SOFT POROUS MEDIA MODEL OF MAGNETIC FLUID

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Summary Mechanical behaviour of magnetic fluids is influenced by magnetic field. In particular ultrasonic tests show anisotropy and dependence of wave parameters on strength of the field. Adopting the physical model of magnetic fluid as a composition chains of clusters (skeleton) in carrier liquid the soft porous media model of the material is considered. The model takes into account mutual interaction of clusters constituting soft skeleton and interaction of clusters with the carrier liquid. The description is used to determine attenuation and phase velocity of mechanical waves for transversally isotropic model of the fluid in constant magnetic field. The results are compared with experimental data for different intensity of magnetic field.

INTRODUCTION

An interesting class of intelligent materials are magnetic fluids which without magnetic field are homogeneous colloidal suspensions of ferromagnetic particles coated with surface-active dispersive medium (typical diameters of particles range from 5 to 10 nm) in a carrier liquids (water, oils, etc.). Under influence of magnetic field certain amount of colloidal particles forms aggregates (clusters) which are joined into chains. The presence of chains induces certain small stiffness and anisotropy of mechanical properties of the materials. In order to describe the above features and incorporate interactions between clusters and surrounding liquid which contribute to the dissipation of energy, [1, 2], a model of soft porous media is considered. It is assumed that the two phases of the medium are: the soft skeleton made of interacting chains of clusters and the liquid composed of carrier liquid with free colloidal particles (particles not gathered into clusters). The mutual interactions of clusters are represented through non-vanishing components of stress tensor for the solid phase. The interactions of clusters with liquid are expressed as the sum of viscous, inertial drag and Basset force. Given the assumed symmetry of the medium (transversal isotropy) induced by DC magnetic field the possible harmonic wave modes predicted by the model in infinite medium are specified. Quantitative results obtained from the model for dependence of wave parameters on strength of magnetic field, angle between directions of magnetic field and wave, and on frequency are compared with experimental data.

EXPERIMENTAL DATA

The techniques which were used to study mechanical (acoustic) properties of magnetic liquids both with and without magnetic field are pulse and continuous wave methods. The methodology can be applied to observe anisotropy of mechanical properties of the liquids in variable strength of magnetic or electric field, study frequency dependence of wave parameters and test the materials in wide range of temperatures. They can be also useful to assess the role of carrier fluids, history of magnetic or electric loads etc. In the reported studies the measuring chamber with magnetic fluid was placed in constant magnetic field with maximum strength 1 T. The Figures 1 and 2 present results for ultrasonic attenuation and phase velocity versus magnetic field obtained from testing of liquid EMG-605 (Ferrofluidics) performed for pulse waves generated by transducer with frequency 1.18 MHz, parallel to the magnetic field. The results show that the attenuation is approaching a maximum value at certain strength of magnetic field and velocity increases monotonically with the field.

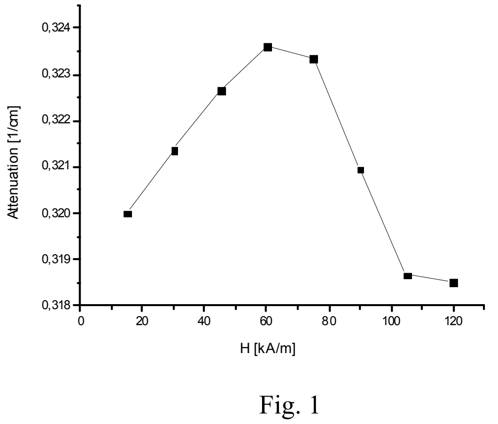

Fig. 1

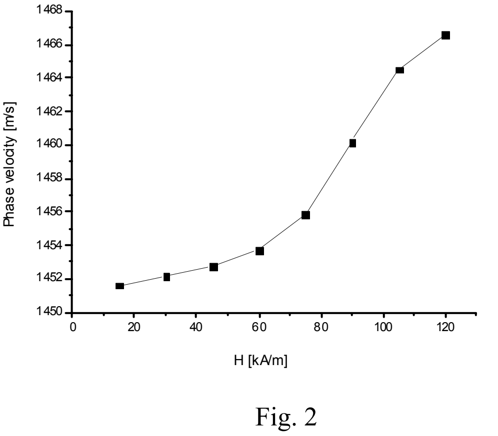

Fig. 2

MODELLING

Formulation of dynamic two-phase model of magnetic liquid is based on equations of balance of linear momentum for solid and fluid phase

$$\rho^s \frac{\partial \mathbf{v}^s}{\partial t} - \Delta \cdot \mathbf{T}^s - \mathbf{R}^s = \mathbf{0}\ , \quad \rho^f \frac{\partial \mathbf{v}^f}{\partial t} - \Delta \cdot \mathbf{T}^f - \mathbf{R}^f = \mathbf{0}\ ,$$

where ρ^s and ρ^f stand for the average mass densities of solid and fluid phase, $\mathbf{v}^s$ and $\mathbf{v}^f$ are macroscopic velocities, $\mathbf{T}^s$ and $\mathbf{T}^f$ denote stress tensors, and $\mathbf{R}^s$ and $\mathbf{R}^f$ are interaction forces between the phases.
Assuming magnetically induced transversal isotropy and field directed along axis z the following set of components of constitutive relationships is proposed (see [3])

$$T^f_{ij} = -\beta p\, \delta_{ij} + \pi_{ij}\,,$$

$$\pi_{xx} = 2\mu\, d_{xx} + \alpha(d_{xx} + d_{yy} + d_{zz})\ , \quad \pi_{yy} = 2\mu\, d_{yy} + \alpha(d_{xx} + d_{yy} + d_{zz})\ , \quad \pi_{zz} = \gamma\, d_{zz} + \beta(d_{xx} + d_{yy} + d_{zz})$$

$$\pi_{xz} = \pi_{zx} = 2\delta\, d_{xz}\ , \quad \pi_{yz} = \pi_{zy} = 2\delta\, d_{yz}\ , \quad \pi_{xy} = \pi_{yx} = 2\mu\, d_{xy}\ ,$$

$$\beta p = -M(e_{xx} + e_{yy}) + Q\, e_{zz} + R\varepsilon$$

$$T^s_{xx} = 2N\, e_{xx} + A(e_{xx} + e_{yy}) + F e_{zz} + M\varepsilon\ , \quad T^s_{yy} = 2N\, e_{yy} + A(e_{xx} + e_{yy}) + F e_{zz} + M\varepsilon\ , \quad T^2_{zz} = C\, e_{zz} + F(e_{xx} + e_{yy}) + Q\varepsilon$$

$$T^s_{xz} = T^s_{yx} = 2L\, e_{xz}\ , \quad T^s_{yz} = T^s_{zy} = 2L\, e_{yz}\ , \quad T^s_{xy} = T^s_{yx} = 2N\, e_{xy}\,.$$

$$R^{sf}_x = -b_T(\upsilon^f_x - \upsilon^s_x) - c_T \frac{\partial(\upsilon^f_x - \upsilon^s_x)}{\partial t}\ , \quad R^{sf}_y = -b_T(\upsilon^f_y - \upsilon^s_y) - c_T \frac{\partial(\upsilon^f_y - \upsilon^s_y)}{\partial t}\ , \quad R^{sf}_z = -b_z(\upsilon^f_z - \upsilon^s_z) - c_z \frac{\partial(\upsilon^f_z - \upsilon^s_z)}{\partial t}\ ,$$

where p is fluid pressure, β denotes volume fraction of carrier liquid, and $\boldsymbol{d}$ and $\boldsymbol{\varepsilon}$ are rate of deformation of fluid and strain of solid phase. The other parameters are coefficients representing elastic properties (*A, C, F, L, M, N, Q, R*), viscosities (α, β, δ, γ, μ) and interface interactions (b_T, b_z, c_T, c_z). Combining the above equations and considering plane harmonic waves in infinite medium one obtains dispersion relationships predicting velocities and coefficients of attenuation of four types of waves which are related to disturbances in plane x, z. Two of them are quasi-longitudinal waves (for which motion of particles of fluid and solid phase take place in or out of phase). The remaining waves are the shear like waves resulting from the existence of the stiffness of solid phase and viscosity of carrier liquid.
The numerical results for wave velocity which qualitatively agree with the experimental data can be derived from the model assuming linear dependence of volume fraction of clusters (solid phase) on strength of magnetic filed and evolution of elasticity parameters as functions of magnetic field according to the logistic equation. The analysis of attenuation shows that for appropriately selected values of parameters of the model the experimental data can be also well fitted but the attenuation is very sensitive to viscosity of liquid phase and terms representing viscous interaction (drag) between solid and fluid phase. As the results further theoretical studies including microscopic considerations of properties of phases and experimental works are necessary to find reliable evolution functions for macroscopic parameters.

CONCLUSIONS

The predicted by porous media model values of attenuation and velocity of fast quasi-longitudinal wave in magnetic fluid can describe some basic ultrasonic data. It justifies assumption that the growth and interaction of clusters, represented by changes of volume fraction and elasticity modulus, may serve as an explanation of the observed evolution of wave propagation parameters with changing magnetic field. The best qualitative prediction can be obtained for the maximum value of bulk modulus about 50 kN/mm^2. It should be noted that the model predicts also the existence of slow quasi-longitudinal wave. Its velocity is about ten times lower, and attenuation over thousand times higher as compared with the parameters of the fast wave. With the currently available measuring methods it is impossible to detect this wave experimentally. The analysis of other predictions of the proposed model, e.g. the effects of anisotropy of the material and the frequency dependence of wave propagation parameters has been undertaken. Directions of further development of the model such as frequency dependence of interactions between phases and possible non-linear effects, e.g. due to magnetic couplings and saturation are discussed.

References

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