VIBRATION ANALYSIS OF MAGNETO-RHEOLOGICAL FLUID SANDWICH BEAM

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Abstract: Nature of magneto-rheological (MR) fluid to vary its rheological properties under effect of magnetic field can be used to provide rapid and compact vibration control mechanism to critical component of large structure**.** This study deals with the vibration analysis of adaptive sandwich beam with magneto-rheological core. A lumped parameter model has been proposed which predicts output of magneto-rheological fluid sandwich beam. Effect of varying magnetic field on stiffness and damping coefficient of magneto-rheological fluid sandwich beam is studied. An equivalent single degree of freedom model is obtained from lumped parameter model. Equivalent single degree of freedom (sdof) model is used to analyze effect of varying magnetic field on resonant amplitude of the magneto-rheological sandwich beam.

Keywords: **MR sandwich beam, lumped model, equivalent sdof model.**

I. INTRODUCTION

Resonant vibration control is important parameter while designing mechanical components. Amplitude in a system due to mechanical vibrations may range from few nanometers to meters. Mechanical vibration in a system may lead to failure of the system, discomfort and decrease in working efficiency of the system. Structural vibrations can be reduced by number of ways such as stiffening, damping and isolation. Compared with passive systems, active vibration control system improves the performance in terms of reduction in vibration amplitude of structures. It could not be justified for application when the added cost and power requirements exceed the performance gains. So, a range of semi active vibration control concepts have evolved for various structural vibration control applications, which could offer significant performance with less cost compared to active vibration control. Electrorheological fluids (ER) consist of semiconducting particles within non conducting carrier fluids. The apparent viscosity of ER fluids changes in response to the applied electric field. ER fluids have been used by many researchers in sandwich structures for vibration control. ER fluids require high voltage and provide low shear strength. However, focus on adaptive structures using ER fluid was more as compared with Magneto-rheological fluids (MR) fluids.

Primary objective of present study is to provide vibration mitigation device in the form of cantilever beam whose stiffness and damping properties can be varied with varying magnetic field. Magnetorheological (MR) fluids are the colloidal suspensions of ferrite particle in carrier liquid such as silicon oil which can change from liquid to quasi solid phase under the influence of external magnetic field. Small sized, magnetic, ferrous particles contained in low permeability oil constitute a MR fluid. When subjected to external magnetic field, these particles are attracted to each other and form chain like and columnar structure in the direction of applied magnetic field and the phase changes from liquid to solid. When external field is removed the phase again changes to liquid. The storage and loss moduli are function of applied magnetic field. This quick response, good reversibility and controllable performance of MR fluids make them suitable for use in various devices. This study deals with dynamic properties of a sandwich beam with magnetorheological fluid as a core material between two elastic structures. MR fluid offers higher yield stress under the influence of magnetic field. Studies have shown that MR fluid is very suitable for higher bandwidth control through rapid changes in its rheological properties under varying magnetic fields.

II. LITERATURE REVIEW

Jerrome E. Ruzika [i] has worked on resonant vibration control in designining structures with help of viscoelstic shear damping mechanism. Viscoelastic damped structure has been developed for the purpose of damping structural vibrations over relatively broad frequency range. Effective ways to calulate loss modulus, storas modulus, loss factors have been described in this paper. A lumped parameter model has been proposed to dtermine design parameters and dynamic characteristics of viscoelasti damped structures.

Rajamohan et al. [ii] in this work, vibration response of a partially treated multi-layered beam with MR fluid as a sandwich layer between two layers of the continuous elastic structure has been analyzed. First, mathematical model of the partially treated MR composite beam was developed in finite element form and Ritz formulation to simulate the dynamic response of the system. The experimental study has then conducted to characterize the MR fluid behavior and to validate the developed formulations. Using the developed finite element formulation, different configurations of a partially treated MR sandwich beam has been studied and then various parametric studies have been conducted to demonstrate the controllable capabilities. It has been shown that the location and length of the MR fluid segments have significant effect on the natural frequencies and the loss factor of the partially treated MR sandwich structure in addition to the intensity of the magnetic field and the boundary conditions. It has been demonstrated that the MR fluid pockets should be located at a particular location depending on the boundary conditions and the mode of vibration to be controlled for the effective vibration suppression. Furthermore, the mode shape of the partially treated MR sandwich beam could be controlled by locating the MR fluid layers at the desired locations.

Mateusz Romaszko et al. [iii] have studied effect of different iron particle concentration on vibrations of MR fluid sandwich structures. Effect of magnetic field on stiffness and damping coefficient of MR fluid has been recorded. Complex modes of vibration have been obtained. This research uses finite element analysis for determining complex vibration modes of a beam, equivalent damping coefficient variation with varying magnetic field strength.

Felipe de Souza Eloy et al. [iv] in this paper, a numerical/experimental investigation about the dynamic response of a sandwich panel made of carbon/epoxy skins and MRE honeycomb core was done for various attractive magnetic field levels and distinctive groupings of magneto/elastomer proportions. The preliminary results show that it is possible to use these devices in situations where it is desired to reduce the vibration levels since they were able to decrease vibration amplitudes and change the natural frequency of the system by only changing the magnetic field intensity. A substantial decrease about 40% in its first natural frequency was observed when using a single group magnet, with magnetic field (current intensity) of 100 kA/m applied to the free end of a cantilevered sandwich panel with MRE honeycomb core.

Mehdi Eshaghi et al. [v] have done research on adaptive sandwich plates using two different MR fluids. Classical plate theory is used to obtain governing equations of MR fluid sandwich plates. Effect of varying magnetic field for different boundary conditions of plates has been studied. Variation of natural frequency and loss factor with varying magnetic field is obtained.

III. STRUCTURE OF A MR FLUID SANDWICH BEAM

Figure 1 shows MR fluid is sandwich between aluminium plates. First and third layer are of aluminium whereas middle layer consists of a MR fluid. Structure has been sealed with the help of rubber. Two permanent neodymium rare earth magnet are provided at the end of cantilever beam which can be moved in transverse direction to length of the beam. When magnets are moved close to MR fluid it increase magnetic field strength applied on MR fluid.

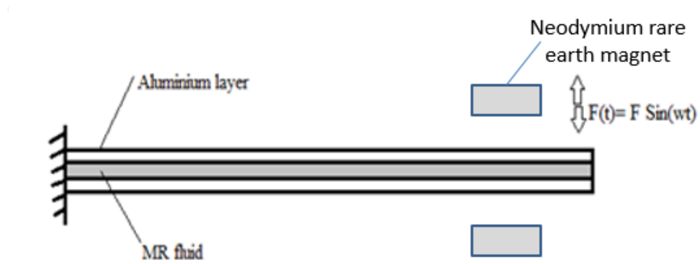

fig. 1 MR fluid sandwich beam

When external magnetic field applied on MR fluid it causes rearrangement of particle which causes increase in yield stress and viscosity of MR fluid. Under the effect of magnetic field, two types of their rheological behaviour in the pre-yield and post-yield regimes are modelled. In the pre-yield regime, MR fluids show linear viscoelastic behaviour that can be characterised by the complex shear modulus G* with the storage modulus G’, which is related to the average energy stored per unit volume of the material during a deformation cycle and loss modulus G” being its real and imaginary parts, a measure of the energy dissipated per unit volume of the material over a cycle [iv].

$$G^{*}= G^{'}(B) + i\, G''(B) \qquad (1)$$

G'= Storage modulus of the MR fluid
G"= loss modulus of MR fluid
B= Intensity of magnetic field in Gauss

IV. MATHEMATICAL MODELING OF MR FLUID SANDWICH BEAM

MR fluid in a pre-yield region behaves like viscoelastic material. Maxwell model [i] is used for representation of MR. Stiffness and damping coefficient in series is mechanical representation of MR fluid as per Maxwell model.

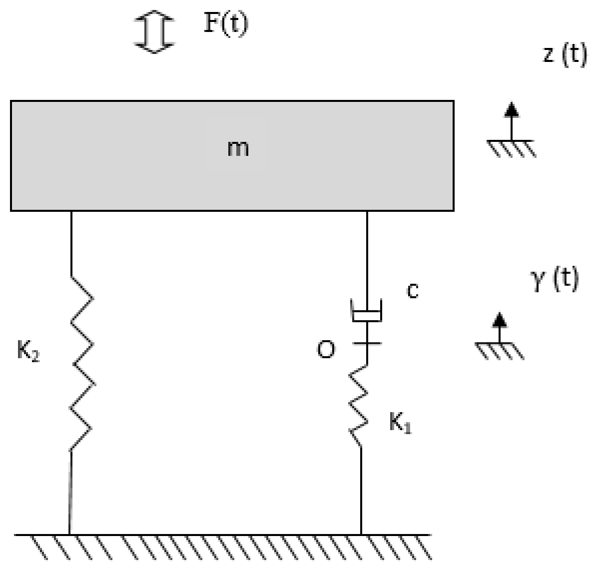

fig. 2 lumped model for MR fluid sandwich beam

m= Effective lumped parameter mass of a MR sandwich beam
K_2= Stiffness due to aluminium layers
K_1 =Stiffness of MR fluid
c= Damping coefficient of MR fluid
F(t)= Excitation provided at end of cantilever beam
Z= Displacement of mass m
γ= Displacement of point O

K_1 and c in series represents MR fluid, as shown in fig. 2. MR fluid viscous nature is taken into account by damping coefficient c and elastic nature of MR fluid taken into consideration by stiffness K_1 lumped parameter model of MR fluid sandwich beam.

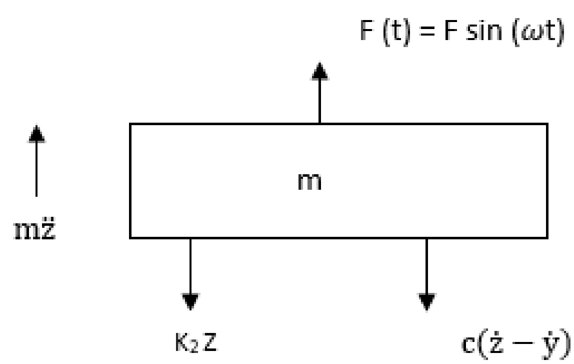

fig. 3 free body diagram of mass m

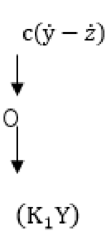

fig. 4 free body diagram of point O

Solve fig. 3 and fig. 4 free body diagrams to get equations (3) and (4)

$$m\ddot{z} + c\dot{z} + k_2 z = F(t) + c\dot{y} \qquad (3)$$

$$c\dot{y} - c\dot{z} + k_1 y = 0 \quad (4)$$

After solving equations (3) and (4) following differential equation of motion is obtained

$$\dddot{z} + \frac{k_1}{c}\ddot{z} + \left(\frac{k_1 + k_2}{m}\right)\dot{z} + \left(\frac{k_1 k_2}{cm}\right)z = P\,\mathrm{Sin}(\omega t + \emptyset) \quad (5)$$

where $p = \sqrt{\left(\frac{k_1 F}{mc}\right)^2 + \left(\frac{\omega F}{m}\right)^2} = \frac{K_1 F}{mc}\sqrt{1 + (\frac{c\omega}{K_1})^2}$ and $\tan(\emptyset) = \left(\frac{\frac{\omega F}{m}}{\frac{k_1 F}{mc}}\right) = \frac{c\omega}{K_1}$

let $P_1 = \frac{k_1}{c}$, $P_2 = \left(\frac{k_1 + k_2}{m}\right)$, $P_3 = \left(\frac{k_1 k_2}{cm}\right)$

After solving differential equation (5)

$$z(t) = \frac{\frac{K_1 F}{mc}\sqrt{1 + \left(\frac{c\omega}{K_1}\right)^2}}{\sqrt{(P_3 - P_1\omega^2)^2 + (\omega^3 - P_2\omega)^2}}\sin(\omega t + \varphi) \quad (6)$$

where $\tan(\varphi) = \frac{(a_1\tan\varphi + a_2)}{(a_1 - a_2\tan\varphi)}$, $(P_3 - P_1\omega^2) = a_1$, $(\omega^3 - P_2\omega) = a_2$

Amplitude from equation (6)

$$Z = \frac{\frac{K_1 F}{mc}\sqrt{1 + \left(\frac{c\omega}{K_1}\right)^2}}{\sqrt{[\left(\frac{K_1}{c}\right)(\omega_n{}^2 - \omega^2)\ ]^2 + [\left[\omega^2 - \left(\frac{K_1}{m} + \omega_n{}^2\right)\right]^2\ \omega^2]}} \quad (7)$$

Resonant amplitude when $\omega = \omega_n$

$$Z_R = \left(\frac{F}{c\omega_n}\right)\sqrt{1 + (\frac{c\omega_n}{K_1})^2} = \left(\frac{\frac{F}{K_1}}{\frac{c\omega_n}{K_1}}\right)\sqrt{1 + \left(\frac{c\omega_n}{K_1}\right)^2} = \left(\frac{F}{K_2}\right)\left(\frac{K_2}{K_1}\right)\sqrt{\frac{1 + \left(\frac{c\omega_n}{K_1}\right)^2}{\left(\frac{c\omega_n}{K_1}\right)^2}} = Z_{st}\sqrt{\frac{1 + \left(\frac{c\omega_n}{K_1}\right)^2}{\left(\frac{c\omega_n}{K_1}\right)^2}}$$

$$\frac{Z_R}{Z_{st}(\frac{K_2}{K_1})} = \sqrt{\frac{1 + \epsilon^2}{\epsilon^2}} \qquad \text{where } \frac{c\omega_n}{K_1} = \epsilon \text{ (loss factor of MR fluid)} \quad (8)$$

It is important to convert lumped parameter model into more generalize equivalent single degree of freedom model so that we can use standard available equation. Figure 5 shows equivalent single degree of freedom model where K_{eq} is equivalent stiffness of a system and C_{eq} is equivalent damping coefficient of a system.

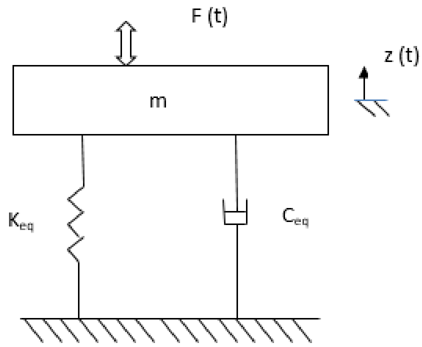

fig. 5 Equivalent single degree of freedom model

$$m\ddot{z} + C_{eq}\dot{z} + K_{eq}z = F(t) \qquad (9)$$

substitute $z = Ze^{i\omega t}$ $F(t) = Fe^{i\omega t}$ in equations (3), (4) and (9)

and equate force F from both the models will lead to following equation

$$\frac{K_2 K_1{}^2 + (K_1 + K_2)c^2\omega^2}{K_1{}^2 + c^2\omega^2} + i\left(\frac{K_1{}^2 c\omega}{K_1{}^2 + c^2\omega^2}\right) = \left(K_{eq} + iC_{eq}\omega\right) \qquad (10)$$

Equate real and imaginary part of equation (10)

$$K_{eq} = \frac{K_2 + [(K_1 + K_2)\left(\frac{c\omega}{K_1}\right)^2]}{1 + \left(\frac{c\omega}{K_1}\right)^2} \qquad (11)$$

$$C_{eq} = \frac{c}{1 + \left(\frac{c\omega}{K_1}\right)^2} \qquad (12)$$

V. CALCULATIONS

Magnetorheological fluid density $\rho_r = 3500$ Kg/m^3 is sandwich between two aluminum sheets of dimensions l=350 mm × b=30 mm × h=1 mm. Magnetorheological fluid layer2 of thickness 1.5 mm is sandwich between layer1 and layer3 of aluminum sheets.

$\rho_{al} = 2700$ Kg/m^3

$V_1 = V_3 = 350 \times 30 \times 1 \times 10^{-9}$ m^3.

$V_2 = 350 \times 30 \times 1 \times 10^{-9}$ m^3.

$M_1 = M_3 = \rho_{al} \times V1 = 0.02835$ kg.

$M_2 = \rho_r \times V_2 = 0.055127$ kg.

$M_t = M_1 + M_3 + M_2 = 0.119$ kg

m= 0.236 M_t = 0.028084 kg. (effective mass)

$$I_{al} = \frac{30 \times 1}{12} + 1 \times 30 \times 1.25 \times 1.25 = 49.75 \text{ mm}^4$$

$$I\ (total) = 49.45 \times 2 = 98.75 \text{ mm}^4 = 98.75 \times 10^{-12} \text{m}^4$$

$$K_2 = \frac{3 \times E \times I}{l^3} = 469.85\ N/m$$

$$\omega_n = \sqrt{\frac{K_2}{m}} = 129 \text{ rad/s}$$

$$\epsilon = \frac{G''}{G'} \cong 2\varepsilon_{eq} \qquad (13)$$

ϵ= loss facor which is dpendent on magnetic field applied , whose value is obatined from secondary data[2]

ε_{eq} = equivalent daping ratio

$C_{eq} = 2m\omega_{neq}\varepsilon_{eq}$

From equation (12),

$$c = C_{eq}\left(1 + \left(\frac{c\omega}{K_1}\right)^2\right)$$

$$K_1 = \frac{c\omega_n}{\epsilon}$$

table 1 calculations

B gauss	ϵ	C_{eq} Ns/m	C Ns/m	K_1 N/m	K_{eq} N/m
0	0.02	0.072343	0.072372	466.800285	470.036645
400	0.044	0.072606	0.072635	470.207972	470.038007
800	0.064	0.232345	0.233297	471.959747	471.775261
1200	0.084	0.305971	0.308129	476.515112	473.188732
1600	0.136	0.509951	0.519946	482.450637	479.124257
1800	0.2	0.732663	0.761969	497.741192	488.999389
2000	0.24	0.888711	0.939901	517.180375	498.017611

VI. RESULTS AND DISCUSSION

Damping coefficient of MR fluid which is 0.07 Ns/m under magnetic field 0 gauss increased to 0.94 Ns/m under magnetic field 2000 gauss, as shown in fig. 6. Fig. 6 is obtained from table 1 calculations in which we have damping coefficient values are calculated under varying magnetic field strength.

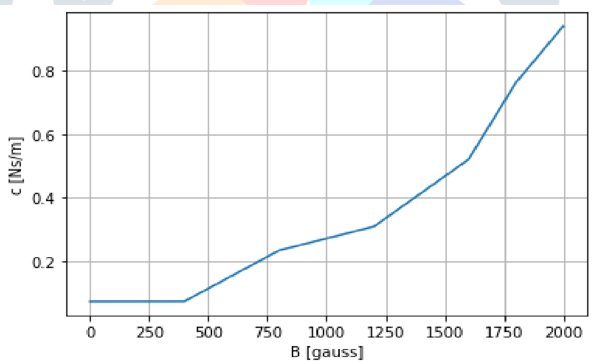

fig. 6 damping coefficient variation

K_1 (stiffness) vs B (magnetic field) is obtained from table 1 calculations. Stiffness of MR fluid which is 466.8 N/m under 0 gauss magnetic field increased to 517.8 N/m under 2000 gauss magnetic field, as shown in fig. 7. There is negligible increase in stiffness of MR fluid when magnetic field is varied from 0 to 2000 gauss.

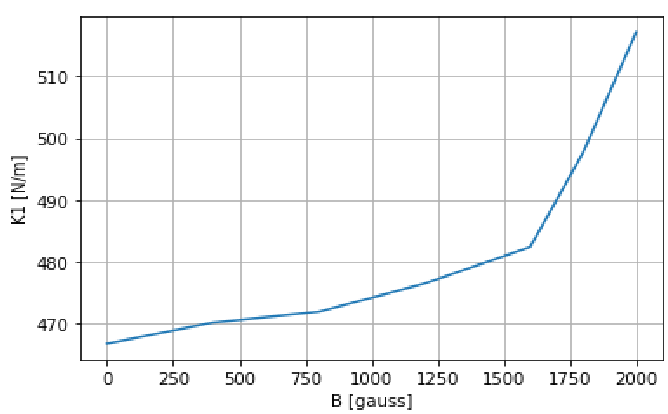

fig. 7 stiffness variation

C_{eq}, K_{eq} under different magnetic field is calculated, as shown in table1. Standard equations of equivalent single degree of freedom model has been used to obtain damped free response of the system. Fig. 8 and fig. 9 show how damped free response varies when magnetic field is varied as 400, 800, 1200, 1600, 1800, 2000 gauss respectively. As magnetic field increases there is decrease in decay time and amplitude.

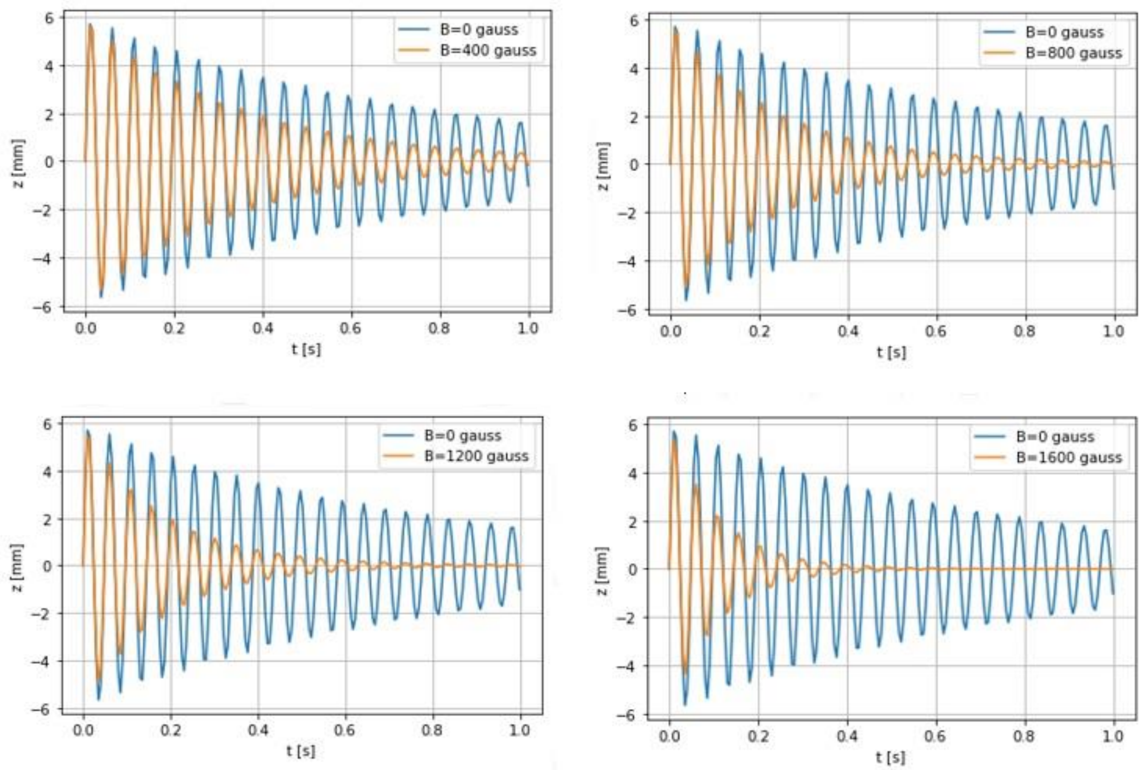

fig. 8 damped free vibration responses-1

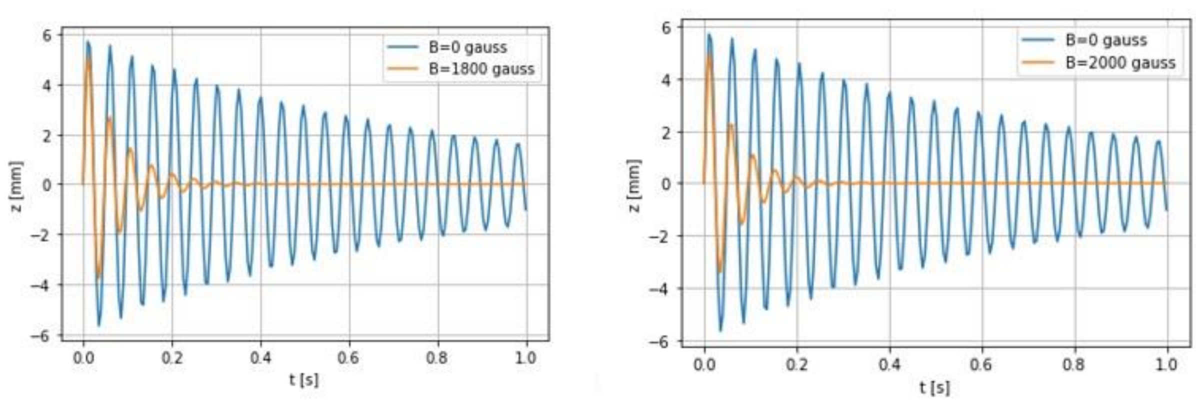

fig. 9 damped free vibration responses-2

K_{eq} and C_{eq} values under varying magnetic field are calculated, as shown in table1. Standard frequency response equations of single degree of freedom model is used to obtain frequency response curves under varying magnetic field, as shown in fig. 10 and fig. 11. It is observed that resonant response (Z/Zst at r=1) is reduced from 50.32 under 0 gauss magnetic field to 3.75 under 2000 gauss magnetic field.

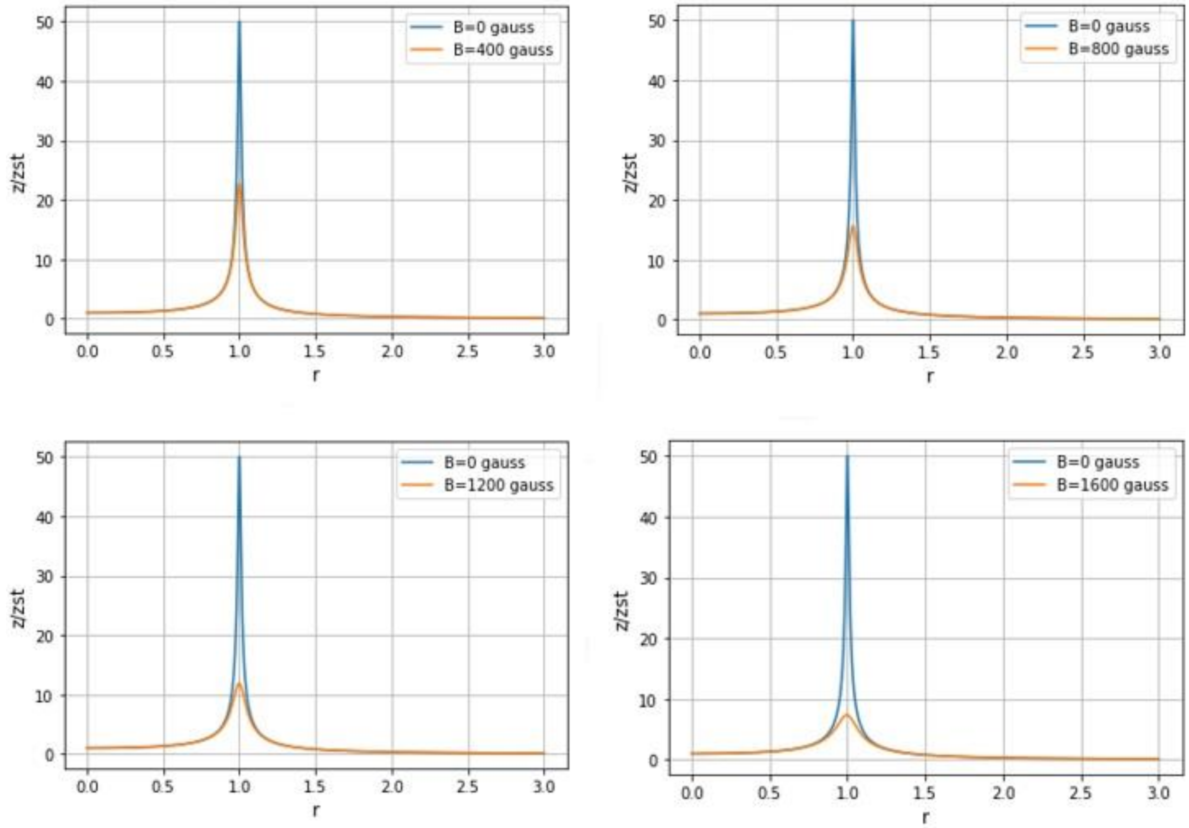

fig. 10 frequency response curves-1

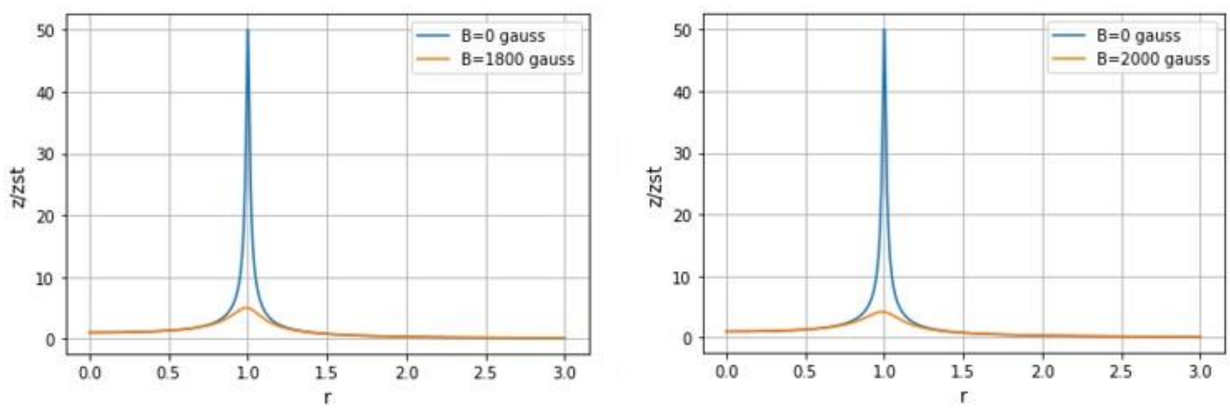

fig. 11 frequency response curves-2

VII. Conclusions

In this study, the magnetorheological fluid sandwich between two elastic aluminum layers has been analyzed using lumped parameter model. It has been shown that damping coefficient of given sandwich structure could be increased by increasing magnetic field strength applied on MR fluid. Negligible increase in stiffness of MR fluid corresponding to increasing magnetic field. Damped free responses and frequency response curves are obtained for different magnetic fields. It has been observed in damped free vibration plot that there is decrease in decay time to certain amplitude with increase in magnetic field. Significant decrease in resonant amplitude takes place with increase in magnetic field applied to MR sandwich structures.

VII. ACKNOLEDGEMENT

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