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Exact physical model of magnetorheological damper

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ABSTRACT

This paper attempts to fill the gap in the literature by introducing and discussing an enhanced physical model of the MR damper. The essence of the presented model is to combine the effect of compressibility of the MR fluid enclosed in each chamber with the effect of blocking the flow between the chambers in the case of a low pressure difference. As it will be shown, the concurrence of both considered phenomena significantly affects mechanical behaviour of the damper, influences its dissipative characteristics, and in particular, it is the reason behind the distinctive 'z-shaped' force–velocity hysteresis loops observed in experiments. The paper presents explanation of the observed phenomena, detailed derivation of the thermodynamic equations governing response of the damper, their implementation for various constitutive models of the magnetorheological fluid and, finally, formulation of the corresponding reduced and parametric models. Experimental validation shows that proper identification of physical parameters of the proposed mathematical model yields the correct shapes of force–velocity hysteresis loops.

1. Introduction

Among many controllable devices applied in the systems of adaptive impact absorption [1–3], one of the most promising is semi-active magnetorheological damper [4]. The crucial problem in the optimal design and control of such devices is the accurate mathematical modelling of their response under external excitation. Since mechanical behaviour of the MR dampers is influenced by diverse thermodynamic and rheological phenomena, the corresponding mathematical models are relatively complex and their derivation is still the subject of intensive research efforts.

Two basic types of models of magnetorheological dampers are widely considered in the literature:

i) Parametric phenomenological models, which are typically based on Bingham plastic model [5,6], Bouc–Wen hysteretic model [7–10] or Duffing's equation [11]. Other types of models are based on sigmoid [12] or hyperbolic tangent function [13] or neural networks [14]. A very good review of parametric models can be found in [15].
ii) Physical models, which typically utilize a viscoplastic model of the MR fluid and the equations that govern its flow through an orifice [16].

Although a large number of various parametric models is already developed, many miscellaneous modifications of these models are permanently proposed. Most of the parametric models can properly capture the dynamic characteristics of the MR dampers, however their disadvantage is a large number of internal parameters, difficult and time consuming procedure of model tuning and the ambiguity of the obtained solution. On the other hand, the physical modelling of the MR dampers is

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much less developed. Physical models often utilize simplified assumptions such as the incompressible Bingham or Herschel–Bulkley plastic models of the fluid and the steady Poiseuille flow through the orifice. It seems that such constructed physical models cannot accurately explain all dissipative properties obtained in experimental tests.

This paper attempts to fill the gap in the literature by introducing and discussing an enhanced physical model of the MR damper. The essence of the presented model is to combine the effect of compressibility of the MR fluid enclosed in each chamber with the effect of blocking the flow between the chambers in the case of a low pressure difference. As it will be shown, the concurrence of both considered phenomena significantly affects mechanical behaviour of the damper, influences its dissipative characteristics, and in particular, it is the reason behind the distinctive ‘z-shaped’ force–velocity hysteresis loops observed in experiments.

The main objective of the paper is twofold. At first, it is to derive the mathematical equations of the exact physical model of the MR damper, to reveal their specific forms corresponding to various constitutive equations of the fluid, and to present different options of their possible simplifications. Secondly, it is to show that after measurement or identification of physical parameters the proposed mathematical model yields the correct shapes of force–velocity hysteresis loops.

The development of the parameter identification procedure and an exact comparison of the numerical and experimental results is out of scope of the current stage of research. Consequently, the model is based on the exact geometry of the damper and the assumption of a quadratic dependence of the yield stress level and apparent viscosity on the applied current. The coefficients are manually adjusted to fit the conducted experiment. The research is concluded by proving that a proper selection of these parameters within their physical range allows to achieve a satisfactory qualitative correspondence between the numerical and the experimental results for a selected set of working conditions.

The considerations start with a presentation of the results obtained during experimental testing of the damper and with their basic explanation. The subsequent section is aimed at a detailed derivation of the mathematical model, which utilizes an analytical model of the viscous flow and fundamental laws of thermodynamics in order to obtain a convenient form of the equations that describe the balance of the fluid volume and the balance of the fluid energy. The consecutive part presents the governing equations and the corresponding numerical results for various constitutive models of the magnetorheological fluid that involve diverse treatments of compressibility. Finally, in the last section, a reduced model is proposed, where the generated force is expressed analytically in terms of the kinematic excitation and a special form of the corresponding parametric model. The basic form of the governing equations based on fluid decomposition theory and their implementation for two constitutive models of the fluid were presented in our previous conference publication [17].

2. The experiment and its basic explanation

A series of dynamic tests was carried out on a magnetorheological fluid damper MRD1003-5 produced by the LORD company. The damper is designed for adaptive systems of vibration damping of driver’s seats in heavy vehicles and it provides the maximal damping force of 2224 N at the piston velocity of 50 mm/s. The schematic view of the tested damper, which can be regarded as an example of a typical MR damper, is presented in Fig. 1b.

The damper consists of two chambers divided by a piston that contains a magnetic circuit. The movement of the piston induces the MR fluid flow through the channel in the presence of the magnetic field, which is perpendicular to the direction of the flow. Additionally, the damper is equipped with a gas spring located at the bottom of the lower chamber, which provides an initial pressure of approximately 2 MPa.

During the tests the damper was subjected to harmonic and linearly varying kinematic excitation with different displacement amplitudes and velocities by means of an MTS hydraulic testing system, consisting of FlexTest GT controller and a linear actuator type 242.01 (Fig. 1a). The experimental stand enabled measurements of force, displacement, velocity of the piston and the temperature of the damper housing, as well as recording analog control signals (voltage and current) of the electronic power amplifier, which was driving the damper.

The tests were conducted for selected range of amplitudes and frequencies of the kinematic excitation. The excitation frequency range was between 0.5 Hz and 4 Hz, and the applied control current varied from 0 A to 1 A. The most important result of the experiment was the occurrence of force–velocity hysteresis loops of a characteristic shape with large internal region in the vicinity of zero velocity. The evolution of hysteresis loops obtained experimentally for different combinations

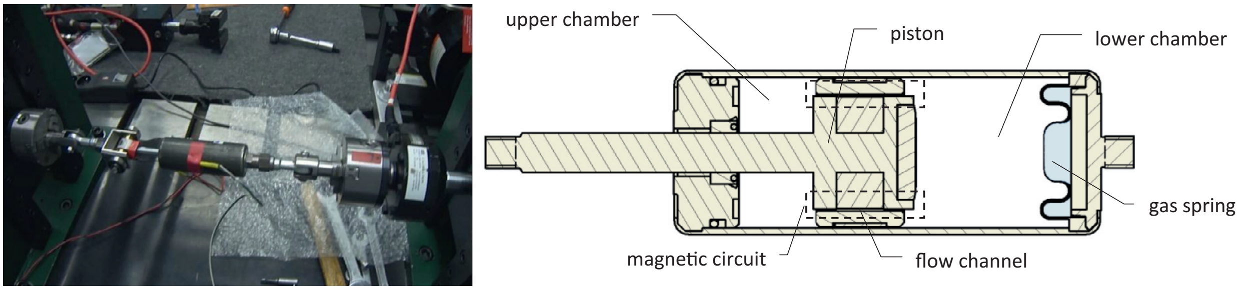

Fig. 1. (a) Experimental stand, (b) schematic model of the MR damper.