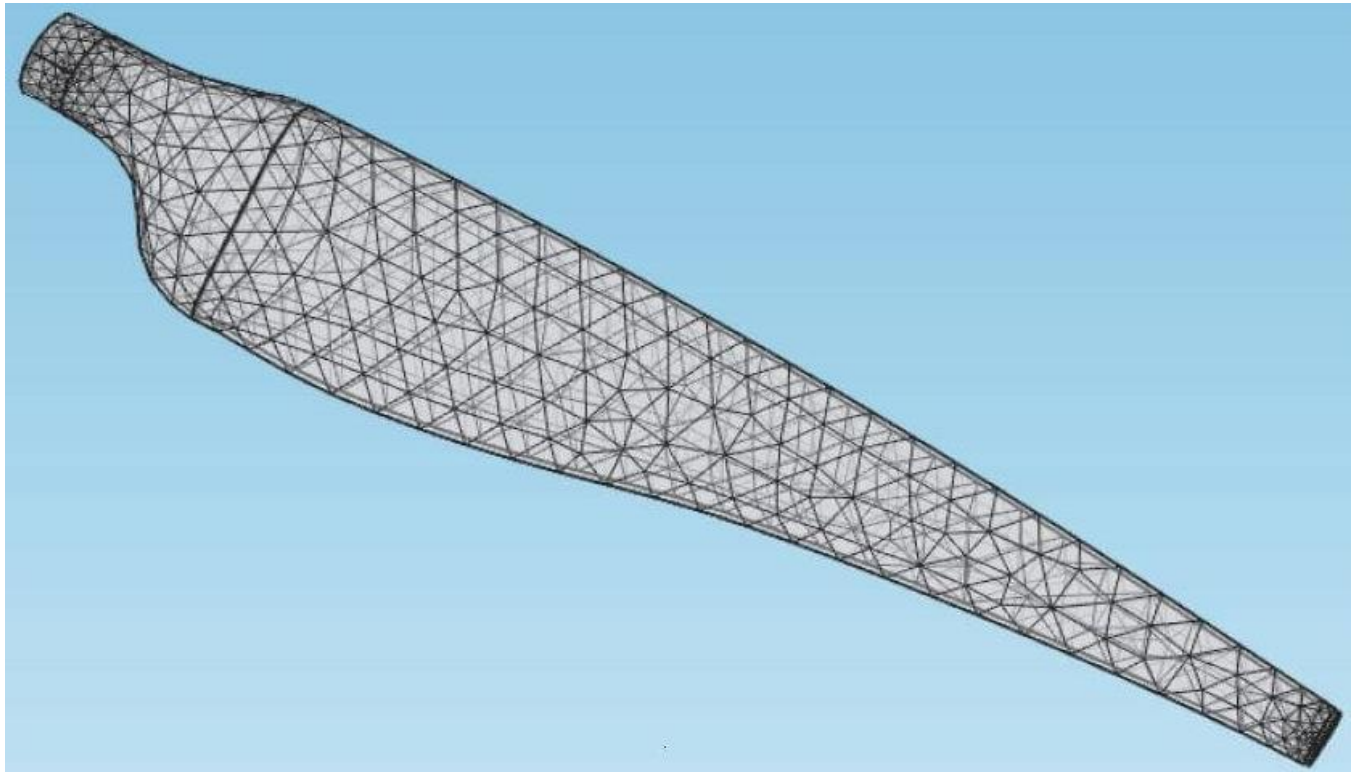
Ansys Hybrid Simulation Demo Video



Hybrid Simulation with Reduced Order Models (ROM)

Hybrid Simulation with Reduced Order Model

- In many cases, FEA models are too complicated to run in real-time. However, the specimens are rate dependent. Therefore, real-time hybrid simulation is a must. The solution is Reduced Order Model (ROM).



ROM for Analytical Structural Dynamic EOMs

$$M_p\ddot{X}_p + C_p\dot{X}_p + K_pX_p = K_p\Gamma x_n + C_p\Gamma\dot{x}_n.$$

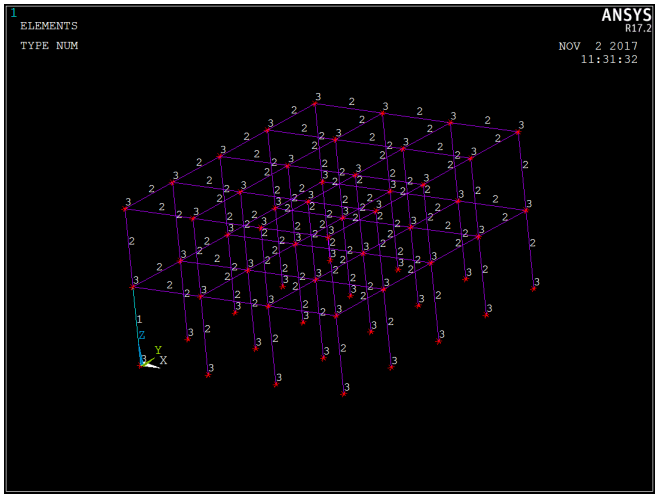
$$\begin{bmatrix}\dot{X}_p\\ \ddot{X}_p\end{bmatrix} = \begin{pmatrix}0_{p\times p} & I_{p\times p}\\ -M_p^{-1}K_p & -M_p^{-1}C_p\end{pmatrix}\begin{bmatrix}X_p\\ \dot{X}_p\end{bmatrix} + \begin{pmatrix}0_{p\times 1} & 0_{p\times 1}\\ -M_p^{-1}K_p\Gamma & -M_p^{-1}C_p\Gamma\end{pmatrix}\begin{bmatrix}x_n\\ \dot{x}_n\end{bmatrix}$$

$$F_p = \begin{pmatrix}k_{n+1} & 0_{1\times p-1} & c_{n+1} & 0_{1\times p-1}\end{pmatrix}\begin{bmatrix}X_p\\ \dot{X}_p\end{bmatrix} + \begin{pmatrix}-k_{n+1} & -c_{n+1}\end{pmatrix}\begin{bmatrix}x_n\\ \dot{x}_n\end{bmatrix}$$

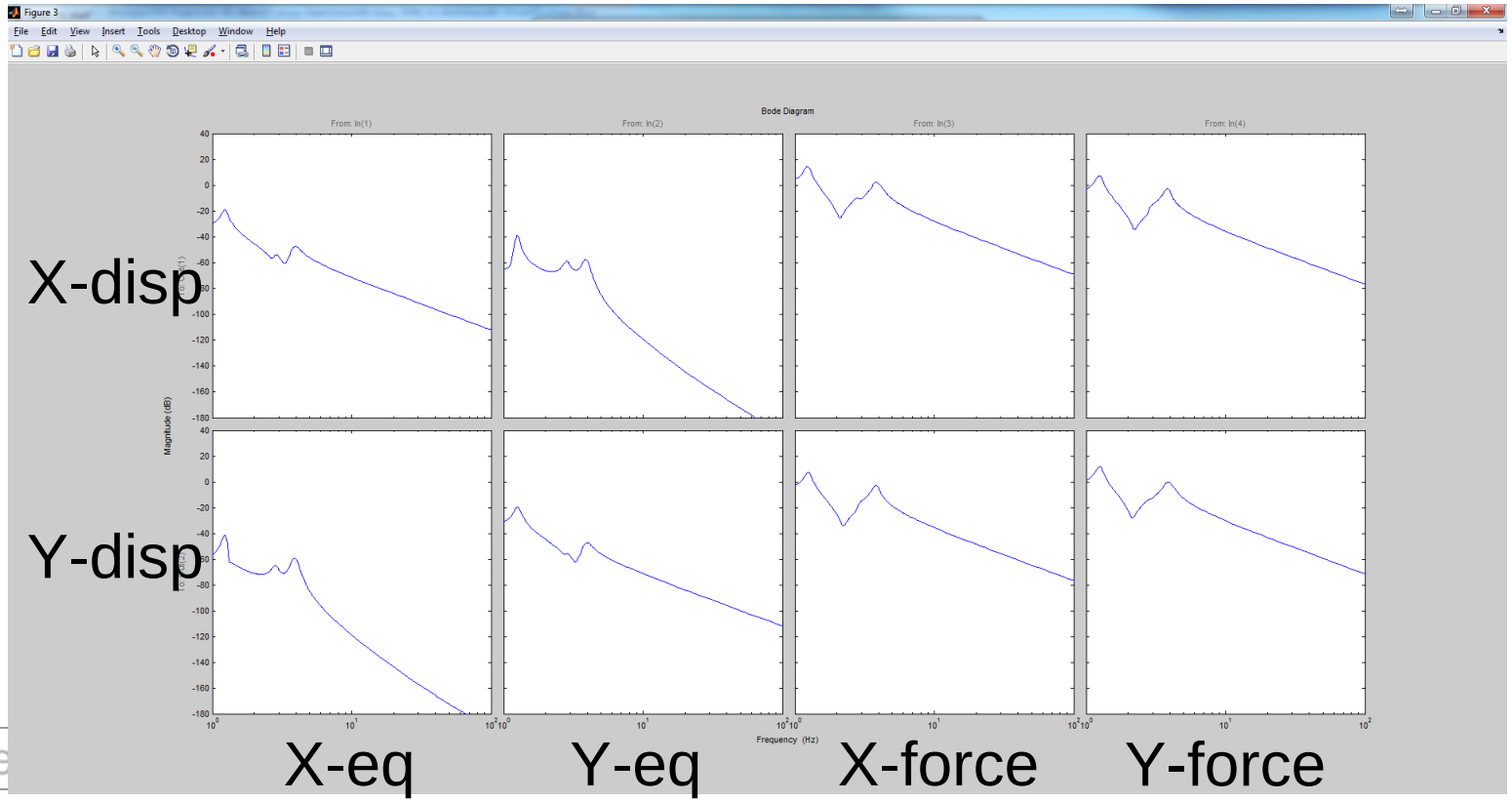
$$\dot{X} = AX + BU$$
$$Y = CX + DU$$

- Convert structural dynamic model (2nd order ODE) into state space model (1st order ODE)
- State space model allows utilization of vast resources of dynamical system analysis and control design tools

ROM for FEA Models (Ansys)

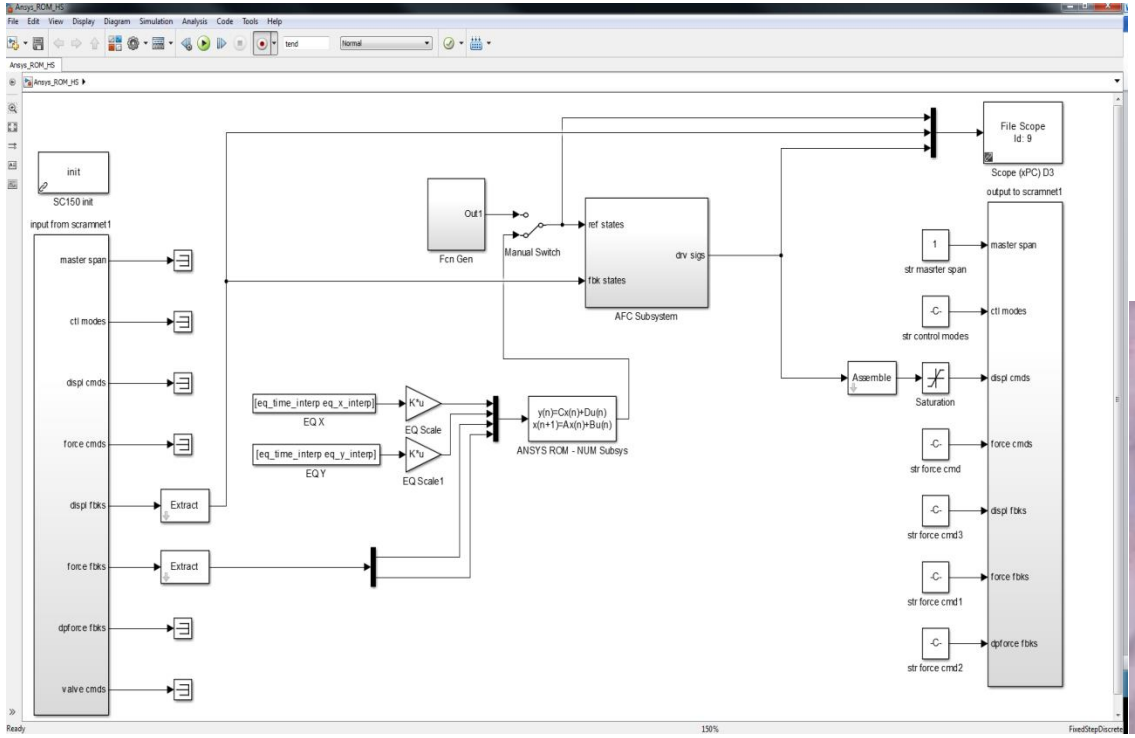


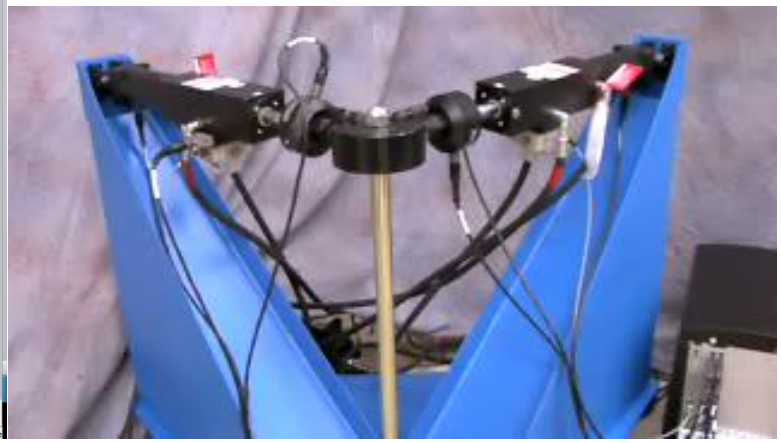
- Use modal superposition approach to construct state space ROM
- Hybrid simulation - analytical substructure ROM 4 inputs, 2 outputs



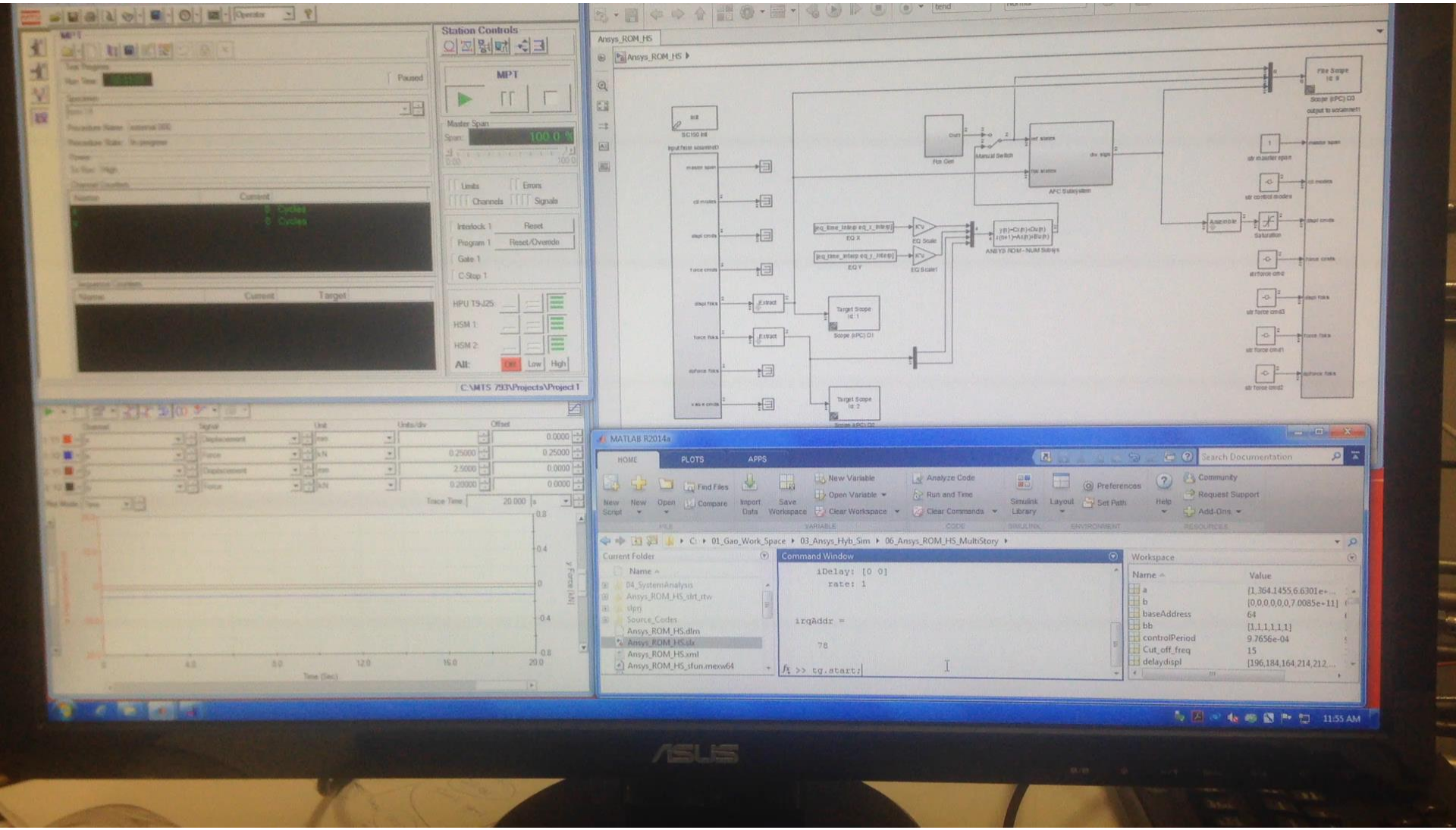
Ansys ROM Realtime Hybrid Simulation Demo

- State space ROM constructed offline
- Hard realtime hybrid simulation, 1024 Hz simulation rate
- No OpenFresco needed





Ansys ROM Realtime Hybrid Simulation



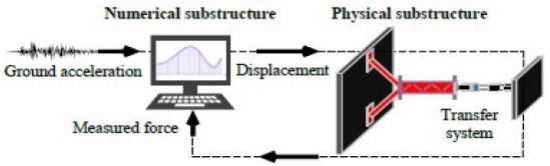
Hybrid Simulation Coupled with Fatigue Testing

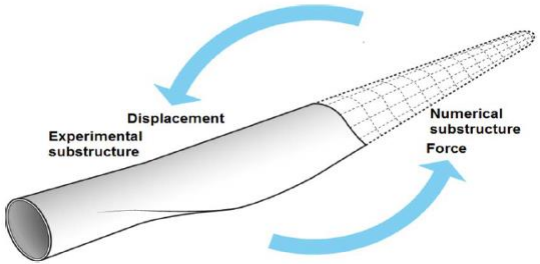
Specimen Degradation During the Services Life

- There are many factors that can cause specimen degrades, such as corrosion, mechanical aging, delamination, and crack propagation.
- Specimen property change will in turn change the loading on the specimen.
- It is important to consider specimen degradation during fatigue tests.

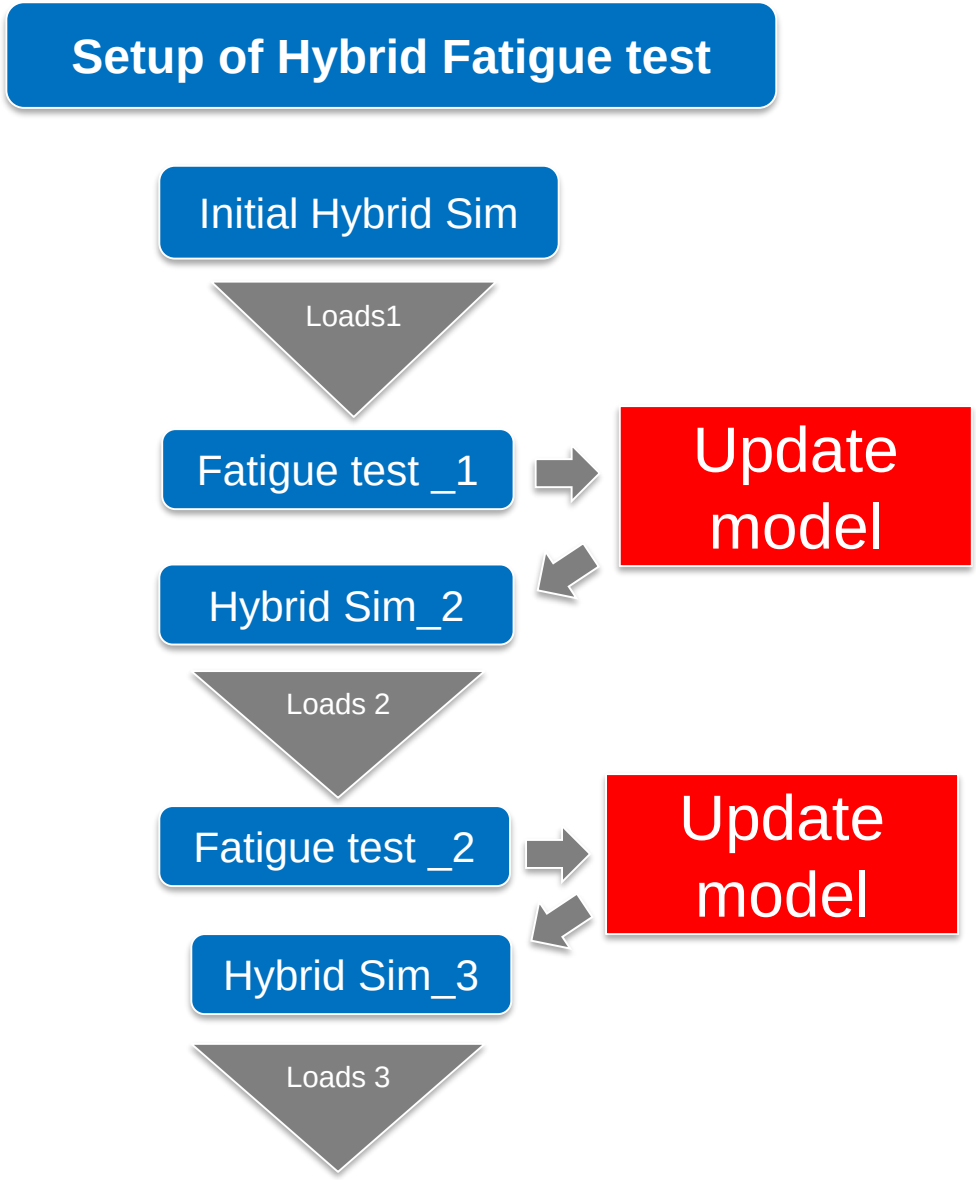
Hybrid Simulation Provides Commands for Fatigue Testing

- During hybrid simulation, ANSYS output interface load to a file in global coordinate in MTS Profile Command format.
- Fatigue testing can be easily setup by repeating the load file.





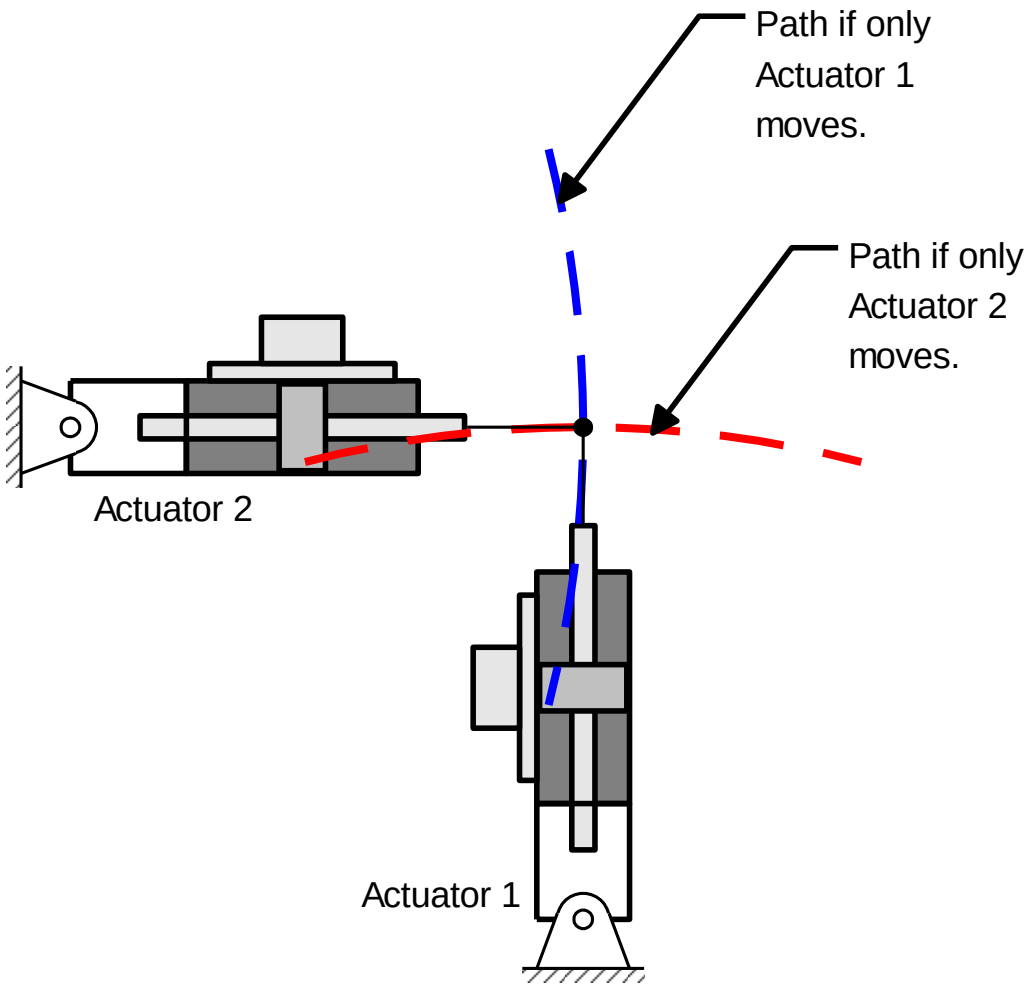
Hybrid Fatigue Test Method



DOF Control – 2 Channel Example

Individual actuator control causes specimen to follow arc path.

Use DOF control to provide pure vertical and lateral motion.

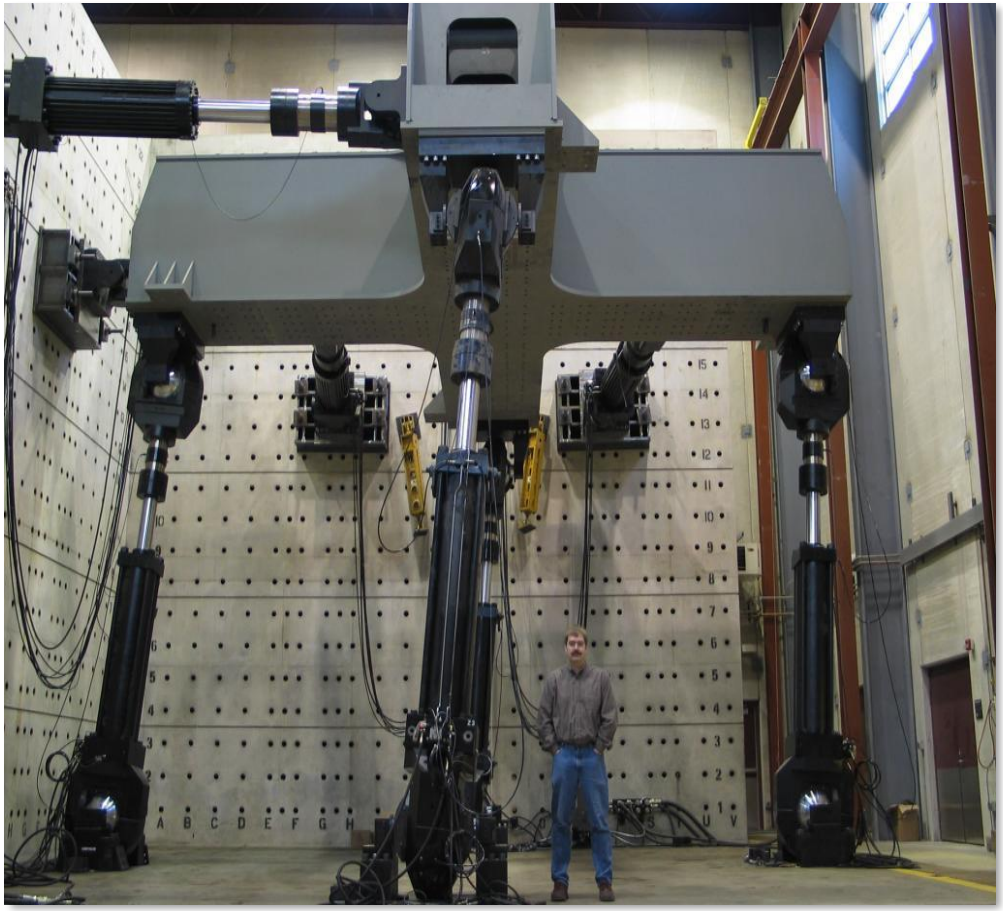


DOF Control

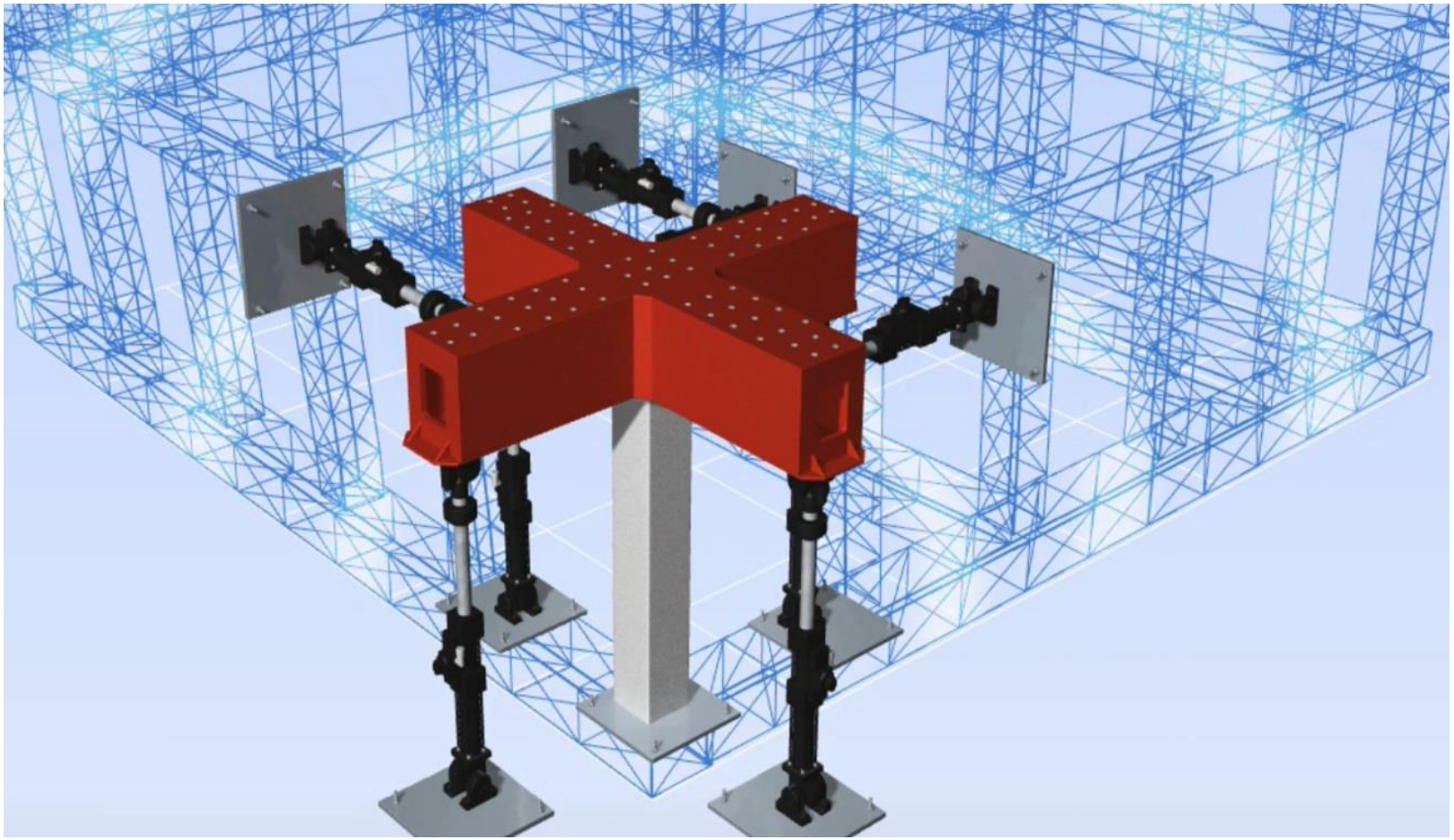
- Controlling motion, force or acceleration of any point in global coordinate system
- Could be any number of actuators
- Mixed control mode (For example, vertical in force control, lateral in displacement control)
- Could be over constrained systems
- Control any degrees of freedom less or equal to 6
- Cross coupling can be dealt with
- External transducer is acceptable
- Fast and accurate solving
- More and more used in hybrid simulation

University of Minnesota

Multi-Axial Sub-assemblage Test (MAST) - Multiple Degree of Freedom



DOF Control Coupled with Hybrid Simulation



Questions