Seismic Control of a 3-Story Frame Building using an MR Damper

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NUMERICAL MODEL FOR FRAME BUILDING

Consider an MDOF structure with *3* degrees of freedom, subjected to a base ground motion $\ddot{x}_g$. Assuming the structure performs within the elastic range, the equation of motion is expressed as:

$$\boldsymbol{M}\ddot{\boldsymbol{x}} + \boldsymbol{C}\dot{\boldsymbol{x}} + \boldsymbol{K}\boldsymbol{x} = -\mathbf{M}\mathbb{I}\ddot{\boldsymbol{x}}_g + \boldsymbol{\Gamma}\boldsymbol{f} \tag{1}$$

where $\boldsymbol{x}$, $\dot{\boldsymbol{x}}$, and $\ddot{\boldsymbol{x}}$ are 3×1 state vectors of relative displacements, velocities, and accelerations. $\boldsymbol{M}$, $\boldsymbol{C}$, and $\boldsymbol{K}$ are 3×3 mass, damping and stiffness matrices respectively. $\mathbb{I}$ is an 3×1 vector of ones and $\boldsymbol{\Gamma}$ is an 3×1 vector of input forces. $\boldsymbol{f}$ contains all potential external forces (e.g. added damper contribution).

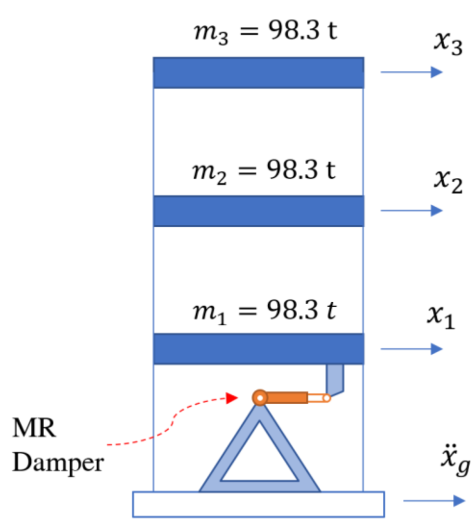

Fig. 1 Three-story building frame

The stiffness and damping properties for the frame shown in Fig. 1 are given below:

$$\boldsymbol{K} = 10^7 \begin{bmatrix} 12.0 & -6.84 & 0 \\ -6.84 & 13.7 & -6.84 \\ 0 & -6.84 & 6.84 \end{bmatrix} \frac{N}{m};\ \ \boldsymbol{C} = 10^4 \begin{bmatrix} 1.04 & -0.34 & -0.08 \\ -0.34 & 1.04 & -0.40 \\ -0.08 & -0.40 & 0.72 \end{bmatrix} \frac{Ns}{m};\ \ \boldsymbol{\Gamma} = \begin{bmatrix} -1 \\ 0 \\ 0 \end{bmatrix} \tag{2}$$

A 1st story MR damper is envisioned in Fig. 1. The behavior and capacity of the MR damper are adjustable in real-time. This feature enables engineers to control the response of the structure through parametric variations. In addition, force control of the MR damper can be through active, semi-active and passive control of damper parameters. In the next section, dynamic model for an MR damper is described.

MR DAMPER MODEL

In this section, a *Bouc-Wen* model is used for characterization of an MR damper. Fig. 2 illustrates the dynamical features for modeling used herein. For a given input displacement x, a nonlinear output can be achieved for a restoring force F.

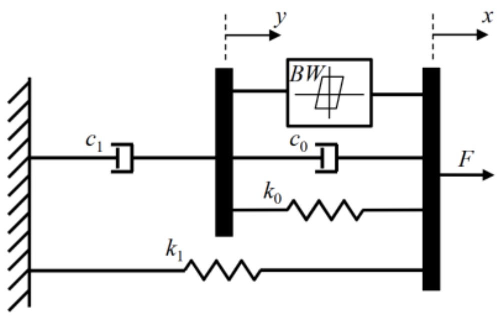

Fig. 2 Phenomenological model of MR Damper

The restoring force can be described by formulating the equation of motion for the setup in Fig. 2, and is described as:

$$F = \alpha z + c_0(\dot{x} - \dot{y}) + k_0(x - y) + k_1(x - x_0) \tag{3}$$

where z is an evolutionary variable used by the Bouc-Wen hysteretic element (Baber and Wn 1981). A more in-depth description of the parameters in (3) and (4) will be provided next.

$$\dot{z} = -\gamma z|\dot{x} - \dot{y}||z|^{n-1} - \beta(\dot{x} - \dot{y})|z|^n + A(\dot{x} - \dot{y}) \tag{4}$$

The following table contains the modeling parameters described by Phillips and Spencer Jr. (2012) for the $200\ kN$ MR damper at UIUC – Nathan Newmark Civil Engineering building, in Fig. 3. These parameters are next used to calculate model variables described in (5)-(10). In these equations, i_c is the current in Amps applied to the MR damper.

Table 1 Model parameters for 200 kN MR Damper

Parameter	Value	Parameter	Value	Parameter	Value
$c_{0,a}$	0.080 kN·sec/mm	$c_{1,a}$	3.0 kN·sec/mm	γ_a, β_a	0.050 mm^{-2}
$c_{0,b}$	0.32 kN·sec/mm	$c_{1,b}$	15.0 kN·sec/mm	γ_b, β_b	0.0020 mm^{-2}
$c_{0,c}$	1.5 A^{-1}	$c_{1,c}$	2.0 A^{-1}	γ_c, β_c	5.2 A^{-1}
k_0	0.0 kN/mm	α_a	0.11 kN/mm	A	300
k_1	0.0 kN/mm	α_b	0.55 kN/mm	n	2.0
x_0	0.0 mm	α_c	1.0 A^{-1}		

Fig. 3 200 kN MR Damper @ UIUC

$$\alpha = \alpha_b + (\alpha_a - \alpha_b) \times \exp(-\alpha_c i_c) \tag{5}$$

$$c_0 = c_{0,b} + (c_{0,a} - c_{0,b}) \times \exp(-c_{0,c} i_c) \tag{6}$$

$$c_1 = c_{1,b} + (c_{1,a} - c_{1,b}) \times \exp(-c_{1,c} i_c) \tag{7}$$

$$\beta = \beta_b + (\beta_a - \beta_b) \times \exp(-\beta_c i_c) \tag{8}$$

$$\gamma = \gamma_b + (\gamma_a - \gamma_b) \times \exp(-\gamma_c i_c) \tag{9}$$

(10)

SIMULINK MODEL

The equation of motion in (1) is next converted to state-space format and discretized for digital implementation. The state-space model of the 3-story frame building and the MR damper model are implemented in the SIMULINK model “*MRsim*”, and the corresponding MATLAB script “*MRscript*”.

$$\dot{\boldsymbol{z}} = \boldsymbol{A}\boldsymbol{z} + \boldsymbol{B_1}\boldsymbol{f} + \boldsymbol{B_2}\ddot{\boldsymbol{x}}_{\boldsymbol{g}} \tag{11}$$

$$\boldsymbol{y} = \boldsymbol{C}\boldsymbol{z} + \boldsymbol{D}\boldsymbol{f} \tag{12}$$

where $\boldsymbol{A}$ is a 6×6 system matrix, $\boldsymbol{B_1}$ is the 6×1 force input vector, $\boldsymbol{B_2}$ is a 6×1 ground acceleration input vector, $\boldsymbol{C}$ is a 6×6 output matrix and $\boldsymbol{D}$ is a 6×1 feedthrough vector. These state-space matrices are next described in terms of $\boldsymbol{K}, \boldsymbol{C},$ and $\boldsymbol{M}$:

$$\boldsymbol{A} = \begin{bmatrix} \boldsymbol{0} & \boldsymbol{I} \\ \boldsymbol{M}^{-1}\boldsymbol{K} & \boldsymbol{M}^{-1}\boldsymbol{C} \end{bmatrix}_{6\times6};\ \boldsymbol{B_1} = \begin{bmatrix} \boldsymbol{0} \\ \boldsymbol{M}^{-1}\boldsymbol{\Gamma} \end{bmatrix}_{6\times1};\ \boldsymbol{B_2} = \begin{bmatrix} \boldsymbol{0} \\ -\mathbb{I} \end{bmatrix}_{6\times1};\ \boldsymbol{C} = \begin{bmatrix} \boldsymbol{I} & \boldsymbol{0} \\ \boldsymbol{M}^{-1}\boldsymbol{K} & \boldsymbol{M}^{-1}\boldsymbol{C} \end{bmatrix}_{6\times1};$$
$$\boldsymbol{D} = \begin{bmatrix} \boldsymbol{0} \\ \boldsymbol{M}^{-1}\boldsymbol{\Gamma} \end{bmatrix}_{6\times1} \tag{13}$$

REAL-TIME HYBRID SIMULATION

The real-time hybrid simulation (RTHS) methodology is a substructuring technique for dynamic testing of structures. It offers a cost-effective solution and is highly practical in confined laboratory settings. In this section, the general architecture of an RTHS experiment is described where the three-story building is modeled as a numerical component and the MR damper is tested experimentally. The general architecture for RTHS testing is illustrated in Fig. 4. RTHS testing requires the use of a tracking controller to compensate for actuator dynamic, disturbance, and computational lag.

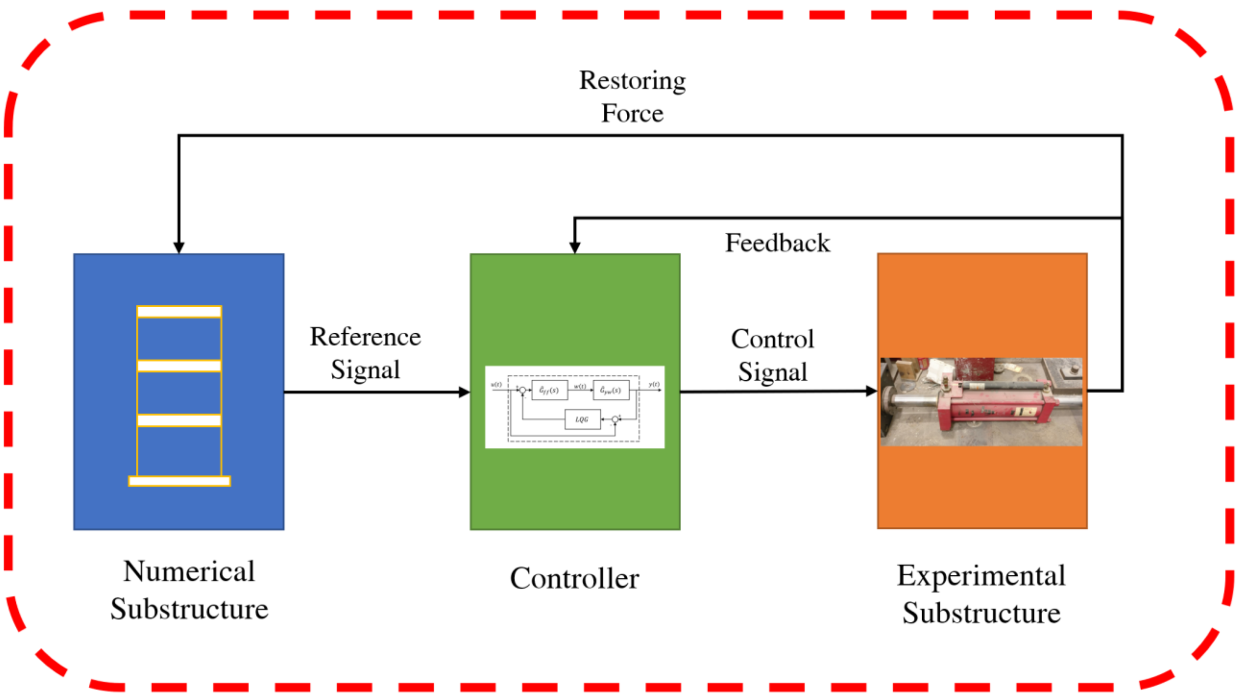

Fig. 4 RTHS architecture

RTHS IMPLEMENTATION

An actuator transfer function model was selected to mimic the behavior of a hydraulic actuator to be attached to the MR damper. The following dynamical model was adopted from Phillips and Spencer Jr. (2012):

$$G(s) = \frac{1.600 \times 10^7}{(s + 151.7)(s^2 + 250.4s + 1.061 \times 10^5)} \tag{14}$$

The model in (14) along with dynamical models of the 3-story building and MR damper are implemented on the MATLAB using the RTHS framework. The 3-story building substructured numerical and the MR damper is considered to be experimental through incorporation of actuator dynamics. Two scenarios are considered: (i) 3-story building with MR damper, and (ii) 3-story building without MR damper. For case (i) two different MR damper current levels are studied. Fig. 5-7 illustrate the displacement, acceleration and hysteretic behaviors under a current level of $0A$. Reductions are observed in both displacement and acceleration behaviors due to passive action of the MR damper.

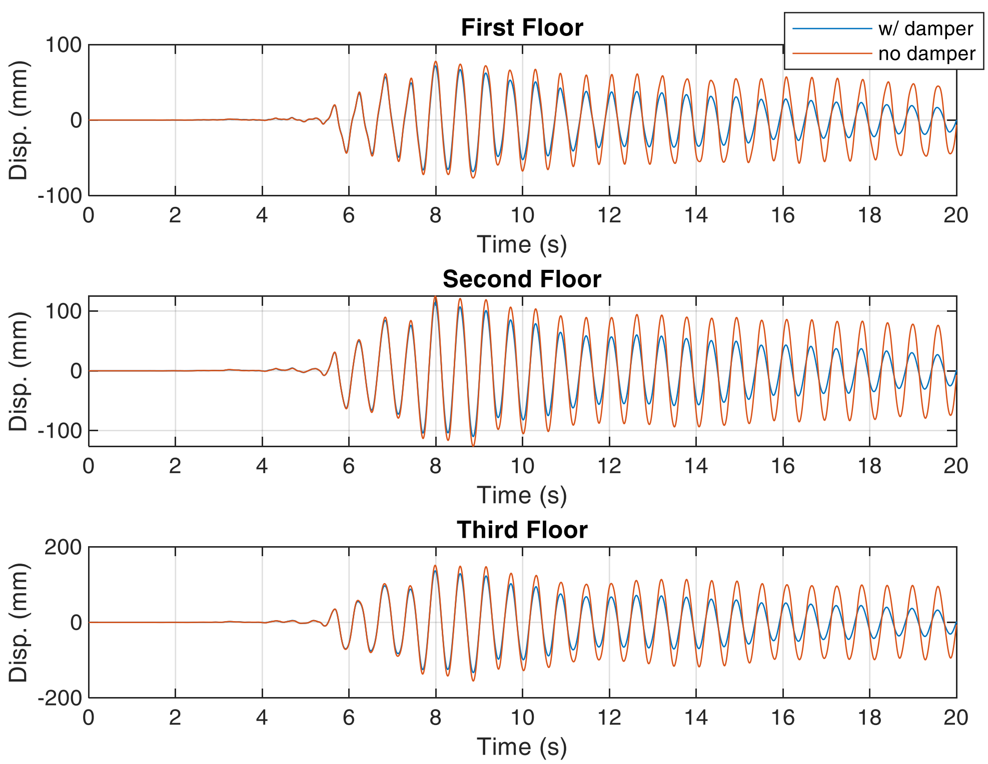

Fig. 5 Floor displacement results – 0A

A current level of $1A$ is next applied to the MR damper. Noticeable reductions are observed in the displacement and acceleration behaviors of the floor in the frame building per Fig. 8-9. A critical component for numerical stability of the MR damper model is the sampling time f_s of the simulation. Due to the large nonlinearities present in this model, a sampling rate of $f_s = 1/1000\ sec$ was used to compile simulations.

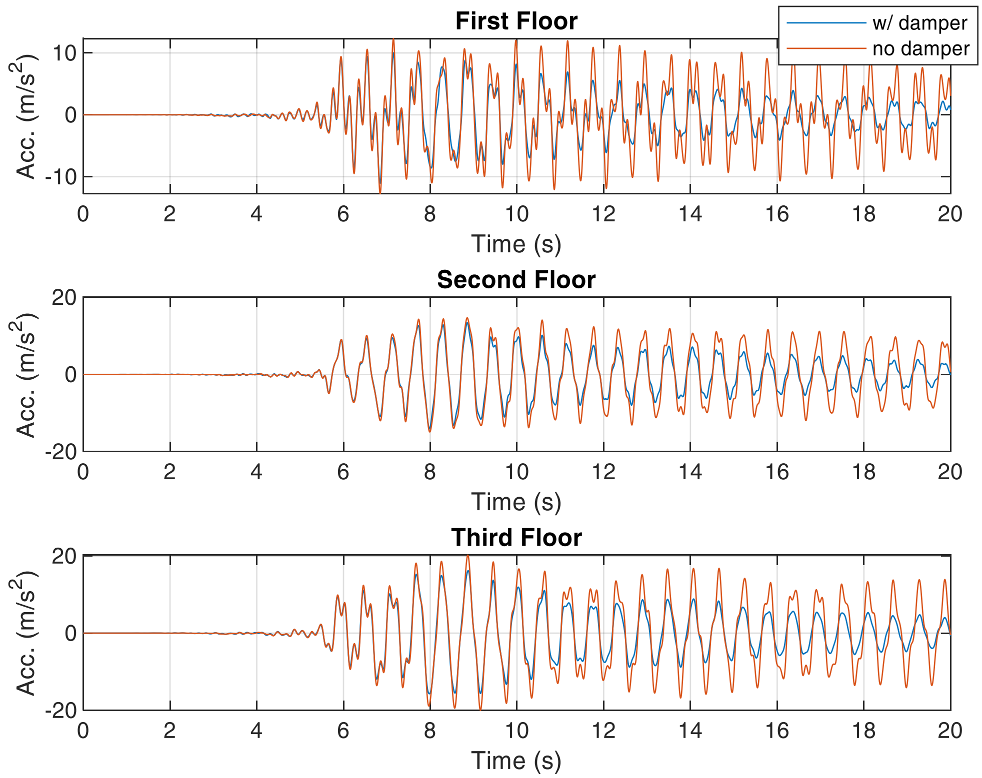

Fig. 6 Floor acceleration results – 0A

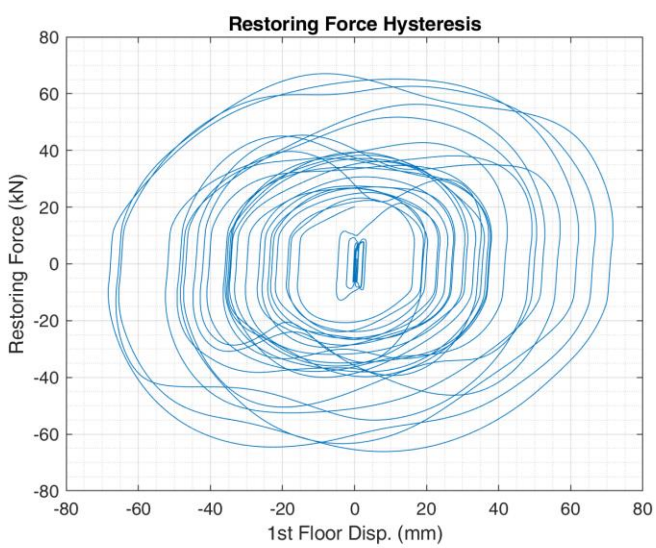

Fig. 7 Restoring force hysteresis of the MR damper – 0A

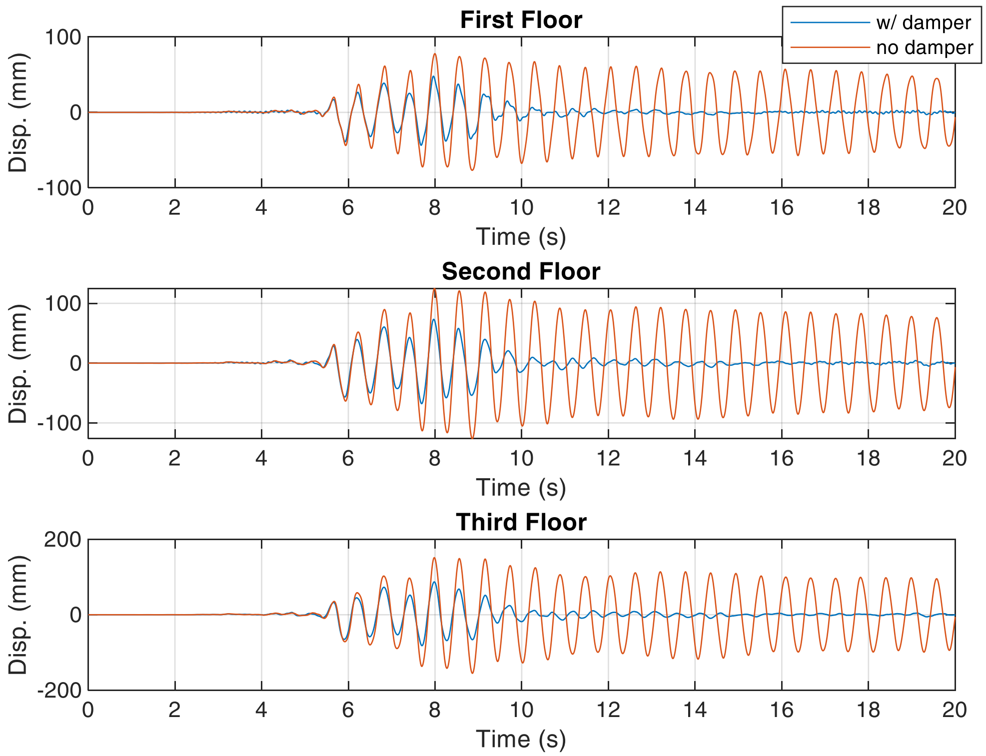

Fig. 8 Floor displacement results – 1A

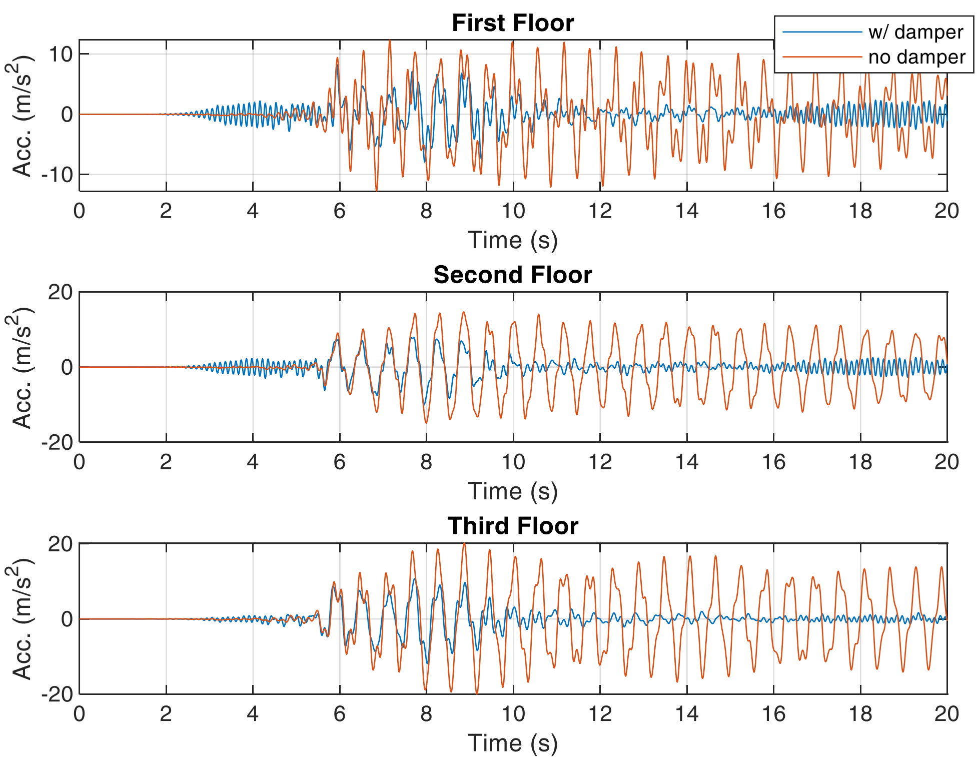

Fig. 9 Floor acceleration results – 1A

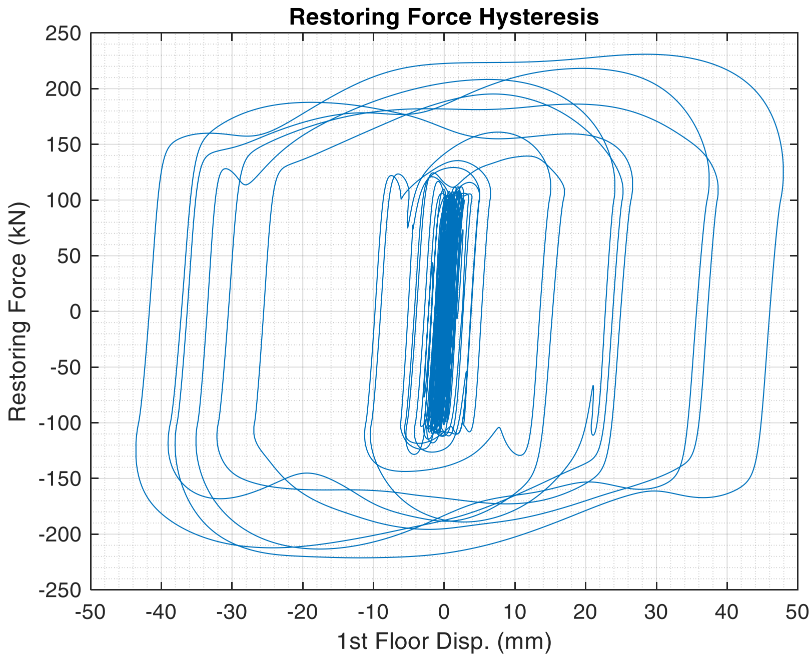

Fig. 10 Restoring force hysteresis of the MR damper – 1A

SUMMARY

The 3-story model described in this document may be replaced by any other structure. The fundamental concepts to the RTHS framework is the input and output from the experimental substructure. A numerical substructure must provide the experimental, with an input displacement stroke. The MR damper in return will provide the numerical substructure with a restoring force. The restoring force is equal and opposite to the force demonstrated in Fig. 2. In this SIMULINK implementation, a controller (i.e. feedback controller) is not implemented as the aim was to demonstrate the effect of the actuator dynamics. A real experimental implementation necessitates the use of a controller.

References:

Baber, T. T., and Wn, Y.-K. (1981). *Random Vibration of Hysteretic Degrading Systems*.

Phillips, B. M., and Spencer Jr., B. F. (2012). “Model-Based Framework for Real-Time Dynamic Structural Performance Evaluation.” *NSEL Report Series*, University of Illinois Urbana-Champaign.