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Characteristics of a magnetic fluid under an orthogonal alternating magnetic field

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A B S T R A C T

Nonlinearity is a primary characteristic of a magnetic fluid. Under an orthogonal alternating magnetic field, the magnetization characteristics change, which produce a variable magnetic field in the magnetic fluid region. A mathematical model of a magnetic fluid under an orthogonal alternating magnetic field is here proposed. The model is solved by an analytic method, and the validity of the solution is verified using the finite element method in addition to experimental results. It is shown that the frequency of the magnetic field in a magnetic fluid is twice that of the orthogonal alternating magnetic field.

1. Introduction

Suspensions of magnetic particles in appropriate carrier liquids are commonly denoted as magnetic fluids. A combination of superparamagnetic behavior with the standard liquid properties exhibited by these magnetic fluids enables the magnetic control of the flow and other properties of such systems. The suspensions contain magnetic single-domain particles with mean diameters of about 10 nm covered with a surfactant that prevents direct contact between the magnetic particles by steric repulsion, and, thus, the suspension is stabilized against agglomeration of the particles due to van der Waals attraction. By the appropriate choice of surfactant, numerous magnetic materials, such as magnetite (Fe_3O_4) and manganese zinc ferrite ($Mn_{0.68}Zn_{0.25}Fe_{2.07}O_3$), can be suspended in various carrier liquids such as water, heptane, or different oils [1]. Owing to the nonlinear characteristics of a magnetic fluid, the application of an orthogonal alternating magnetic field [2] and a constant magnetic field generates variations in the magnetic field within the magnetic fluid region that can be detected by a measurement coil, where the measurement accuracy of the coil increases with an increasing number of turns. Experimental studies show that an accuracy of 0.1 A can be attained. Based on past work [3], the present study builds a mathematical model of the magnetic fluid under an orthogonal alternating magnetic field, and the model is solved using a previously developed analytic method [4]. Also, the validity of the obtained solution is verified by FEM and physical experiments. Exploring the characteristics of the magnetic fluid under an orthogonal alternating magnetic field contributes to novel applications of magnetic fluids such as for nuclear measurements.

2. Theoretical analysis

Fig. 1 shows a model of a magnetic fluid under an orthogonal alternating magnetic field. The green line represents the direct current (DC) I_0 derived from the DC coil. The yellow circle represents the measurement coil. The blue circle represents a non-magnetic dielectric material such as glass. The black shadowed region represents the alternating current (AC) coil. The magnetic fluid is represented by the white area filling the space between the black shadowed region and the blue circle. The magnetic fluid is therefore surrounded by the non-magnetic dielectric, and is affected by a constant DC I_0 and an AC $N_1 i$, where I_0 is perpendicular to $N_1 i$. The position A is a random location within the magnetic fluid. A position P is selected randomly, where a very small area ds that follows along the normal direction of the cross section [5] is obtained. This yields the following dimensions.

$$\begin{aligned} &OM = L \\ &l = PQ = L - r\cos\theta. \\ &ds = r\cdot dr\cdot d\theta \end{aligned} \tag{1}$$

Because of Brownian motion, the magnetic fluid provides no magnetic field in the absence of an externally applied magnetic field. Magnetic particles within the magnetic fluid are aligned in

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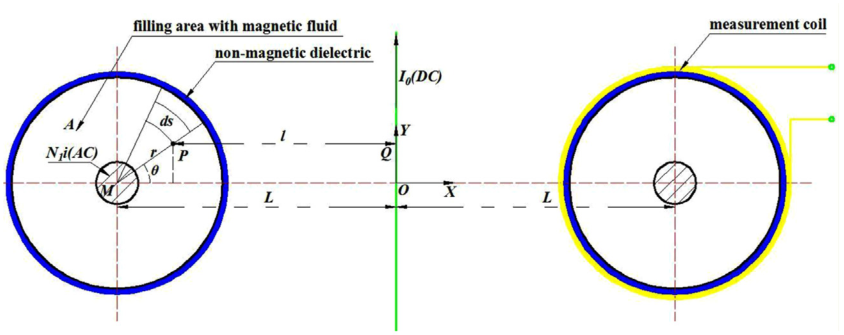
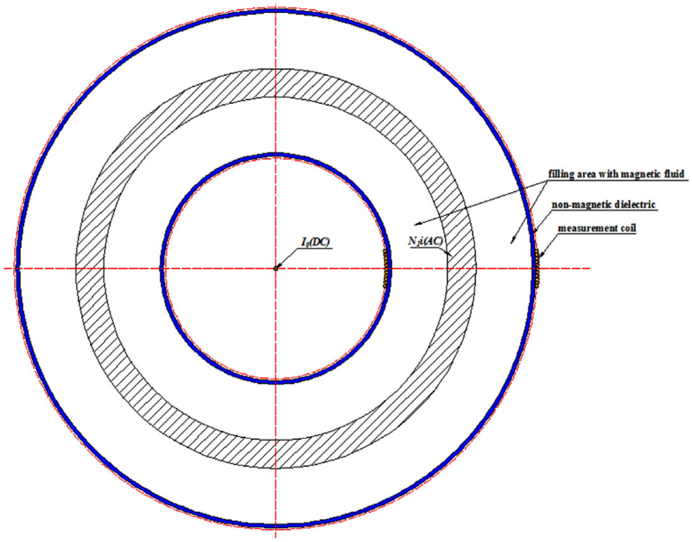
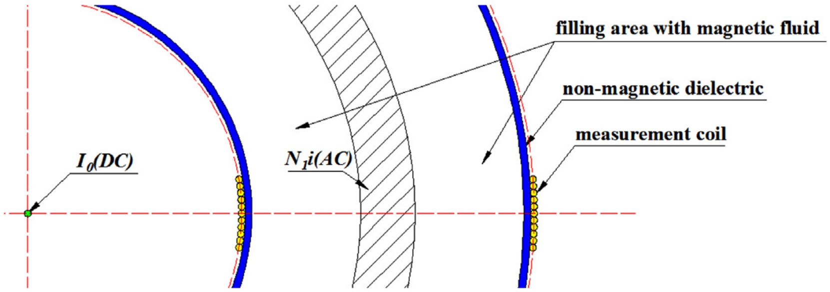


(a) Plane view of the model



(b) Top view of model



(c) Magnified section of the model given in (b)

Fig. 1. Model of a magnetic fluid under an orthogonal alternating magnetic field N_1i. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

the same direction as the external magnetic field after magnetization.

The magnetic intensity produced by the DC at P is given by

$$H_x = \frac{I_0}{2\pi(L - r\cos\theta)}. \tag{2}$$

The AC field at P yields

$$H_y = \frac{N_1 i}{2\pi r}. \tag{3}$$

From (2) and (3), the complex magnetic intensity can be written as

$$H_c = \sqrt{H_x^2 + H_y^2} = \frac{1}{2\pi}\sqrt{\left(\frac{N_1 i}{r}\right)^2 + \left(\frac{I_0}{L - r\cos\theta}\right)^2}. \tag{4}$$

We define ψ as the angle between $\vec{H_x}$ and $\vec{H_c}$ for subsequent analysis. The complex magnetic flux density [7] at P can be obtained as

$$B_c = H_c \times \mu. \tag{5}$$

where the permeability μ is given as

$$\mu = \mu_0\left(1 + \frac{M}{H}\right) = f(H). \tag{6}$$

here, μ_0 is the permeability of vacuum ($4\pi \times 10^{-7}$ N/A^2). By