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Stability Analysis of Real-Time Hybrid Simulation with a Tuned Liquid Damper

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ABSTRACT: Real-time hybrid simulation (RTHS) is a form of testing where the physical component of structure communicate with numerical model which simulates the behavior of the rest of the structure. Interface forces between the experimental and computational substructure are imposed by an actuator. The resulting displacement and velocity of the experimental substructure are fed back to the computational engine to determine the interface forces applied to the computational and experimental substructures for the next time step. In this paper, the RTHS technique is used to conduct experiments with a numerically simulated structure and physically tested tuned liquid damper (TLD). One very important factor which causes instability in RTHS is the actuator's inability to perform the commands from the simulator in real-time. In RTHS, an actuator dynamic is approximated by a pure time-delay, and the time-delay in the closed loop system causes inaccuracy results or even instability. Therefore, Delayed Differential Equation (DDE) is used to determine the critical time-delays depending on the TLD parameters. Then, the compound stability condition is investigated for a general case and the results show that the mass ratio has a lower limit for low delays and upper limit for high delays to remain stable. As frequency and amplitude ratios increase, the margin of stability for the mass ratio increases.

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1- Introduction

Recently, the tuned liquid damper (TLD) is increasingly being employed to suppress the dynamic response of tall buildings due to its efficiency, low cost, and ease of implementation [1]. A TLD is generally designed as a rectangular or cylinder-shaped device, installed at the top of structures [2]. Real-time hybrid simulation (RTHS) is a novel experimental technique to investigate the dynamic behavior of structures [3]. Several studies introduced the RTHS method in detail for investigating the dynamic behavior of a TLD-structure system [4, 5]. In the present study, the stability of RTHS with rectangular TLD is performed using eigen value approach.

2- Mathematical Model

A two-story structure with a TLD, modeled as a shear building, is shown in Fig. 1. The governing Eq. (1-3) is used to describe the vibration behavior of the structure.

$$\begin{aligned} m_1\ddot{x}_1+c_1\dot{x}_1+k_1x_1&=-m_1\ddot{x}_g+c_2\dot{x}_2+k_2x_2\\ m_2\ddot{x}_2+c_2\dot{x}_2+k_2x_2&= \end{aligned} \quad (1)$$

$$c_s\dot{x}_s+k_sx_s+\frac{m_2}{m_1}(-c_2\dot{x}_2-k_2x_2+c_1\dot{x}_1+k_1x_1) \quad (2)$$

$$c\dot{x}+kx=\frac{m}{m_2}(-c\dot{x}-kx+c_2\dot{x}_2+k_2x_2) \quad (3)$$

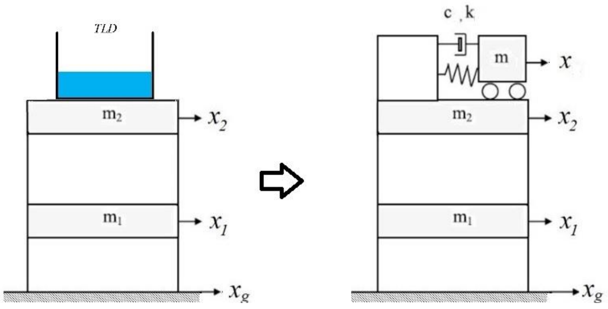

Fig. 1. Model of a two-story building with TLD

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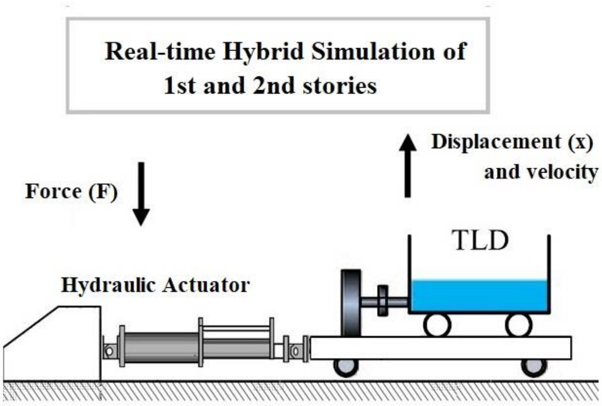

Fig. 2. Schematic of a RTHS for damper testing

The schematic of RTHS for TLD testing is illustrated in Fig. 2.

The TLD is modelled as an equivalent solid mass damper with non-linear stiffness and damping as shown in Fig. 3.

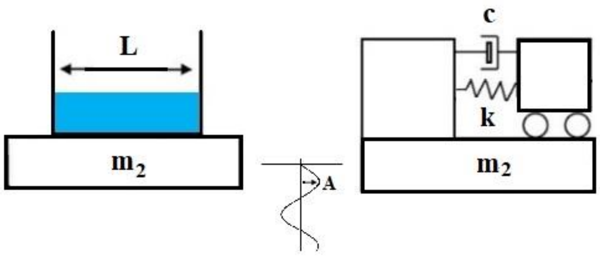

Fig. 3. Effective parameters for stability analysis of hybrid simulation for TLD

The non-dimensional amplitude is defined as Eq. 4

$$\Lambda = \frac{A}{L} \tag{4}$$

The nonlinear damping and stiffness ratios can be defined using non-dimensional amplitude as follows.

$$\xi = 0.05\ \Lambda^{0.35} \tag{5}$$

$$k = \begin{cases} 1.075\ \Lambda^{0.25} & \Lambda < 0.03 \\ 2.52\ \Lambda^{0.25} & \Lambda > 0.03 \end{cases} \tag{6}$$

for deriving the state-space model of the structure, state vector (***X***) is selected according to Eq. (7).

$$X = \left[x_1\ x_2\ x\ \dot{x}_1\ \dot{x}_2\ \dot{x}\right]^T \tag{7}$$

The state-space model of a linear time-invariant (LTI) system with a fixed time-delay (τ) can be written as Eq. (8).

$$\dot{X}(t) = A_0 X(t) + A_1 X(t-\tau) \tag{8}$$

The characteristic equation of differential Eq. (8) is derived as follows.

$$\det\left(\lambda I - A_0 - A_1 e^{-\tau\lambda}\right) = 0 \tag{9}$$

The non-dimensional parameters are defined as Eq. (10).

$$\begin{aligned} &\omega_1 = \sqrt{\frac{k_1}{m_1}} , \quad \zeta_1 = \frac{c_1}{2\sqrt{k_1 m_1}} \\ &\omega_2 = \sqrt{\frac{k_2}{m_2}} , \quad \zeta_2 = \frac{c_2}{2\sqrt{k_2 m_2}} , \quad \mu_2 = \frac{m_2}{m_1} \\ &\omega = \sqrt{\frac{k}{m}} , \quad \zeta = \frac{c}{2\sqrt{km}} , \quad \mu = \frac{m}{m_2} \end{aligned} \tag{10}$$

The matrices A_0 and A_1 are defined as Eq. 11 using nondimensional parameters.

$$A_0 = \begin{pmatrix} 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ -\omega_1^2 & \mu\omega_2^2 & 0 & -2\zeta_1\omega_1 & 2\mu_2\zeta_2\omega_2 & 0 \\ \omega_1^2 & -\omega_2^2(1+\mu_2) & \mu\omega^2 & 2\zeta_1\omega_1 & -2\zeta_2\omega_2(1+\mu_2) & 2\mu\zeta\omega \\ 0 & 0 & -\omega^2 & 0 & 0 & -2\zeta\omega \end{pmatrix}$$

$$A_1 = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \omega_2^2 & -\mu\omega^2 & 0 & 2\zeta_2\omega_2 & -2\mu\zeta\omega \end{pmatrix} \tag{11}$$

Using matrices A_0 and A_1, the stability analysis of RTHS can be performed by solving delay differential Eq. 9.

3- Results and Discussion

The effect of equivalent mechanical properties including effective mass, natural frequency, and damping ratio of the TLDs, on the stability of RTHS, is investigated. The root locus of the unstable root versus time-delay of the actuator is depicted in Fig. 4 using eigen value method. The stability margin in (Λ , τ)-plane and (μ , τ)-plane are shown in Fig. 5 and Fig. 6, respectively.

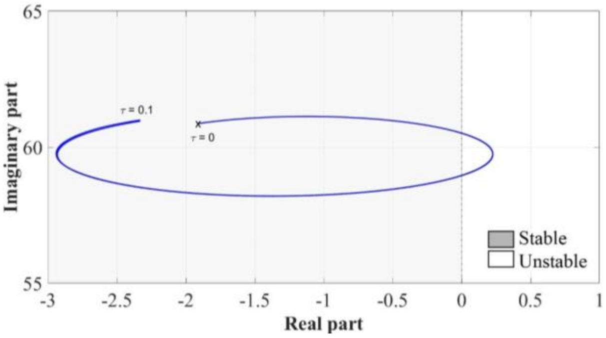

Fig. 4. Root locus of unstable root versus time-delay of the actuator using μ=0.05 and Λ=0.03 for 0 < τ < 0.1 sec

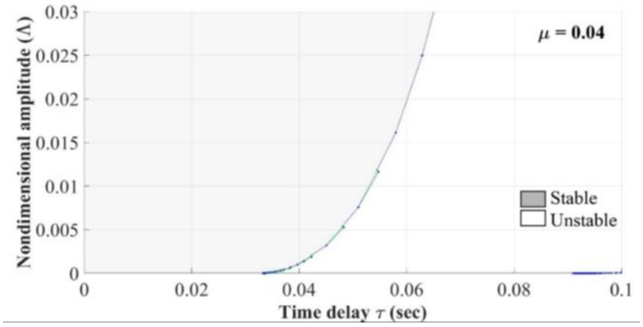

Fig. 5. Stability margin in (Λ , τ)-plane for μ=0.04

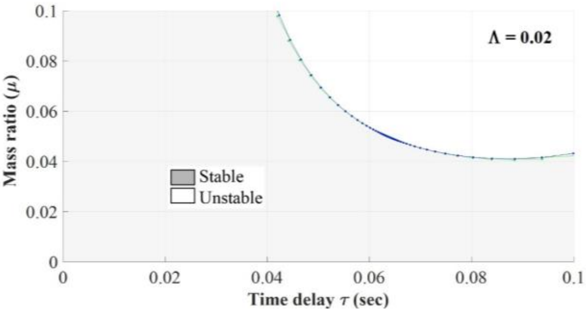

Fig. 6. Stability margin in (μ , τ)-plane for Λ=0.02

4- Conclusions

The effect of geometric sizes of TLD and time-delay of the hydraulic actuator on the stability of real-time hybrid simulation is discussed. The stability analysis is carried out by numerically simulating the structure and experimentally testing TLD device. It is found that the stability margin for time delay increases as non-dimensional amplitude is increases. Moreover, the stability margin for time delay decreases as the mass ratio of TLD increases. The root locus also shows, half bifurcation due to increase of actuator time delay.

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