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DEVELOPMENTS TOWARDS BROADENING THE APPLICATION RANGE OF REAL-TIME HYBRID SIMULATION

M. S. Günay[1] and K. M. Mosalam[2]

ABSTRACT

This paper reports three individual developments aimed towards broadening the application range of real-time hybrid simulation (RTHS). The first of these developments is a standalone RTHS system which can accommodate integration time steps as small as 1 milisecond. The fast execution feature eliminates the approximations that would be introduced by the application of a predictor-corrector smoothing technique and increases the applicability range of explicit integration methods. The second development is the use of an efficient equation solver in RTHS which reduces computation time. This efficient solver, which decreases the computation time by factorizing the Jacobian of the linear system of equations only once at the beginning of the simulation, is especially beneficial in RTHS which involves analytical substructures with large number of degrees of freedom. The third development is a novel use of a three-variable control (TVC) for RTHS on a shaking table configuration. Although the TVC, which employs velocity and acceleration control in addition to the typical displacement control, is commonly used in conventional shaking table tests, this development is the first application of TVC in RTHS.

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Developments Towards Broadening The Application Range Of Real-Time Hybrid Simulation

M. S. Günay[1] and K. M. Mosalam[2]

ABSTRACT

This paper reports three individual developments aimed towards broadening the application range of real-time hybrid simulation (RTHS). The first of these developments is a standalone RTHS system which can accommodate integration time steps as small as 1 milisecond. The fast execution feature eliminates the approximations that would be introduced by the application of a predictor-corrector smoothing technique and increases the applicability range of explicit integration methods. The second development is the use of an efficient equation solver in RTHS which reduces computation time. This efficient solver, which decreases the computation time by factorizing the Jacobian of the linear system of equations only once at the beginning of the simulation, is especially beneficial in RTHS which involves analytical substructures with large number of degrees of freedom. The third development is a novel use of a three-variable control (TVC) for RTHS on a shaking table configuration. Although the TVC, which employs velocity and acceleration control in addition to the typical displacement control, is commonly used in conventional shaking table tests, this development is the first application of TVC in RTHS.

Introduction

Hybrid simulation (HS) is a testing method for examining the seismic response of structures using a hybrid model comprised of both physical and numerical substructures. Because of the unique feature of the method to combine physical testing with numerical simulations, it provides an opportunity to investigate the seismic response of structures in an efficient and economically feasible manner. It is this feature of the method which made it gain widespread use in recent years.

Hybrid simulation can be divided into three categories as follows: (1) Slow hybrid simulation (SHS) in a discrete actuator configuration, (2) Real-time hybrid simulation (RTHS) in a discrete actuator configuration, and (3) RTHS in a shaking table configuration. In the first category, SHS, the experimental substructure(s) is directly connected to actuator(s), physical mass generally does not exist and the test rate is slower than the computed velocity. Starting from the initiation of the method in [1], considerable amount of research has been conducted on conventional SHS in the last forty years including the works in [2, 3] among others. Second

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category, RTHS, is similar to the first one except that the loading is applied to the experimental substructure(s) at a rate equal to the computed velocity. Conventional HS with slow rates of loading is sufficient for substructure testing in most of the cases where rate effects are not important. However, for rate-dependent materials and devices, such as viscous dampers or friction pendulum bearings, RTHS becomes essential. Dynamic actuators and a digital servo-mechanism have been used by Nakashima et al. [4] as the first progress of RTHS. After the development of actuator-delay compensation methods by Horiuchi et al. [5], research on RTHS gained momentum. Rapid development of computing technologies and control methods increased the number of RTHS research in recent years such as [6, 7] among others. Unlike the first two categories, in the third HS category, i.e. RTHS on a shaking table, the experimental substructure(s) is not connected to actuator(s), but located on shaking table(s). Although conventional shaking table testing is well-established in many laboratories and there is considerable amount of accumulated experience on RTHS in the recent years, research and development on the combination of these two, RTHS on a shaking table, is limited. The use of shaking tables in RTHS similar to the approach presented in this paper, where the analytical substructure represents a lower portion of the hybrid structure, has been reported in [8-9] among others. Shao et al. [10] used a shaking table together with dynamic actuators, where it was possible to model analytical substructures both on top and bottom of the experimental substructure. Recently, Nakata and Stehman [11] proposed a method that allows the modeling of analytical substructures above the experimental substructure where the latter is tested on the shaking table. It should be mentioned that an increase in shaking table RTHS applications is expected in the coming years. This is especially true considering the development of shaking table grids in various laboratories around the world, such as Tongji University or the NEES facility at the University of Nevada, Reno. Günay and Mosalam [12] demonstrated that RTHS on a shaking table configuration can be used as an effective and economical testing method as an alternative to conventional shaking table tests for electric substation equipment.

This paper presents three recent developments on the two RTHS categories mentioned above, i.e. in actuator and shaking table configurations. Details of these three developments are discussed in the subsequent sections.

Development I: Standalone Real Time Hybrid Simulation System

First development is an RTHS system that can accommodate integration time steps as small as 1 milisecond. This system is developed at the Structures Laboratory of the Civil and Environmental Engineering Department of the University of California, Berkeley. The components of the developed RTHS system, namely the shaking table, controller, data acquisition (DAQ) system, and the test specimen (an insulator post of a high voltage vertical switch in an electric substation in this case), are shown in Fig. 1. As indicated in the figure, the DAQ system also represents the computational platform via the digital signal processor (DSP) module. An outline of the communication process between the components of the developed RTHS system is as follows:

1. The computations are conducted on the DSP card (computational platform).
2. The displacement computed by the DSP card is physically transferred to the controller with a standard BNC (Bayonet Neill–Concelman) connector to BNC connector cable.
3. The controller commands the computed displacement to the actuator connected to the uniaxial shaking table.

4. At the completion of the displacement command within the allocated time, that is equal to the integration time step for real-time compatibility, the algorithm proceeds starting from step 1 above for the next time step, using the force feedback acquired by the DAQ system.

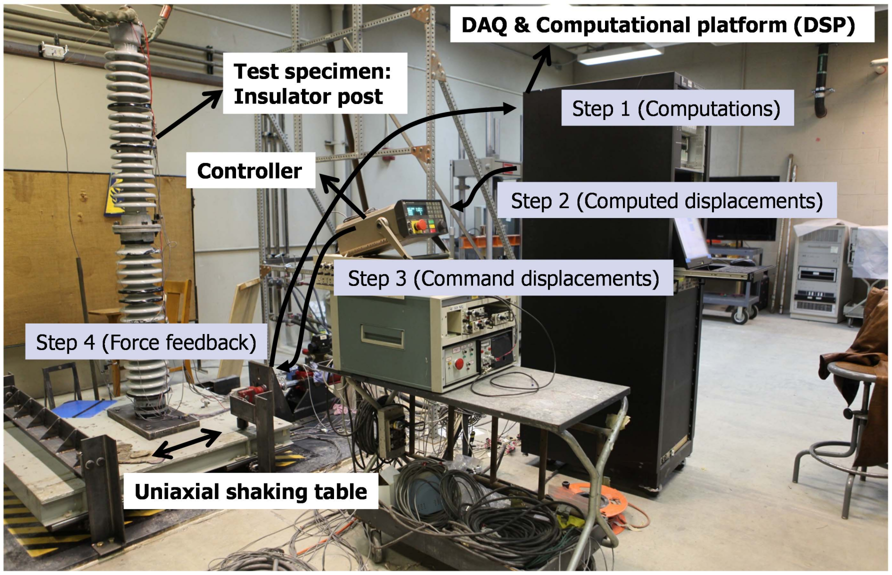


Figure 1. Components of the developed RTHS system and communication between them for Development I

The fast execution time of an integration time step, i.e. completion of all four steps listed above and shown in Fig. 1, as small as 1 milisecond is realized by a combination of the computation power introduced by the DSP card (communication step 1), the physical cable transfer between the computational platform and the controller (communication step 2), and the real-time compatible PID (proportional-integral-derivative) control technology of the controller together with the servo-hydraulic system (communication step 3).

Explicit integration methods are more suitable than the implicit ones for RTHS. Implicit methods require at least two iterations, where the number of iterations is in general dictated by the convergence checks, while the explicit ones require no iterations. It is important to note that the number of iterations, if any, in an integration scheme used in RTHS should be constant and small in order to be able to allocate a fixed and practically applicable time for the completion of each iteration. Moreover, the displacement increments in all iterations of an integration time step should be as close as possible to each other to avoid velocity and acceleration oscillations within the integration time step. Although implicit integration methods with constant number of iterations have been developed for HS, e.g. Schellenberg et al. [13], the small number of iterations has the potential of introducing larger numerical errors since the convergence criteria are not controlling the advancement of the integration in this case. A limiting factor which restricts the applicability of explicit integration is the conditional stability criterion, $\Delta t < T_n / \pi$, where Δt is the integration time step and T_n is the period of the highest mode of vibration of the structure. In that regard, the ability to use integration time steps as small as 1 millisecond within the developed RTHS system allows the use of real-time compatible explicit integration for a broader range of analytical and experimental substructure configurations.

Another advantage introduced by the 1 milisecond integration time step is the assurance of continuous movement of the actuator of the smart shaking table, since a command is sent to the controller in every millisecond. It is noted that the controller operates at a rate (~1 kHz) such that it expects a command every millisecond. Since the developed RTHS system is capable of executing integration time steps equal to a millisecond, the computed displacement is directly sent to the controller as the command. If it were not possible to complete the integration time step in a millisecond, it would not be possible to send the computed displacement as the command. This is attributed to the fact that at the end of the current millisecond, where the next command is expected by the controller, the computed displacement would still be in the determination stage. In this case, a predictor-corrector smoothing algorithm, e.g. Mosqueda et al. [14], would need to be invoked to determine the command to the controller and to assure continuous movement of the actuator, while the computed displacement is still being determined. Although the predictions in these predictor-corrector algorithms can be sufficiently accurate due to the use of high order functions, they can still be considered as approximations introduced to the loading path of the specimen. An example of such an approximation is illustrated in Fig. 2. Such an approximation is eliminated in the developed RTHS system with the ability to execute integration time steps corresponding to the operating rate of the controller.

The developed RTHS system was utilized extensively for RTHS of electrical disconnect switches as reported in [12, 15]. Although the RTHS system is developed and validated for a shaking table configuration, it is worth noting that there are no restrictions that prevent the use of the developed system for RTHS in an actuator configuration.

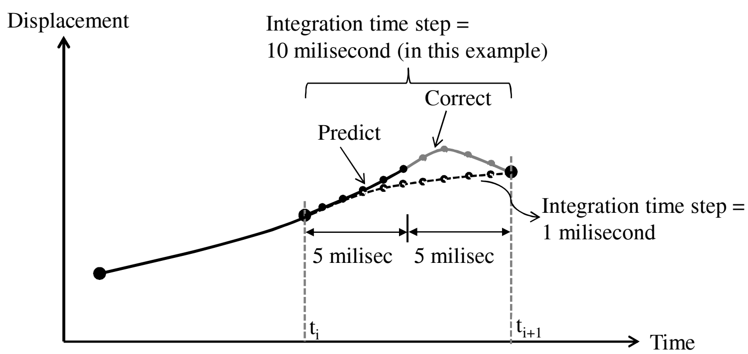


Figure 2. Approximation in the loading path due to a predictor-corrector smoothing algorithm

Development II: An Efficient Equation Solver

A proper computational platform is one of the essential requirements of a HS system. In the first development, the DSP card served as the computational platform, which was an important factor for the RTHS capability to accommodate integration time steps as small as 1 milisecond. Similarly, real-time functioning Simulink models, such as those operating on a workstation that runs Mathworks xPC real-time operating system provide the same fast computational platform option. However, as opposed to the advantage offered by the fast computation capability, these computational platforms require case-specific programming and therefore do not offer a versatile usage. Furthermore, they require a considerable training period to be completed by a novice HS user. The Open System for earthquake engineering simulation (OpenSees) [16] offers relatively slower computations compared to the mentioned fast computational platforms. However, OpenSees possesses the basic features such as being a well-established, versatile, research-oriented, open-source and HS-compatible platform, which makes it one of the most suitable candidates to be utilized as a computational platform in HS. The second development presents an efficient equation solver to increase the computation speed of OpenSees, especially for the RTHS of structures possessing analytical substructures with large number of degrees of freedom (DOF).

The most time consuming part of a time stepping numerical integration method is the solution of the linear system of equations, needed in every time step. This is especially true for a hybrid system with a large number of DOF in the analytical substructure. Therefore, in order to reduce the computation time, the utilized efficient solver seeks to reduce the computation time by reducing the duration of the solution of the linear system of equations. Solution of the linear system of equations requires the coefficient matrix, i.e. the Jacobian matrix, to be factorized. Although the Jacobian matrix is constant and does not change during the full course of integration in some of the numerical integration methods, standard equation solvers execute this factorization for each integration time step regardless of the selection of the integration method, which leads to an unnecessary increase of the computation duration. However, there is a special, efficient solver in OpenSees, defined by the syntax, "system UmfPack -factorOnce", which does this factorization only once at the beginning of the simulation.

The efficient solver is used for the RTHS of the hybrid structure in Fig. 3 which possesses a generic analytical framed substructure with varying number of bays and stories. Fig. 4 compares the computation time per integration time step with the efficient and standard solvers as a function of the number of DOF. It is to be noted that the computation times in this figure are obtained from pure analytical simulations where the experimental substructure is replaced with another analytical column. The number of DOF is varied by changing the number of stories for a fixed number of four bays. Fig. 4 clearly demonstrates the reduction in computation time due to the efficient solver, where it is observed that this efficient solver results in more than 2.5 times reduced computation time compared to the standard solver. It was possible to conduct RTHS of the hybrid structure in Fig. 3 with the efficient solver accurately up to 720 DOF while this number was limited to only 240 DOF with the standard solver.

As mentioned, the Jacobian matrix is not constant during the entire time history for all the integration methods, e.g. in Implicit Newmark which includes the tangent stiffness matrix. Hence, the efficient solver cannot be used together with such integration methods. However, it can be used with commonly used HS-compatible integration methods such as Explicit Newmark [17] or α-Operator-Splitting integration [18].

Development III: Three-Variable Control Implementation

In the third development, an advanced control method, namely the three-variable control (TVC), developed by the MTS Corporation, is implemented in the HS system of the nees@berkeley laboratory for RTHS on a shaking table configuration. Proper displacement tracking may not be adequate for the accuracy of RTHS on a shaking table configuration, because a small displacement error may translate into larger acceleration errors for high frequencies according to the relationship between the pseudo-spectral acceleration ($Sa = \omega^2 Sd$) and the spectral displacement (Sd). If the natural frequency (ω) of a specimen is high, then the force feedback used in the computations will be erroneous since the force feedback of a specimen on a shaking table strongly depends on the acceleration of the shaking table. An example of such phenomenon is shown in Fig. 5, where in Fig. 5(a) it is observed that the feedback displacements satisfactorily follow the command displacements during the full time history with a slight overshoot at the displacement peaks as shown in Fig. 5(b). This slight overshooting of displacements translates into large acceleration differences for periods smaller than 0.4 sec. as shown in the 1% damped response spectra in Fig. 5(c).

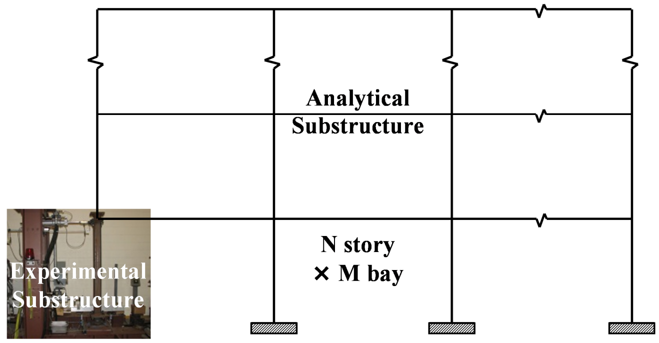


Figure 3. Hybrid structure with varying DOF used in Development II

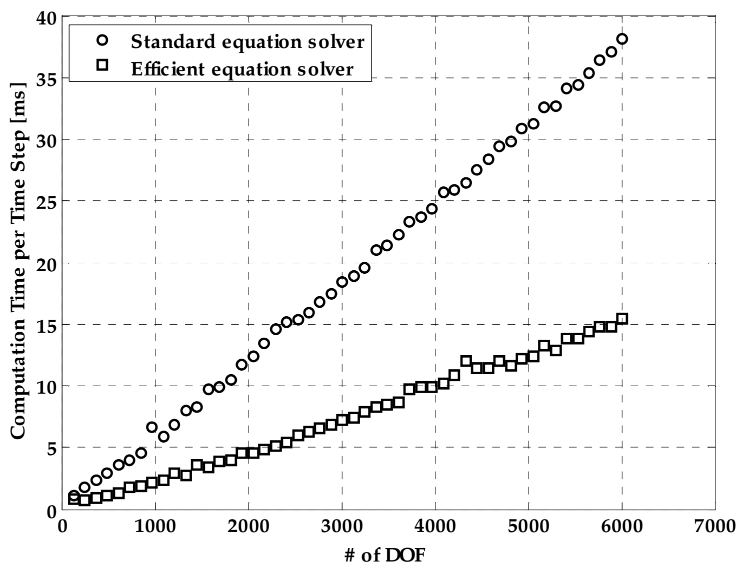
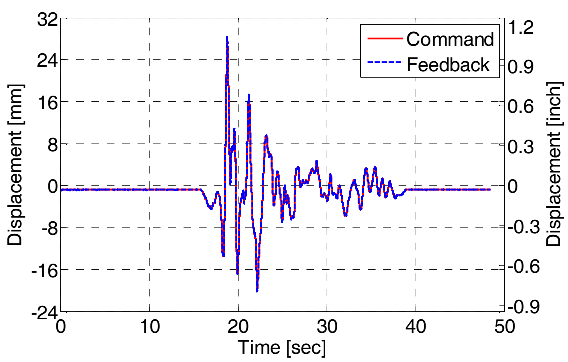
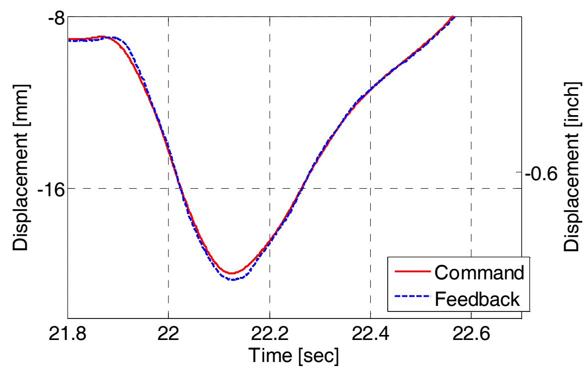


Figure 4. Computation time reduction due to the efficient equation solver

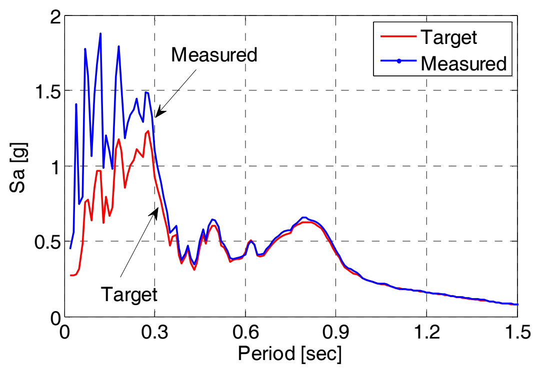
There is an inherent delay in the actuator response, which can be eliminated by using the feed-forward gain offered by a servo-hydraulic controller which does not necessarily offer additional features for a shaking table control. The feed-forward gain is multiplied by the rate of the command, i.e. command velocity, and added to the servo-valve command. This additional valve command minimizes or completely eliminates the time delay. The effectiveness of similar feed-forward error compensation is demonstrated in [15]. However, the feed-forward gain results in overshooting of peak displacements, which can be explained by the fact that the command rate is close to zero around the peak displacements, leading to almost no feed-forward benefit near these regions. It is this same reason that is responsible for the overshooting of displacement peaks in Fig. 5(b) and the corresponding acceleration errors in Fig. 5(c). It is noted that the time delay does not introduce a problem on a conventional shaking table configuration as long as the target displacements and accelerations are realized as intended. However, phase lag induces not only errors but also negative damping which may lead to instability during RTHS, the reasons of which are explained in [14, 19]. Accordingly, there is a need for an advanced control to improve the acceleration response at the high frequencies without sacrificing from the elimination of the time-delay. TVC is decided to be an adequate control method for this purpose. Since the HS controller of the nees@berkeley laboratory is not a shaking table controller, TVC is implemented in this controller for the improvement of RTHS on a shaking table configuration. This implementation is achieved by adopting and modifying the TVC Simulink model provided by MTS to the HS system of nees@berkeley and by using a feature of the controller to bypass the servo-valve control to an outside resource, while maintaining all other controller features. Implementation is not only conducted for HS, but also for a conventional shaking table configuration. Details of the implementation process are not presented herein due to space limitations.



(a) Satisfactory displacement tracking



(b) Slight overshooting of a displacement peak



(c) Acceleration response spectra of target and measured accelerations

Figure 5. Acceleration mismatch at small periods despite satisfactory displacement tracking

TVC is a modified version of state variable control enhanced with additional features. In addition to the conventional displacement feedback, two additional kinematic variables, namely velocity and acceleration, are used in the control process. TVC is currently being utilized for the control of many conventional shaking tables including those in the NEES facilities of University of California at San Diego, University of Nevada at Reno, The University at Buffalo and the PEER shaking table at the University of California, Berkeley. The internal structure of TVC is presented in [20]. A modified version of this scheme, as adopted for the implementation described herein, is shown in Fig. 6 where the adopted scheme consists of four main parts: (1) reference generator, (2) feedback generator, (3) Delta-P stabilization term, and (4) determination of servo-valve command.

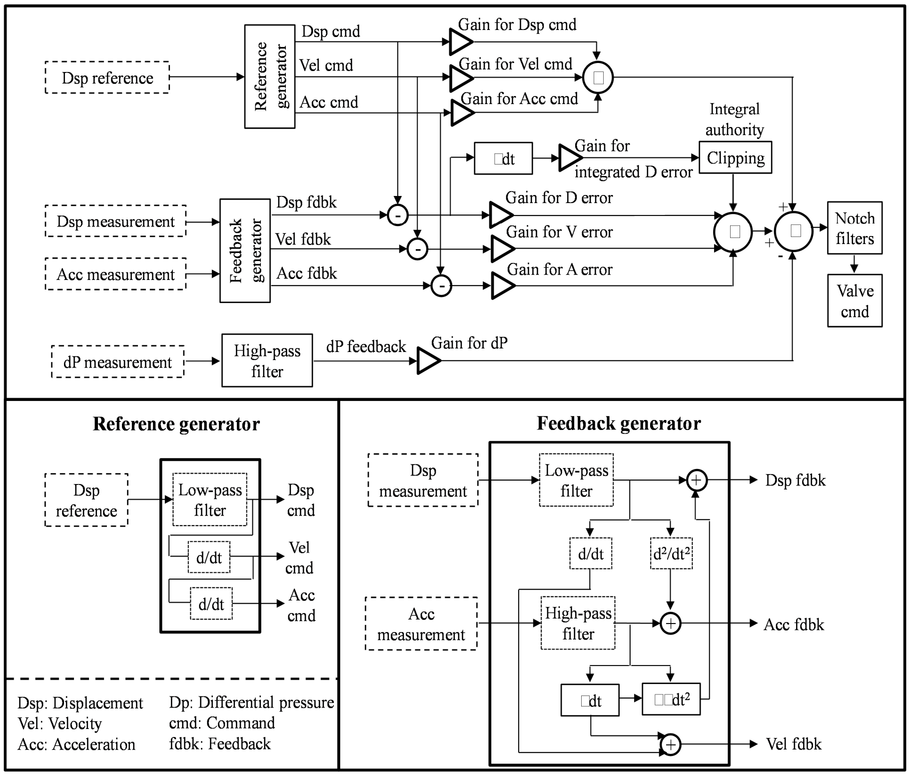
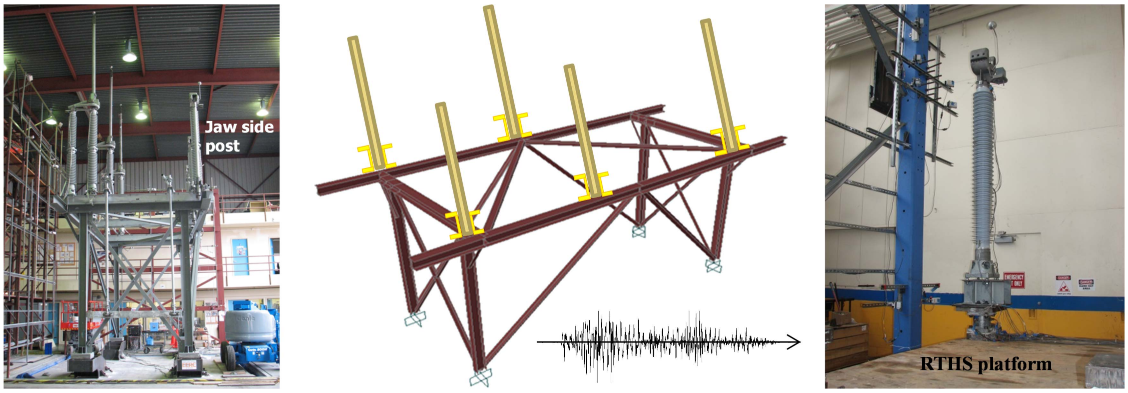


Figure 6. Schematic of TVC as implemented for RTHS in nees@berkeley

After a sufficiently acceptable tuning, the TVC is used in RTHS of 230-kV electrical vertical disconnect switches, Fig. 7(a), where the experimental substructure, Fig. 7(b), is a jaw side post insulator of the disconnect switch and the analytical substructure consists of a 3D model of the steel support structure and the remaining insulators, Fig. 7(c). In addition to the TVC utilization, the conducted RTHS features other novel HS characteristics, first of which is the 3D analytical substructure, where the band-width of the Jacobian matrix increases due to the presence of 12 DOF per element. This situation introduces a computational time challenge in RTHS. In order to overcome this challenge, the efficient solver mentioned in the second development is utilized together with the RTHS-compatible α-Operator-Splitting integration [18]. It is to be noted that it was not possible to use Explicit Newmark integration [17] since the infinite frequency modes introduced by the massless rotational DOF violated the stability criterion.

The ratios of the Sa of accelerations measured on the platform to that of computed accelerations at the top of the support structure, at the corner node where the experimental substructure is attached to the analytical substructure, are plotted in Fig. 8 for the cases of displacement control and TVC. Similar to the case of conventional shaking table configuration, TVC is successful in bringing the measured accelerations closer to the computed ones, which increases the accuracy of RTHS by reducing the force feedback errors. This is also valid at the natural period of the tested insulator post, which is represented with the vertical line in Fig. 8. Although it may be possible to further reduce the measured accelerations with further tuning to bring the above ratios closer to 1.0 in the high frequency range, i.e. for periods smaller than about 0.3 sec, the current results are indeed indicative of the benefits of the TVC, validating the objective of the implementation of TVC in the HS system of the nees@berkeley laboratory.



(a) 230-kV vertical switch (porcelain posts) tested on a shaking table

(b) Analytical substructure of the switch (3D braced steel frame as the support structure + other posts)

(c) Experimental substructure (polymer composite post)

Figure 7. Hybrid model of the electrical disconnect switch tested with RTHS using TVC

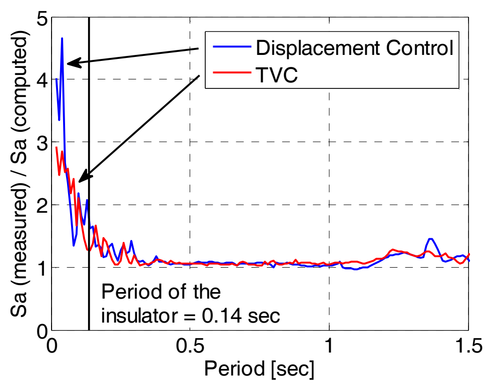


Figure 8. Improvement of the acceleration response in RTHS of disconnect switches due to TVC

Conclusions

This paper presented three recent developments aimed towards broadening the application range of real-time hybrid simulation. As the first development, a standalone RTHS system is developed which can execute integration time steps of 1 milisecond, increasing the applicability range of RTHS compatible Explicit Newmark integration and reducing the potential approximations in the load path. Towards the objective of improvement of the more general and versatile computational platform OpenSees, an efficient linear equation solver is utilized in the second development to decrease computation time. The additional challenge introduced by acceleration control in RTHS on a shaking table configuration is addressed in the third development by the adaptation of the three-variable control.

Acknowledgments

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