Study and Vibration Response Analysis of MR Cantilever Beam

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***Abstract* - A magnetorheological (MR) fluid including magnetically soft particles suspended in a carrier solvent is disclosed. The MR fluid also includes additive particles of smaller size than the magnetically soft particles and a bridging polymer. The additive particles and polymer form a gel-like material which provides a blanket or coating around the magnetically soft particles. The MR fluids possess improved stability and redispersibility, as well as favorable mechanical properties. The concept of vibration controllability with smart fluids within flexible structures has been in the center of interest in the past two decades. Although much research has been done on structures with embedded electrorheological (ER) fluids, there has been little investigation of magnetorheological (MR) fluid adaptive structures. The magnetorheological response of MR fluids results from the polarization induced in the suspended particles by application of an external field. The interaction between the resulting induced dipoles causes the particles to form columnar structures, parallel to the applied field. The relationship between the magnetic field and the complex shear modulus of MR materials in the pre-yield regime is researched using oscillatory rheometry techniques. A structural dynamic modeling approach is discussed and vibration characteristics of MR adaptive structures are predicted for different magnetic field levels. In addition to the model predictions, actual MR adaptive beam is fabricated and tested. Both studies illustrate the vibration minimization capabilities of the MR adaptive beam at different magnetic field levels.**

***Keywords*- Magnetorheological, Electrorheological, Redispersibility, Smart fluids**

I. INTRODUCTION

One of the main issues in various structures is the undesirable excessive vibration. The control of structural vibrations can be implemented different ways such as modifying stiffness, mass, damping and shape by providing passive or active counter forces. The work presented in this paper constitutes the initial study of a magnetorheological (MR) fluid-based actuator as a structural element for vibration mitigation applications. An underpinning principle for the proposed MR actuator is tuning the total structure's stiffness and damping properties by means of the MR fluid effect. As well known, MR fluids change from a fluid state to a quasi-solid one when activated by a magnetic field. Such a behavior is linked to their structure. MR fluids contain magnetic particles (usually iron) in a carrier liquid; the size of the particles ranges typically from 1 to 10 μm. Under the application of a magnetic field, the particles magnetize and form chains in the direction of the field lines. This rearrangement causes a non-linear increase in the apparent yield stress. With increasing field strength, MR fluids exhibit increasing resistance to flow (apparent viscosity) or increasing stiffness (elastic modulus) depending on deformation. It is generally assumed that MR fluids behave as non-Newtonian fluids in the absence of field.

MR fluids have higher stiffness compared to ER fluids and therefore can facilitate higher controllability. While ER fluids achieve a yield stress between 2-5 kPa, MR fluids achieve 50-100 kPa. Besides, MR fluids do not need high voltage sources and have a wider range of operating temperatures. Still, an experimental work with MR fluids can be quite challenging. In ER fluid sandwich beams, the external layers of the beam (face plates) are the electrodes generating the electric field; whereas in MR fluid beams, the magnetic poles are not a part of the beam, and the magnetic field is generated externally. In a steady-state position, the magnetic field lines are perpendicular to the MR beam.

However, once the MR beam is excited, it vibrates within the static magnetic field, continuously changing the angle between the magnetic field lines and the beam's axis. Moreover, since the magnetic poles are outside the beam, it might be rather demanding to generate a strong and homogeneous magnetic field at the fluid gap. In addition, the material of the outer faces should be non-magnetic so that the MR effect can be studied. Moreover, it is important to remember that the MR fluid contains magnetic particles and therefore is attracted to the magnetic poles. This could cause bending of the beam depending on the thickness and stiffness of the face plates and magnetic field strength. The vibration characteristics of ER and MR fluid simply supported sandwich beams were experimentally investigated. Results showed that MR materials have higher stiffness values and are recommended for vibration suppression of structures, which operate with high frequencies. However, their work presented some difficulties since their MR beam bended with the presence of magnetic field.

The dynamic behaviors of flexible beams, plates and shells are critical to the effective operation of many structures such as automobiles, aircrafts and space platforms. With appropriate control, fatigue failure can be avoided and undesirable resonance can be eliminated. Passive damping treatments have been successfully applied to various structures to attenuate their vibration response and eliminate vibration-induced noise. In recent years, attention has been directed towards the use of various active and semi-active damping treatments. Distinct among these treatments are those in which controllable fluids are used that are embedded in a laminated composite to control its vibration. Electrorheological (ER) materials and magnetorheological (MR) materials, due to their semi-active control capabilities, are candidate materials, which can cause changes in both damping and stiffness of the structure simultaneously. Their utilization in proposed applications is based on the concept of optimized control with minimum energy addition via semi-active control. While studies involving ER material based adaptive structures have been continuing over the past decade, the MR material based adaptive structures are in their initial research state. With currently attractive and steadily improving properties, ER and MR materials show promise for their use in adaptive structural applications in the future.

II. Design and Manufacturing of Sandwich Beam

A simple sandwich cantilever beam system is selected to study the performance of MR fluids in adaptive structures. Cantilever beams are frequently used to study different behavior's because of their relatively simple mechanical model and as a basis for more complex structures. In this case, the controllable capabilities of MR fluids in adaptive structures were analyzed in real time. The studied cantilever beam is formed by three layers: two elastic face plates and an MR fluid core. An external magnetic field controls the rheological properties of the fluid, and hence the dynamic characteristics of the structure. Modal analysis was conducted to obtain the natural frequencies of vibration of the cantilever beam in the absence and presence of magnetic field. Use of different materials for the face plates: aluminum and polyethylene terephthalate (PET). The middle frame, made of PET in both cases, keeps a uniform MR fluid layer inside the beam. The specimens are referred to as 'aluminum beam' and 'PET beam' in this paper.

It was decided to employ aluminum in one of the beams due to its light weight, low damping and relative high stiffness (compared to PET). Since its relative magnetic permeability is equal to unity, aluminum does not affect the strength and distribution of the magnetic field. Each of the two MR sandwich beams is composed of three 1 mm thick layers. The aluminum plates were machined and the PET parts were laser-cut to the dimensions shown in figure 1.

The manufactured layers were glued together with Super Glue and sealed to avoid any leakage. Next, to be able to fill the cavity of the sandwich beam, a hole of 0.6 mm diameter was drilled in each side of the beam. One hole was drilled in the free end of the beam and the other one in the opposite side, very close to the clamping part.

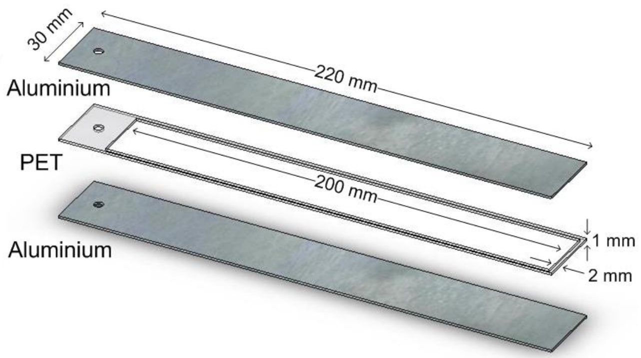

Figure 1 Design of the aluminum MR beam

III. Mathematical Modelling of the MR Fluid Sandwich Beam

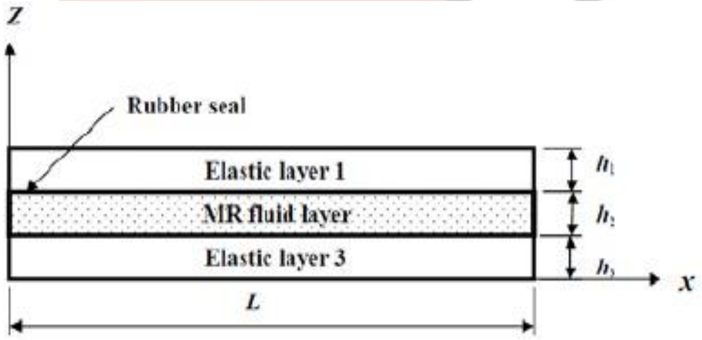

Figure 2. The MR fluid sandwich beam;

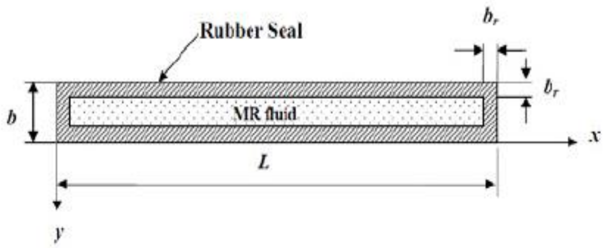

Figure 3. Plane view of the MR fluid layer

A sandwich beam with MR fluid as the core material and elastic layers as the face material (Fig. 2) is considered for development of the finite element model. As the Young's modulus of the MR fluid is nearly negligible compared to that of the elastic layers, the normal stresses in the fluid layer are neglected. It is also considered that the flexural wavelengths of the face layers are less than ten times the cross sectional dimensions and thus the shear deformation and rotary inertia effects of the face layers are included in the formulation. Hence, the plane sections which are normal to the deformed centroidal axis do not remain plane after bending. The damping due to elastic layers is also assumed to be negligible. Furthermore, the transverse displacement w in a given cross-section is assumed to be uniform. Let the longitudinal displacements of the mid-planes of the elastic layers in the x-direction be u1 and u3 and the longitudinal displacement component of any point in the MR fluid be u. The mid-layer is further assumed as a neutral layer in the transverse plane. The top and bottom surfaces are thus considered to undergo axial compression and tension, respectively. Consequently, the axial displacement of the sandwich beam is considered to be equivalent to the axial displacement at the MR fluid layer of the beam.

$$\gamma = \frac{\partial w}{\partial x} + \frac{\partial u}{\partial z}$$

--------------------------------- (1)

$$\frac{\partial u}{\partial z} = \frac{(h_1 + h_3)}{2h_2}\frac{\partial w}{\partial x} + \frac{(u_1 - u_3)}{h_2}$$

………………………… (2)

This yields the shear strain as a function of the layer thickness as:

$$\gamma = \frac{D}{h_2}\frac{\partial w}{\partial x} + \frac{u_1 - u_3}{h_2}$$

……………………… (3)

$$\text{where } \; D = h_2 + \frac{1}{2}(h_1 + h_3).$$

……………………… (4)

Let the longitudinal forces in each of the elastic layers be denoted by *F*1 and *F*3 with their lines of action in the Midplanes of the elastic layers. These forces can be expressed as,

$$F_1 = E_1 A_1 \frac{\partial u_1}{\partial x}; \qquad F_3 = E_3 A_3 \frac{\partial u_3}{\partial x}$$

………..…………… (5)

Where *A*1 and *A*3 are the cross-section areas of layers 1 and 3, respectively and *E*1 and *E*3 are the corresponding Young's moduli. Since the beam is assumed to be free of longitudinal forces, i.e., *F*1 + *F*3 = 0, Eq. (5), yields the following relationship between the longitudinal deflection of the elastic layers:

$$E_1 A_1 \frac{\partial u_1}{\partial x} = -E_3 A_3 \frac{\partial u_3}{\partial x}.$$

……………………….. (6)

By integrating with respect to *x*, the above relation can be simply expressed as a function of the longitudinal deflections.

$$u_3 = -e u_1$$

……………………… (7)

$$e = \frac{E_1 A_1}{E_3 A_3}.$$

A sealant material, Buna-N rubber, is also considered around the edges of the MR fluid layer to ensure uniform layer thickness and containment of the MR fluid within the sandwich beam (Fig. 3). The mid-layer of the sandwich beam comprising the rubber seal and the MR fluid, however, is modelled as a homogeneous material layer with equivalent shear modulus expressed by moduli and widths of the two materials, such that:

$$\overline{G} = G_r\left(\frac{b_r}{b}\right) + G^*\left(1 - \frac{b_r}{b}\right)$$

……………………… (8)

Where *G* is the equivalent shear modulus of the homogeneous layer, *br* and *b* are the widths of the rubber and entire beam, respectively, *Gr* and *G** are the shear modulus of the rubber and MR fluid, respectively. In the preyield regime, the MR material demonstrates viscoelastic behavior, which has been described in terms of the complex modulus *G** and given by,

$$G^* = G' + iG''$$

……………………. (9)

Where *G* is storage modulus of the MR fluid, which is related to the average energy stored per unit volume of the material during a deformation cycle, and *G* is the loss modulus, a measure of the energy dissipated per unit volume of the material over a cycle.

IV. EXPERIMENTS ON MR ADAPTIVE BEAM

The first step of the test beam preparation is the selection of the elastic surface plates. Thin aluminum strips are chosen for this purpose because of its low damping properties and relatively high stiffness properties compared to that of the MR material. Additionally, aluminum has a relative magnetic permeability equal to zero, which indicates that it does not affect the distribution and strength of the magnetic field. The second concern is to keep a uniform gap distribution between the elastic layers in order to have a uniform MR layer. This is maintained by utilizing plastics pacers. 2mm _ 1mm plastic spacers are uniformly bonded onto two long edges of one of the aluminum plates. The other aluminum strip is allowed to slide freely on the surface of the spacers. The third step in fabricating the MR adaptive test beam is to seal the edges of the elastic plates in order to keep the liquid MR material inside. Silicone sealant is used for this purpose. Since the silicon sealant is light and flexible, its effect on constraining the motion of the surface plates and MR materials is slight.

After the beam is sealed, the next step is to fill the cavity remaining inside the beam with the MR material. To achieve this, two small holes are left open at each end of the beam. The beam is then held vertical and the MR material is injected into the beam cavity using a hypodermic needle inserted through one hole at the bottom side of the beam. The air existing in the cavity is let out from the other end. This method results in the best filling of the MR beams without empty space left between surface plates.

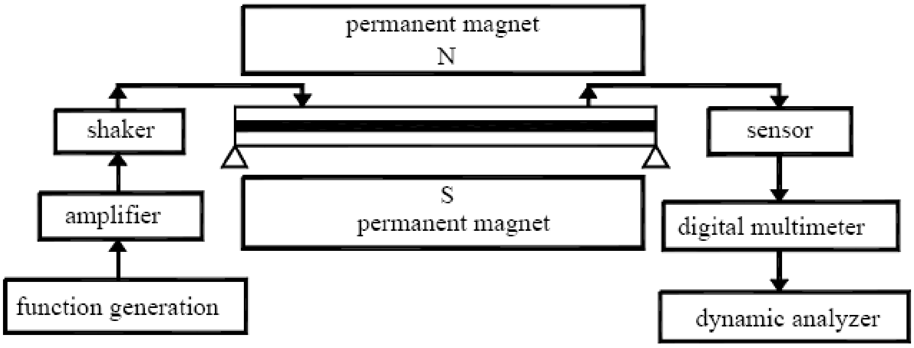

Figure 4: Experimental set-up.

The experimental set-up is integrated with sensing, actuation and signal analysis equipment as shown in Fig. 4. The instruments used in the experiment include a fiber-optic sensor, shaker, amplifier, function generator, digital multi meter and dynamic analyzer. The functions and properties of each instrument in the experimental set-up are presented as follows. A sensor is used to measure the vibration displacement at a single location. This sensor could sense the displacements from 0 to 10 mm. A shaker generates the excitation force applied over the MR beam. This specific shaker could generate a force up to 4.5 lb with a displacement of 5mm and a bandwidth from 0 to 10 000 Hz. The shaker is driven by an amplified voltages signal generated by a function generator. A dynamic analyzer is used for the fast Fourier transformation of the acquired analog signals from the fiber-optic sensor. Vibration response in frequency domain, natural frequencies and amplitudes of the vibration are presented in the output of the analysis results. Loss factors are evaluated from the vibration response information in the frequency domain.

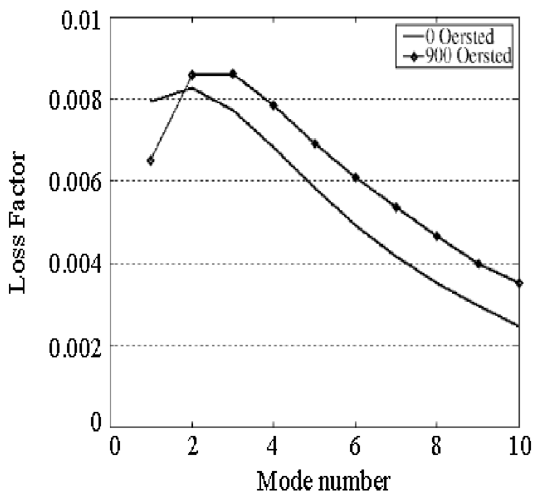

Figure 5: Loss factor variations for different magnetic fields

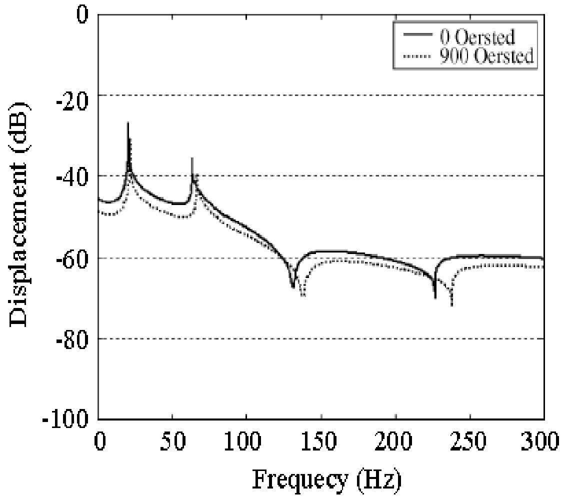

Figure 6: Transverse vibration response based on different Levels of magnetic field.

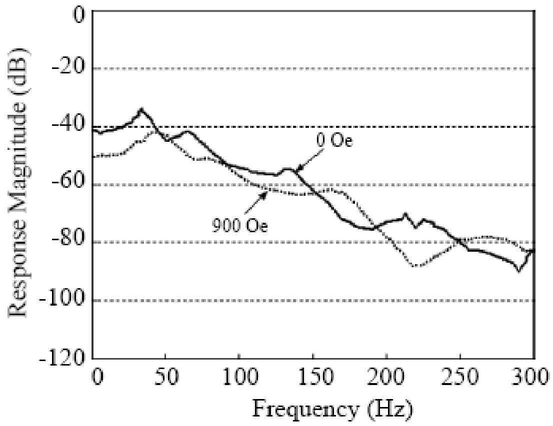

Figure 7: Experimental loss factors for magnetic field Strengths of 0 and 900 Oe.

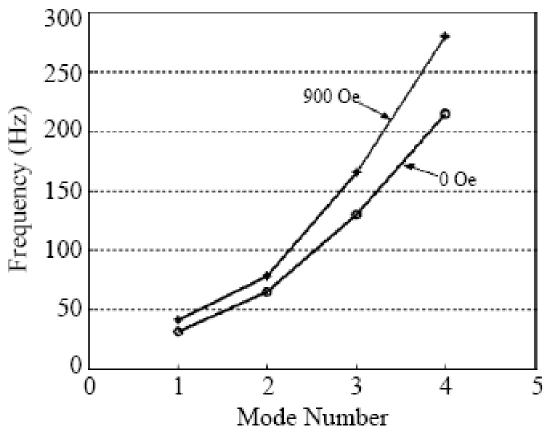

Figure 8: Experimental natural frequencies for Magnetic field strengths of 0 and 900 Oe.

The effect of the magnetic field on the vibration response of the MR beam is presented in Fig. 6 for magnetic field levels of 0 and 900 Oe. The 900 Oe magnetic fields is the highest Magnetic field level that could be applied by the permanent magnets used in the experimental study. In the figure 8, as the magnetic field strength increases, the natural frequencies increase; meanwhile the peaks of the curves, representing the vibration amplitudes at natural frequencies, become flatter due to the higher loss factors.

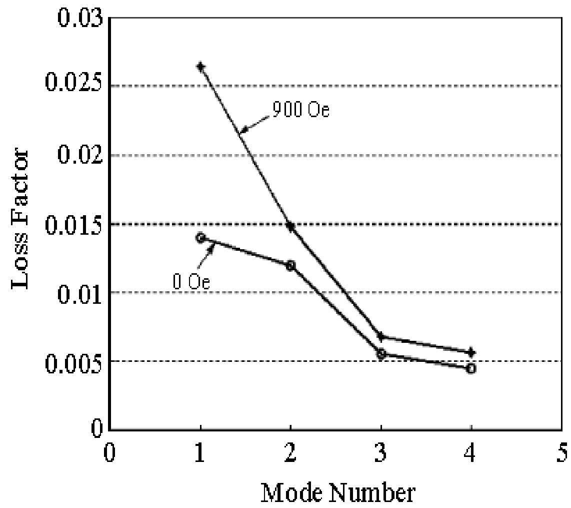

Figure 9: Experimental loss factors for magnetic strengths of 0 and 900 Oe.

The effect of the magnetic field on the loss factors is evaluated in Fig. 9. As the magnetic field strength increases, the loss factors of same mode number increase. This observation is in agreement with the theoretical prediction at higher modes. However, at the first mode the theoretical prediction based on the energy method illustrated in Fig. 5 shows that a higher magnetic field strength implies a lower loss factor.

V. CONCLUSION

The controllable capabilities of MR adaptive beam structures have been investigated. The relationship between the magnetic field and the complex shear modulus of MR materials in the pre-yield regime has been studied using oscillatory rheometry techniques. For MR materials' applications, a theoretical model was developed based on the energy method. From the analysis results, it was observed that MR material presents vibration control capabilities. Vibration amplitudes are decreased with variations in the applied magnetic field for MR material. Furthermore, the natural frequencies shift to higher frequencies when the magnetic field levels are increased. In addition to the model predictions, actual MR adaptive beam was fabricated and tested. Both studies illustrate the vibration minimization capabilities of the MR adaptive beam at different magnetic field levels. But application of magnetic field over the MR layer is becoming an important design criterion in using MR adaptive structures; it can be quite a challenging task to generate a magnetic field over a MR layer. The particular case of cantilever sandwiched beam was considered, but the principle can be applied to more complex structures. The stiffness and damping characteristics of the MR beams were investigated as a function of different magnetic field configurations and intensities. The beams were tested in free vibration and with an excitation force generated either with an electrodynamic shaker or an impact hammer.

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