Linearized State-Space Model of the behavior of MR-Fluid Dampers

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Abstract—**Magnetorheological (MR) dampers are semi-active control dampers that use MR fluids to provide controllable damping characteristics. MR dampers have proven to be more effective than passive dampers in protecting civil structures during seismic events. While passive dampers have been thoroughly analyzed and understood by researchers, active and semi active dampers are still under investigation by many researchers. MR dampers added protection is achieved by adjusting the damping characteristics of the device so as to minimize structural dynamic loads. Models of the MR dampers highly nonlinear and difficult to adapt for active control, therefore, in this work, the MR damper model presented by Spencer et al will be solved numerically to obtain force-velocity data points. The data obtained from numerical solution of the damper model will be used to construct a linearized state-space model for control purposes. The state space model is obtained via system identification techniques and its agreement with the nonlinear model is discussed.**

Keywords— **MR fluid dampers, system identification, seismic isolation, active damping**

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I. Introduction

Magnetorheological (MR) dampers are widely used in civil structures due to their high force output and fast response. MR dampers are favorable in structural damping because of their simple design yet massive force output as mentioned earlier. The simple design stems from the fact that they have no moving parts besides the damper piston [1]. The distinguished characteristic of these fluid dampers is the ability of MR fluid to change from liquid to semi-solid instantaneously. This ability is due to the micro-sized magnetic particles which can be polarized with a low-power low-voltage magnetic field. For extensive details on the operation and the mechanics of MR dampers see [1-5]. In this work, the model developed by Spencer et al. which represents an extension to the Bouc-Wen model is used to predict the behavior of MR fluid dampers [5]. The model is highly nonlinear but provides a superior prediction of the dampers behavior under various displacement-force characteristics. The aforementioned model is numerically solved using Matlab ODE code to generate values of dampers force corresponding to certain damper's velocity, displacement and coil voltages. The data obtained from numerical solution is then used to construct a state space model representing the relation between force as the output and the velocity, displacement and voltage as the input. The model is constructed using Matlab System Identification toolbox. The state-space model obtained via system identification is then used at a later stage in developing and active control scheme incorporating MR dampers for structural seismic isolation purposes.

II. MR DAMPER MODEL

The general structure of the MR fluid damper is shown in Figure 1 which is taken from Spencer et al. [6]. The damper has moving piston with a magnetic choke moving in a MR fluid medium. In the passive state, the fluid is liquid and the flow through the choke resembles that of a common fluid damper. However, when the coil in the magnetic choke is activated, the magnetic field causes the MR fluid to instantly change into a semi-solid causing obstruction to the fluid flow on both sides of the piston. This in essence varies the damping ratio of the damper alters the force-velocity characteristics of the damper.

To make the simulation realistic, the MR damper has to be properly modeled. The damper model must be accurate enough as to capture the dynamic characteristics of the real damper, yet simple enough as to carry the computation in real-time on a low power microprocessor. To bridge the gap between these two competing requirements, System Identification (SI) was used to derive an 8^{th} order Nonlinear Auto regression (Narx) model. Spencer et al. [5] have presented a model of the MR damper based on the Bouc-Wen Model Hysteresis. In this model, the force-displacement, force-velocity, and force as a function of time were computed. The damper model equations are presented here for convenience:

$$F = C_1 \dot{y} + k_1 (x - x_o) \tag{1}$$

$$\dot{y} = \frac{1}{c_o + c_1} \left[\alpha z + c_o \dot{x} + k_o (x - y) \right] \tag{2}$$

$$\dot{z} = -\gamma |\dot{x} - \dot{y}| z |z|^{n-1} - \beta (\dot{x} - \dot{y}) |z|^n + A(\dot{x} - \dot{y}) \tag{3}$$

$$\alpha = \alpha_{a+} \alpha_b u \tag{4}$$

$$c_1 = c_{1a+C_{1b}u} \tag{5}$$

$$c_o = c_{oa+C_{ob}u} \tag{6}$$

$$\dot{u} = -\eta (u - v) \tag{7}$$

Where F is the damper's force x and y are piston's end displacements and the remaining parameters are listed in Table 1. In this work, numerical solutions of Equations 1-7 have been performed and time history of all states were validated by checking against previously published solutions [6].

III. SYSTEM IDENTIFICATION RESULTS

System Identification relating input to output has been performed to derive a simple nonlinear model. Different SID techniques, using the Matlab SID toolbox were employed yielding excellent matching. The derived models have been thoroughly tested and proved to match the nonlinear model behavior to a high degree of accuracy over a wide range of inputs. Among the different methods employed, the Narx method provided the best matching. Responses of various models obtained by the different SID techniques are shown in Figure 2.

Polynomial Model obtained from Narx is converted to state-space format and compared to the nonlinear model. The comparison is shown in Figure 4. The state space model is expressed as:

$$x_f = A_f x_f + B_f u_f \tag{8}$$

$$Y_f = C_f x_f + D_f u_f \tag{9}$$

Where x_f the state vector of the MR state-space model is, u_f is the input, and Y_f is the output (i.e., Damper force). The quadruple (A_f, B_f, C_f, D_f) represent the dynamic, input, output and direct input matrices of the MR damper model. The following figure shows the results obtained from the Narx model and the nonlinear model. Excellent dynamic behavior matching is demonstrated, Figure 3:

State space model obtained from Narx has the following numerical values for the MR damper with parameters listed in Table 1.

$$A_f = \begin{bmatrix} -558.4 & 3343 & 7530 & -5854 \\ 484.5 & -3305 & -2090 & 5683 \\ 1 & 1 & -4605 & 1 \\ 898.7 & -6021 & 2.415e+004 & -3804 \end{bmatrix}$$

$$B_f = \begin{bmatrix} 1876 \\ 1201 \\ -2748 \\ 1.891e+0004 \end{bmatrix}$$

$$C_f = \begin{bmatrix} -25.02 & 0 & 0 & 0 \end{bmatrix}$$

$$D_f = \begin{bmatrix} 0 \end{bmatrix}$$

Simulation of the State-space model response (i.e. Damper Force F) to input velocities obtained from nonlinear solution are shown in Figure 2. Which shows good agreement with the Force generated by the nonlinear model presented by Equations 1-7.

IV. CONCLUSIONS

In this paper, the Spencer et al. modified model of the Bouc-Wen MR damper is solved numerically using Matlab ODE and the force-velocity data set is obtained. The data is then used in Matlab System Identification tool box to obtain a polynomial relationship between damper force-velocity. The polynomial is then used to generate a control adaptable state-space model relating the damper force to piston velocity. Simulation results show good agreement between the original nonlinear and the linearized state-space model. The model latter is to be used in digital control scheme for structural seismic isolation purposes.

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Table 1: Parameters for the generalized model

Parameter	Value	Parameter	Value
C_{0a}	21.0 N.sec/cm	α_a	140 N/cm
C_{0b}	3.5 N.sec/cm.V	α_b	695 N/cm.V
k_0	46.9 N/cm	γ	363 cm^{-2}
C_{1a}	283 N.sec/cm	β	363 cm^{-2}
C_{1b}	2.95 N.sec/cm.V	A	301
k_1	5 N/cm	n	2
x_0	14.3 cm	η	190 $\sec^{-1}$

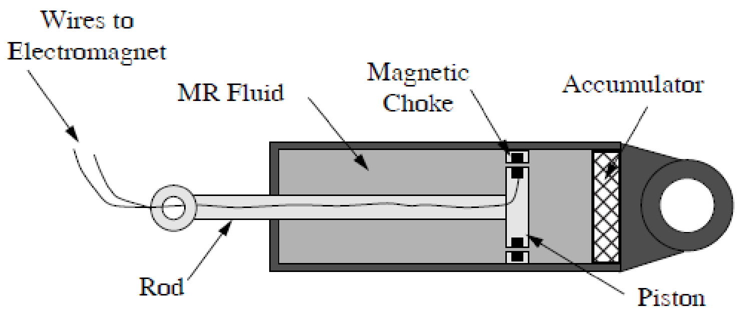

Figure 1: Schematic of MR Fluid damper presented in Spencer et al.

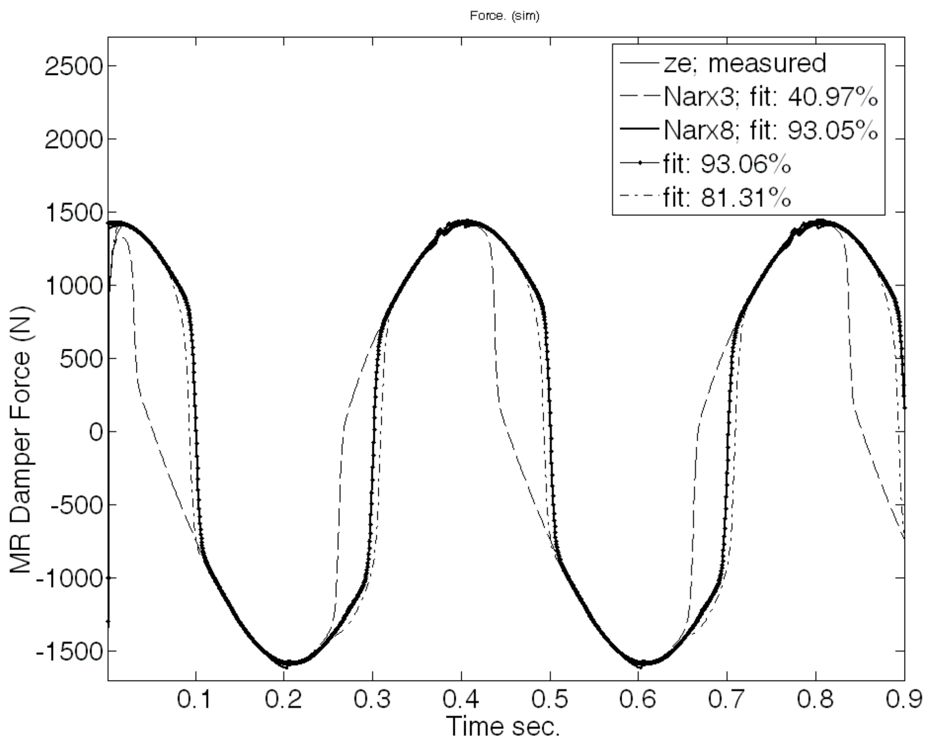

Figure 2: Various Matlab System Identifications generated models for MR damper response

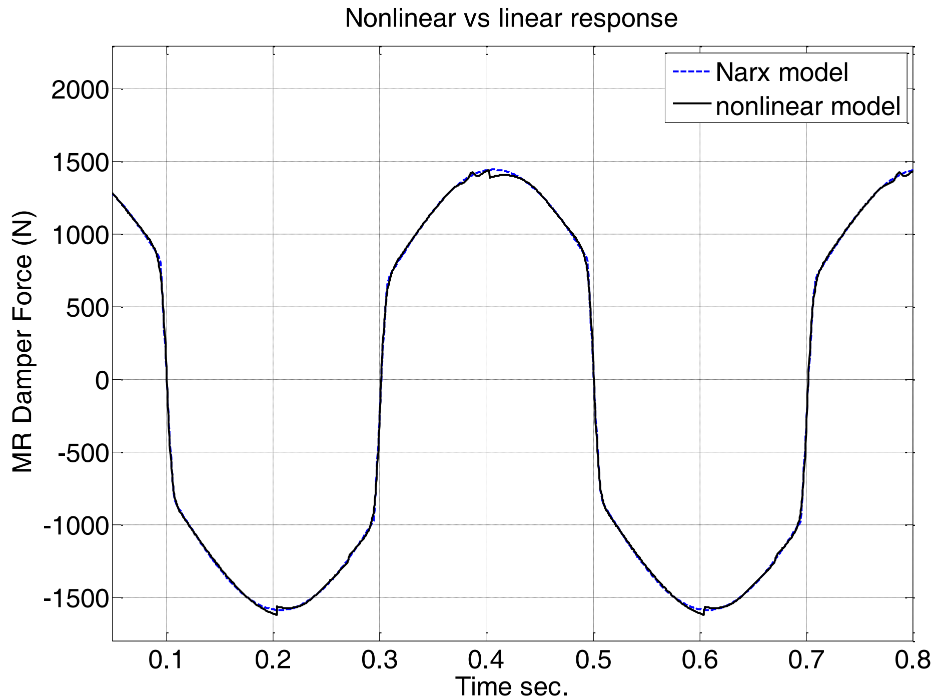

Figure 3: comparison between linearized State-space in Eq. 8 and 9, and Spencer et al. nonlinear model.