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Resistor-capacitor (RC) operator-based hysteresis model for magnetorheological (MR) dampers

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ABSTRACT

Aiming at efficiently and precisely describing and predicting the rate-independent nonlinear hysteresis characteristics of magnetorheological (MR) dampers, this paper investigates a resistor-capacitor (RC) operator-based hysteresis model for MR dampers. The model is under the frame of the "restructured model" proposed by Bai et al. ("Principle and validation of modified hysteretic models for magnetorheological dampers," *Smart Materials and Structures*, 24(8), 085014, 2015) with the RC operator substituting the Bouc-Wen operator. The essence of the RC operator is the theoretical generalization of the hysteresis phenomenon that the RC circuit presents in charging and discharging processes. In detail, a virtual displacement variable and updating laws for reference points are employed. The virtual displacement keeps positive in uploading (i.e., RC circuit in charging process) while negative in downloading (i.e., RC circuit in discharging process). The hysteresis output is achieved through applying algebraic expressions, which realizes the RC operator. Based on the experimental results of a MR damper, the comparison and analysis of the RC operator-based model and the Bouc-Wen operator-based hysteresis models, including the Bouc-Wen model and the restructured model, are conducted.

1. Introduction

Magnetorheological (MR) dampers based on the smart material – MR fluids, have the advantages of simple structure, fast responses, continuous tunable damping force, and large dynamic force range. They are widely used in vibration and/or shock control systems, such as construction structures [1–3], gun recoil systems [4], steering and suspension systems of vehicles [5–7] and other fields [8,9]. In engineering applications, only if an accurate mathematical model for MR dampers is obtained, could the controller rapidly and precisely regulate the control signal to realize the efficient MR semi-active control. However, due to the inherent strong nonlinear hysteresis characteristics of MR dampers, it is difficult and is a challenge task to develop an efficient and precise mathematical model to describe and predict their nonlinearity. Consequently, one category of hysteresis models based on the damping force versus velocity curves of MR dampers have been proposed, such as polynomial model [10], neural network model [11,12], sigmoid model [13], and division-based model [14]. These models are formulated to fit the tested hysteresis loops under the certain excitations, and they are unable or inefficient to predict the damping forces of MR dampers. Another category of hysteresis models based on the damping force versus displacement curves of

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MR dampers have also been investigated. For example, the Bouc-Wen operator-based hysteresis models [15–17] have attracted much attention because of the powerful performance to describe the hysteresis phenomenon. The Bouc-Wen model, which is initially formulated by Bouc [18] and later modified by Wen [19], is versatile for capturing hysteresis characteristics by adjusting the model parameters [20]. Experimental research shows that the Bouc-Wen model can well portray the typical hysteresis behavior even under random excitations [15]. The schematic of the Bouc-Wen model is presented in Fig. 1. According to Fig. 1, the Bouc-Wen model is expressed as

$$F = c_0\dot{x} + k_0 x + \alpha z + f_0 \tag{1a}$$

$$\dot{z} = -\gamma|\dot{x}|z|z|^{n-1} - \beta\dot{x}|z|^n + A\dot{x} \tag{1b}$$

where F is the output damping force; c_0, k_0, and α are the damping coefficient, stiffness coefficient, and hysteresis coefficient, respectively; β, γ, n, and A are the hysteresis factors; x, $\dot{x}$, and f_0 represent the displacement excitation, relative velocity, and offset elastic force due to initial displacement, respectively; z is the Bouc-Wen hysteresis operator. According to Eq. (1), the nonlinearity and hysteresis of output F can be controlled by adjusting the parameters.

Spencer and Dyke [15] presented a phenomenological model based on the Bouc-Wen model. The phenomenological model enhances the accuracy for describing the damping force characteristics of MR dampers with an improved performance of the Bouc-Wen model at small velocities. But the model complexity increases a lot. Miah et al. [21] proposed an enhanced Bouc-Wen model to describe nonlinear hysteresis characteristics of a rotational MR damper. Ismail et al. [16] demonstrated that some parameters of the Bouc-Wen model are unnecessary and introduced a normalized Bouc-Wen model based on a normalization concept. Bai et al. [22] presented a restructured model base on the phenomenological model and the normalization concept, as shown in Fig. 2. The model decreases the number of the parameters, reduces the model complexity, and at the same time describes the nonlinear hysteresis characteristics of MR damper more efficiently. However, due to the differential expression of the Bouc-Wen operator (referring to Eq. (1b)), demanding requirement of computational hardware is required to conduct the parameter identification of the Bouc-Wen operator-based hysteresis models.

Consequently, in this study, a resistor-capacitor (RC) operator-based hysteresis model in the frame of the restructured model is presented to describe and predict the rate-independent hysteretic nonlinearity of MR dampers and other smart actuators based on smart materials, structural elements, mechanical systems, and energy dissipation systems. The model is based on hysteresis phenomenon occurring in the RC circuit in charging and discharging processes. Utilizing an established

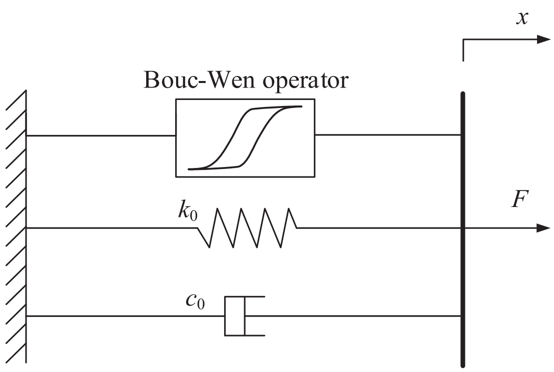

Fig. 1. The schematic of the Bouc-Wen model.

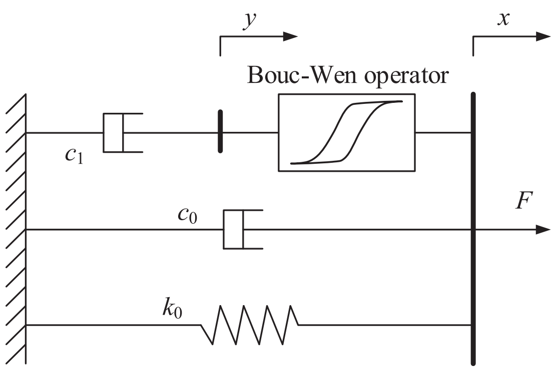

Fig. 2. The schematic of the restructured model [22].