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Eccomas Proceedia SMART (2023) 1322-1329

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X ECCOMAS Thematic Conference on Smart Structures and Materials
SMART 2023
D.A. Saravanos, A. Benjeddou, N. Chrysochoidis and T. Theodosiou (Eds)

DEVELOPMENT OF A FIELD-DEPENDENT PRANDTL-ISHLINSKII MODEL FOR A LARGE CAPACITY BY-PASS MAGNETO-RHEOLOGICAL FLUID DAMPER

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Abstract. Magneto-rheological (MR) fluid dampers (MRFDs) are fail-safe semi-active devices that offer real-time controllable damping properties. These adaptive dampers show high nonlinear hysteresis behavior in their force-displacement and force-velocity responses that depends on the applied current, displacement amplitude and excitation frequency. Prediction of hysteretic force-displacement and force-velocity characteristics is essential for effective design of control strategies for smart devices based on MRFDs. This study presents a novel stop operator-based Prandtl-Ishlinskii (PI) model for estimating the nonlinear hysteresis properties of a prototyped large-scale bypass MRFD as a function of the applied current. The force-displacement and force-velocity responses of the designed MRFD were experimentally characterized under broad ranges of applied currents (0-2A), excitation frequency (0.5-4Hz) and displacement amplitude (1-2.5mm). Subsequently, a novel field-dependent generalized PI model was formulated considering multiple hysteresis operators with minimum parameters to be identified. The validity of the proposed PI model was evaluated using the experimental data. The results demonstrated that the proposed PI model could accurately characterize nonlinear hysteresis properties, including force-displacement and force-velocity, of the MRFD under the ranges of applied currents considered. Further generalization of the developed PI models, considering the effects of deformation and deformation rate, can be considered for controller design of smart structures based on MRFDs, given the fact that the derivation of its analytic invertible models can be realized in a quite straightforward manner.
Keywords:

Key words: Bypass magnetorheological fluid damper, Variable damping, Hysteresis modeling, Prandtl-Ishlinskii model.

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Peer-review under responsibility of the organizing committee of SMART 2023.
doi: 10.7712/150123.9879.440289

1 INTRODUCTION

Ground vehicles can cause a variety of negative effects due to vibration, which can range from mild discomfort or annoyance to severe degeneration of the spine and supporting structures [1]. In particular, the perception of whole-body vibration (WBV) induced by road conditions is a significant concern for human occupants of automated vehicles, as it can increase the risk of motion sickness in addition to discomfort and annoyance [2]. To address this issue, significant progress has been made in the development of semi-active suspensions, such as magneto-rheological fluid (MRF) dampers, which aim to reduce the transmission of WBV to vehicle occupants [3, 4].

Significant work has been dedicated to modelling MRF dampers in order to predict their force-displacement and force-velocity hysteresis characteristics under different levels of mechanical excitation and applied currents. These models are essential for advancing the development of control strategies for active or semi-active vibration control devices based on smart MRF dampers. These models may be classified into quasi-static and dynamic models. Most of the studies have focused on developing quasi-static models, which generally have considered Bigham plastic (BP) and Herschel-Buckley (HB) behavior for MR fluids (e.g, [5, 6]). Nonetheless, despite their advantages for purpose of early stage of design, they are not able to predict the typical hysteresis characteristics (force-displacement and force-velocity curves).

Dynamic models for MRF dampers have typically utilized either physics-based or phenomenological-based approaches to predict their force-displacement and force-velocity characteristics in relation to applied current and loading excitations. Phenomenological models are generally preferred over physics-based models, as the latter often rely on significant simplifying assumptions [7]. Phenomenological models encompass a variety of approaches, including differential equation-based models such as the Bouc-Wen model [8], as well as operator-based models such as the Preisach [9] and Prandtl-Ishlinkii [10] models. Among these, the operator-based Prandtl-Ishlinskii (PI) model has been favored for controller design due to its simplicity and analytic invertibility [11, 12].

Although operator-based hysteresis models have been widely used to describe nonlinear hysteresis phenomena in smart material actuators [13], their application to modeling the nonlinear hysteresis of MRF dampers has been limited. For example, Wang et al. [10] developed a generalized hysteresis PI model that predicts the dynamic behavior of an MRF damper under specific loading conditions using 14 parameters, which also depend on the level of applied current. However, developing effective field-dependent dynamic models, particularly with reduced number of parameters, could greatly facilitate the development of control strategies for active or semi-active vibration control devices based on MRF dampers.

In this study, we propose a field-dependent generalized PI model that predicts the dynamic characteristics of an MRF damper as function of applied current using only six parameters. The model is developed based on the measured force-displacement of a prototyped by-pass MRF damper under different levels of field current and harmonic excitations. We identify the model parameters from these measurements, and then demonstrate the validity of the proposed model by comparing its predicted force-displacement and force-velocity characteristics with the measured data over the entire range of applied current. Overall, the results show that the proposed model accurately predicts the dynamic behavior of the MRF damper.

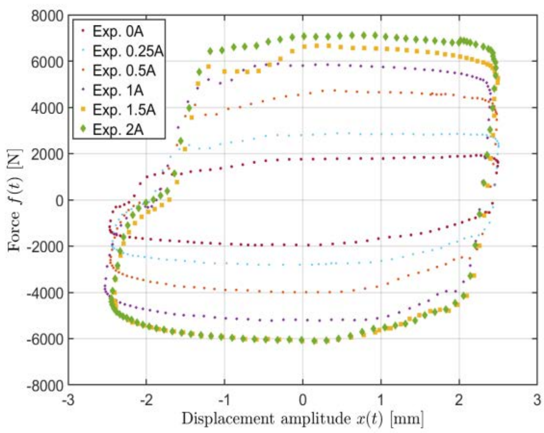
2 MRF DAMPER

A novel MRF damper with an annular-radial bypass valve was designed and prototyped for the study, as it has been reported in [14]. Briefly, the MRF damper comprised of a main piston with piston rod inside a cylindrical housing, internal spring, and an external by-pass magneto-rheological valve (MRV) with annular-radial gaps. Variations in damping was realized by controlling the magnetic field applied to the annular-radial by-pass MRV.

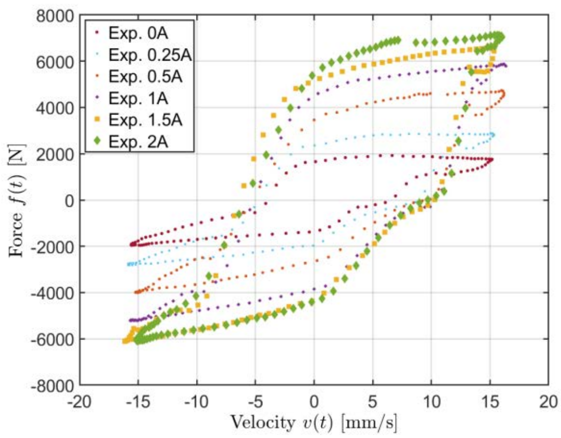
3 DYNAMIC CHARACTERIZATION

To evaluate the dynamic behavior of the proposed bypass MRF damper, an experiment was conducted to measure the force-displacement and force-velocity characteristics. The test setup consisted of an electro-hydraulic actuator integrated within a Material Testing System (MTS), as previously described in [14]. The upper part of the damper was clamped to the actuator, while the lower part of the damper (rod) was connected to a fixed frame via a load cell. A series of harmonic excitations were applied in the 0.5-4Hz frequency ($\boldsymbol{f}$) range, with a displacement amplitude ($\boldsymbol{X_0}$) ranging from 1-2.5mm. The MRV coil current ($\boldsymbol{I}$) was varied from 0 to 2 A. The force and displacement signals were acquired using a data acquisition system (National Instrument) and analyzed in LABVIEW to obtain the force-displacement and force-velocity characteristics.

In Figure 1(a), the force-displacement response of the MRF damper prototype is displayed for the entire range of applied current (0-2A) under a loading frequency of 1Hz and displacement amplitude of 2.5mm. The figure illustrates changes in the damping of the damper, which can be seen from the increase in the area enclosed by the hysteresis loop as the applied current is varied from 0 to 2A. Furthermore, the slope increment in the force-velocity curves, as depicted in Figure 1(b), indicates the controllability of damping. Similar trends were observed in other loading conditions.



(a)



(b)

Figure 1: Variations in the measured force relative to the input displacement (a) and velocity (b) based on the level of the applied current ($f\ = 1$Hz, X_0 =2.5mm).

4 MODEL DEVELOPMENT

This section introduces a generalized Prandtl-Ishlinskii model on the basis of hysteresis stop operators to predict the dynamic response of the bypass VSVD-MRFD within the range of applied current.

4.1 Prandtl Ishiliskii (PI) Hysteresis Model

The Prandtl Ishlinskii (PI) can be built using either the play or stop hysteresis operators. These operators are continuous hysteresis functions that can describe the input-output relationship for smart materials. The play and stop hysteresis operators exhibit counter-clockwise and clockwise hysteresis behavior, respectively, and are characterized by the input $v(t)$ and threshold r. Here, the stop hysteresis operator, as shown in Figure 2, is employed as it corresponds to materials/systems clock-wise hysteresis characteristics (e.g., magneto-active devices, MRF dampers) [12]. The prediction of output from the input can be achieved by a weighted superposition of the basic stop operators. For example, the force response $f(t)$ of an MRF damper subjected to an input displacement $x(t)$ can be obtained as:

$$ {}_{PI}(t) = \int_{0}^{R} p(r) E_r[x](t)dr \cong \sum_{j=1}^{N} p\left(r_j\right) E_{r_j}[x](t) \tag{1} $$

The variable $p(r)$ represents a density function that meets the condition $p(r) > 0$. The weights of the stop operators are given by $E_r[x](t)$, where $R = +\infty$ is assumed for the sake of simplicity, meaning that $p(r)$ will become negligible as r increases significantly. For any input $x(t) \in C_m[0,T]$, the value of $E_{r_j}[x](t)$ can be defined as [13]:

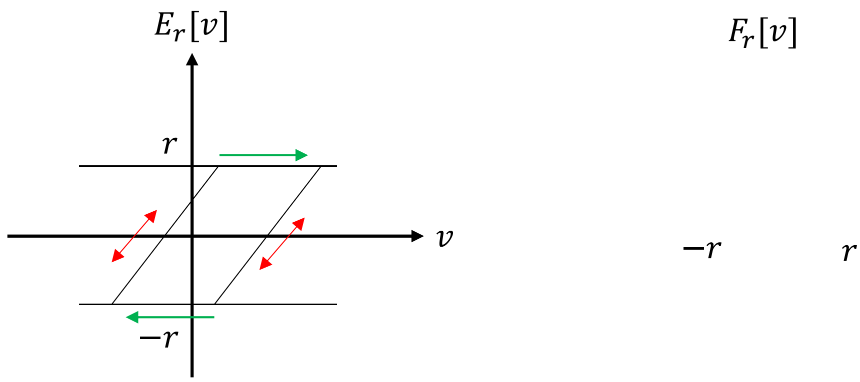


Figure 2: Stop hysteresis operator [13].

$$ \begin{cases} E_r[x](t=0) = E_r\big(x(0)\big) \\ E_r[x](t) = e_r\big(x(t) - x(t_i) + E_r[x](t_i)\big);\ t_i < t \leq t_{i+1};\ 0 < i \leq N-1 \\ e_r(x) = \min\left(r, \max\left(-r, x\right)\right) \end{cases} \tag{2} $$

The assumption made is that the space of piecewise monotone continuous functions is denoted by $C_m[0,T]$, where $[0,T]$ represents the time interval and t_i denotes a point in time within this interval. Moreover, N is used to indicate the number of stop operators that are being considered, where j is used as an index for the stop operators $(j = 1, \ldots, N)$.

4.2 Formulation of the proposed generalized PI Model

In order to estimate the force-displacement and force-velocity responses of the fabricated bypass MRF damper using the PI model presented in Eq. (1), we consider the following exponential functions for both the threshold and density functions to adequately describe the output saturation:

$$r_j = ae^{-bj}; \quad p(r_j) = \gamma r_j^{-\delta} = \alpha j^{\beta}; \; j = 1, 2, 3, \ldots, N \tag{3}$$

The above-defined threshold function, r_j, is classically being presented as function of index j. However, to consider the field-dependency, the following generalized threshold functions is suggested as:

$$r_j = (ae^{-bj})(\frac{1}{1+ce^{-dI}}); \quad j = 1, 2, 3, \ldots, N \tag{4}$$

where a,b, c, d, α, and β are positive coefficients. The chosen fractional-exponential function $(\frac{1}{1+ce^{-dI}})$ in Eq. (4) permits consideration of magnetic saturation phenomenon.

5 IDENTIFICAITON O4F MODEL PARAMETERS

In this section, a method is described for obtaining the model parameters for a proposed PI model using a cost function. The cost function, $J(I)$, is defined as:

$$J(I) = \sum_{k=1}^{M_k} \sum_{I=1}^{N_I} (\ _{Exp.}(t;I) - \ _{PI}(t;I)) \tag{5}$$

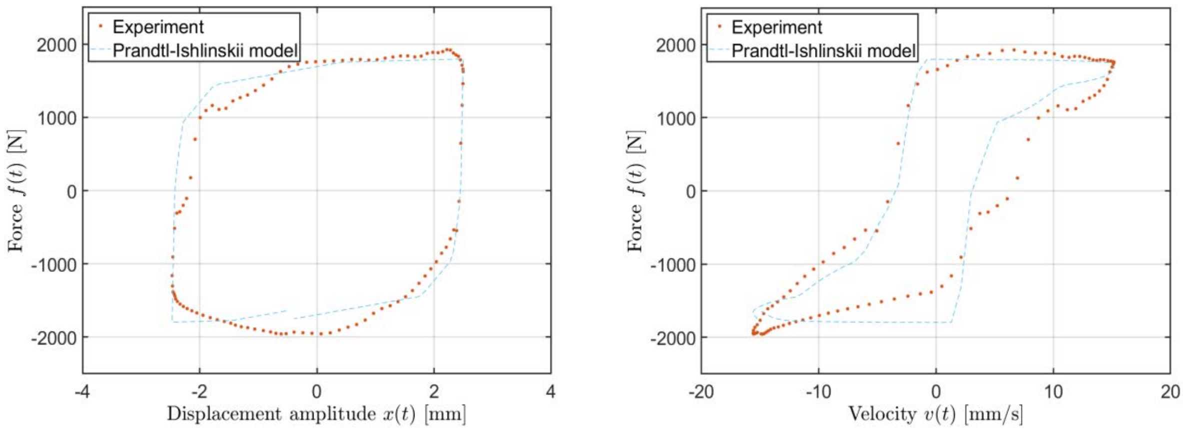
where I is the applied current and a, b, c, d, α, and β are the model parameters. The goal is to minimize the cost function by adjusting the model parameters to obtain the best fit between the model-predicted force (f_{PI}) and the measured force (f_{Exp}), simultaneously for all the applied currents. To solve the optimization problem, the lower and upper bounds of the parameters are initially defined, and the problem is solved in two stages. In the first stage, a genetic algorithm (GA) is used to identify near global model parameters. The output of the GA is then imported to a gradient-based algorithm based on the sequential quadratic programming (SQP) in the second stage. The solutions obtained from SQP ensure the true global minima. Table 1 presents the identified parameters.

Table 1: The identified model parameters.

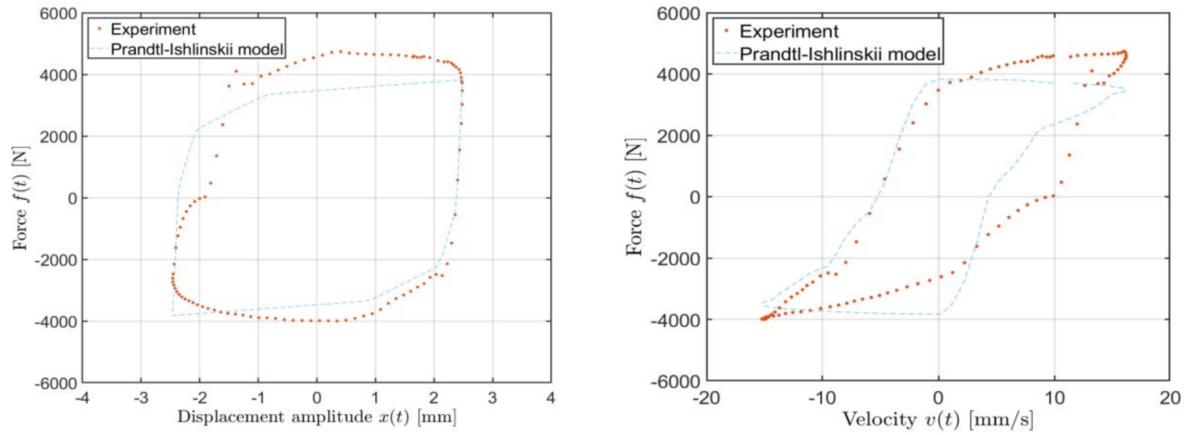
a	b	c	d	α	β	R^2(%)
5.721	1.392	2.758	2.751	9.276	1.896	92.68

6 MODEL VALIDATION

In this section, the validity of the proposed PI model is demonstrated by comparing the model-predicted responses with those obtained experimentally for a wide range of applied currents. Figures 3(a) and 3(b) show the comparison of the model-predicted force-displacement and force-velocity hysteresis responses of the VSVD-MRFD, as an example, under the applied current of 0A and 0.5A, respectively. The results correspond to a loading frequency of 1Hz and a displacement amplitude of 2.5mm.



(a)



(b)

Figure 3: Comparison of the model predicted force-displacement and force-velocity responses of the VSVD-MRFD with respect to those experimentally obtained: *I*=0A (a), and (b) *I*=0.5A.

The results show reasonably good agreements between the dynamic behavior of MRFD predicted by the proposed PI model and the measured responses. This indicates that the proposed PI model is a valid representation of the dynamic behavior of the MRFD under the given excitation conditions. It should be noted that further development of the proposed model would allow the prediction of the dynamic behavior of the MRFD under a wide range of excitation amplitude and frequency. This suggests that the proposed PI model has the potential to be a useful tool for predicting the behavior of the MRFD under various operating conditions.

7 CONCLUSIONS

In this paper, a novel field-dependent generalized Prandtl-Ishlinskii (Pi) model with only six parameters is formulated using the stop hysteresis operator to predict the dynamic behavior of a prototyped bypass MRF damper under a wide range of applied current, ranging from 0 to 2A. The results showed that the developed model can effectively predict the force-displacement and force-velocity responses of the variable stiffness and variable damping MRF damper over the entire range of applied current. Despite the field dependent characteristics of the proposed PI model with reduced number of parameters, further development of the proposed model would be desirable for predicting MRF damper responses as functions of the excitation displacement and velocity.

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