A modified free decay test apparatus for the characterization of soft magnetic gels in the presence of magnetic fields

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Abstract

This paper presents the development of a simple free decay test apparatus that can be a cost effective alternative to the popular expensive dynamical mechanical analyzers useful for characterization of the dynamic characteristics of soft magnetic composite gels in the presence of variable magnetic field. This apparatus also addresses the common difficulty faced in dynamical mechanical analyzers to conduct the characteristics of deformation dependent mechanical characteristics especially for large deformations, sometimes to the order of 100% that may be necessary for highly compliant polymeric materials. In addition, this apparatus can easily be fitted or modified to facilitate the application of magnetic field. The apparatus is designed to test thin sheet specimens of the magnetic gels in the shear mode at room temperature. As an example, magnetic composite gels prepared with micron sized polarizable particles (carbonyl iron particles) interspersed in a polymer matrix gel are used to show the effectiveness of the apparatus. The compliance of this magnetic gel can be varied under the influence of an external magnetic field. Deviations from the linear material behavior can be captured using the appropriate equations that relate the linear assumptions made. Such deviations can then be used in determining the large deformation dependent characteristics of the gel specimen. Thus, it is demonstrated that the apparatus is a cost effective and useful tool for purposes of testing soft and compliant magnetic composite gels used for damping applications.

Key words: Magneic composite gel, shear mode free decay test, storage modulus and loss factor.

1. INTRODUCTION

Magnetorheological elastomers (MREs)/ magnetic composite gels constitute a new generation of materials used in vibration control and damping devices. Apart from the passive damping properties, it is possible to control the properties of these materials under the influence of a magnetic field [1]. Primarily the storage modulus (stiffness coefficient) and the damping are the properties that are controlled in the applications. The performance of an MRE is dependent on the tunability of these properties. Based on unique characteristics of MREs, an adaptive tuned vibration absorber (ATVA) has been developed by Deng et al. [2]. Elastomeric isolator acts as a filler, amplifying or reducing the initial frequency content of the seismic motion [3]. There are also other applications of these MREs such as controllable membranes in micro-pumps [4]. In structural vibration control system applications, the transmitting force of a vibrating structure to the base through the support depends on the dynamic characteristics of the support [5]. If the dynamic characteristics of the supports are tunable then it will be possible to isolate large range of vibrations at the base of the structure. This tunability can be brought about by using magnetorheological gels in which the characteristics (typically storage moduli) is varied by applying an external magnetic field. To estimate these dynamic characteristics of a magnetic gel specimen that is deformation dependent and nonlinear, a suitable test is to be performed with the prepared magnetic gels in the presence of a magnetic field.

In the literature, various ways of performing the tests are identified to estimate the dynamic characteristics of MREs in the presence of magnetic field. Gong et al. [5], Hu et al. [6] and Wang et al. [7] have measured the mechanical properties of MREs using a custom-made system developed by them. In this system, the MRE sample sandwiched between copper slabs is subjected to shear mode forced vibration in the presence of an electromagnet with the help of an exciter, a power amplifier, a dynamic signal analyzer and piezoelectric acceleration transducers. Fuchs et al. [8] have obtained the storage and loss moduli of the MREs by the dynamic frequency scan program of the DMA instrument. Chen et al. [9] have characterized the dynamic performances of MREs by using a modified dynamic mechanical analyzer (DMA) system. The DMA system is modified by introducing a self made electromagnet which can generate a variable magnetic flux density upto 1 T. In this experiment the dynamic strain amplitude is set at 0.3% only. Zhou [10], conducted the experiment testing the damped free vibration of a system composed of a MRE and a mass in order to determine the shear storage modulus and damping factor. In this experiment the MRE is placed between the vertically arranged magnetic pole pieces in such a way that one side of the MRE is attached to the surface of lower pole and the other side is attached to the brass cover board. Here, this brass cover board acts as a mass and provides an initial displacement to the MRE when it is excited by an impulse hammer. This type of arrangement may not facilitate large deformation measurements in MRE.

Lokander and Stenberg [11] have measured the dynamic shear modulus for a double lap shear specimen using an Instron 8032 dynamic testing machine equipped with an electromagnet. The resulting electromagnet induction through the samples due to this electromagnet was 0.24T only. It was not clear regarding the possibility of more variation of magnetic induction in this test rrangement. This test was done with the small deformations (small amplitude strain range of 0.6% to 2.5%) only. Shen et al. [12] carried out the shear test on polyurethane MREs using tensile testing machine with a negligible shear deformation rate of 1 mm/min. Sun et al. [13] used DMA and MRE samples were analyzed in tensile mode at a strain of 0.5%. Abramchuk et al. [14] measured the shear modulus of the MREs using the uniaxial compression method. Popp et al. [15] investigated the MRE performances under both shear and squeeze modes. But in these tests the shear strains used is 0.1% to 10%. This set up provides the magnetic field strength of 0.15 T only when the coil current is 3A. Stepanov et al. [16] and Bose and Roder [17] studied the rheological measurements of MREs in the oscillation mode in a rheometer equipped with a magnetorheological measuring unit. In the later one, the experiments were carried out at an amplitude of 1% only.

Mostly, in the literature [2,67,9,13], it was observed that the experiments were conducted using Dynamic Mechanical Analyzer (DMA) testing machines for identifying the dynamic characteristics of MR elastomers. However, one important difficulty apart from having to introduce the magnetic field while using DMA is to be able to characterize the gel that undergoes large nonlinear deformations. The setup envisaged for use in this work would accommodate for both strong magnetic field up to 1 T when the coil current is 3A and the large nonlinear deformations. Therefore, for the characterization of dynamic characteristics of magnetic composite gels, a dynamic shear mode experiment (free decay test) is to be conducted in the presence of magnetic field.

Thus, the objective of this work, as a first step, is to prepare isotropic magnetorheological gels with different concentrations of well-dispersed micron sized magnetically polarizable particles and to develop a simple experimental setup to study and obtain the dynamic characteristics of the magnetic composite gel under varying magnetic fields in the shear mode. The uniqueness of this experimental set up is that, the experiment is performed on the gels in direct shear mode instead of indirect shear mode (either by tensile or by compressive loading) in order to obtain the shear characteristics of the gels. The dynamic characteristics are obtained in terms of storage moduli and loss factor.

The paper is arranged in three sections: methodology, results and discussion and conclusions. To show the effectiveness of the apparatus, in methodology as an example; procedures for the preparation of magnetic composite gel, description of the development of experimental set up that is designed and fabricated in conducting free decay test and data analysis performed are discussed. The static shear test is also conducted to observe the strain range above which the magnetic gel behaves as a nonlinear material. The results obtained for various compositions of the magnetic gels prepared by conducting free decay test at various magnetic field influences are discussed before making the concluding remarks.

2. METHODOLOGY

To show the effectiveness of the apparatus, a free decay test is conducted in shear mode for the determination of dynamic characteristics of soft magnetic composite gels in the presence of electromagnetic field.

There are three stages involved in finding the dynamic characteristics of soft magnetic composite gel under dynamic shear conditions. They are

1. Magnetic gel sample preparation,
2. Free decay test under varying magnetic field, and,
3. Data analysis.

And then conducted the static shear test in order to identify the shear strain above which the response is non linear.

2.1 Magnetic gel sample preparation

The magnetic gel samples are prepared using the constant ratio of polystyrene-hydrogenated polybutadiene-polystyrene triblock copolymer [18] to mineral oil gel matrix with various proportions 10%, 30%, 50%, & 70% by weight of carbonyl iron particles of size 2 to 10 µm. The detailed procedures for the preparation of this magnetorheological gel can be found in ref. [19]. The cured samples at room temperature are cut into small rectangular magnetic gel strips of 20x20x3mm to be suitable for use in mechanical characterization tests. This magnetic gel strip is then sandwiched between two non-magnetizable thin plates and adhesively bonded to them to form testable samples.

2.2 Free decay test under varying magnetic field

2.2.1 Experimental setup and test procedure

In order to facilitate large deformations with magnetic composite gel and to accommodate the magnetic field, a simple free decay test apparatus has been designed and fabricated in-house. This apparatus is used for obtaining the magnetic field dependent dynamic characteristics such as storage modulus and loss factor at room temperature and ambient conditions. The photographs of experimental set up are shown in Figure 1. The magnetic gel specimen part of the test apparatus is placed between two magnetic poles for the application of the magnetic field. The direction of the magnetic field is, thus, in the direction perpendicular to the plane of shear action when the rod oscillates.

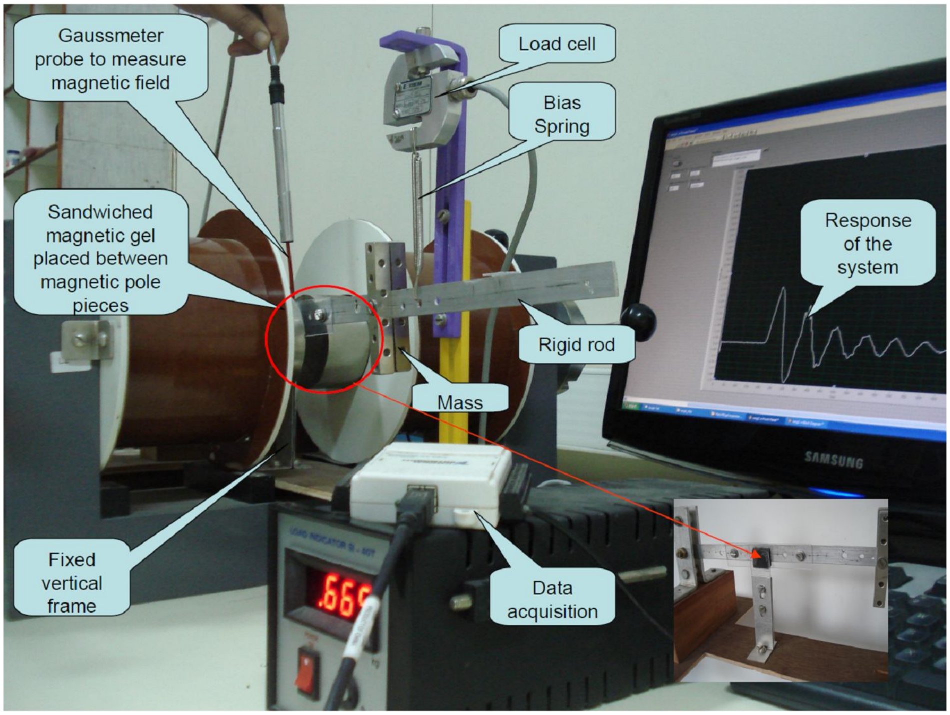


FIGURE 1: The magneto-mechanical coupled free decay testing instrument on magnetic gel under shear mode oscillation.

This instrument consists of a rigid rod with negligible mass hinged at one of its ends and hung by connecting a tensile spring at the other end. A mass is attached to the rigid rod at a known distance from the hinge. A load cell is connected to the rigid rod through a tensile spring to measure the instantaneous force exerted in the load cell. This instantaneous force is proportional to the displacement of the spring. The force exerted in the load cell is recorded through a data acquisition card as a computer data file using LabVIEW (Laboratory Virtual Instrumentation Engineering Workbench) software [20].

One plate of the magnetic gel strip specimen is fastened to the rigid rod while the other plate is fixed to the frame. The specimen gel plate which is fastened to the rigid rod can be removable from the rigid rod in order to facilitate in measuring the dynamic properties of the system in the absence of the gel. Here, the rigid rod, gel plates and the fasteners are chosen as the non magnetic materials.

The idea of this test is to determine the natural frequency and damping ratio of gels using the changes in dynamic properties of an oscillating rod in the system. In order to do this, first the dynamic characteristics of the free oscillating rod (without the magnetic gel specimen attached to the rod) should be measured so that appropriate changes can be registered and used to obtain the gel characteristics in the actual tests on the gel specimens. Therefore, as a first step in the absence of magnetic gel, initial excitation is given to the rod. Due to the presence of the spring and the mass, the rod starts to oscillate and the response of the system is measured using a load cell. The transient response due to the initial excitation dies down due to air friction and other damping conditions.. Once this initial characteristic of the rod-mass-spring assembly is registered, then, the magnetic gel is placed appropriately in the system that allows a shear mode vibration of the gel sample. Once again, the system is excited and a fresh response measurement is made on the system. The above test procedure is repeated under various magnetic fields in the range of 0 to 0.7 T for different gels prepared.

2.2.2 ***Data analysis***

The dynamic response of the system for the given initial excitation depends primarily on the three dynamic attributes of the system – the stiffness of spring elements, the dissipation due to internal friction of the system and the inertia due to mass. If the gel sample is also attached, the stiffness and the damping associated with the gel specimen also affect the dynamic characteristics. The testing system is assumed to be linear. Tests on the system dynamic characteristics were conducted to validate this assumption.

With the mass of the system known, a simple straightforward procedure is adopted to estimate the other two attributes of the system, namely, the storage part (stiffness of the spring) and the dissipation part (damping coefficient). Using a free decay test (by introducing a small initial disturbance / excitation to the system), these attributes are then calculated from the measured response data obtained from the load cell. The procedure and the principle used to calculate the above mentioned system attributes are discussed below.

The equation of motion for the system in the absence of the gel specimen can be written using the moment equilibrium about the hinge as,

$$ml_m^{\,2}\ddot{\theta} + c_s l_s^{\,2}\dot{\theta} + k_s l_s^{\,2}\theta = 0 \tag{1}$$

where m is the mass and, l_m and l_s are the distances from hinge support to the mass and the spring respectively. c_s and k_s are chosen such that the response of mathematical model matches closely with the obtained response. Typically, the damping frequency of the system, ω_d in Hz and the damping ratio, ε_d, are used in the response calculations to match with the experimentally obtained response and then the stiffness, k_s, and the damping coefficient, c_s, of the system are calculated by using the following expressions and these are assumed to be constants irrespective of whether the magnetic gel is mounted or not.

$$k_s = 4\pi^2 m \frac{l_m^{\,2}}{l_s^{\,2}} \frac{\omega_d^{\,2}}{1-\varepsilon_d^{\,2}} \tag{2}$$

$$c_s = 4\pi m \frac{l_m^{\,2}}{l_s^{\,2}} \frac{\omega_d \varepsilon_d}{\sqrt{1-\varepsilon_d^{\,2}}} \tag{3}$$

Figure 3 shows the schematic of the vibrating test system with the gel. The gel is represented using a spring and dashpot in parallel attached to the horizontal bar of the system. With the gel mounted to the system, the equation of motion of the system can be written using moment about the hinge in the Fig. 3 as,

$$ml_m^{\,2}\ddot{\theta} + (c_s l_s^{\,2} + cg\,\mathrm{l_g}^{2})\dot{\theta} + (k_s l_s^{\,2} + k_g\,\mathrm{l_g}^{2})\theta = 0 \tag{4}$$

where l_g is the distance of the center of the mounted gel from the hinge support as shown in Fig.3. Thus, the stiffness and the damping coefficient (k_g, c_g) of the gel can be calculated with the known values of c_s and k_s obtained earlier by using the following expressions [21]..

$$k_g = \frac{4\pi^2 m l_m^{\ 2} \omega_d^{\ 2}}{(1-\varepsilon_d^{\ 2})\mathrm{l_g}^{\ 2}} - \frac{K_s l_s^{\ 2}}{\mathrm{l_g}^{\ 2}} \tag{5}$$

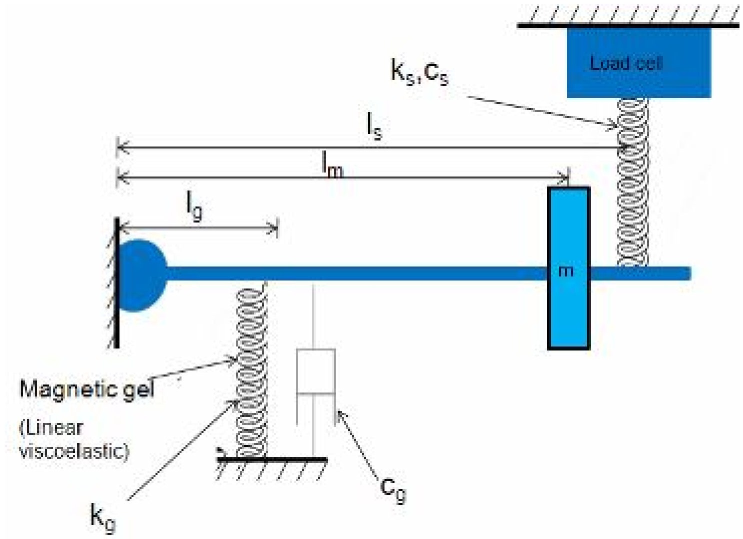


FIGURE 3: A schematic diagram of the testing system with the magnetic gel mounted. The magnetic gel is assumed to be of linear viscoelastic nature.

$$c_g = \frac{4\pi m l_m^{\ 2} \omega_d \varepsilon_d}{\left(\sqrt{1-\varepsilon_d^{\ 2}}\right)\mathrm{l_g}^{\ 2}} - \frac{c_s l_s^{\ 2}}{\mathrm{l_g}^{\ 2}} \tag{6}$$

The solution of the equation of motion in equations (1) and (4) is in the following form:

$$\theta = \Theta e^{-\varepsilon_d \omega_n t} \sin(\sqrt{1-\varepsilon_d^{\ 2}}\,\omega_n t) \tag{7}$$

Where Θ is initial amplitude and θ is amplitude with time t.
These dynamic properties are used to calculate the storage modulus, *G'*, the loss modulus, *G*" and the loss factor, η , of the gel using following equations.

$$G^{'} = \frac{k_g t}{lb}; \tag{8}$$

$$G^{"} = \frac{c_g t \omega_d}{lb}; \quad \text{and} \tag{9}$$

$$\eta = \frac{G^{"}}{G^{'}} \tag{10}$$

where, *t* is the thickness of the gel strip, *l* is the length of the gel strip, and *b* is the breath of the gel strip.

2.3 Static shear test

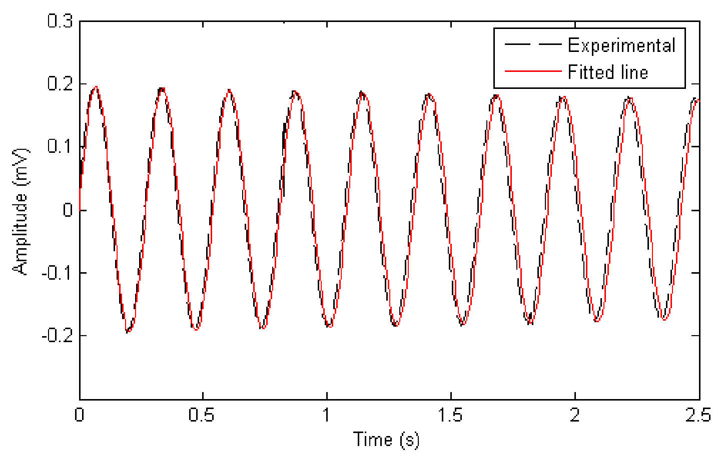
The static shear test is performed in order to identify the shear strain above which the response is non linear. The same basic experimental set up used for free decay test is used even for static shear test with some modifications. This setup consists of a rigid rod (the same rod, which is considered for dynamic shear test) with negligible mass hinged at one of its ends and the rod is hung by connecting a tensile spring at the other end. Then, an LVDT probe for displacement measurement is placed at a known distance at which bar will balance in straight horizontal position. A load cell is connected to the rigid rod through a spring to measure the balancing force caused in the load cell. At this moment, the initial reading (at zero displacement) measured using LVDT.

Now, the gel plate is connected to the rigid rod while the spring attachment is removed from the rod. The displacement at this configuration is noted down. The difference in the above two readings gives the displacement at zero load. Knowing the displacement at the LVDT probe, the displacement at the gel and hence the shear strain can be calculated. At this zero load position, the force in the gel can be calculated by using force equilibrium conditions. The force vs. deflection of the gel specimen is used to find the shear stress to shear strain variation in the gel specimen.

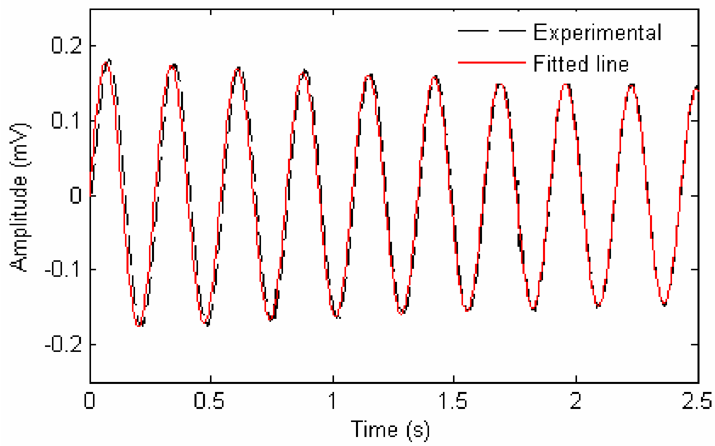
3. RESULTS AND DISCUSSION

In this section, on the basis of system dynamic response and the gel specimen dynamic response, results obtained for one of the various compositions of the magnetic gels prepared by the earlier mentioned procedures using free decay test under varying magnetic field are discussed.

3.1 Free decay test-Determination of test system dynamic characteristics with out gel.



(a)



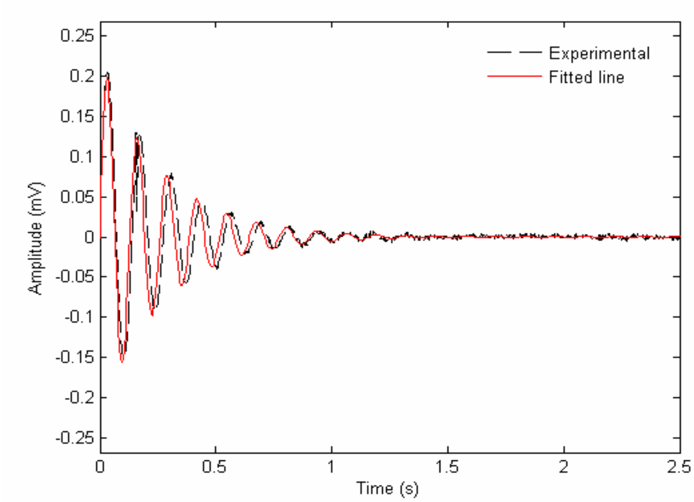
(b)

FIGURE 4: The response of the system measured using load cell in the absence of the gel. (a) without magnetic field, (b) With a magnetic field of 0.7T.

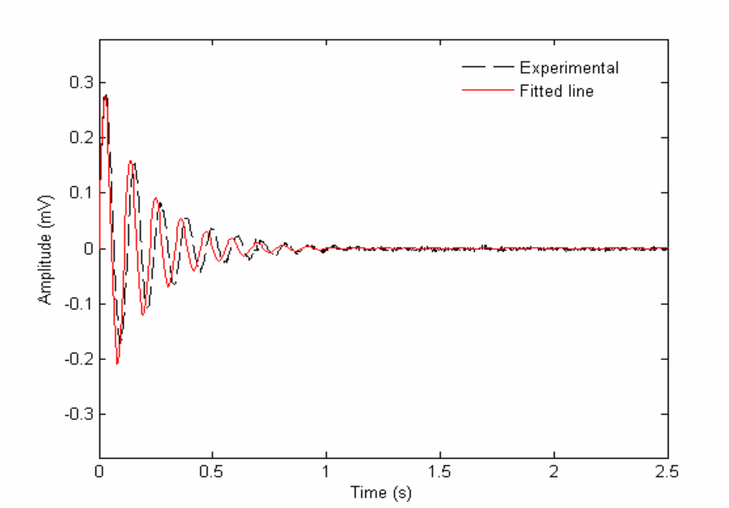
Figures 4(a) & (b) show the response of the system measured using load cell in the absence of the gel with and without magnetic field respectively. The voltage output is measured which is proportional to the displacement of the system. In these figures, dashed line shows the fitted experimental data obtained using load cell and the curve with solid line shows the matching response from the solution (eq.(7)) of the mathematical model obtained from the equation of motion upon choosing appropriate amplitude, frequency and the damping ratio.

The frequency and the damping ratio of the response are obtained to be the same for the system with and without magnetic field (ω_d = 3.722 Hz, damping ratio, ε_d = 0.024). Using these identified damped oscillation frequency and the damping ratio, the stiffness and damping coefficients of the system are found to be . c_s= 0.3446 Nm/s and k_s=167.9181 N/m. It is observed that there is no change in the response of the system due to the applied magnetic field. Here a linear spring response can be proved as a linear material from the exact curve fitting of the solution obtained from the linear equation to the experimental response

3.2 Free decay test response –with magnetic gel



(a)



(b)

FIGURE 5: The response of the system measured using load cell in the presence of the gel with 50% by weight of carbonyl iron particles (a)without magnetic field, (b) with 0.7 T magnetic field. It can be seen that the oscillations die down fast in the presence of magnetic gel.

With the test system characteristics determined, the gel is mounted on the test system and the free decay vibration test is conducted with varying magnetic field. Depending on the initial excitation given, though small, shear strains up to 50% could be realized in the gels. From the response of the test system with the gel mounted, the damping frequency and the damping ratio are first determined under 0 to 0.7 T of magnetic field. The stiffness and damping coefficient (k_g, c_g) of the gel are then calculated using equations (5) and (6) respectively.

The response of the test system with the gel mounted (dashed lines) under 0 and 0.7T magnetic field and the matching responses (solid line) from the solution (eq.(7)) of the mathematical model obtained from the equation of motion are presented in Figures 5 (a) & (b) respectively. Here the shear strain experiences about 33%. On keen observation, one can identify that the curve obtained through mathematical model on the basis of equation of motion is exactly fitting with the experimental response at both extreme ends of the decayed curves. But, in the middle of the curves, a shift is observed. This could be due to the non linear nature of the gel. This nonlinearity due to large deformations can be observed from the following static shear test results also.

3.3 Static shear test: stress-strain behavior of gel due to large deformations

As shown in Figures 6, whenever the deformation is reaches about 30% of it's thickness, the stress-strain behavior is started showing non linear in nature.

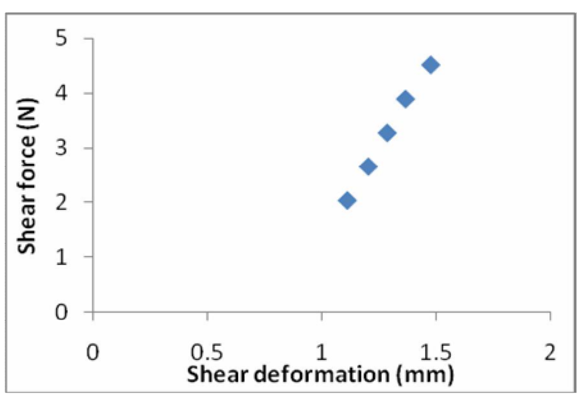
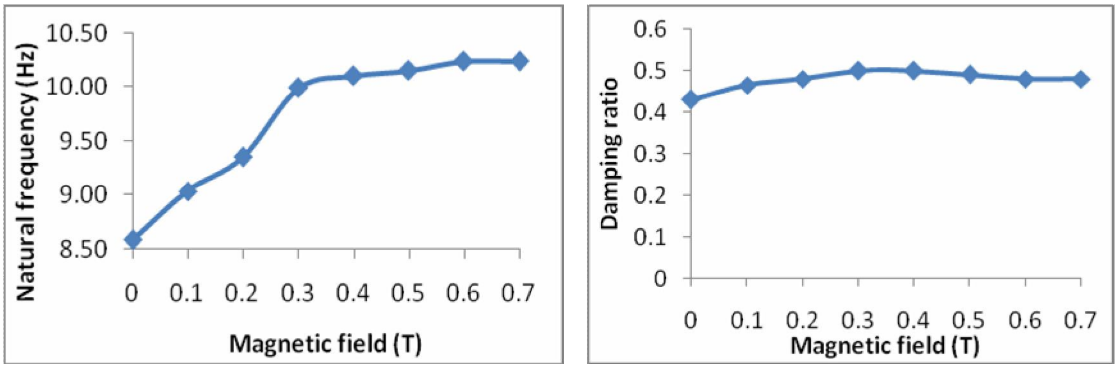


FIGURE 6: Static shear force vs shear deformation of magnetic composite gel with 50% by wt. of carbonyl iron particles at 0.7 T magnetic field.

3.4 Determination of dynamic characteristics of the magnetic gel

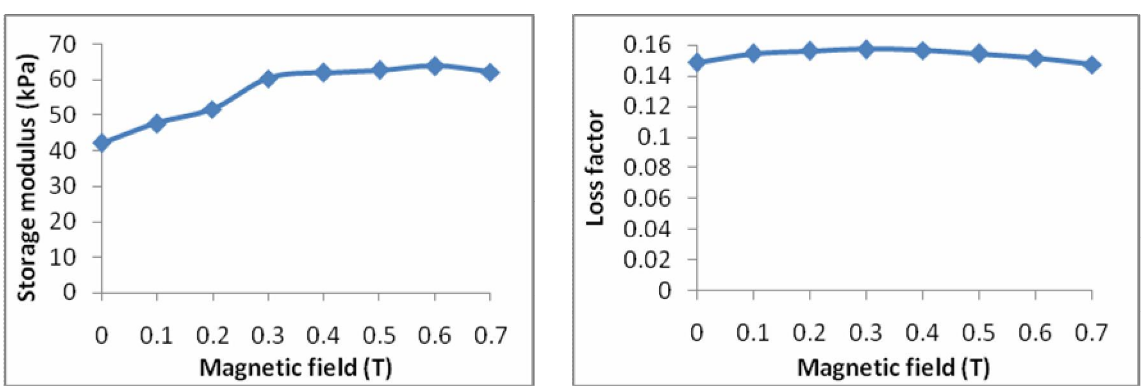


(a) (b)

FIGURE 7: The response of the system measured in terms of (a) *natural frequency and (b) damping ratio* with a gel (consists of 50% by weight of carbonyl iorn particles) mounted under varying magnetic field.

The total system characteristics in terms of the natural frequency and the damping ratio are first determined from the response curves. The natural frequency with respect to the applied magnetic field is presented in Fig. 7(a). One can also observe that there is a significant change in the natural frequency in the range of 0.1 T to 0.4 T in the gels so that the properties of the gel can be significantly controlled in this range of the magnetic field. There are no observable changes seen in the damping ratio for varying magnetic fields (see Fig.7(b)). This is an important observation in the context of application of the magnetic gel to damping applications.

The shear storage modulus and loss modulus are calculated appropriately using equations (8) and (9) for various magnetic field values. The shear storage modulus, from Fig. 8(a), about 52% change is observed over 0.6 T of applied magnetic field in the gel prepared with 50% by weight of carbonyl iron particles. In other words, a change in storage modulus of 41.387 kPa to 65.835 kPa can be achieved with 0.7 T of magnetic field. This capability is required for vibration control applications. Here, three tests were run at every magnetic field. From those three tests, the deviation in the results obtained in storage modulus and loss factor are less than 4%. Due to this very less deviation, the average of the three tests results were presented in the Figs.8(a) and (b). As can be seen in Fig.8(b), loss factor obtained from equation (10) does not change significantly, indicating that the change in damping is marginal.



(a) (b)

FIGURE 8: (a) Storage modulus, and (b) loss factor of the gel with 50& by weight of carbonyl iron particles under different magnitudes of magnetic field.

It is shown in this work that the improvement in storage modulus due to magnetic field of as high as 59% is achievable with isotropic soft MR gels. This is significantly higher than reported in literature [5, 6, 13] (nearly 30% or less improvement in the storage modulus). The authors believe that this increase could be due to the soft elastomeric matrix used in this work.

4. CONCLUSIONS

Since, dynamical mechanical analysis tests are difficult to conduct in the presence of large deformations (of the order of 50%) and strong magnetic fields, a simple, cost effective free decay test apparatus is designed, fabricated and used to conduct the magnetic field dependent shear response tests on soft magnetic gels under dynamic conditions at room temperature.

It is shown in this paper, that the dynamic response of the gel can be obtained. The dynamic characteristics of the gel can be calculated from this response using a linear model for the gel.

The apparatus also provides for the possibility of obtaining deviations from the linear behavior that, if modeled appropriately, can fetch the nonlinear characteristics of the gel due to large deformations. The deviation from linearity is also confirmed from the static tests conducted.

For a future work, the authors are planning to incorporate the above deviation in behavior as a measurement for nonlinear response. In the experimental procedures, while giving a free excitation to the rigid rod, sometimes the rigid rod may be subjected to minor lateral oscillations. This may leads to small error in the response of the system. In future, the authors are also trying to improve the experimental setup in order to avoid this minor lateral oscillations of the rigid rod .

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