Advances in Engineering Materials and Applied Mechanics – Zhang, Gao & Xu (Eds)
 ISBN 978-1-138-02834-0

Acoustic absorption of MRF under different external field

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ABSTRACT: This paper presents an equivalent of the shear moduli of MRF, which is an important parameter in the Biot theory based on the relaxation spectrum. The Biot's model is used to calculate the complex wave numbers of the two compressional waves propagating in MRF at normal incidence. The surface impedances and the acoustic absorption of MRF under different external field are simulated. The results agree with the test by Guicking and the absorption of MRF can be changed and improved with the application of external field.

1 INTRODUCTION

Magnetorheological Fluid (MRF) is a kind of smart material, which dramatically changes the rheological properties in the presence of an external magnet field (Rabinow 1948). The suspension particles of MRF interact with each other and form a fiber structure and its other properties except rheological property, such as acoustic property (Nahmad-Molinari et al. 1999, Nahmad-Molinari et al. 2000), change with the external field. The sound wave propagate in MRF can be modeled by the Biot theory (Biot 1956, Biot 1956, Biot 1961) that the MRF is treated as an equivalent porous material while an external field employed. For the controllable acoustic property of MRF, the composite structure involves MRF has a great potential as a smart acoustic active absorber, and this paper gives a basic study on the acoustic property of MRF. The key to implement the Biot theory is the parameters' equivalent and the equivalent of the shear modulus of MRF is investigated by using the relaxation spectrum theory (Mahjoob et al. 2012).

2 BIOT'S MODEL

The Biot's model considers that two compressional waves and one shear wave can propagate in a porous medium simultaneously. In the case of normal incidence, which is the case discussed throughout the paper, the shear wave is not excited. Note that a harmonic time dependence of the $e^{j\omega t}$ type will be assumed and will therefore not appear in the equations given. The Biot theory gives an approach to calculate the complex wave numbers of the compressional waves:

$$\delta_1^2 = \omega^2\left[P\rho_{22} + R\rho_{11} - 2Q\rho_{12} - \sqrt{\Delta}\right]\Big/2\left(PR - Q^2\right) \tag{1}$$

$$\delta_2^2 = \omega^2\left[P\rho_{22} + R\rho_{11} - 2Q\rho_{12} + \sqrt{\Delta}\right]\Big/2\left(PR - Q^2\right) \tag{2}$$

$$\Delta = \left[P\rho_{22} + R\rho_{11} - 2Q\rho_{12}\right]^2 - 4\left(PR - Q^2\right)\left(\rho_{11}\rho_{22} - \rho_{12}^2\right) \tag{3}$$

where ρ_{11}, ρ_{12} and ρ_{22} are the modified Biot's densities, ω is the circular frequency, P, Q and R are the elastic coefficients of the porous material, which can be evaluated from the "gedanken experiments" suggested by (Biot 1957). In the case, the compressibility modulus of the elastic solid from which the frame is made K_s, is much greater than the compressibility modulus of the porous frame K_b, the simplified expressions of the coefficients are as follows:

$$P = 4N/3 + K_b + K_f(1-\varphi)^2/\phi$$
$$Q = K_f(1-\varphi),\ R = \varphi K_f \tag{4}$$

where the dynamic elastic moduli are:

$$K_b = 2N(\nu+1)/3(1-2\nu) \tag{5}$$

where K_f is the bulk modulus of the fluid, N is the shear modulus, and v is the Poisson ratio.

The expression of the surface impedance of a single layer of porous material placed against a rigid wall as shown in Figure 1 was worked out by (Allard 2009):

$$Z = -j\left(Z_1^s Z_2^f \mu_2 - Z_2^s Z_1^f \mu_1\right)/D \tag{6}$$

where

$$D = (1-\varphi+\varphi\mu_2)\left[Z_1^s - (1-\varphi)Z_1^f\mu_1\right]\tan(\delta_2 l)$$
$$+(1-\varphi+\varphi\mu_1)\left[Z_2^f\mu_2(1-\varphi) - Z_2^s\right]\tan(\delta_1 l) \tag{7}$$

in which Z_i^s (analogously, Z_i^f) denotes the characteristic impedance of the ith compressional wave in the solid (fluid) part of the porous medium. The parameters that describe the acoustical properties of the acoustical materials and structures are the reflection coefficient and absorption coefficient and they can be directly obtained from the surface impedance. While a plane wave impinges upon a layer of acoustical medium, the reflection coefficient R_s and absorption coefficient α_s of the layer can be expressed as follows:

$$R_s = (Z_s - Z_c)/(Z_s + Z_c),\ \alpha_s = 1 - |R_s|^2 \tag{8}$$

where Z_c is the characteristic impedance of the medium neighboring to the layer, and Z_s is the surface impedance at normal direction of the layer.

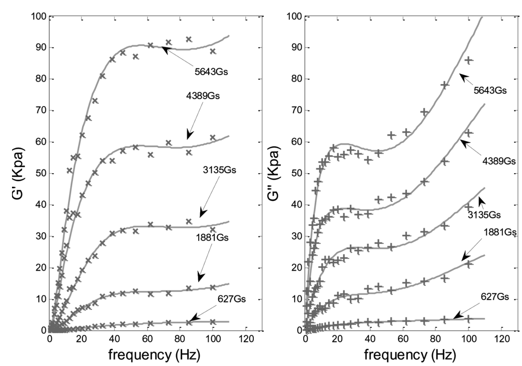

Figure 1. Test and estimated storage/loss modulus of MRF under different external magnetic field.

3 SHEAR MODULUS EQUIVALENT

It can be found that there are eleven parameters in the Biot model, which are the density ρ_0, the dynamic viscosity η and the bulk modulus K_f of the fluid phase; the density ρ_1 and the bulk modulus K_s of the solid phase; the shear modulus N, the Poisson ratio v, the static permeability q_0, the porosity φ, the tortuosity α_∞ and the viscous characteristic length Λ of the porous frame. It is not easy to obtain the frame parameters during the application of the Biot theory. Therefore, the equivalent of the parameter is very important and the equivalent of the frame shear modulus by the relaxation spectrum theory is discussed in this part.

The rheological dynamic moduli (i.e. loss and storage moduli) can be measured using a rheometer, which is the shear modulus from the definition of the dynamic moduli.

$$G(i\omega) = (\cos\theta + i\sin\theta)\sigma_0/\gamma_0 = G'(\omega) + iG''(\omega) \tag{9}$$

where $G'(\omega)$ is the storage modulus, $G''(\omega)$ is the loss modulus, and $\tan\theta$ is the loss factor.

The dynamic moduli are measured in the oscillation mode of rheometer while the applicable angular frequency range is 0.01–100 rad/s. Therefore, the dynamic moduli of MRF can only be measured directly up to 100 rad/s. Nevertheless, the frequency range involved in acoustic application is higher, such as 20Hz–20KHz for the audible sound. Herein, the relaxation spectrum is used to estimate the dynamic moduli of MRF indirectly beyond the measured range.

The parameters associated with the relaxation spectrum of a viscoelastic fluid are connected to experimental results obtained in rheology test by the (Fredholm) first-order integral equation (Mohammad et al. 2012). The relationship between the relaxation spectrum parameters and the storage/loss moduli (test results) are as follows:

$$G'(\omega) = \sum_{i=1}^{n} H_i(\lambda_i)\omega^2\lambda_i^2/(1+\omega^2\lambda_i^2) \tag{10}$$

$$G''(\omega) = \sum_{i=1}^{n} H_i(\lambda_i)\omega\lambda_i/(1+\omega^2\lambda_i^2) \tag{11}$$

where λ_i is the ith discrete relaxation time and $H_i(\lambda_i)$ is the corresponding discrete relaxation spectrum, and n is the number of the relaxation time point. The discrete relaxation spectrum can be calculated by using test data by the minimizing the function given below:

$$\sum_{j=1}^{m}\left(\left(1-\sum_{i=1}^{n}\frac{1}{G'(\omega_j)}H_i(\lambda_i)\frac{\omega_j^2\lambda_i^2}{1+\omega_j^2\lambda_i^2}\right)^2+\left(1-\sum_{i=1}^{n}\frac{1}{G''(\omega_j)}H_i(\lambda_i)\frac{\omega_j\lambda_i}{1+\omega_j^2\lambda_i^2}\right)^2\right)=\min \tag{12}$$

where m is the testing number of the moduli. The relaxation time should be appointed before solving Eq. (12). Generally, the reciprocal of the testing upper and lower limit frequency are chosen as the original relaxation time. Then the relaxation time value linear distributed from the minimum time of test to the max time at the logarithmic coordinates,

$$\lambda_i = \lambda_{\min}(\lambda_{\max}/\lambda_{\min})^{(i-1)/(n-1)} \tag{13}$$

where $\lambda_{\min}$ and $\lambda_{\max}$ are the lower and upper limit relaxation time.

Figure 1 show the experiment results (Mohammad 2012) of storage and loss moduli of MRF and their estimated value under different external magnetic field. While the magnetic field is wake, the viscosity of MRF dominates the whole testing frequency band compared with the elasticity. The domination of viscosity and elasticity of MRF is governed by

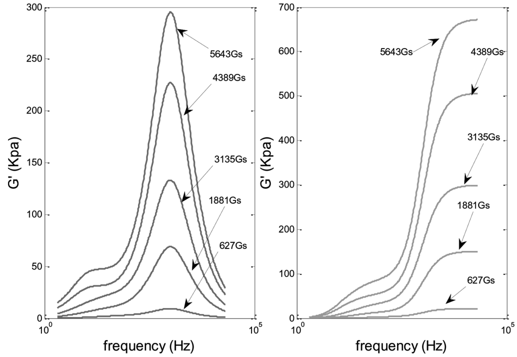

Figure 2. Estimated storage/loss modulus of MRF in global frequency range.

Table 1. Parameters of MRF (SI).

ρ_0	ρ_1	R	c_0	c_1	η
997.04	6889	4×10^{-6}	1496.7	5900	0.042
l	φ	α_∞	q_0	Λ	
0.025	0.746	1.38	1.91×10^{-7}	110×10^{-6}	

frequency while the magnetic field is moderate. While the magnetic field is high, the viscosity dominates at low frequency, otherwise the elasticity dominates. Altogether, the storage and loss moduli of MRF are growing with the external magnetic field.

The estimated storage and loss moduli of MRF in global frequency range are plotted in Figure 2. The shear modulus of MRF is growing with the external field while the storage modulus gradually increases to a steady state, and the loss modulus increases to a max and then decreases rapidly.

Other parameters of the frame, i.e. the static permeability q_0, the porosity φ, the tortuosity α_∞ and the viscous characteristic length Λ value refer to similar acoustic media. For example,

$$\varphi = 1 - V_c \tag{14}$$

where V_c is the volume ratio of the suspension particles, α_∞ is in the range of 1 to 2. The parameters of MRF are listed in Table 1.

4 RESULTS AND DISCUSSION

The helixes of the normalized impedance of MRF under different external magnetic field are plotted in Figure 3. Those helixes rotate clockwise and gradually move to the location (1, 0), which indicates that the absorption coefficient of MRF approach to one with the increase of frequency. Each circle of the helixes represents a peak of absorption curve. While there is no external field, the center location of the first circle of the helix is about (13, 0) while the left limit is (0, 0). The peaks and troughs of the absorption are not obvious then.

Zooming Figure 3(a) and the comparison of the helixes becomes clearer, as shown in Figure 3(b). The centers of those helixes approach the location (1, 0) while the radius decrease which indicates that the troughs become flatter with higher external field. Those helixes cutting their horizontal axis at about the same location (0.4, 0) which means that the peak values

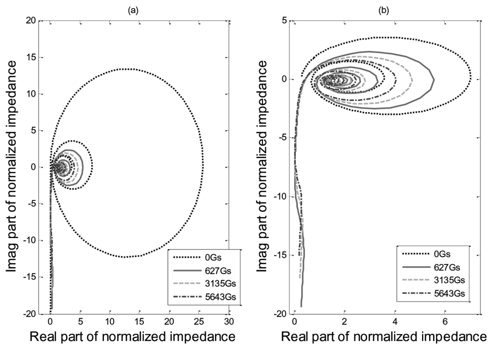

Figure 3. Helix of normalized impedance of MRF under different magnetic field. Dots: 0 Gs; Solid: 627 Gs; Dashed: 3135 Gs; Dash-Dot: 5643 Gs.

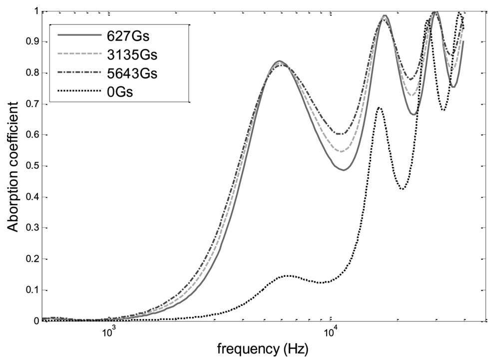

Figure 4. Absorption coefficients of MRF under different magnetic field. Dots: 0 Gs; Solid: 627 Gs; Dashed: 3135 Gs; Dash-Dot: 5643 Gs.

of different external field are the same. These simulated characteristics agree with the testing results by (Guicking et al. 2002).

The acoustic absorption coefficients of MRF under different magnetic field are given in Figure 4. The absorption of MRF is improved by the application of external field that changes the internal micro-structure, and the resonance of the layer is more obvious. With the increase of the field, the peak value almost not change while the trough becomes flatter and the absorption becomes better then.

5 CONCLUSION

The acoustic absorption of MRF is studied based on the Biot theory in this paper while the shear modulus of MRF under an external magnetic field is equivalent by the relaxation spectrum theory. The simulation of this work shows that the absorption coefficients of MRF improved by the applying of an external field. The impedance of MRF layer changes with the external field so that the MRF may be used as an active sound absorber material.

ACKNOWLEDGMENT

This work was supported by the National Natural Science Foundation of China (No. 51175195).

REFERENCES

Allard J.F. & Atalla N. 2009. Propagation of Sound in Porous Media: Modelling Sound Absorbing Materials, *John Wiley & Sons Inc, Chichester*.

Biot, M.A. 1956. Theory of Propagation of Elastic Waves in a Fluid-Saturated Porous Solid. I. Low-Frequency Range. *The Journal of the Acoustical Society of America*, 28(2): 168–178.

Biot, M.A. 1956. Theory of Propagation of Elastic Waves in a Fluid-Saturated Porous Solid. II. Higher-Frequency Range. *The Journal of the Acoustical Society of America*, 28(2): 179–191.

Biot, M.A. 1961. Generalized Theory of Acoustic Propagation in Porous Dissipative Media. *The Journal of the Acoustical Society of America*, 34(2): 1254–1264.

Biot, M.A., Willis, D.G. 1957. The Elastic Coefficients of the Theory of Consolidation. *J. Appl. Mechanics*, 24: 594–601.

Guicking, D. & Wicker, K. & Eberius, C. 2002. Electrorheological Fluids as an Electrically Controllable Acoustic Medium: I. Experimental Arrangement and Application to an Absorber of Underwater Sound. *Acta Acustica United with Acustica*, 88: 886–895.

Mahjoob M.J. & Mohammadi, N. & Malakooti, S. 2012. Analytical and experimental evaluation of magnetic field effect on sound transmission loss of MR-based smart multi-layered panels. *Applied Acoustics*, 73(6): 614–623.

Nahmad-Molinari, Y. & Arancibia-Bulnes C.A. & Ruiz-Suárez J.C. 1999. Sound in a Magnetorheological Slurry. *Physical Review Letters*, 82(4): 727–730.

Nahmad-Molinari, Y. & Ruiz-Suárez, J., 2000. Reply. *Physical Review Letters*, 84(2): 397.

Rabinow, J. 1948. The Magnetic Fluid Cluth. *AIEE Transaction*, 671308-6.