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Earthquake Engineering Simulation



Hybrid Simulation Primer and Dictionary



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Abstract

The purpose of this document is to provide users who are new to hybrid simulation with a general introduction to hybrid simulation, its components, capabilities, and the procedures by which a simulation is typically performed. After reading this document, we anticipate that users new to hybrid simulation will have the fundamentals to plan a simple simulation, and will understand how the physical and computational components work together during the execution of a hybrid simulation.

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1 Introduction

Seismic evaluation of structural systems has traditionally been explored using either experimental methods or analytical models. Dynamic testing using full-scale shake tables is generally viewed as the most realistic method for the seismic evaluation of structural systems. However, this testing method requires full-scale shake tables, which are not readily available in structural labs due to the large space they typically occupy. Furthermore, issues of scale, equipment capacity and availability of research funding continue to limit the full-scale shake table testing of complete structures. Analytical models, on the other hand, are limited to solving specific types of problems and in many cases fail to capture complex behaviors or failure modes at structural system-levels. Combining both experimental and analytical tools in a single simulation, while taking advantage of what each tool has to offer, is referred to as hybrid simulation.

In hybrid simulation, shown conceptually in Fig. 1, the structure can be portioned into various components comprising of experimental or numerical substructures or a combination of both. The attractiveness of this simulation technique lies in the fact that it can utilize various models for different components to represent the entire structural system. In general, well-understood components are modeled computationally as the numerical substructure while components that are difficult to model are physically tested as the experimental substructure. Thus, hybrid simulation provides an efficient and cost-effective approach for seismic evaluation of structural systems.

With over 30 years of development, hybrid simulation techniques have gained a level of acceptance that warrants further exploration and development. As the range of experiments that need to be performed using the hybrid simulation techniques is extended, the methods must evolve to meet these challenges. Thus, the capacity to run more complex simulations is expanding to meet the demands of the engineering community.

The purpose of this document is to provide users who are new to hybrid simulation with a general introduction to hybrid simulation, its components, capabilities, and the procedures by which a simulation is typically performed. After reading this document, we anticipate that users new to hybrid simulation will have the fundamentals to plan a simple hybrid simulation, and will

understand how the physical and computational components work together during the execution of a hybrid simulation. Researchers that are interested in conducting hybrid simulations are expected to have experience with typical structural engineering laboratory equipment such as hydraulic actuator and data acquisition, as well as modeling approaches and solution procedures in structural dynamics. More detailed resources on hybrid simulation can be found at NEEShub.

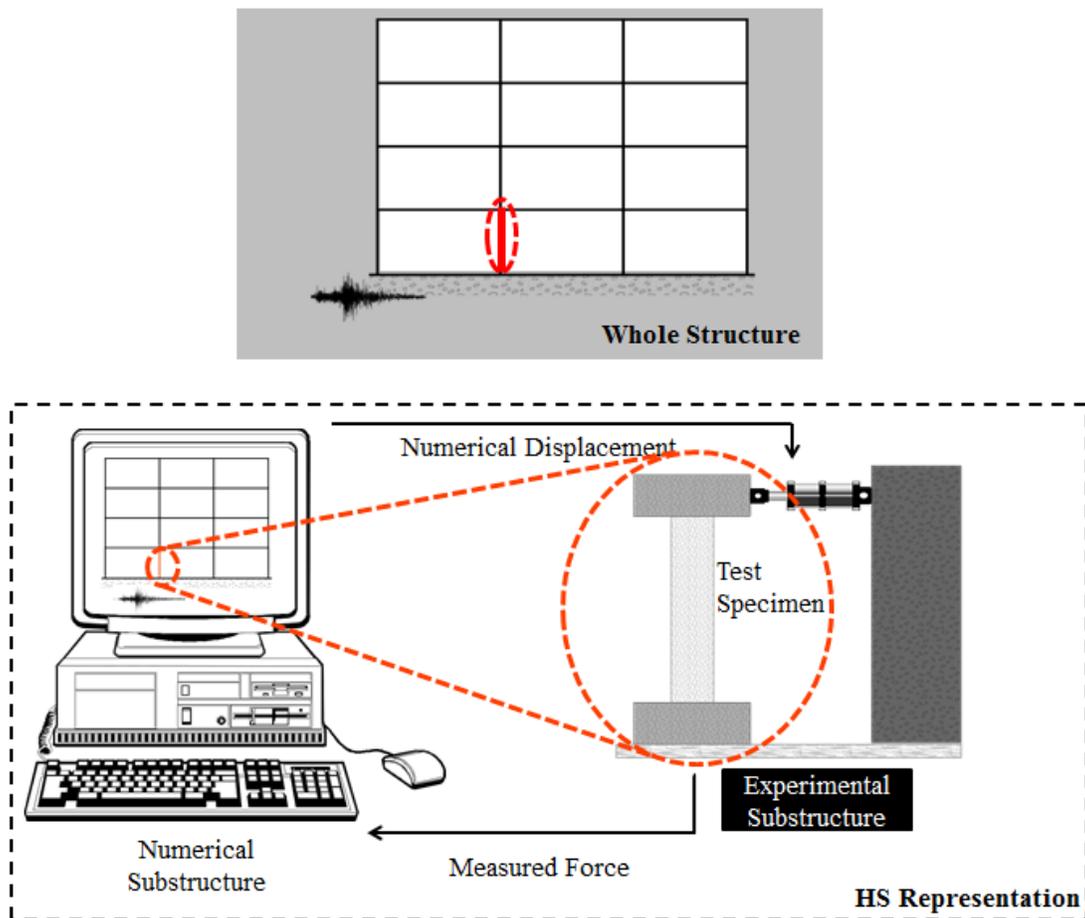


Fig. 1. Whole Structure Model Representation in Hybrid Simulation

2 Background

2.1 Basic components

In its most basic application, a hybrid simulation requires a numerical model of the structure with at least one physical component. Starting with a complete numerical model of the structure being analyzed represented by the dynamic equilibrium *equation of motion*, the component to be tested in the lab is removed numerically and replaced through a specialized link to the laboratory that allows data interchange at each integration step. For purposes of this primer, it is assumed that there is only one computational and one physical component.

Fig. 2 shows a configuration of basic components in such a hybrid simulation. In a typical hybrid simulation, the computational component sends *target displacement* to the physical component and the physical component returns *measured force*. Details of the basic components along with the fundamental theory are explained below. Further, some potential variations are also described in later sections of this document.

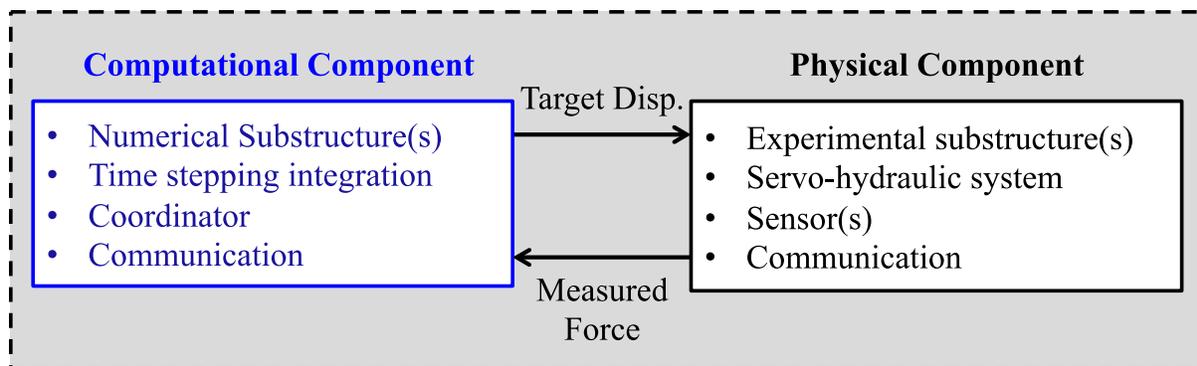


Fig. 2. Basic Components in Hybrid Simulation

2.2 Physical Component

The equipment used for *quasi-static testing* in most structural testing facilities can be utilized to conduct hybrid simulation. The basic components of a hybrid simulation test setup and their interconnections are illustrated in master overview form in Fig. 2. The required laboratory setup includes: (1) a *servo-hydraulic system* consisting of an actuator, controller, and pressurized hydraulic oil supply; (2) a *physical specimen* with the actuators attached at the degrees of freedom where the displacements are to be imposed; and (3) *sensors* to measure the responses of



the physical specimen. The major addition to standard equipment typically available in structural testing laboratories is a computer that can be programmed to solve the equation of motion for the whole structure. This computer can be linked to [hydraulic controllers](#) and data acquisition either by digital means or via analog/digital converters to send and receive analog signals to the equipment. In a hybrid simulation, an experimental substructure can have one or more degrees of freedom and thus the experimental setup will have one or more actuators. Additionally, a hybrid simulation can have multiple experimental substructures.

2.3 Computational Component

The laboratory equipment above should be linked to a computer hosting the numerical simulation that is capable of computing a target displacement based on feedback from the laboratory transducers and then sending this displacement as a new command to the actuators. This may require custom coding to program the simulation and communication protocols with the laboratory; however there are now some standard packages (UI-SIMCOR, OpenFresco) to accomplish these tasks to link to the experimental setup.

A hybrid simulation requires a controlling simulation component, often called the [master simulation](#) or [simulation coordinator](#), that encapsulates the whole structural model including all substructures. This master simulation/simulation coordinator controls a [time-stepping integration algorithm](#) and coordinates the communication between substructures.

2.4 Fundamental Theory and Procedure

The problem statement posed in hybrid simulation is to determine the seismic response of a structural model composed of experimental and numerical substructures. To this end, the complete structural model is idealized as a [discrete parameter system](#) with a finite number of degrees of freedom. The time-discretized equation of motion of the [master model](#) (combined experimental and numerical substructures) is expressed as:

$$\mathbf{M}\mathbf{a}_i + \mathbf{C}\mathbf{v}_i + \mathbf{r}_i = \mathbf{f}_i \quad (1)$$

in which \mathbf{M} and \mathbf{C} are mass and damping matrices of the master model in hybrid simulation; \mathbf{f} is the external force vector; \mathbf{v} and \mathbf{a} are velocity and acceleration vectors, respectively; \mathbf{r} is the



restoring force vector that consists of the measured force in the experimental substructures \mathbf{r}_e and the simulated force in the numerical substructure \mathbf{r}_n ; and the subscript i denotes responses at the i -th integration step. If the numerical substructure is linear elastic, \mathbf{r}_n can be expressed as \mathbf{Kd} where \mathbf{K} is the stiffness matrix of the numerical substructure and \mathbf{d} is the displacement vector. Note that the experimental restoring force vector may include strain rate-dependent, damping, or inertial forces, depending on the characteristics of the experimental substructure.

Similar to pure numerical simulations, time-stepping integration procedures are applied to solve the equation of motion in Eq. (1). A variety of integration methods have been proposed for hybrid simulation with explicit methods being the simplest to implement. Implicit methods, though often preferred for numerical simulation of structural responses are challenging to implement for hybrid simulation due to the required iterations.

In a typical hybrid simulation, the solution proceeds as follows:

(i) The equation of motion in Eq. (1) is solved for the displacement at each step using responses at the previous steps. For example, if the explicit time-stepping integration algorithm is adopted, the displacement vector at the $i + 1$ step is expressed as:

$$\mathbf{d}_{i+1} = \mathbf{d}_i + \Delta t \mathbf{v}_i + \frac{1}{2} \Delta t^2 \mathbf{a}_i \quad (2)$$

in which Δt is the integration time step of the simulation.

(ii) Displacements in Eq. (2) are then sent and imposed on the experimental and numerical substructures as the target displacement.

(iii) The corresponding restoring forces, measured forces from the experimental substructure \mathbf{r}_e and simulated forces from the numerical substructures \mathbf{r}_n , are fed back to the equation of motion in Eq (1).

(iv) The remaining responses at the $i + 1$ time step including the velocity and acceleration are calculated based on the restoring and the external forces.

Then, the process is repeated by returning to (i) to proceed to the subsequent step and calculates the target displacement at the $i+2$ step. The same procedure is executed until the end of the simulation time.

Fig. 3 shows a diagram of this procedure and the flow of a hybrid simulation framework. As shown in Fig. 3, the processes at each step includes solution of the equations of motion; execution of the target displacement; measurement of the restoring force; and communication. It should be noted that while these processes are essential in most hybrid simulations, there are many different ways to configure these tasks depending on hybrid simulation software, laboratory equipment, and numerical models, etc. In particular, configurations for the conventional hybrid simulation and real-time hybrid simulation can be slightly different due to constraints and requirements. More details for configuration of the conventional and real-time hybrid simulations are described next.

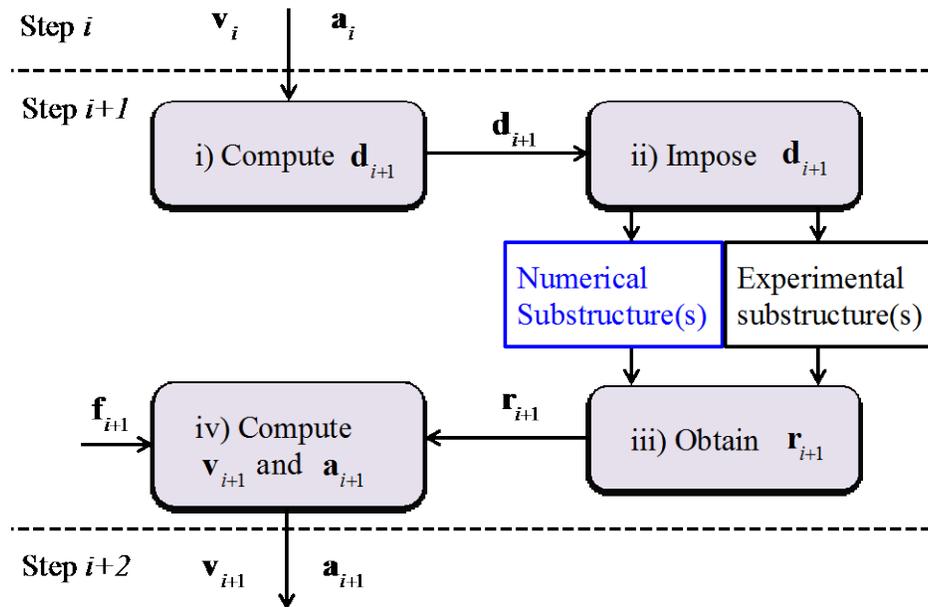


Fig. 3. Time stepping procedure in a typical hybrid simulation



3 Hybrid simulation

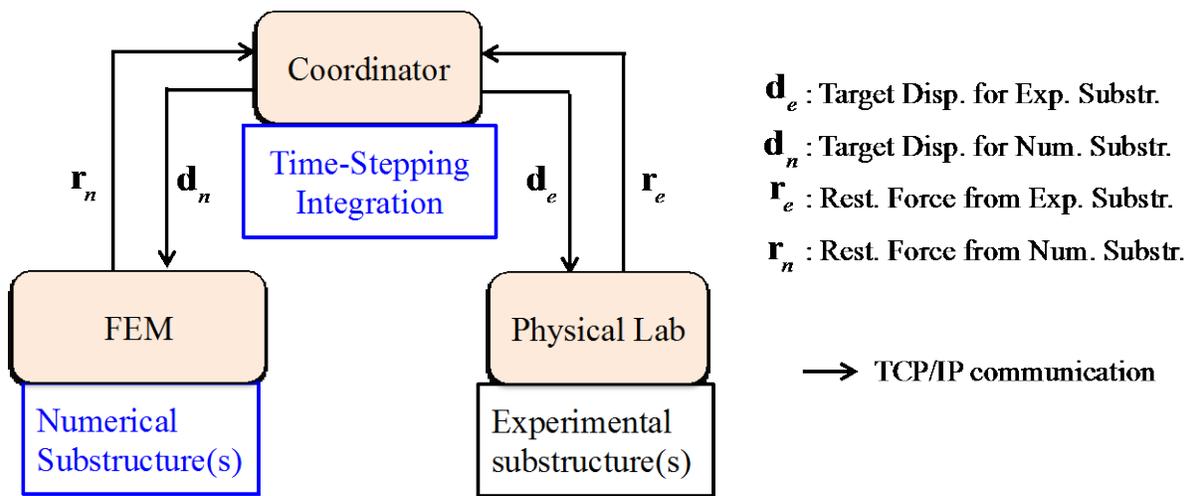
While the concept of hybrid simulation is not difficult to understand, configuration and implementation are not always straight-forward for those who are new to hybrid simulation. To facilitate development of new hybrid simulation facilities and enhancement of existing facilities with hybrid simulation, this section discusses configurations of hybrid simulation, covering the state of the art approaches. Because configurations of hybrid simulation are highly dependent on available and selected tools in computational and physical components, such as hybrid simulation software, laboratory equipment, and numerical models, etc., the configurations presented are therefore component-based.

3.1 Computational components

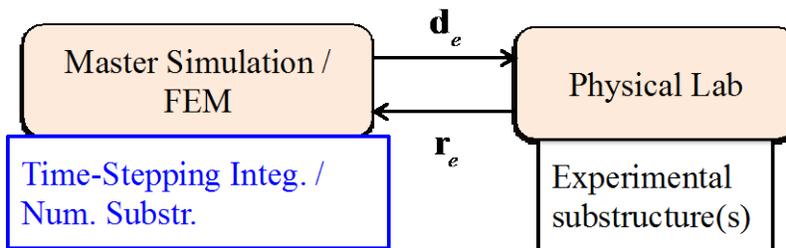
The computational components in hybrid simulation include the computational model of the numerical substructure, the time-stepping integration algorithms to solve the equation of motion, and communications between the numerical and experiment substructures. Due to the need for coordination of the components, in most hybrid simulations, one component serves or is designated as a so-called “coordinator”. Fig. 4 shows two typical configurations of the computational components in hybrid simulation.

Configuration I has a designated coordinator to define a hybrid simulation. In this configuration, the time-stepping integration algorithm and communications are handled by the coordinator. The numerical and experimental substructures are outsourced to finite element program and a physical laboratory, respectively. Advantages of this configuration are: i) all of the substructures are equally handled by the coordinator (no differences between the numerical and experimental substructures at the coordinator) and; ii) it is relatively easy to define multiple/different components to represent substructures in hybrid simulation. However, a disadvantage of this configuration is that all of the target displacements and restoring forces have to be transferred via network at each time step. Thus, if the sizes of the models become large, communication and duration of the simulation can become problematic. Hybrid simulation software UI-Simcor falls into this type.

In Configuration II, there is no designated coordinator, but finite element software serves as the master simulation that handles communication with the physical laboratory. In this configuration, the time-stepping integration algorithm and the numerical substructures are processed in the master simulation, and the experimental substructures are treated as outsourced elements. The advantage of this configuration is that it does not require network communication of data in the numerical substructures. Thus, it is suitable for a hybrid simulation with a large number of degrees-of-freedom. However, the disadvantage is that capabilities and functionalities are limited by the finite element software package adopted as the master simulation. OpenSees uses this configuration to conduct hybrid simulation.



Configuration I: With a designated coordinator



Configuration II: Master Simulation / FEM

Fig. 4. Example configurations of the computational components in hybrid simulation.



It should be noted that while these two configurations have different pros and cons, both can theoretically perform the same hybrid simulation (e.g., multiple substructures, *geographically distributed hybrid simulation*). The user shall select the configuration based the availability of software packages and their familiarities to those tools.

Besides the configurations, there are other issues that should be mentioned in the computational components. Some of such are listed in the following bullets.

- Numerical mass, damping and stiffness terms from both numerical and experimental substructures as well as ground motion input are stored where the time-stepping integration is performed.
- Due to the interactive nature of the hybrid simulation, the adopted computational tool shall be able to: 1) realistically simulate the (nonlinear) behavior of structural components that are part of the numerical substructure; 2) enable a flexible user interface to extract the data of the current and previous time steps and output as needed; 3) receive displacement/rotation input and output the restoring forces/ moments at desired DOFs.
- An appropriate time stepping integration scheme is also needed to solve the master numerical model. Common integration schemes include explicit, implicit and operator splitting methods. Implicit schemes, although appropriate for numerical simulations, cannot be directly applied to hybrid simulation. User should be careful in choosing the integration scheme that is appropriate to the problem at hand and be able to modify for specific problems as needed.
- The coordinator can be a simple communication linkage between the computational and physical components by passing through the displacement and restoring forces at interface DOFs.

3.2 Physical components

The tasks of physical components in hybrid simulation are to receive the *target displacements* from the computational components, either through coordinator or master simulation; impose the target displacements to the experimental substructure; extract corresponding *measured forces*

from the experimental substructure; and send the restoring forces back to the computational components. To complete those tasks, certain laboratory equipment is needed. This section presents a brief description of the physical components in hybrid simulation.

Fig. 5 shows a schematic of the essential physical components in hybrid simulation. Note that the physical components discussed here are independent from the configurations of the computational components in the previous section. Therefore, the computational components are not included in this figure.

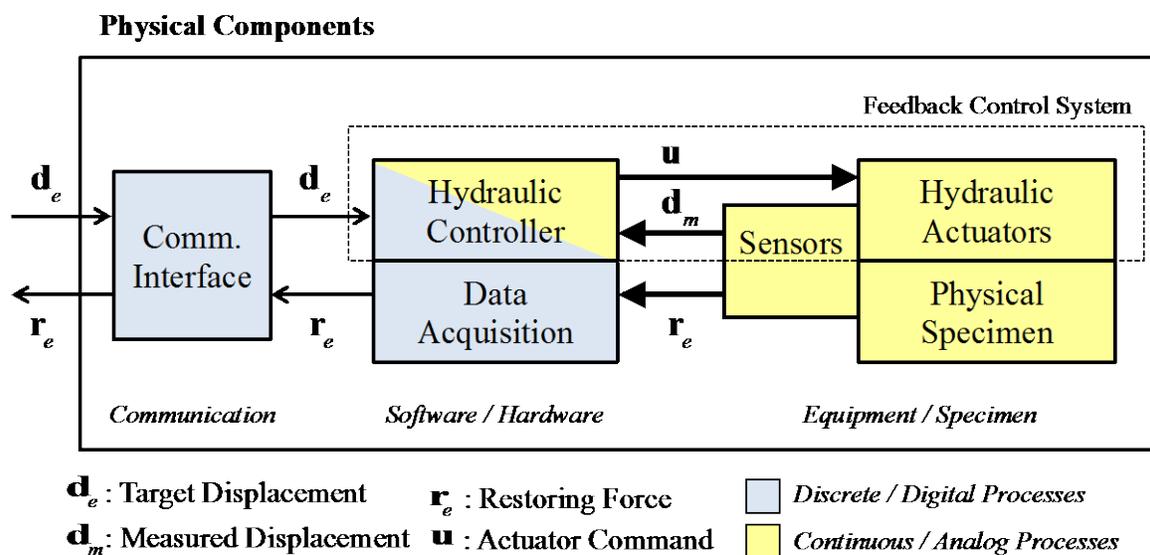


Fig. 5. Schematic of the physical components in hybrid simulation.

One of the essential functionalities in the physical components is the communication interface that allows for receiving the target displacements from and returning the restoring forces to the computational components. The received target displacements have to be made available for the hydraulic controller of the actuator. This functionality can be in different forms depending on how the [hydraulic controller](#) takes the target displacement. Three examples are provided: 1) Some commercial hydraulic controllers provide network capabilities so the interface is included as a part of the controller; 2) Some controllers take only analog signals from [external input](#), which requires conversion of the target displacement into the analog signal; and 3) user-developed interface, either digital or analog, so that specific hydraulic controller can take the



target displacement via network. In the same way, the physical components shall be able to send the restoring force back to the computational component through the [data acquisition](#).

The enclosed section in the dashed line represents the servo-hydraulic feedback control system that consists of the [hydraulic actuator](#), hydraulic controller and [sensors](#). Actuators are used to impose the target displacements to the [physical specimen](#) and sensors are needed for measurements. Due to the large force and velocity requirements in civil engineering experiments, hydraulic actuators are usually used in hybrid simulation. In most laboratories, the servo-hydraulic feedback control system is provided by manufacturers, including a hydraulic controller, hydraulic power supply, service manifold, etc. As shown in the figure, hydraulic actuators in hybrid simulation are typically in displacement control. It should be mentioned that the servo hydraulic feedback control system can vary significantly, for example, analog or digital, conventional PID-based controller or advanced controller, and so on. For the development of new hybrid simulation system, it is strongly recommended to check compatibility of the available hydraulic system as well as the needs of the test.

Data acquisition, often referred to as DAQ, is the equipment that allows for digitization of sensor data. It is generally an independent system, but in some cases, it can be integrated with the hydraulic controller. Note that some data acquisition systems have network communication capabilities which include the network interface in the figure.

The physical specimen represents the experimental substructure in hybrid simulation. It should be securely anchored to either a reaction wall or strong floor so that the target displacements are accurately imposed and the corresponding restoring forces are properly measured by sensors such as load cells. Careful attention should be paid to the boundary conditions, scaling factors, effective degrees-of-freedom of the physical specimen, etc.

In the conventional hybrid simulation, computational and physical processes are performed in a sequential manner as described in Fig. 3, where the physical components receive the target displacements and return the restoring forces. This means that if the above components and functionalities are available, the system can serve as a physical component in hybrid simulation regardless of the rest of the configuration. It should be noted that the physical components and



functionalities introduced herein include only the essential ones in hybrid simulation and not all hybrid simulation systems can be represented as that of Fig. 5; some systems have an integrated controller/DAQ/network interface and some systems have additional components such as SCRAMNet for data sharing between multiple machines.

Besides the items listed above, several factors have to be carefully considered for the physical components in hybrid simulation. Some of those, including challenges, are listed below.

- First and foremost, users of hybrid simulation have to become familiar with structural testing. It is highly recommended that the users learn the fundamentals of hydraulic systems, data acquisition, and sensors prior to or as a part of hybrid simulation.
- To enhance existing hydraulic systems with the hybrid simulation capabilities, the network communication needs to be added to remotely/externally control hydraulic actuators. First, this network communication has to be secure and reliable. Then, the network interface has to follow the same protocol used in the computational components, either coordinator or master simulation to enable meaningful communications.
- Proper tuning of the hydraulic controller is critical. Because errors are inevitably propagated in hybrid simulation, accuracy of actuator control will greatly influence the accuracy of the overall hybrid simulation results.
- Despite the long history, there remain many challenges in structural testing that are relevant to the physical components of hybrid simulation. Those challenges include, but are not limited to, multi-degrees-of-freedom control; control of rotational degrees-of-freedom; testing of extremely rigid specimens; measurement of large deformation with geometric nonlinearities, etc.

4 Real-time hybrid simulation (RTHS)

Real-time hybrid simulation (RTHS) is a special family of hybrid simulation that allows for the evaluation of structural systems with strain rate-dependent elements and members. Because of the numerous advantages, it has gained significant attention by the research community in the last several years. While the general procedure in RTHS is the same as those in hybrid simulation (see Fig. 3), configurations and implementation can be slightly different from the conventional hybrid simulation because of additional constraints and requirements in RTHS. This section presents a brief introduction and a simple configuration of RTHS as well as issues that should be considered in RTHS.

The main difference between hybrid simulation and RTHS is that in RTHS the test is intended to be executed in real-time. This means that if the integration time step (i.e. sampling of the simulation, time discretization) is 0.01 second, all of the processes in each step (see tasks i)-iv) in Fig. 3) would be completed within 0.01 second. To meet such a demanding constraint, there are certain system requirements in RTHS as discussed in detail below. Furthermore, computational and physical components have to be configured together, accounting for specifications of each other; unlike the conventional hybrid simulation, computational and physical components cannot be configured independently.

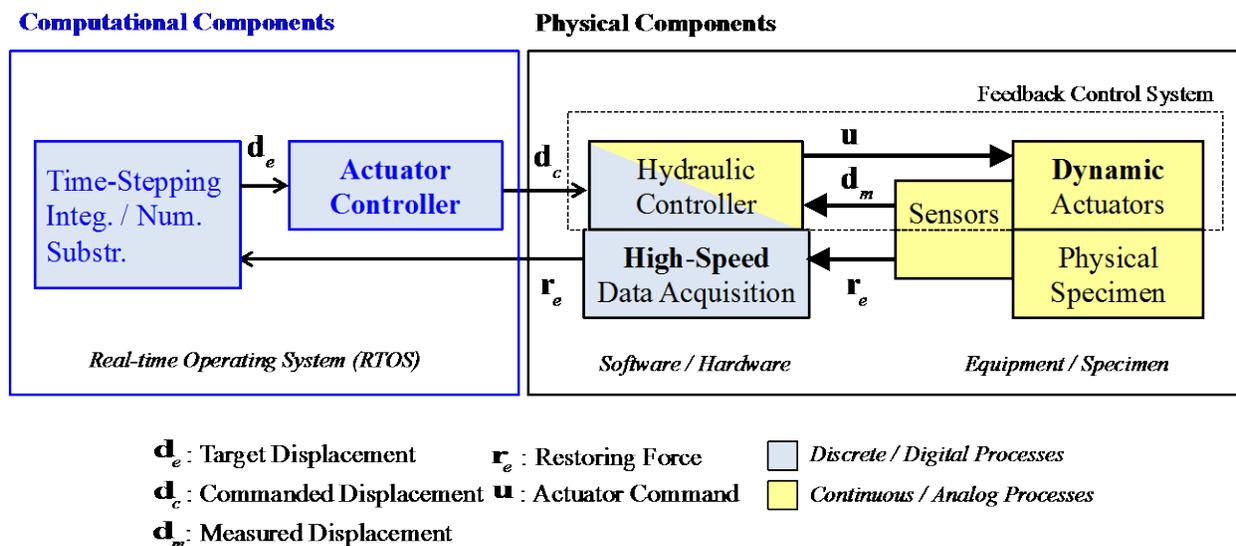


Fig. 6. An example of an RTHS configuration.



Fig. 6 shows an example configuration of RTHS. In this configuration, the time-stepping integration algorithm and the numerical substructure are combined together as a computational component. Note that the layout of the components in RTHS can be slightly different (one may say data acquisition should be in the computational components). Most importantly, the figure includes the essential components in RTHS.

On the physical side, in order to achieve the target displacements in real-time, RTHS requires dynamic actuators that are capable of producing required velocity. This requirement may require additional investigation of the hydraulic system such as flow rate of hydraulic power supply, capacities of accumulator, and rated-flow of the servo valve, etc. The other requirement in the physical components in RTHS is high-speed data acquisition system that allows sampling of sensor data faster than the sampling of the simulation.

On the computational side, the time-stepping integration, analysis of the numerical substructure, and input /output (I/O) between the physical components (I/O) have to be realized in real-time. To meet these objectives, computational components in RTHS require a real-time operating system (RTOS) that ensures execution of tasks in a fixed rate. In most RTHS, the time-stepping integration and the numerical substructures are integrated into a single program to increase computational efficiency and eliminate unnecessary communication time.

One of the critical components in RTHS is the actuator controller. Despite the use of dynamic actuator and RTOS, it is not possible to achieve the target displacement in the physical testing at any given moment. It is mainly due to the inherent dynamics of hydraulic actuators and inevitable communication delays and process time. To successfully perform RTHS, the actuator controller is often essential to compensate for adverse effects of actuator dynamics and delays. The actuator controller is usually designed to generate the command displacements from the target displacements such that the measured displacements are close to the target displacements. In most cases, the actuator controller is placed outside the hydraulic controller as shown in Fig. 6 so that the users do not need to look into the hydraulic controller. Note that this is the most common practice in the current RTHS community, but it does not ensure the best practice in control.



In addition to the basics of RTHS presented above, some remarks on RTHS are listed below.

- RTHS has an enormous potential as an enabling technology for efficient and cost-effective means of seismic performance evaluation of structural systems. Furthermore, RTHS can be expanded to enhance capabilities in structural testing. Examples of those include, but are not limited to, substructure shake table testing, dynamic force control testing, and soil-structure interaction testing, etc.
- There are numerous ways to configure RTHS, probably more than hybrid simulation. When it comes to setup an RTHS system, it is advised to review the specifications of available equipment and the required functionalities to meet the needs prior to a selection of tools, equipment and software. Be aware that not a single configuration satisfies all the needs in RTHS.
- Significant research in RTHS has been made toward the development of actuator controllers and time-stepping integration algorithms in recent years. Establishing best practices toward acceptance criteria for those developments are currently in progress by the NEES Hybrid Simulation Task Force. Interested users are recommended to frequently check ‘Acceptance Criteria in RTHS’ at NEEShub.

5 Summary

This document presents a brief introduction of hybrid simulation and real-time hybrid simulation including procedures and components. It is intended to help new users get a better understanding of hybrid simulation, identify the proper type of hybrid simulation for their research, and conduct hybrid simulation for their research needs. The Hybrid Simulation Task Force will continue to make efforts to provide support for new users. We welcome feedback and suggestions to improve this document.

6 Terminology

Actuator controller

A controller that receives the target displacement from the master simulation / simulation coordinator and sends the command displacement to the hydraulic controller. Actuator controller is necessary in most RTHS and is designed to compensate for actuator dynamics and communication delay.

Synonyms: actuator compensator, delay compensation

Actuator dynamics

A hydraulic actuator is an electro-magnetic-mechanical device that has inherent complex dynamics. Actuator dynamics has a large influence on the accuracy in real-time hybrid simulation.

Analytical models

Representation of structure including mass, damping, stiffness and behavior in a mathematical form

Synonyms: numerical model, computational model

Command displacement

Displacement command that is sent to the controller of hydraulic actuator to achieve target displacement. In real-time hybrid simulation, command displacement is often different from target displacement to compensate for dynamics of hydraulic actuator.

Communication delay

Time and associated delay to complete digital and analog process as well as communication and exchange data between machines, software and hardware, analog and digital in real-time hybrid simulation.

Synonyms: process delay, time delay

Computational component

Computer programs, numerical models and digital processes that are required in order to perform hybrid simulation. Computational components include the time-stepping integration algorithm, analysis of numerical substructure, communication and more.



Synonyms: numerical component

Conventional hybrid simulation

A family of hybrid simulation where the target displacement in experimental substructure is imposed in a ramp-and-hold fashion. In general, actual test takes much longer than the simulation time.

Synonyms: conventional slow-speed pseudodynamic test

Data acquisition

A device/equipment that converts analog signals from transducers into digital data. Hybrid simulation requires a data acquisition that has communication capabilities and data storage.

Discrete parameter system

A system of which behavior is represented by a finite number of parameters at discrete points. Hybrid simulation is based on the equation of motion of discrete parameter system.

Dynamic actuator

A hydraulic actuator with dynamic loading capabilities. The dynamic actuator is usually equipped with a servo valve. It also requires a certain level of hydraulic oil flow and accumulators to prevent pressure drop.

Equation of motion

An underlying mathematical formula of the dynamics of structure, which is in the second-order differential equation. Hybrid simulation is based on the solution of EOM in a time-stepping manner.

Acronyms: EOM

Experimental substructure

A part of the structural model in hybrid simulation that is physically modeled and experimentally tested in laboratory.

Synonyms: physical substructure, experimental module

External input



Most of the commercial hydraulic controllers take an external input to drive actuator. In hybrid simulation, the command displacement is sent to hydraulic controller through an external input port. The input port can be either digital or analog.

Synonyms: external reference, external set point

Geographically distributed hybrid simulation

A family of hybrid simulation where the process of one or more of experimental and numerical substructures are performed at remote site.

Hybrid simulation

A simulation technique that combines physical experimentation with computational simulation via a communication exchange to evaluate how structures and lifelines respond to simulated earthquakes.

Synonyms: hybrid testing, pseudodynamic testing, online testing, internet-based simulation, dynamic structure testing

Acronyms: HS, HT PSD

Hydraulic actuator

A mechanical device to impose controlled loading to test specimen, powered by pressurized hydraulic fluid. It usually requires a closed-loop feedback control system with a position sensor and a servo valve for high-precision control.

Synonyms: transfer system

Hydraulic controller

An inner-loop servo controller for hydraulic actuator. Most commercial hydraulic controllers are PID (proportional-integral-differential) controller.

Synonyms: inner-loop controller

Master model

An analytical model for the whole structure that includes individual models of both the computational and experimental substructures.

Master simulation / Simulation coordinator



Computational process that solves equation of motion and handles communication with experimental and numerical substructures. Structural parameters such as mass, damping and stiffness are stored in the master simulation / simulation coordinator.

Measured force

Force that is measured from the experimental substructure when the target displacement is imposed.

Numerical simulation

A simulation technique to obtain seismic response of structural systems using only numerical models.

Synonyms: computational simulation

Numerical substructure

A part of the structural model in hybrid simulation that is numerically modeled and simulated in computational software.

Synonyms: computational substructure, analytical module

Physical component

Physical/laboratory equipment, elements, and devices that are required in order to impose the target displacements and extract the restoring forces in experimental substructure. Physical components include physical specimen, hydraulic actuator, hydraulic controller, data acquisition, sensors, and other laboratory equipment.

Synonyms: experimental component

Physical specimen

Physical model that represents a part of structural system. It is experimentally tested and measured in laboratory.

Quasi-static testing

An experimental technique to obtain stress-strain or displacement-force relations of the physical specimen. Input is usually a pre-specified protocol such as triangle input, and the loading is imposed in a slow speed to avoid inertial effects in the measurement.

Real-time hybrid simulation



A family of hybrid simulation where the entire processes of hybrid simulation are performed at the true rate of the simulation. It is particularly advantageous for the simulation of systems with rate-dependent components in the experimental structure.

Synonyms: real-time pseudodynamic test, dynamic substructuring test

Acronyms: RTHS, RTHT

Real-time operating system

An operating system that is designed to execute requests in a deterministically small time window. RTOS is an essential piece of equipment/hardware in real-time hybrid simulation.

Acronyms: RTOS

Restoring force

Force that corresponds to the target displacement in hybrid simulation.

Synonyms: measured force, simulated force, interface force

Sensor / Transducer

A device/equipment that provides digital or analog signals that corresponds to physical measurements. Most traditional sensors in hybrid simulation are analog and their signals are processed in data acquisition.

Servo hydraulic system

A system that consists of hydraulic actuator, service-manifold, hydraulic power supply, and a hydraulic controller

Synonyms: transfer system

Simulated force

Numerically simulated force that represents the restoring force from the numerical substructure when the target displacement is applied.

Simulation time

Period of the earthquake ground motion in hybrid simulation. The simulation time is not always equal to the actual time of testing. In RTHS, simulation time is the same as the actual testing time.

Strain-rate dependent



A term used to describe structural materials and members of which behavior is dependent on the rate of loading. Examples are viscous dampers, rubber bearings, etc.

Target displacement

Prescribed displacement obtained from solution of equation of motion using a time-step integration algorithm. Target displacements are sent to experimental and numerical substructures at every step in hybrid simulation.

Synonyms: reference displacement, desired displacement

Time-stepping integration algorithm

A technique to solve the discretized equation of motion for the target displacement. Most integration methods calculate the target displacements from system parameters (e.g., mass, damping and stiffness), past response states, and restoring forces.

Synonyms: integration method, solver