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Acoustic velocity and attenuation coefficient of magnetorheological fluids under electromagnetic fields

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ABSTRACT

Magnetorheological fluid (MRF) is a class of smart material whose acoustic properties can be varied rapidly and reversibly by the applied magnetic field. The MRF is proposed to be as actively sound barriers or acoustical metamaterial. This paper presents a theoretical model to study acoustic propagation in MRF under fields based on the Biot–Stoll model. The model considers the coupling interaction between ferro particle and base fluid. This paper investigated the acoustic velocity and attenuation of a commercial MRF dependence on the different parameters such as carrier fluid viscosity, permeability and intensity of magnetic field. The calculated results show that the attenuation is increased with small field strengths and independent on field strength when the magnetization begins to saturate.

1. Introduction

Both Electrorheological fluid (ERF) and magnetorheological fluid (MRF) are "smart materials" whose mechanical properties exhibit fast strong and reversible changes under electro or magnetic fields, which resulting in drastic changes in acoustic properties. Recently, the ERF and MRF are proposed to be as actively sound barriers or acoustical metamaterial [1–3]. Controlling applied voltage or magnetic field may enable more advanced acoustic capabilities such as cloaking or super-lensing [2,3]. However, ER material exhibits a number of shortcomings compared to the MR material including low yield strength, requirement of high voltage and greater sensitivity to common impurities. Hence, this paper is focused on MRF.

The MRF consists of micron size magnetically permeable particles suspended in a carrying liquid such as the mineral or silicon oil, as shown in Fig. 1. It is can be seen from Fig. 1a that the ferromagnetic particles are scattered randomly in the liquid carrier in the absence of magnetic fields. Fig. 1b shows that a magnetic dipole moment is induced particles tend to align chain-like structures under magnetic fields, giving rise to significant variation in acoustic properties.

The acoustic properties of MRF are very complex under magnetic field. Since discovery of the MRF, several theoretical and experimental studies have been conducted to investigate the acoustic properties in MRF.

Malinnovsky et al. [2,3] considered MRF as a linear chain consisting of the effective mass-spring oscillator. In their study, the theoretical model of acoustic wave propagation in MRF is based on one dimensional wave equation in the elastic medium.

Howarth et al. [4] conducted a series of acoustic experiments at the National High Magnetic Field Laboratory in Tallahassee, Florida. The acoustic sound speed of MR fluids was measured as functions of applied magnetic field strength, normal and orthogonal field orientations, and acoustic frequency. Their presentation discussed measurement methodology and preliminary results about the MRF.

Bramantrya et al. [5,6] focused on the experimental measurement of ultrasonic propagation velocity in the MRF change with an external magnetic fields intensity, interval time and angle of the magnetic field. They measured ultrasonic propagation velocity in MRF precisely and the clustering structures of MRF were analyzed in terms of elapsed time dependence, effect of external magnetic field strength and angel. A comparison of ultrasonic velocity propagation between magnetic and MRF was discussed.

López et al. [7] measured ultrasonic acoustical velocity of a commercial MRF in static conditions (when the fluid is not flowing). In their experimental study, sound velocity and wave amplitude at 1 MHz were analyzed as a function of the uniformity, direction and intensity of the magnetic field. The anisotropy and rearrangement micro-structure of MRF was analyzed in terms of sound speed and amplitude changes.

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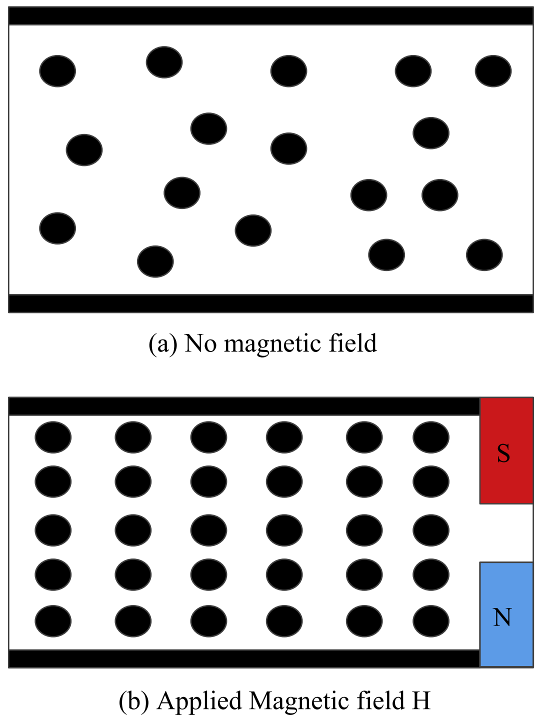

Fig. 1. The MR effect: (a) the particles in the absence of magnetic fields; and (b) particles magnetized and form columns when applied field.

Previous theoretical models [2,3] study the sound propagation in MRF based on the one-dimensional wave equation of the elastic medium. However, coupling interaction of the ferromagnetic particle to the base fluid is not considered in present research. Hence, we propose a more accurate theoretical model to study acoustic propagation in MRF based on the Biot–Stoll theory which considers the coupling interaction of ferro particle skeletal frame to the base fluid. The other researchers [4–7] are restricted to the experimental investigation qualitative analysis the sound velocity and attenuation in MRF by ultrasonic technique. The sound propagation in relation to the inner structures of MRF and magnetic field is still not clear. Hence, this paper presents an analytical model for wave propagation in MRF based on Biot–Stoll theory, which has been developed for porous elastic media saturated by a compressible fluid [8–10]. In order to predict the effective material behavior of the composite, the MRF is regarded as homogeneous on macro scale. Then, we submit a new rheological model for description non-linear material effect of MRF under magnetic field. The flow viscosity is modeled as function of the shear rate under magnetic field. In Section 4, we discuss the corresponding numerical calculations for the acoustic attenuation and velocity relation on its viscosity, permeability inner properties and magnetic field.

2. The sound wave propagation in MRF

In presence of an external magnetic field, MRF is composed of assemblage ferromagnetic grains, which is the skeletal frame, and base fluid saturating the pores, which is the pore fluid. So the structure of MRF behaves as a skeletal frame filled with a base fluid, suggests an attempt of modeling its mechanical behavior by the Biot–Stoll theory.

Biot developed a comprehensive model of acoustic wave propagation in porous, elastic, solid medium saturated by a viscous fluid. In order to predict the acoustic properties of unconsolidated granular sediments. Stoll extended the Biot's model by considering friction between the grains by making the frame bulk and shear modulus complex. Nowadays, this extended Biot model is called the Biot–Stoll model. In Biot–Stoll model, there existences of two longitudinal waves in the medium and a shear wave at the interface of the medium. One of two longitudinal waves is called "the first kind". The other longitudinal wave is called "the second kind". The "first kind" is comparable to the usually observed longitudinal wave in a homogeneous medium (frame and fluid oscillate essentially in phase). In contrast, the longitudinal wave of the "second kind" is highly attenuated (frame and fluid oscillate essentially in anti-phase).

Only the first kind is important in MRF. The wave of the second kind is highly damped, because the oscillations of frame and fluid are nearly out of phase. This wave can be omitted. For the shear wave will not propagate in fluid state. In the solid state, a shear wave might exist, but because of the dominant fluid character will not become applicable and is omitted here, too.

In this study, we will treat only the first kind of longitudinal wave. Let u is displacement of the frame, U is displacement of the pore fluid relative to the frame. Then e is the dilation of a volume element attached to the frame and ζ is the relative dilatation between the frame and the fluid is expressed by

$$\begin{aligned} e &= div(u) \\ \zeta &= \beta div(u-U) \end{aligned} \tag{1}$$

where β is the porosity.

The wave equations for the longitudinal wave in the porous saturated media derived by Biot are expressed as follows [8,9]:

$$\nabla^2(He - C\zeta) = \frac{\partial^2}{\partial t^2}(\rho e - \rho_f \zeta) \tag{2}$$

$$\nabla^2(Ce - M\zeta) = \frac{\partial^2}{\partial t^2}(\rho_f e - \rho_c \zeta) - \frac{\eta}{B_0}\frac{\partial \zeta}{\partial t} \tag{3}$$

where the η is fluid viscosity, the B_0 is the dynamic permeability of the skeletal frame, ρ is the total density of the volume element of composite material $\rho = (1-\beta)\rho_r + \beta\rho_f$, ρ_f is density of the fluid material and ρ_r is the density of the solid grains.

Most of these authors calculate the added mass factor ρ_c is expressed as follows:

$$\rho_c = \frac{\rho_f}{\beta}\gamma \tag{4}$$

where γ is the structure factor account for the apparent increase in fluid inertia caused by the tortuosity of the pores and β is the porosity.

The complex parameters H, C and M describe the elastic porous medium and can be obtained from the complex elastic module of the components by

$$H = \frac{(K_r - K_b)^2}{D - K_b} + K_b + \frac{4}{3}G_b \tag{5}$$

$$C = K_r \frac{K_r - K_b}{D - K_b} \tag{6}$$

$$M = \frac{K_r^2}{D - K_b} \tag{7}$$

$$D = K_r\left[1 + \left(\frac{K_r}{K_f} - 1\right)\beta\right] \tag{8}$$

where K_f is the bulk modulus of the fluid: $K_r = K_r' - iK_r''$ the bulk modulus of the solid material composing the porous frame (the bulk modulus of the individual particles in the case of granular media); $K_b = K_b' - iK_b''$ the bulk modulus and $G_b = G_b' - iG_b''$ the shear modulus of the assemblage of particles measured for the case of constant pressure of the fluid in the pores.