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Experiments and modeling of a new magnetorheological cell under combination of flow and shear-flow modes

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ABSTRACT

Magnetorheological (MR) fluid is a suspension of small iron particles, where, in the presence of a magnetic field, the solid particles arranged themselves as deformable chains. The deformation of the chain structure can be performed in three common modes known as flow mode, shear mode and squeeze mode. Among the three, the flow and shear modes have been widely investigated and used in commercial applications. Nevertheless, limited focus has been given to the combination of both modes. Furthermore, the existing combination between the flow and shear mode has been always defined at the same effective area, which is commonly known as the shear-flow mode. This paper provides a new perspective of mixed mode by arranging in series the different modes in the same MR cell. In order to manifest the theoretical model, an effective area representing the shear-flow mode is positioned separately with another effective area of the pure flow mode. The magnetic circuit design is validated by using the finite element method in 2D simulation. Moreover, the simulated results of magnetic flux density in the MR fluid are used to predict the force produced by the flow and shear-flow modes. The fabricated cell is tested under quasi-static loading and the results are compared with those that were predicted. It can be concluded that, to a certain extent, the obtained experimental results have been successfully predicted by the proposed model.

1. Introduction

Smart fluids or field responsive fluids are materials for which the viscosity can be reversibly controlled depending upon the value of the external field applied. Magnetorheological (MR) fluids, electrorheological (ER) fluids and ferrofluids are amongst the well-known smart fluids used for research and applications [1]. The dramatic rheological change exhibited by the fluids leads to a complex deformation behavior that is nothing like classical elasticity or fluid mechanics. In the case of MR fluids, the existence of micron-sized magnetically soft particles suspended in the fluid medium causes the formation of particle aggregates and chains under the presence of a magnetic field [2,3]. In this condition, the induced material state is nearly similar to that of a solid. The strength of this breakable structure is defined by the yield stress point after which the plastic deformation behavior can be identified.

The induced structure of MR fluids can be deformed in three different ways, which are commonly known as flow mode, shear mode and squeeze mode [4]. The concept of these three operational modes is illustrated in Fig. 1. In all modes, the MR fluid is always situated between two magnetic pole plates and the direction of the magnetic flux lines is always perpendicular to the plates in respect of the agreed fundamental chain structure. The region where the flux lines cross the MR fluid from one plate to the other perpendicularly can be defined as the effective area (see Fig. 2). In the flow mode (see Fig. 1(a)), the activated MR fluid is deformed by the difference in pressure drop in the direction of the fluid flow. In the literature, many variants of the term have been used by researchers regarding the flow mode, such as valve mode [4–6], Poiseuille flow mode [7], pressure-driven flow mode [7–9] or simply flow mode [10,11]. In terms of application, the use of a valve as a fluid flow regulator in conventional devices is replaced by this concept of flow mode in MR fluid based-devices, such as servo valves, hydraulic controls, dampers, actuators and shock absorbers [12].

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In the shear mode (see Fig. 1(b)), the activated MR fluid is deformed by moving one of the plates in a parallel direction to the plate, through which two types of movement can be identified – either translating or rotating perpendicularly to the magnetic flux lines. The former has been called the direct shear mode by some researchers [9,13] and the latter is sometimes termed the torsional mode [5]. Other variant terms referring to the shear mode in the literature are the Couette flow mode [14] and clutch mode [4,11]. The concept of shear mode is appropriate for medium-frequency devices like clutches, brakes, locking devices, breakaway devices and small displacement dampers [12].

Meanwhile, in the squeeze mode (see Fig. 1(c)), the semi-solid MR fluid is deformed by compression or tension movement. Some researchers refer to this mode as the squeeze-flow mode [15–18], as the fluids experience inevitable radial flow motion to the outside of the pole plates. While some other researchers prefer to used the term squeeze-film mode [4,5,9], as the high force is attained when the distance between the pole plates is small. Thus, the squeeze mode can be applied in the applications that require low motion or small displacement like in engine mounts, impact dampers and vibration suppression devices [4,11].

Alternatively, the existing operational modes can be combined and are commonly known as mixed mode [6,19,20], which can be divided into two categories of understanding. The first one is the mixed mode with the same effective area. Some scholars believe that there are working modes that cannot be operated in isolation, especially in practice [9]. For example, Sung et al. [10] anticipated a mixed shear-flow damper for a building structure by using a double rod end piston (see Fig. 3). When the piston moves, the activated MR fluid is sheared in the gap, and, at the same time, the fluid is forced to flow from one chamber to another by the difference in pressure in the closed system damper.

In another study, a similar concept of mixing shear and flow modes in an MR damper that was developed by General Motors Research and Development was studied by Browne et al. [21] in which the shear and flow modes shared the same effective area. The damper consists of a single rod end piston in which the electromagnetic coil is wound around the piston. Meanwhile, Choi et al. [22] devised an MR mount for the vibration control of a structural system (see Fig. 4). The same concept of combination shear and flow modes was proposed in which the activated MR fluid in the effective region is deformed under flow pressure and by the moving plate at the same time. However, the electromagnetic coil was placed in the housing of the MR mount and not in the piston as in the previously identified MR devices.

The squeeze and flow modes were also believed to be an inseparable mode [1,15,16,18], as when the fluid is compressed between the plates, the fluid will certainly outflow in a radial direction concurrently. Although both modes share the same effective area,

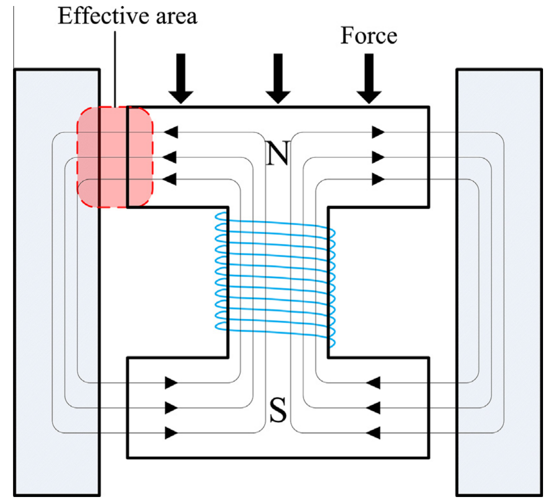

Fig. 2. An example of electromagnetic coil wound around a bobbin showing one of the effective areas.

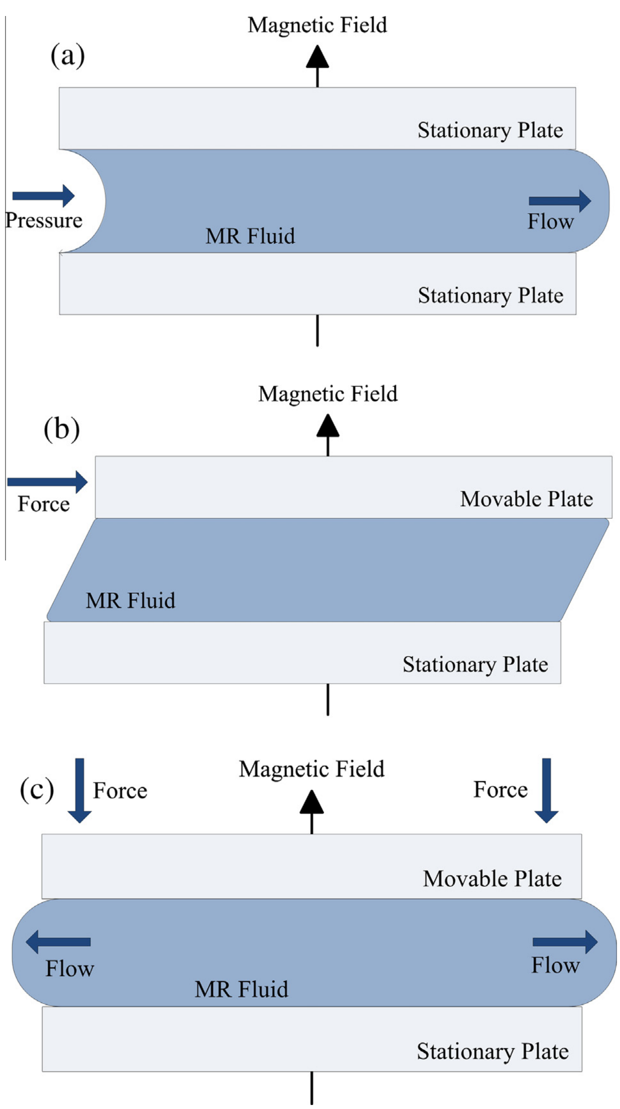

Fig. 1. The concept of basic operational modes of MR fluids; (a) flow mode, (b) shear mode, and (c) squeeze mode.

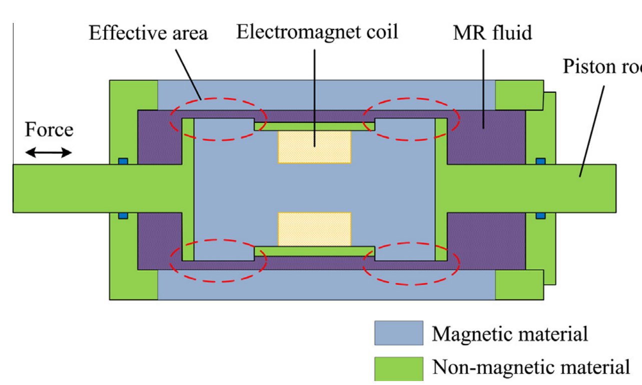

Fig. 3. The mixed mode MR damper by Sung et al. [10] where the flow and shear modes shared the same effective area (in dashed lines).