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Procedure to Restart an Interrupted Hybrid Simulation: Addendum to PEER Report 2010/103

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ABSTRACT

A hybrid simulation can be intentionally or unintentionally interrupted. This document describes a procedure to restart an interrupted hybrid simulation. The restart of an interrupted hybrid simulation involves restoration of the state of the hybrid model to the state at the beginning of time step at the point at which the interruption occurred (the interrupt time step). Then the hybrid simulation from this point continues and the time steps until the planned simulation break or end occurs. The state of the hybrid model comprises the state of the hybrid simulation integrator (the outer loop), the states of each of the numerical portions (numerical sub-structures) of the model, and the states of each of the physical portions (specimens) of the model. The principal obstacle in restoring these states is that the response of the hybrid model to the applied dynamic excitation depends on the excitation history, and the potential geometric and material nonlinear response of the hybrid model components.

The states of the integrator and the numerical portions of the hybrid model can be restored by repeating the simulation from the beginning. Repeating the simulation using numerical models of the physical portions of the hybrid model can closely restore the state of the numerical portion of the hybrid model to the interrupt state. This simulation should be prepared by developing shadow numerical models of the specimens and, if necessary, the test set up, including the servo-hydraulic actuation systems. These shadow numerical models should be calibrated using any data available from the original simulation to simulate, as closely as possible, the response of the specimens up to the interrupt point. The interrupt state of the specimens can be approximated by bringing the specimens close to the interrupt state following the trajectory it took through its state space during several time steps before the interruption occurred.

The hybrid model has to be re-constituted at the restart point. The shadow numerical models should be removed from the hybrid model and replaced by the interfaces to the physical portions of the hybrid model while maintaining the restart point states. Another aspect of re-constitution of the hybrid model is the transfer of actuator servo-loop control signal generation from the software used to move the physical portions of the hybrid model to the restart point to the hybrid simulation control loops, namely, the middle predictor-corrector loop. The objective is to avoid a sudden change in the control signal and a sudden motion of the actuators. To do this, the hybrid simulation integrator and predictor-corrector loops must obtain the measured force and deformation state of the physical portions of the hybrid model from the servo-loop controllers. Those values are then used as the initial state data for the physical portions of the model to generate the trajectory between the restart point and the next target state of the model.

Restart of a hybrid simulation is a tedious, sensitive process that needs to be carefully planned and executed. Although there are many ways to restart a hybrid simulation, the investigation of the hybrid simulation restart problems and strategies presented in this document provides a basis for design of an actual restart procedure. The restart procedure utilized by Terzic and Stojadinovic (2010) is provided as an example. This procedure is specific to the MTS STS servo-hydraulic controller and the versions of OpenSees and OpenFrecso used at that time at the *nees@berkeley* Equipment Site, and needs to be modified to suite the conditions of the specific simulation.

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1 Introduction

This document describes a procedure for restarting a hybrid simulation that has been intentionally or unintentionally interrupted. Hybrid simulation is a method to compute the response of a prototype structure to dynamic excitation using a hybrid model. A hybrid model comprises numerical and physical substructures. In this document we assume that a hybrid simulation is implemented using a three-loop structure comprising an outer-most hybrid simulation time-step integration loop, an intermediate synchronization (predictor-corrector) loop, and an innermost servo-hydraulic control loop.

Interruptions are events characterized by a discontinuity in the command generated by the outer-most loop indicating the next target state for the physical portions of the hybrid model. The duration of the command signal interruption is longer than the duration of the slow-down phase of the predictor-corrector loop such that the hybrid simulation has to be restarted using other means. The principal consequence of the command signal discontinuity is a loss of the state of the servo-hydraulic actuation system for the physical portion(s) of the hybrid model. This means that either the force or the displacement or both of the actuators change beyond the error tolerance levels after the interruption. An additional consequence is an erroneous determination of the state of the entire hybrid model based on the data acquired from the post-interruption state of the physical portion(s) of the model.

The interruption events are classified into two groups: (1) planned interruptions due to a phased execution of a hybrid simulation; and (2) unintended interruptions due to mechanical or electrical failures of the pumps, actuators, or the servo-hydraulic controllers, instability of the test setup, incorrect calibrations or failures of the data acquisition systems, failures of the digital signal processors hosting the predictor-corrector loops, failures of the computers hosting the numerical portion of the hybrid model, or interruptions in the communication between the parts of the hybrid model. A typical unintended interruption is one where the servo-hydraulic controller displacement or force limits are triggered due to an unanticipated response of the physical portion of the hybrid model. This typically leads to an interrupt of the hydraulic power at the hydraulic manifold i.e. a sudden drop of pressure in the servo hydraulic-system.

Behavior of the physical portion of the hybrid model (the specimen) depends on the details of the servo-hydraulic installation. If the check valves are present (and extremely responsive), the actuators will lock and maintain the attained displacement and force. In a more typical installation, the actuators will lose the ability to resist the potential energy accumulated in the specimen before the interruption and will allow the specimen to move towards a state of minimal potential energy (post-interruption at-rest state). This state is usually different from the state the specimen was in when interruption occurred, unless the interruption was planned to occur exactly at the state when the physical portions of the hybrid model are at-rest. Furthermore, this state is usually different from the initial state of the specimen at the beginning of the simulation, unless the specimen response during the hybrid simulation before the interruption occurred was in the elastic response range within acceptable tolerances. Moreover, boundary conditions imposed on the specimen that are not controlled by the hybrid simulation, such as constant axial forces applied by independent actuators or physical out-of-plane motion restrainers, may induce additional forces in the specimen at-rest state. Regardless of the nature of test interruption, common laboratory safety protocols require that actuator forces are as close as possible to zero before any other work can be done on the specimen or the test set up. Restarting the hydraulic system at low pressure and manually moving the actuators until the forces they carry are sufficiently low is standard protocol.

Behavior of the numerical portion of the hybrid model also depends on implementation details. If the intermediate hybrid simulation loop can receive a hydraulic power interrupt signal from the innermost servo-control loop, it can be programmed to stop the update of the state of the numerical portion of the hybrid model, thereby preserving the state of the model at the beginning of the time step when the interruption occurred. More typically, however, the state of the hybrid model will be incorrectly updated using the state of the interrupted physical portions of the model, the incorrect state targets for the next time step will be computed, and the outer-most integrator loop will be left in the "wait" state, expecting the physical portions of the hybrid model to attain the (incorrect) target states.

2 Restart Problems and Solution Strategies

The restart of an interrupted hybrid simulation involves restoration of the state of the hybrid model to the state it had at the beginning of time step at the point at which the interruption occurred (the interrupt time step). Then the hybrid simulation from this point continues and the time steps until the planned simulation break or end occurs. The state of the hybrid model comprises the state of the hybrid simulation integrator (the outer loop), the states of each of the numerical portions (numerical sub-structures) of the model, and the states of each of the physical portions (specimens) of the model. The principal obstacle in restoring these states is that the response of the hybrid model to the applied dynamic excitation depends on the excitation history, and the potential geometric and material nonlinear response of the hybrid model components.

The states of the physical portions of the hybrid model are physical: they depend on response history the specimens experienced during the hybrid simulation before it was interrupted. Typically, a specimen will be in a state other than the virgin state at the beginning of the simulation, most often due to damage induced during the simulation, but also due to handling of the specimen while the causes of the interruption are investigated. Furthermore, the directions of specimen deformation and the rates of specimen internal damage mechanisms in the post-interruption time step depend on the path and the rates taken by the specimen through its state space before the interruption occurred. Moreover, the state of the test set up—regarding the oil pressures and the displacements and velocities of the actuators—also depends on the state history the test set up experienced during the hybrid simulation before it was interrupted.

Therefore, the first problem in restarting an interrupted hybrid simulation is how to restore the states of the physical portions of the hybrid model. This problem can be correctly solved only if the responses of the specimens were entirely in their elastic response ranges before the interruption occurred. Typically, one or more of the specimens suffer irreversible damage. If this occurs, it is impossible to accurately restore a specimen to the state it had before simulation interruption. It is, however, possible to approximate the interrupted state by bringing the specimen close to the interrupted state following, as closely as possible, the trajectory it took through its state space during several time steps before the interruption occurred. The process of moving the specimen from its at-rest position (where it was left for safety reasons) to the approximately restored state position should be conducted such that the specimen is restored to the displacement state space to handle potentially nonlinear response. The trajectory to take the specimen from the at-rest state to the interrupted state should be programmed using smooth (spline, for example) interpolation between the at-rest state and the interrupt state through several states that immediately preceded the interrupt state. Such approximations should enable the specimen to arrive at the interrupted state from the same direction and at the same rate it did just before the original simulation was interrupted.

The state of the integrator and the states of the numerical models are digital. If such data is available, they can be restored from the state data recorded at the beginning of the interruption time step. If this data is not available, the states of the integrator and the numerical portions of the hybrid model must be restored by repeating the simulation from the beginning. However, the simulation cannot be readily repeated because the physical portions of the hybrid model that participated in the original simulation have likely incurred damage and are not in their virgin state. Therefore, the second problem in restarting an interrupted simulation is how to restore the numerical portion of the hybrid model.

Repeating the simulation using numerical models of the physical portions of the hybrid model can closely restore the state of the numerical portion of the hybrid model to the interrupt state. This simulation should be prepared by developing shadow numerical models of the specimens and, if necessary, the test set up including the servo-hydraulic actuation systems. These shadow numerical models should be calibrated using any data available from the original simulation to simulate, as closely as possible, the response of the specimens up to the interrupt point. Then, the shadow models should be integrated with the numerical portions of the original hybrid model, and the simulation re-run from the start up to the interrupt time-step.

Using the strategies proposed above, the physical and the numerical portion of the hybrid model can be restored (as closely as possible) to the state they attained at the interrupt point (i.e., the beginning of the time step when the interrupt occurred in the original hybrid simulation). These restart states of the physical and the numerical portions of the hybrid model are not necessarily the same because the physical and the numerical portions of the model were brought to the restart point separately. Thus, an error will be introduced into the hybrid model at the restart point, which is manifested by differences in the displacements and forces at the interface between the physical and numerical models. The difference in forces will cause an equilibrium error in the hybrid model manifested as a set of additional external impulse forces at the interfaces between the physical and the numerical portions of the hybrid model applied at the restart point. The differences in displacements represent discontinuities in the hybrid model that have to be closed. The closure will be accomplished by deforming the numerical or the physical portions of the hybrid model such that the displacements at the interfaces between the two portions of the hybrid model become the same. This deformation will introduce additional potential energy into the hybrid model. Therefore, two issues remain: how to re-constitute the hybrid model at the restart point, and how to continue the simulation after the restart point.

The hybrid model has to be re-constituted at the restart point. The shadow numerical models should be removed from the hybrid model and replaced by the interfaces to the physical portions of the hybrid model while maintaining the restart point states. This means that the actuation of the physical portions of the model must be paused and the state of the physical portion of the hybrid model held during the time needed to replace the shadow numerical models with the interfaces to the physical models. The hybrid model integrator will then have access to the state of the physical portions of the hybrid model (instead of the state of the shadow numerical models). Holding the physical portions of the model in a constant state for a longer period of time may be impossible because of creep deformation of the specimens and leakage of oil across the servo-valves in the actuators. Thus, to avoid introducing further state errors, a strategy to maintain the forces and displacements on the specimen while the hybrid model is re-constituted must be developed.

Another aspect of re-constitution of the hybrid model is the transfer of actuator servo-loop control signal generation from the software used to move the physical portions of the hybrid model to the restart point to the hybrid simulation control loops, namely, the middle predictor-corrector loop. The objective is to avoid a sudden change in the control signal and a sudden motion of the actuators. To do this, the hybrid simulation integrator and predictor-corrector loops must acquire the measured force and deformation state of the physical portions of the hybrid model from the servo-loop controllers. These values are then used as the initial state data for the physical portions of the model to generate the trajectory between the restart point and the next target state of the model. Thereby, the servo-hydraulic control loop error at the point when control is transferred to the hybrid simulation system will be zero or minimal.

Next, the hybrid model integrator should be used to compute the target state for the hybrid model at the next time step using the restart states of the numerical and the physical portions of the hybrid model. Following this approach, the discontinuity in the hybrid model will be closed at the end of the restart step, introducing additional potential energy into the model that did not exist in the original simulation. In addition, the equilibrium error at the restart state will be included in the model as a set of external impulse forces that did not exist in the original simulation. Thus, the response of the hybrid model will be changed at the restart point. In addition, the effect of these errors at the final outcome of the hybrid simulation can be simulated using the shadow numerical models. The goal of such simulations is to evaluate the largest acceptable magnitude of force and displacement errors at the restart point.

Finally, the reconstituted hybrid model is moved to the target state at the end of the restart time step. The numerical portions of the model will update their state using numerical integration procedures. The physical portions of the model will move from the restart state at the beginning of the restart time step to the target state at the end of the restart time step using a smooth trajectory generated by the predictor-corrector algorithm of the intermediate hybrid simulation loop. Once both the physical and the numerical models have attained their states at the end of the restart step, the hybrid simulation integrator will use this state and excitation data to compute the hybrid model target state at the end of the next time step and, thus, continue the restarted hybrid simulation.

3 A Restart Procedure

There are many possible ways to restart an interrupted hybrid simulation following the approach outlined above. The procedure proposed in this document had been used to restart a hybrid simulation of a seismic response of a bridge conducted by the authors [Terzic and Stojadinovic 2010]. In this hybrid simulation the response of a typical California overpass bridge to severe ground shaking was investigated. The physical portion of the model—a single column specimen—was actuated with five actuators, four of which were controlled using the hybrid simulation algorithm and the fifth was controlled in an independent closed loop to maintain a constant axial force on the specimen. Due to an error in the experimental set up (the result of an erroneous calibration of the load cell of one of hybrid simulation controlled actuators), the simulation was aborted at the time the physical portion of the hybrid model was already damaged. The state of the physical portion of the model was lost because a limit-state interrupt in the servo-hydraulic controller was triggered (based on a fault force reading), which automatically cut the hydraulic power at the manifold. In addition, the specimen was further manipulated to detach, inspect, recalibrate, and re-attach the actuators. The state of the numerical portion of the model changed because the model updated using the state of the specimen measured after the loss of hydraulic power.

The numerical portion of the hybrid model and the hybrid simulation integrator were instantiated in OpenSees [McKenna 2004]. OpenFresco middleware [Schellenberg 2009] was used as the interface between the numerical and physical portions of the hybrid model. The predictor-corrector hybrid simulation loop was instantiated on a digital signal processor programmed within the OpenFresco environment. The servo-hydraulic control loops were implemented using the MTS STS servo-hydraulic controller.

The first restart problem, restoring the state of the specimen to the configuration before the interrupt occurred, was solved by using the ability of the MTS controller to move the hydraulics through a predefine set of displacement-controlled states. A smooth state trajectory from the at-rest state of the specimen to the interrupted state was computed using second- and third-order Lagrange polynomials. A total of 16 states preceding the interrupt point were used to ensure that the specimen arrived at the interrupted state from the same direction as in the original hybrid simulation, and that the at-rest state of the specimen was not too far from the first of the 16 pre-interrupt states. The state trajectory was computed on-line using the data on the at-rest state of the specimen acquired from the servo-hydraulic controller at the time the hydraulic pressure was turned to a low level to minimize the control loop error at the start of the motion. The trajectory was then recorded in a file (the “player” file) and made available to the MTS controller to execute. Note that the displacement transducers of actuators typically have nonzero readings at the beginning of the hybrid simulation. These initial readings as well as readings at the interrupt and at-rest points had to be recorded and used in creating the player file. Once the specimen was brought to the interrupted state, it was held there by the control system in displacement control until restart.

The second restart problem, restoring the state of the numerical portion of the hybrid model and the hybrid simulation integrator to the interrupted state, was solved by developing a shadow numerical model of the specimen. This model was made using the force-based fiber-section beam-column element in OpenSees. The model was calibrated using the data from the original hybrid simulation recorded up to the interrupted point (with a correction for the forces measured by the miss-calibrated load cell). This shadow model of the specimen was used to constitute an all-numerical model of the prototype structure. This model was made in OpenSees; the option to use OpenFresco to do the same task was not used. The response of the all-numerical model to the same ground motion used in the original hybrid simulation was computed using the same time steps up to the interrupted time step. The state of the hybrid model was recorded and held.

The third restart problem, re-constitution of the hybrid model at the restart point, was accomplished in two steps. First, a procedure to replace the shadow model of the specimen with the OpenFresco interface to the physical specimen was executed in OpenSees. The code to do this task is shown in Figure 3.1.

```
set points 2000; # number of analysis steps
set  n 562; # break point
for { set i 1 } { $i < $points } { incr i } {
    if { $i == [expr $n+1] } {
        remove element 12002; #the shadow specimen element
        remove loadPattern 12001; #load pattern of element 12002
        remove recorder 5; #recorder of element 12002
        puts "element 12002 removed"
        expSite RemoteSite 1 "127.0.0.1" 8090; # setup experimental site
        expElement beamColumn 12004  10120  12002 10 -site 1  -initStif 9009910.25449507 0 0 0/
        0 0 0 422339.543179456 -1609113.65951373 0 0 0 0 -1609113.65951373 8174297.39032974 0 0/
        0 0 0 0 422339.543179456 1609113.65951373 0 0 0 0 1609113.65951373 8174297.39032974 0 0/
        0 0 0 0 1777021.17181081; # define experimental element
        puts "element 12004 added"
    }
}
```

Figure 3.1 OpenSees code for replacing the shadow model of a specimen with the OpenFresco interface to the physical specimen.

Second, the OpenFresco ExperimentalSetup subclass that provides the implementations for the experimental set up was modified to enable using the state of the specimen measured at the restart point to offset the state of the specimen. Two offsets were defined within ExperimentalSetup subclass. The first offset was applied on experimental beam-column element displacements that were zero at the restart point and then shifted its state to the state of the specimen measured at the restart point. The second offset was applied on command displacements of actuators to assure the first command sent to the MTS servo-controller was calculated relative to zero. This made it possible for the MTS servo-controller to smoothly restart the hybrid simulation. The modified instance of the ExperimentalSetup OpenFresco subclass is available at the nees@berkeley Equipment Site software library.

The fourth restart problem, smooth continuation of the hybrid simulation from the restart point, was accomplished in two ways. First, the calibration of the shadow numerical model for the specimen and the restoration of the interrupted state of the physical specimens were done such that the state of the numerical portion of the hybrid model was very close to the state of the specimen at the restart point. This ensured that the errors induced by the difference in forces and displacements at the interface degrees of freedom were acceptably small. Second, to insure smooth motion of the specimen during the restart time step, the D3D3 OpenFresco predictor-corrector algorithm was used to instantiate the predictor-corrector loop. This predictor-corrector used third-order Lagrange polynomials based on the target state of the specimen and the states of the specimen in three previous time-steps (the restart point and the ones before it) to generate a smooth path through the restart time step (from the restart state to the target state at the end of the restart time step).

The procedure used by Terzic and Stojadinovic [2010] is summarized as follows:

1. Record the state of the hybrid simulation integrator (e.g., time step of analysis), numerical portion of the hybrid model and the specimen at the interrupt point.
2. Unload the specimen manually to assure zero forces in actuators.
3. Identify and repair the flaw that caused the interrupt. This may involve removing and re-attaching actuators, causing changes in the state of the specimen. The at-rest state of the specimen after actuator re-attachment is recorded.
4. Develop and calibrate the shadow model of the specimen.
5. Prepare a player file generator.
6. Recompile OpenFresco using the restart version of the *ExperimentalSetup* subclass. Compile and load the D3D3 predictor-corrector on the xPC.
7. Conduct the restart step:
    a. Turn the hydraulic power on and apply the specimen axial load using an independent controller (this step is specific to the test setup used by Terzic and Stojadinovic [2010].
    b. Record the at-rest state of the specimen, generate the player file, and move the specimen from the at-rest state to the restart state using the MTS servo-hydraulic controller.
    c. Run the all-numerical hybrid simulation up to the interrupt step to bring the numerical portion of the hybrid model to the restart state.
    d. Replace the shadow specimen numerical model with the OpenFresco interface to the physical specimen, the experimental element.
    e. Using the restart state as the benchmark, the hybrid controller computes the target state at the end of the restart time step.
    f. Execute an OpenSees state update to move the numerical portion of the hybrid model and the specimen to the end of the restart time step.
8. Continue the hybrid simulation until its planned end.

4 Conclusions

Restart of a hybrid simulation is a tedious and sensitive process that needs to be carefully planned and executed. Although there are many ways to restart a hybrid simulation, the investigation of the hybrid simulation restart problems and strategies presented in this document provides a basis for design of an actual restart procedure. The restart procedure utilized by Terzic and Stojadinovic [2010] is provided as an example. This procedure is specific to the MTS STS servo-hydraulic controller and the versions of OpenSees and OpenFrecso used at that time at the *nees@berkeley* Equipment Site and needs to be modified to suite the conditions of the specific simulation.

The quality of the restarted hybrid simulation, measured by the difference between the original and the restarted simulation, depends on the errors induced at the restart step and the changes in the physical specimen that occurred during the interruption, which might affect its response in the remainder of the restarted hybrid simulation. Further research is needed in three areas:

1. Investigation and quantification of the restart state errors to develop a set of restart criteria governing a tolerable difference between the restart states of the physical and numerical portions of the hybrid model.
2. Fundamental investigation into how changes in the state of the specimen during the interruption affect its response during the restarted simulation.
3. Guidelines for design and calibration of the shadow numerical models for the physical portions of the hybrid model.

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