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Parameter Identification of Bouc-Wen Model for MR Damper

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Abstract: The non-linear behavior of the MR damper was modelled using the generalized model of Bouc-Wen. The work methodology of this work was divided into three parts. Three control strategies as a function of the applied current, excitation frequency and displacement amplitude. The model parameter is validated using experimental measured values and modified predict values. The approach for the nonlinear dynamic model of Bouc-Wen was obtained using a method to find and fit optimal values locally. The method of nonlinear optimization of multidimensional variables adopted was the Nelder-Mead simplex search method. It finds the local minimum of the function of 16 variables, starting at an initial estimate value. In order to provide optimal values, the displacement function was also optimized using the same method. With the aim of find the local minimum of the sinusoidal displacement. The error minimization is done using Nelder-Mead simplex search method algorithm, the error is a second order function that minimizes the sum of the squared deviations of the scores.

Keywords: Bouc-Wen, Nelder-Mead Simplex method, MR damper

INTRODUCTION

In recent years, automotive industries have shown interest in the development of new techniques for vibration control. Among the technological solution is the magneto rheological damper used in semi-active automotive suspension system (Sassi et al. 2018). Bearing that in mind, researchers have investigated and explored some existing gaps and obstacles to propose a more forceful strategy that allows the implementation of this technological solution. The magneto-rheological damper is the most promising technology solution for vibration control in several applications, such as: building protection of seismic events (Jung et al. 2006) and (Sun et al. 2018), automotive suspension (Pepe, Roveri, and Carcaterra 2019) and (Feng et al. 2020), aircraft landing gear system (Kang et al. 2020) and (Luong, Jang, and Hwang 2020), knee prosthesis (Fu, Pan, and Xu 2019) and (Ochoa-Diaz et al. 2014), precise manufacturing machines (Kim et al. 2018), seat suspension (Du et al. 2018)and high-speed railway vehicle suspension (Liao, Liu, and Yang 2019) and (Jin et al. 2020).

The nonlinear hysteretic behavior of the MR damper requires a mathematic model to explain and characterize the physical meaning of some parameters. The mathematical model adopted in the present work for the parameter identification was the modified dynamic model of Bouc-Wen, which aims to characterize the experimental behavior through a mathematical model that can be optimized. The main contribution of this study is to provide a phenomenological approach to the nonlinear dynamic behavior of the MR damper, evaluating the dependence of excitation frequency and current. Tests were carried out to characterize the MR damper, using the universal tensile testing machine. The experimental methodology was divided into three control strategies: frequency variation for the same displacement and current condition, displacement variation for the same frequency and current condition and variation of applied current (that changes the magnetic field in the coils). The parameter estimation is essentially a multidimensional numerical optimization problem that aims to find a dynamic model to better represent the experimental data, this optimization was performed using the Nelder-Mead simplex search method.

Modified Bouc-Wen Model

The modified model to describe the non -linear hysteresis of the damper force/velocity improving the standard Bouc-Wen model proposed by (Spencer Jr. et al. 1997) is illustrated in Fig. 1.

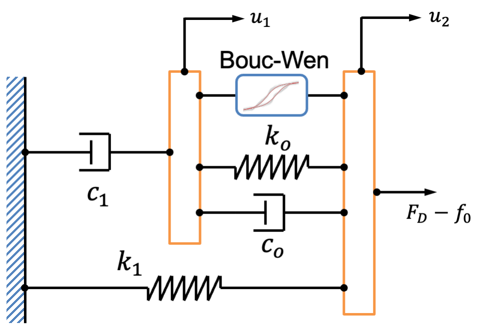

Figure 1 – The modified phenomenological Bouc-Wen model of MR damper schematic.

The damping force (F_D) present in the Modified Bouc-Wen system is given by (Talatahari and Rahbari 2015):

$$F_D = c_0(\dot{u}_2 - \dot{u}_1) + k_0(u_2 - u_1) + k_1(u_2 - u_0) + \alpha z = c_1\dot{u}_1 + k_1(u_2 - u_0) \quad (1)$$

The hysteretic displacement z is given by

$$\dot{z} = A(\dot{u}_2 - \dot{u}_1) - \beta(\dot{u}_2 - \dot{u}_1)|z|^n - \gamma z|\dot{u}_2 - \dot{u}_1||z|^{n-1} \quad (2)$$

in which $\dot{u}_2$ is defined by the following equation according to Fig. 1.

$$\dot{u}_2 = \frac{1}{(c_0 + c_1)}\{\alpha z + c_0\dot{u}_2 + k_0(u_2 - u_0)\} \quad (3)$$

A symmetrical triangular displacement waveform gives nominally constant velocity over the whole stroke, equal in the two directions. This is why the tests were performed using a sinusoidal motion, to properly characterize the hysteresis behavior, several amplitudes would be needed using triangular displacement. On other hand, the sinusoidal motion may be more realistic as real automotive motions are nearer to sinusoidal (Dixon 2007).

The predict displacement (u) is given by the equation $u = A\,sin(2\pi ft + \phi)$, where A is the amplitude, f is the frequency and ϕ is the phase angle. The predict velocity is the derivative of the displacement function given by the equation $\dot{u} = 2\pi f\ A\,cos(2\pi ft + \phi)$.

Numerical Parameter Identification

The modified Bouc-Wen model cannot be applied to describe the hysteretic force-velocity characteristics under continuous variations in the control current and excitation conditions. To imitate the nonlinear dynamic hysteretic behavior of the MR damper (Wang et al, 2004) implemented a parameterized model synthesis based upon the experimental dynamic behavior of the MR damper and employed a method to fit symmetric and asymmetric sigmoid functions based on experimental data.

By adjusting 16 parameters ($f_0, I_0, I_1, a_0, a_1, a_2, a_3, a_4, k_o, k_{1c}, k_{1e}, k_2, k_3, k_4, k_5\ and\ k_6$) of modified Bouc-Wen model, it's possible to predict the response of a MR damper to any random inputs (displacement and applied current) before and after the yield areas. The asymmetric and hysteretic force -velocity characteristic was formulated by (Wang et al, 2004) introducing the offset parameters expressing the damping force as a function of control current and velocity.

The Nelder-Mead simplex optimization method seeks to find variable values that optimize a multivariate objective function under a set of constraints. The objective function is the quadratic residue, given by the square sum of the difference between signal of experimental displacement/force and simulated displacement/force.

The magnitude of the peak velocity v_m can be derived from the instantaneous values of position u and acceleration ($\ddot{u}$), $v_m = a_m.\omega = \sqrt{(\dot{u})^2 - \ddot{u}.u}$ (a_m is the amplitude and ω is the frequency) so the transition force, can be expressed

$$f_t = f_0(1 + e^{a_1 v_m})1 + \left(\frac{k_2}{1+e^{-a_2(i+I_0)}} - \frac{k_2}{1+e^{-a_2(I_0)}}\right) \quad (4)$$

The zero-force velocity intercept v_h, offset velocity v_d and force f_d, and constants $\alpha, k_{vc}\ and\ k_{ve}$ can be expressed as:

$$v_h = sgn(\ddot{u})k_4 v_m \left(\frac{k_3}{1+e^{-a_3(i+I_1)}} - \frac{k_3}{1+e^{-a_3(I_1)}}\right) \quad (5)$$

$$\alpha = a_0/(1 + k_0.v_m) \quad (6)$$

$$k_{vc} = k_{1c}e^{-a_4 v_m};\ k_{ve} = k_{1e}e^{-a_4.v_m} \quad (7)$$

$$f_d = k_5 f_t; v_d = k_6 v_m \quad (8)$$

The characteristic parameters ($f_t, f_d, v_h, v_d, \alpha, k_{vc}, k_{ve}$) described in equations 4 - 8 are not only dependent on the excitation condition (frequency ω and amplitude a_m) but also on the applied current for the MR damper. Where k_{vc}, k_{ve} are constants, α is the constant used to adjust the slope of the hysteresis curve, f_t is the transition force, v_h is the (zero-force velocity intercept), v_d and f_d are offset parameter and describe the bias or offset in velocity and force.

The asymmetric and hysteretic force-velocity characteristics of the MR damper, is generalized represented by the Fig. 2.

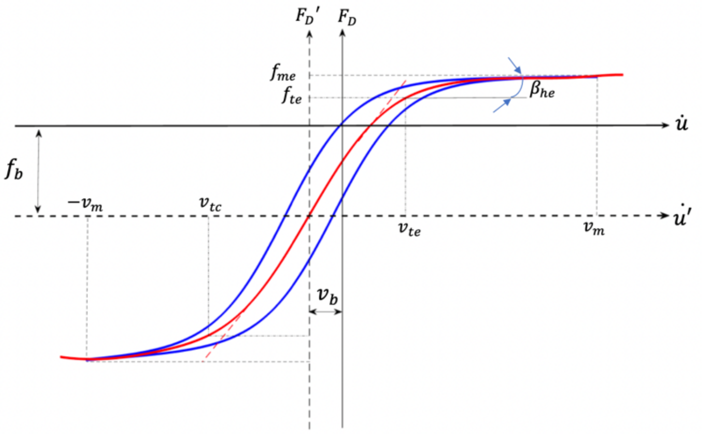

Figure 2 – Generalized hysteretic force-velocity characteristics (adapted of Wang et al., 2004)

EXPERIMENTAL SETUP

The experimental methodology adopted was to impose a sinusoidal excitation trough the servo hydraulic actuator on the Universal Machine testing. The process was repeated for several magnetic fields over a nominal operation current range of 0 – 0.5 A. For each current a damping force was expected, to generate the graphic Fig 3. These currents were generated by an external alimentation source DC. The universal machine testing has internal sensors of displacements and force, controlled by an electronic control unit LVDT (Linear Variable Displacement Transducer) able to provide the piston displacement and applied force. The frequency of the sinusoidal wave was defined according to the literature, because in this way it will be possible to compare with the experimental values obtained. The velocity was derived from numerical differentiation of the displacement.

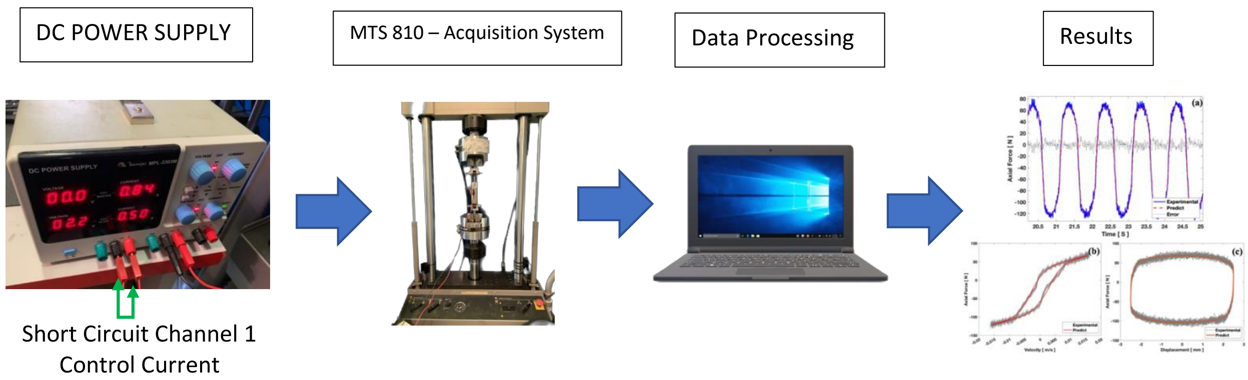

Figure 3 – Data Processing Process

Fig. 4 presents experimental procedures where temporal force and displacement as function of electric current.

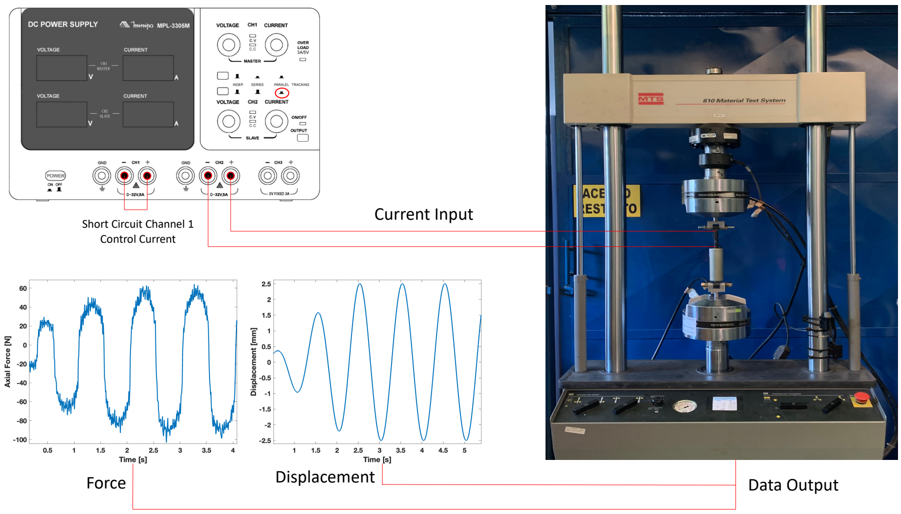

Figure 4 - MTS Output Data Response

RESULTS

The optimization method applied using Nelder-Mead simplex search method was employed to find the optimal values of displacement function to represents the modified Bouc-Wen model. The Fig. 5 (a) illustrate the first 25 seconds time history of the nonlinear behavior of the force and errors between predicted responses obtained using estimated parameters by modified Bouc-Wen dynamic model. The Fig 5 (b) and Fig. 5 (c) illustrate the comparison between the estimated and experimental responses under a 1 Hz sinusoidal excitation with amplitude of 2.5mm for 0 A of current.

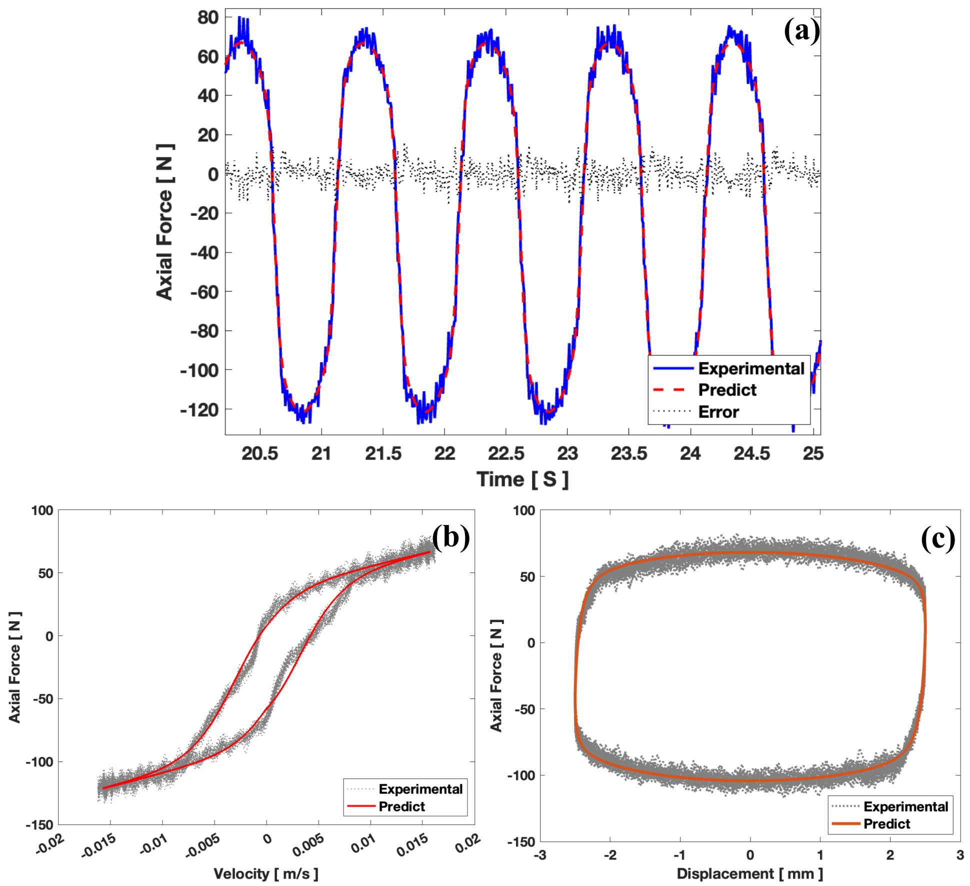

Figure 5 – Comparation between Experimental and Predict with excitation frequency of f = 1 Hz, A = 2.5 mm and I = 0 A: (a) F(t) (b) F (u_2) and (c) F $(\dot{u}_2)$

The force-displacement Fig. 6 (a) and force-velocity Fig. 6 (b) characteristics for experimental values is represented for five current levels.

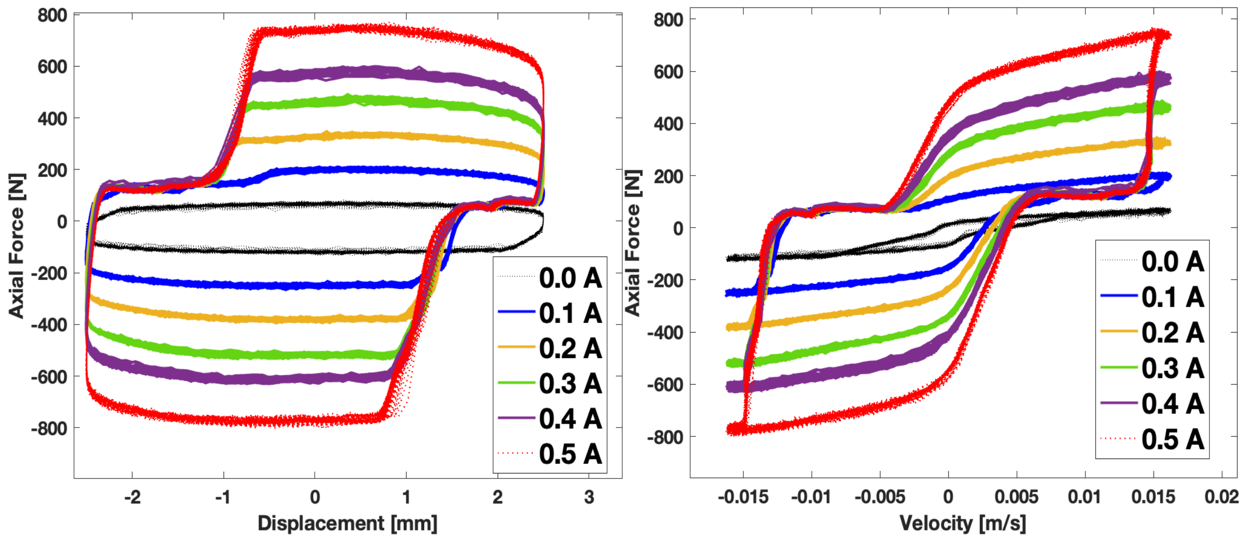

Figure 6 – (a) Force vs Displacement (b) Force vs Velocity

PARAMETER IDENTIFICATION

Asymmetric characteristics obtained over a wide range if control current (0 – 0.5 A), and excitation frequency of (1 Hz) and displacement amplitude of 2.5mm are applied to identify the model parameters. The parameters after optimization are given by the Tab. 1 and 2.

Table 1 – Physical Constants

CTE	0 A	0.1 A	0.2 A	0.3 A	0.4 A	0.5 A
a_0	11309	2109	1982	1688	656,56	895
$a_1(m/s)^{-1}$	-23,2	-33,85	34,81	36,99	81,85	121,74
$a_2(amp)^{-1}$	118,6	0,13	0,116	0,11	0,11	0,062
$a_3(m/s)^{-1}$	-1,55	37,48	36,72	28,51	72,90	78,02
$a_4(m/s)^{-1}$	33,59	-39,71	-44,15	-40,44	28,57	5,80
$I_0\ (amp)$	0,147	-0,05	-0,065	1,66	-0,168	-0,10
$I_1\ (amp)$	4,09	-0,51	-0,487	0,02	-0,836	-0,93
$f_0\ (N)$	36,55	136,20	145,19	175,78	95,69	67,23

Table 2 – Hysteresis Parameters

CTE	0 A	0.1 A	0.2 A	0.3 A	0.4 A	0.5 A
k_0	1433,8	29,35	36,58	55,18	134,14	219,13
k_{1c}	93,84	49,62	65,59	66,33	24,12	21,07
k_{1e}	40,85	14,62	13,40	13,78	20,50	25,63
k_2	-6109	-189	-91,5	-54,3	14,87	22,54
k_3	-1046	1,31	1,07	1,03	-1,76	-2,95
k_4	-0,15	-0,46	-0,46	-0,47	-0,52	-0,48
k_5	0,42	0,39	0,46	0,46	0,08	0,03
k_6	0,007	0,33	0,34	0,33	0,10	0,06

VERIFICATION AND VALIDATION OF SIMULATION MODEL

The validation is considered an important stage as a part of the model development or implementation process. The validation process was carried out to ensure that the model implemented is sufficiently accurate for the purpose of representing the nonlinear behavior of the MR damper (Tsioptsias, Tako, and Robinson 2016). The Fig. 5 represents the approach and the fitting results proposed by (Santade 2017) e compared with predicted and experimental results. An efficient identification parameter of a non-linear hysteretic dynamic Bouc-Wen model to represents a MR damper is extremely dependent on robust experimental methods. During the repeatability test of experimental results, it was verified significant discrepancies were found in relation to experimental damping force for tests carried out under the same conditions. These discrepancies found justify the small variation found between literature and predicted results.

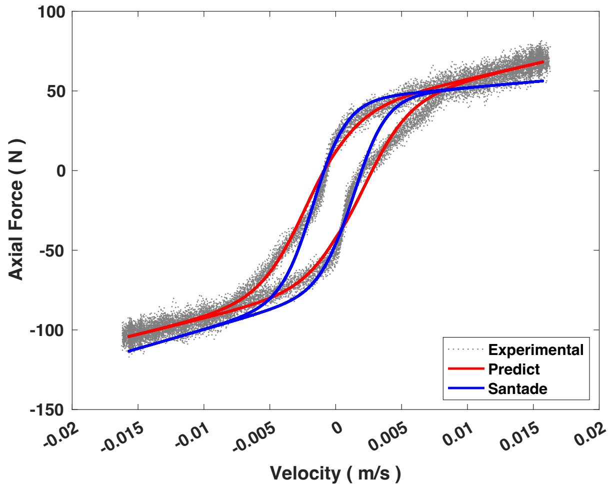

Figure 5 – Literature Validation

Applying the histogram with a normal distribution fit is possible to see that the force error function has a gaussian distribution Fig. 6 and is a random error.

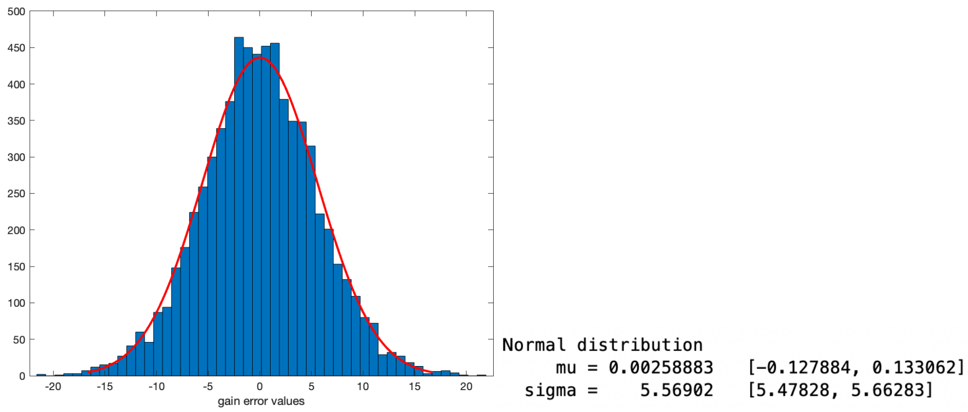

Figure 6 – Force error histogram

The Fig.7 displays a quantile-quantile plot of the quantiles of the sample of the force error versus the theoretical quantile values from a normal distribution. Is possible to see that the force error distribution is normal because the data plot appears linear.

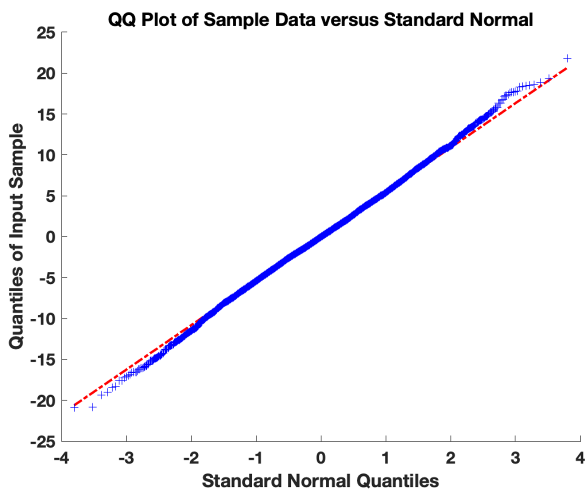

Figure 7 – Force error Quantile-Quantile Plot

CONCLUSION

The modified Bouc-Wen model was able to reproduce the nonlinear dynamic behavior of the MR damper in the conditions considered by a sinusoidal excitation. The results were validated with the current condition of 0A and the literature, in which the parameter adjustment was satisfactory because the result did not present clearances during the execution of the experiment. These small clearances in the system made the mathematical model not fit perfectly to the experimental data. As an objective for future work, a fine-tuned pin has already been designed and manufactured in order to avoid clearances in the system and provide a better fit for the parameters of the Bouc-Wen modified dynamic model and propose a new optimization method with uncertainty determination.

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