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Principle, modeling, and testing of an annular-radial-duct magnetorheological damper

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ABSTRACT

Aiming at improving the efficiency of magnetorhelogical (MR) dampers, the principle of an annular-radial-duct MR damper (ARDMRD), in which annular-radial ducts in series in MR fluid flow channel are integrated, is presented and the prototype of the ARDMRD is designed and fabricated. The mathematical model of the ARDMRD considering the nonlinear flow effect of the MR fluid in the flow channel is established. The finite element analysis (FEA) is utilized to validate the principle of the ARDMRD and obtain the magnetic properties of its magnetic circuit. The controllable damping force and equivalent damping of the ARDMRD are tested on the established experimental setup based on MTS 849 shock absorber test system and compared with the theoretical results based on the mathematical model and FEA. The tested controllable damping force of the ARDMRD under excitation velocity of 0.19 m/s is as high as 3149 N and the tested damping force range of the ARDMRD under excitation velocities of 0.025–0.19 m/s is 140–3149 N. The research results show that the designed magnetic circuit structure of the ARDMRD is beneficial to improving the efficiency of the MR damper and the established mathematical model of the ARDMRD can describe and predict its damping force performance accurately.

1. Introduction

Magnetorheological (MR) fluids [1–3], as one kind of typical active materials, have attracted considerable interests recently as it can provide a simple and rapid response interface between electronic control and mechanical systems. MR dampers, which take the advantages of MR fluids, have excellent performances as one promising semi-active actuator, including rapid response, controllable damping force, simple structure, and low power consumption. Even the control systems fail to work, MR dampers can still act as passive actuators in semi-active control systems based on MR dampers.

Over the past two decades, MR dampers with various magnetic circuit structures have been presented, studied, and applied in semi-active control systems [4–10]. Carlson and Chrzan [11] presented a MR damper principle with an annular fluid flow channel in 1994 and developed a commercially available MR dampers (type: RD-1005-3, LORD Corp.). Later, Carlson and Spencer [10] presented a full-scale MR damper with the same structure used in civil structures with the maximum controllable damping force of as high as 20 kN. However, the volume of the MR fluid in one MR damper is over 5 l. Thence, MR dampers with bypass valves [12–14] and with bifold valves [15] have been studied. The controllable damping force of the MR dampers with bypass valves is much larger than that of the traditional ones, whereas the MR dampers always occupies much larger installation space. As for the MR damper with bifold valves, two identical MR valves are set at the two ends of the cylinder of the MR damper, which makes the structure of the MR damper complex. How to improve the controllable damping force and the efficiency simultaneously and guarantee the installation space of MR dampers is a challenge which should be confronted and solved when designing MR dampers. Besides, in order to control the MR dampers based semi-active systems efficiently, the mathematical models of the MR dampers, i.e., the damping force performance, should be described and predicted efficiently by the established models. For the MR dampers that are applied in low-speed environments, the quasi-steady models [16,17] are adequate to describe the damping force of the MR dampers. While for the high-speed applications, the nonlinear flow effect of the MR fluid [14,18,19] or the effect of MR fluid-walls of the MR dampers [20–23] are of significance and not negligible.

Ai and Wang [24,25] presented an MR valve with both annular and radial fluid flow resistance gaps and the efficiency of the MR valve was improved apparently. Nguyen et al. [26,27] further

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Table 1
Structural dimensions and materials' properties of the developed ARDMRD.

Parameter	Symbol	Value
Damper length	l_D	185 [mm]
Damper radius	r_D	24 [mm]
Radius of piston rod	r_{pr}	5 [mm]
Piston radius	r_p	20 [mm]
Radius of circular disk	r_d	12.84 [mm]
Radius of core	r_c	10.54 [mm]
Radius of central hole of core	r_o	3.5 [mm]
Height of annular duct	h_a	8.6 [mm]
Thickness of radial duct	t_r	1.0 [mm]
Thickness of annular duct	t_a	1.0 [mm]
Thickness of core cylinder	t_c	6.36 [mm]
Core height	h	30 [mm]
Piston maximum displacement	s	50 [mm]
Exciting coil turns	N	280 [Turns]
Magnetic steel material		20# steel
Nonmagnetic steel material		304# steel
Density of MR fluid	ρ	3.08×10^3 [kg/m^3]

simulated and optimized the structure of the MR valve based on the principle for optimizing MR valves and MR dampers with constrained volume presented by Rosenfeld and Wereley [28], and obtained the same results with those by Ai and Wang [24,25].

Based on the structural principle of the MR valve presented by Ai and Wang [24,25], this paper presents an annular-radial-duct MR damper (ARDMRD) with integrated annular-radial ducts in series in the MR fluid flow channel. The prototype of the ARDMRD is designed, fabricated, and mathematically modeled. The principle and performances of the ARDMRD are theoretically and experimentally validated. In addition, the performances of the developed ARDMRD are compared with a commercially available MR damper (type: RD-1005-3, LORD Corp.).

2. Principle and prototype

Fig. 1(a) and (b) shows the structural principle and three-dimensional (3D) drawing of the ARDMRD, respectively, and Fig. 1(c) shows the photograph of the exploded components of the ARDMRD fabricated with the structural dimensions and materials' properties as listed in Table 1. Observing Fig. 1, the ARDMRD comprises the piston unit, piston rod, and damper cylinder. The piston unit consists of a magnetic core with a through-hole in center, two magnetic circular disks, an exciting coil wound on the nonmagnetic bobbin, a magnetic core cylinder, nonmagnetic washers, and nonmagnetic positioning pins. Two identical circular disks are connected to the two ends of the magnetic core by pins and the radial ducts are formed. The washers that are coaxially installed with the corresponding pins guarantee the thickness of the radial ducts. The core that is housed in the bobbin and connected with two circular disks is coaxially positioned in the core cylinder. Then the annular ducts are formed between the inner circumference of the core cylinder and the outer circumferences of the circular disks, as shown in Fig. 1(a) and (b). As it can be seen in Fig. 1(a) and (b), as the piston compresses (rebounds) relative to the damper cylinder, the MR fluid flows from the lower (upper) annular duct into lower (upper) radial duct. Then the MR fluid flows into the upper (lower) radial duct through the central hole of the core. At last, the MR fluid flows out of the piston through the upper (lower) annular duct. The MR fluid is filled in to flow in the channels by a pressure drop, which is controlled by the magnetic field.

The magnetic field generated by the exciting coil with current starts from the core, goes though the radial duct, circular disk, annular duct, along the core cylinder, through the annular duct, circular disk, and radial duct to complete a closed magnetic circuit. When applying a magnetic field, the MR fluid flowing through the annular-radial duct will give rise to pressure drop at the two ends

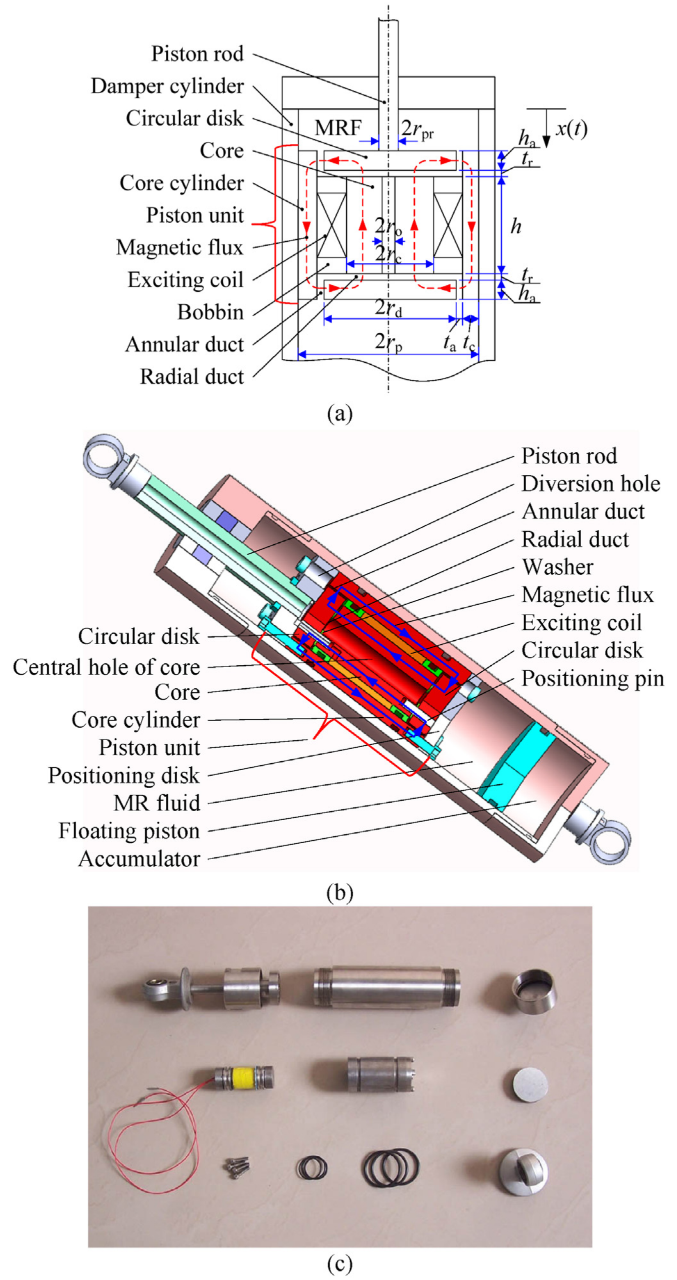

Fig. 1. Developed ARDMRD: (a) the structural principle, (b) the 3D drawing, and (c) the photograph of the exploded components.

of the duct because of the yield stress of the MR fluid. The yield stress continuously increases with increasing the current applied to the exciting coil before the magnetic field strength for the MR fluid/ARDMRD structure is saturated. In this way, the damping force generated by the ARDMRD can be controlled continually by tuning the current applied to the exciting coil.

3. Theoretical modeling

As it can be seen from Fig. 1, the operation mode of the MR fluid in the ARDMRD is the valve mode [2]. The damping force of the ARDMRD can be expressed as

$$F = (\Delta P_a + \Delta P_r + \Delta P_{ml})A_p + f_a \quad (1)$$

where ΔP_a and ΔP_r are the pressure drops through the annular ducts and the radial ducts, respectively; ΔP_{ml} is the minor loss