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Large Scale Real Time Dynamic Hybrid Testing Technique –

Shake Tables Substructure Testing

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Introduction

Testing of large-scale specimens and models is currently possible in a few earthquake-engineering laboratories around the world. However, full-scale laboratory seismic testing of entire civil engineering structures (e.g., cable-stayed bridges, multi-story office buildings, industrial facilities, and pipeline distribution systems) is not likely in the near future due to the prohibitive costs associated with such testing. Not only would the materials, labor, and time associated with full-scale testing exceed available research resources, but the testing of full-scale specimens and entire structures might even be counter-productive, making it difficult to study localized or specific problems within the complex system.

It is believed that a better approach to experimentally generate the data needed for the development of reliable and accurate models of behavior is to compliment large *scale* model testing with innovative testing methods that make it possible to conduct complementary tests simultaneously, and seek to supplement such experiments with real-time interactive computational simulations. The technique presented in this paper is based on dynamically testing large substructures using shaking tables, while simultaneously applying at the boundary of the specimens actively controlled dynamic forces generated by a digitally compensated controller. This controller calculates the forces based on real time measurements from the physical shaking table test and from a *real time structure simulator* (RTSS). The RTSS simulates the behavior and interactions of the rest of the structure that includes the tested substructure. Conceptually, this allows a researcher to focus on specific problems in the most realistic conditions using emerging computational power in tandem with control systems. Such procedures and set-ups significantly extend the testing capabilities by integrating large-size physical subcomponents into virtual complete systems of unlimited size and configuration.

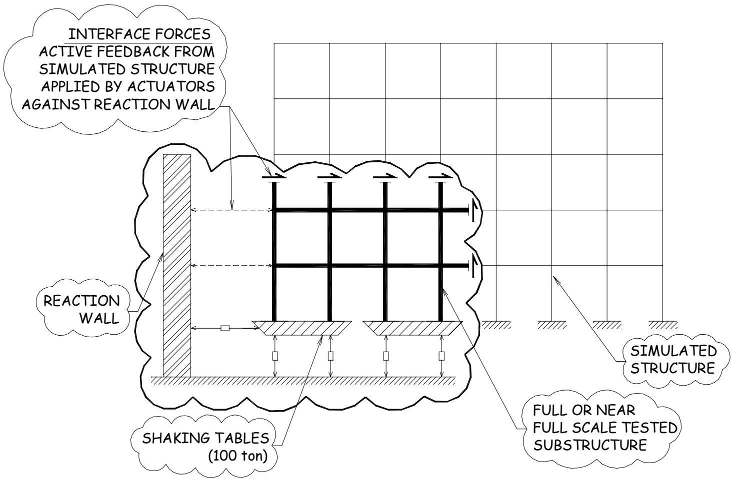

Fig.1. Real-Time Hybrid Seismic Testing System (Substructure Dynamic Testing)

The aforementioned RTSS can also house or interface to a “model-base” developed prior to testing and

UB - Real Time Dynamic Hybrid Testing (RTDHT) Controller (rev.3.1)

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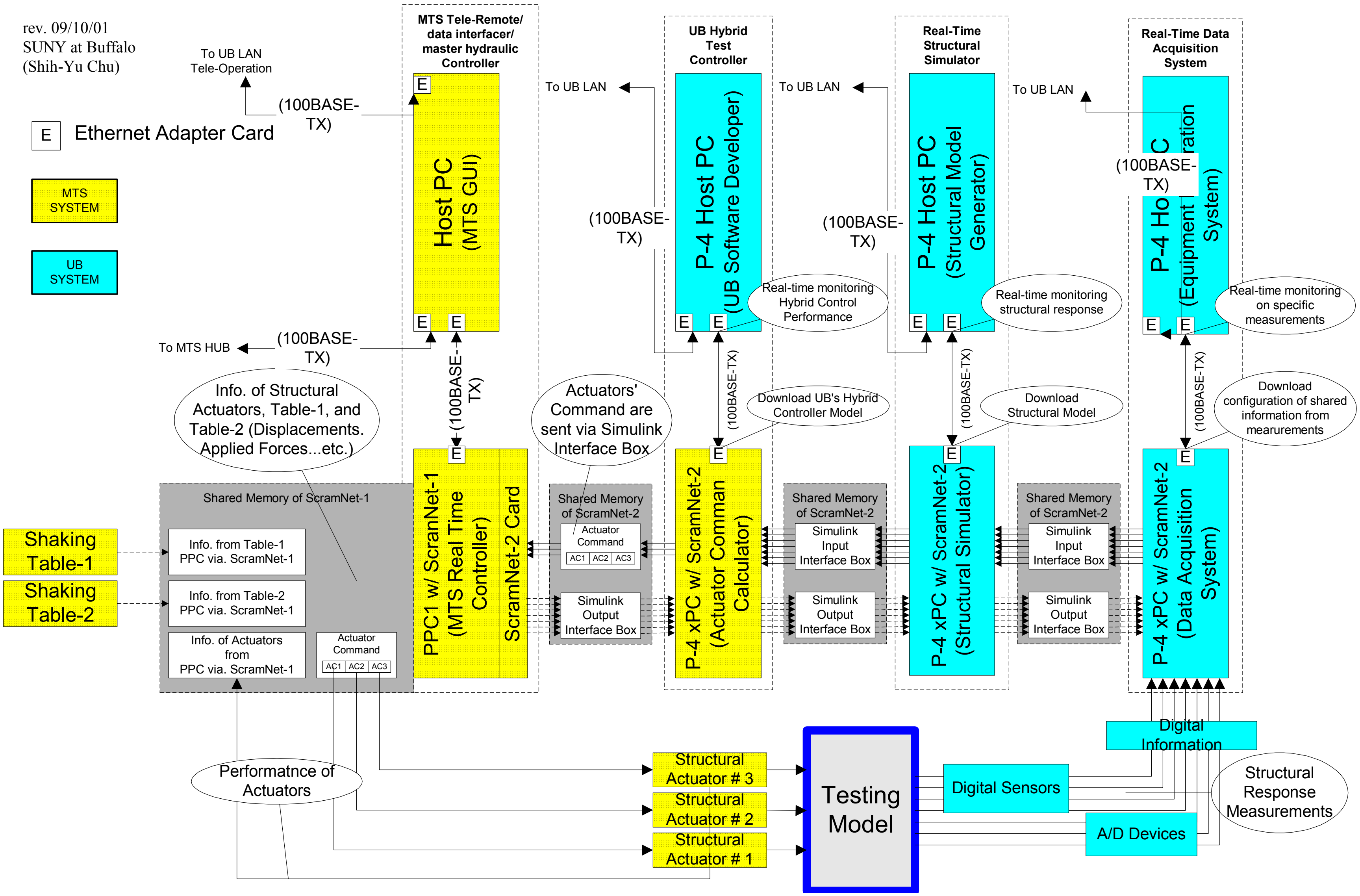


Fig. 2- Real-Time Dynamic Hybrid Testing System - Controller Hardware Architecture

continuously refined with data and information acquired from testing. This "model-base" becomes the learning tool for all users linked through the NEES collaboratory, who can also contribute to its improvement using knowledge from past experimentation or computational efforts, or through real time parallel testing or processing anywhere on the collaboratory. It is expected that each experiment would therefore contribute to the "model-base" which then will be transformed into computational tools for the industry. Hence, platforms such as IDARC, DRAIN, 3DBASIS, OPENSEES, stand-alone or integrated in commercial programs such as LARSA, SAP2000, ABAQUS, would become vehicles for improved modeling and overall structural evaluation.

Substructure Formulation

The substructure testing was developed in the 80's and formulated by numerous researchers (Nakashima 1985, Mahin et al 1985 ., Shing et al, 1985, 1991) In the substructure testing only a smaller part of the whole system is tested. In the further formulation the tested part will be designated as the experimental component, subscripted as ***e***. The remaining part of the structure will be designated as the analytical ***a*** structure. At the interface ***i*** between the substructure and the rest of the structure there will be interaction forces. The equation of motion for the whole structure (see for example Fig.3 showing a shear building) includes components of the experimental substructure, interface and analytical substructure in sub-matrix form:

$$\begin{bmatrix} \mathbf{D}_{ee} & \mathbf{D}_{ee} & \mathbf{0} \\ \mathbf{D}_{ie} & \mathbf{D}_{ii}{}^{e} + \mathbf{D}_{ii}{}^{a} & \mathbf{D}_{ia} \\ \mathbf{0} & \mathbf{D}_{ai} & \mathbf{D}_{aa} \end{bmatrix} \begin{Bmatrix} \mathbf{U}_{e} \\ \mathbf{U}_{i} \\ \mathbf{U}_{a} \end{Bmatrix} = - \begin{bmatrix} \mathbf{M}_{\mathbf{ee}} & \mathbf{M}_{\mathbf{ei}} & \mathbf{0} \\ \mathbf{M}_{\mathbf{ie}} & \mathbf{M}_{\mathbf{ii}}{}^{\mathbf{e}} + \mathbf{M}_{\mathbf{ii}}{}^{\mathbf{a}} & \mathbf{M}_{\mathbf{ia}} \\ \mathbf{0} & \mathbf{M}_{\mathbf{ai}} & \mathbf{M}_{\mathbf{aa}} \end{bmatrix} \ddot{u}_{g} \tag{1}$$

or abbreviated

$$\mathbf{D}\,\mathbf{U} = -\mathbf{M}\,\ddot{u}_{g} \tag{2}$$

where **D** is defined as a dynamic matrix operator, $D_{ij}U_{j} = M_{ij}\ddot{u}_{j} + C_{ij}\dot{u}_{j} + K_{ij}u_{j}$

The forces applied to the degrees of freedom at the interface are given by the second equation in (1):

$$\mathbf{D}_{ie}\mathbf{U}_{e} + \mathbf{D}_{ii}\mathbf{U}_{i} = -\mathbf{M}_{ie}\ddot{u}_{g} - \mathbf{M}_{ii}\ddot{u}_{g} + \mathbf{F}_{in} \tag{3}$$

and the equation of motion of the *substructure* can be written as:

$$\begin{bmatrix} \mathbf{D}_{ee} & \mathbf{D}_{ei} \\ \mathbf{D}_{ie} & \mathbf{D}_{ii}{}^{e} \end{bmatrix} \begin{Bmatrix} \mathbf{U}_{e} \\ \mathbf{U}_{i} \end{Bmatrix} = - \begin{bmatrix} \mathbf{M}_{ee} & \mathbf{M}_{ei} \\ \mathbf{M}_{ie} & \mathbf{M}_{ii}{}^{e} \end{bmatrix} \ddot{u}_{g} + \begin{bmatrix} \mathbf{0} \\ \mathbf{F}_{\mathbf{in}} \end{bmatrix}$$
(4)

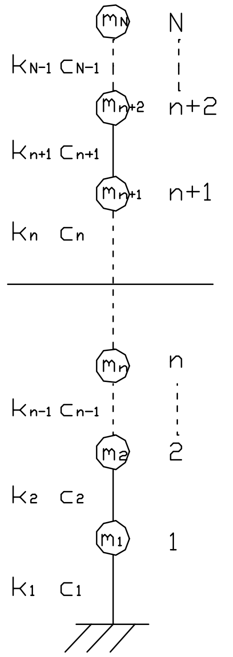


Fig.3 Structure Model

The explicit form of the interface force is:

$$\begin{aligned} \mathbf{F}_{in} &= -\mathbf{D}_{ii}{}^{a}\mathbf{U}_{i} - \mathbf{D}_{ia}\mathbf{U}_{a} - (\mathbf{M}_{ii}{}^{a} + \mathbf{M}_{ia})\ddot{u}_{g} \\ &= -\mathbf{M}_{ii}{}^{a}\ddot{u}_{i} - \mathbf{M}_{ia}\ddot{u}_{a} - \mathbf{C}_{ii}{}^{a}\dot{u}_{i} - \mathbf{C}_{ia}\dot{u}_{a} - \mathbf{K}_{ii}{}^{a}u_{i} - \mathbf{K}_{ia}u_{a} - (\mathbf{M}_{ii}{}^{a} + \mathbf{M}_{ia})\ddot{u}_{g} \end{aligned} \tag{5}$$

The implementation of the interface force requires simultaneous computation of the structure response and a compensation for the structure changes during the generation of the force with a hydraulic system.

***Interface Force Application**:*

The suggested hybrid testing system will use dynamic actuators of large stroke acting against the tested substructure at one end and against large size reaction walls at the other end as shown in Fig 1. The implementation of the force requires the estimate of the forces formulated in Eq. (5) with updated information of the states of the structure and conversion of such estimates into the mechanical physical forces. This is done by hydraulic actuators with digital controllers which must track the desired signals. Due to inherent time delays in the actuators execution process and due to computational delays, it is required to precondition the signals such that the implemented forces will follow the desired values

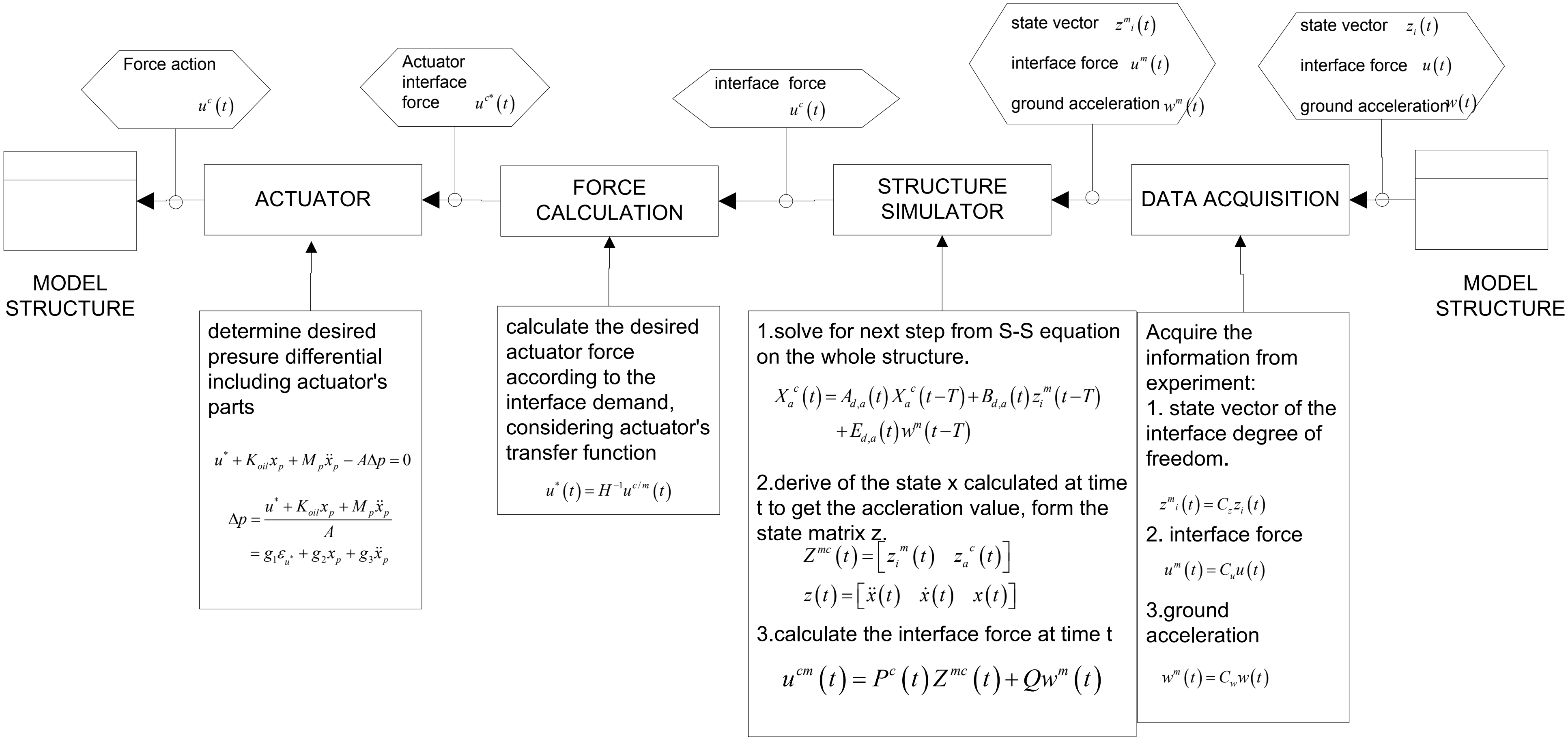
The time domain numerical simulation of structures under dynamic excitation in the civil engineering is usually carried out by using either the modal superposition method (for elastic structures), or by direct integration methods. Appropriate assumptions have to be made in order to predict and calculate the response of the simulated structure. In particular, the direct integration methods utilized in dynamic testing are actually performed step-by-step within every sampling time. Not only the analytical error will be accumulated gradually, but the selection of sampling period will affect the accuracy of this integration process that also limits the testing rate adversely. Moreover, for the testing method suggested herein, the effect of time delay should be compensated in time domain by forecasting the system states either based on the kinematic compensation method or the dynamic compensation method. Owing to the trend of using digital controllers in both experimental and practical applications, it is thus important to adopt a discrete time derivation when performing the time domain analysis. By applying the system's transition matrix derived from the exact solution in a specific sampling period, the integrated response is exact without any assumption that is made in aforementioned traditional methods (Chu et al., 2002). Moreover, many practical issues, such as, multi-sampling rates and time delay can also be taken into the derivation for optimal compensation and performance. Such a technique is shown in the flowchart in Fig 4.

Controller design

In order to minimize the time delay and associated noise, as well as to ensure the robust integrated communication with the new UB dual-table system, the model-base simulator and the control command compensator, high-speed digital controllers and a state-of-the-art network transmission technique are deployed in the UB-NEES laboratory at University at Buffalo.

The controller is designed to allow for separate collection of data form the models structure, separate simulation of the structure behavior with possible identification of the structural properties, separate calculation of the interface forces including preconditioning of the control signals, and separate control implementation of the desired forces using combined force and motion feedback. Such separation is built in the architecture of the controller shown in Fig.2. The link between the separated computers is provided through a shared memory network link (SCRAMNET^{TM}) which is updated frequently (at 1μsec intervals) without interference in the local processing. As such information in each of the components of the network is used when available without waiting for events to occur. The separation allows for the various computing components to be replaced and updated with network high performance computers

The calculation flowchart for the ideal case is shown in Fig. 4. Each component in the hardware system performs an independent computation. A similar computation is performed using however, the information on the delays of the signals from one step to another. The force calculator serves then as an intermediary, which compensate for the delays and predicts the action at the execution stage. The compensation is based on an adaptive algorithm, which compares the desired, and the achieved forces and provides the control gains for the actuators.



determine desired presure differential including actuator's parts

$$u^* + K_{oil}x_p + M_p\ddot{x}_p - A\Delta p = 0$$

$$\Delta p = \frac{u^* + K_{oil}x_p + M_p\ddot{x}_p}{A} = g_1\varepsilon_{u^*} + g_2x_p + g_3\ddot{x}_p$$

calculate the desired actuator force according to the interface demand, considering actuator's transfer function

$$u^*(t) = H^{-1}u^{c/m}(t)$$

1.solve for next step from S-S equation on the whole structure.

$$X_a{}^c(t) = A_{d,a}(t)X_a{}^c(t-T) + B_{d,a}(t)z_i{}^m(t-T) + E_{d,a}(t)w^m(t-T)$$

2.derive of the state x calculated at time t to get the accleration value, form the state matrix z.

$$Z^{mc}(t) = \left[z_i{}^m(t) \quad z_a{}^c(t)\right]$$

$$z(t) = \left[\ddot{x}(t) \quad \dot{x}(t) \quad x(t)\right]$$

3.calculate the interface force at time t

$$u^{cm}(t) = P^c(t)Z^{mc}(t) + Qw^m(t)$$

Acquire the information from experiment:

1. state vector of the interface degree of freedom.

$$z^m{}_i(t) = C_z z_i(t)$$

2. interface force

$$u^m(t) = C_u u(t)$$

3.ground acceleration

$$w^m(t) = C_w w(t)$$

Fig.4 Flow diagram of real time computation (ideal case)

A 3-DOF model-base is used as the reference model to calculate the boundary forces needed to apply on a SDOF substructure installed on the shaking table under earthquake excitation. The achieved measurements on the substructure contain also the model behavior of the full-scale 3DOF system. This flexible module feature allows researchers to implement different kind of compensation algorithms in the real time command compensator. The core inside the model-base RTSS can be further extended to more complex full-scale models associated with adaptive compensation algorithms to achieve the large scale dynamic real time hybrid testing. The presentation will introduce the audience to the computing hardware architecture (see Fig 2) and the computational technique (see Fig 4).

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