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Stability Anaysis of Real-time Hybrid Simulation for a Multi-story Structure Considering Time-delay of Hydrolic Actuator

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ABSTRACT: Real-Time Hybrid Simulation (RTHS) is a kind of simulation in which an experiment part of a structure tested within the real-time simulation of its other parts. In this article, a building with multi-story structure divided into numerical and experimental substructures and the vibration behavior of experiment story studied among the numerical simulation of other stories. To apply the effect of static and inertial forces produced by the other stories to the experimental story, an electrohydraulic actuator is used. The dynamic of the electrohydraulic actuator can be estimated by pure time-delay and this delay in the loop of simulation can reduce accuracy and cause the system instability. Therefore, Delayed Differential Equation (DDE) used to determine the critical time-delay depending on the system parameters. The results of simulation show the effect of non-dimensional parameters and time-delay in stability margin of hybrid simulation.

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1-Introduction

The Real-Time Hybrid Simulation (RTHS) technology is a powerful and economic experimental approach that provides a virtual environment to address the test of a structure in real dynamic conditions and establish a better understanding for verification by engineers. Using this method, the critical parts of a structure for which there is no accurate and trustworthy model, is evaluated and tested among the numerical simulation of other parts of the structure [1]. This simulation requires transfer systems in order to connect the experimental part to the simulated part. In order to have a more accurate simulation, the added dynamic effect from transfer systems is needed to be mitigated. This simulation consists two parts; the first part includes the experimental structure and the other part is related to the mathematic model of the other parts of the structure. Force transfer between these two parts is done through the hydraulic actuators and the shake-table; however, the displacement and velocity produced by the experimental structure are measured using the sensors and are sent to the simulator. Regarding that, here the system has just a small damping; the time-delay produced by the hydraulic actuator can have a great effect on the simulation stability. In order to achieve a stable and accurate hybrid simulation, an appropriate understanding of the different parameters effect in that hybrid simulation is required. In this article, the time-delay effect produced by the hydraulic actuator in hybrid simulation of a multi-story structure building addressed using delayed differential equation. In addition, the effect of non-dimensional parameters studied in the simulation stability considering time-delay. So far, different methods are presented by the researchers to reduce and compensate the actuators dynamic effect in RTHS, including polynomial extrapolation [2-4], Smith prediction [5], emulator-based control [6] and so on.

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2. Methodology

A 3-story building shown in Figure 1 is considered as a sample and the purpose is to test the structure of 2nd story in reality among the simulation of the other stories movement.

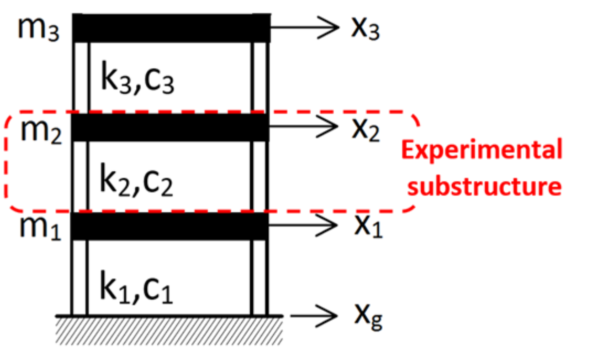

Figure 1. Three-story building model and experimental substructure

Regarding just the horizontal movement of the structure, equations describing the vibration behavior of the structure are derived.

Depending on the choice of the experimental stories, the applied force on that story can be considered with time-delay. For example, if the 2nd story is chosen as an experiment substructure, it will be necessary to simulate the static and inertial forces produced by the 1st and 3rd stories movement in numerical form and then will be applied on the 2nd story using the hydraulic actuator. Considering the hydraulic actuator time-delay effect (τ) in applying the static and inertial forces on the 2nd floor structure and ignoring the sensors time-delays, the governing differential equations can be presented in the form of delayed differential equations. Figure 2 demonstrates the general scheme of hybrid simulation for testing the 2nd story structure of a 3-story building.

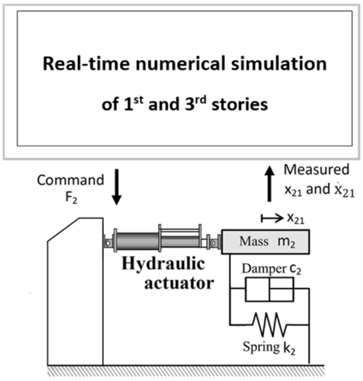

Figure 2. Schematic of RTHS for testing the 2nd story of a 3-story building

In order to study the stability of RTHS of the experimental substructure, the method of DDE is employed to model substructure system and the corresponding characteristic equation is used to analyze and derive the stability region of the simulation depends on the actuator time-delay.

3. Results and Discussion

The hydraulic actuator effect is considered as a fixed time-delay (τ) and effect of different parameters on the stability region of the system will be studied. According to the 6-dimentional state space model of the system, the characteristics equation of the system has 6 complex roots those are symmetric relative to real axis. In the s-plane, the imaginary axis shows the stability boundary and system instability; this means if the roots are on the left-hand side of the s-plane, the system is stable and if they are on the right-hand side, the system is unstable. Figure 3 demonstrates the roots of the characteristics equation in the s-plane. The root locus, due to the actuator time-delay, shows that by increasing the time-delay in range of $0 < \tau < 0.03$sec, a pair of roots move towards the right hand of the s-plane and cross the imaginary axis. Figure 4 illustrates the real parts of the roots versus the actuator time-delay and shows the instability of the system in $\tau = 0.012$ sec. This means if the hydraulic actuator has a time-delay greater than 0.012 sec in applying the force, then the hybrid simulation will be unstable.

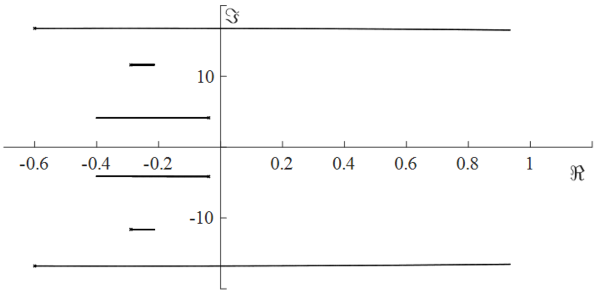

Figure 3. Root locus according to actuator time-delay

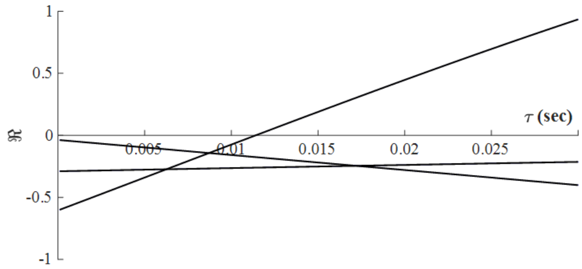

Figure 4. Real part of root locus according to actuator time-delay

Considering the same damping ratio and frequency for all stories, system stability studied again due to the change of system damping ratios and frequencies. As shown in Figure 5, the allowable range of actuator time-delay is reduced when the frequencies are increased or damping ratios are decreased.

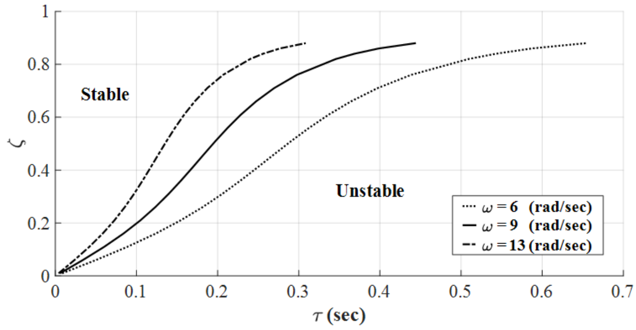

Figure 5. Stability margin considering the same damping ratios and frequencies for all stories (ς1= ς2= ς3 , ω1= ω2= ω3) in several frequencies

4. Conclusions

The stability of real-time hybrid simulation was analyzed using delayed differential equation for a three-story structure. Regarding that a hydraulic actuator was used to apply both static and inertial forces, the effects of actuator time-delay in hybrid simulation stability was studied for different parameters of the structure. The effects of parameters such as damping ratios and frequencies were demonstrated. The results showed the limiting role of the second story in high frequencies and the limiting role of the third story in low frequencies and it was observed that the third story damping ratio makes more severe ranges for stability region. Considering the same damping ratios and frequencies for all stories, system stability studied again due to the change of system damping ratios and frequencies. The allowable range of actuator time-delay was reduced when the frequencies are increased or damping ratios are decreased.

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