Dynamic Response of magnetorheological fluid tapered Laminated Beams Reinforced with Nano-particles

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Abstract: Non-uniform laminated composite structures are being used in many engineering applications where the structures are subjected to unpredicted vibration. Recently to mitigate the vibration response of these structures, magnetorheological fluid (MR) is added to non-uniform (tapered) thickness laminated composite structures to achieve a new generation of smart composite as MR tapered beam. However, due to the nature of MR fluid, especially the low stiffness, MR tapered beam exhibit lower stiffness and in turn, lower natural frequencies. To achieve the basic design requirements of the structure without MR fluid, one may need to apply a predefined magnetic field to the structures, requiring a constant source of energy. In the present work, the effects of adding nano particles on the dynamic response of MR tapered beam has been investigated. It is observed that adding nano particles up to 3% may significantly modify the natural frequencies of the structures and achieve dynamic behavior of the structures before addition of MR fluid. Two Models of tapered structures have been taken into consideration. It is observed that adding only 3% of nano particles backs the structures to its initial dynamic behavior.

Keywords: Non-uniform laminated structures, MR fluid, nano particles, vibration, stiffness.

1. INTRODUCTION

Non-uniform laminated composite beams are being used in many engineering applications such as aircraft fuselage, helicopter blades and arms of the robots. Recently, to mitigate and control excessive vibration and improve the stiffness of structures, MR fluids have been added to the structures at designated locations inside the structure.

Zabihollah et al. [1] experimentally tested the dynamic behavior of tapered laminated composite beams reinforced with nano particles. Farghaly and Gadelrab [2] discussed the free vibration of stepped-designed Timoshenko composite beams. Pol et al. [3] discussed the effect of adding nano particles from 0% to 7% on natural frequencies and damping ratios of the uniform-thickness beams. Similar investigation on the effect of adding nano particles on resin during manufacturing of laminated composites structures have been presented in literatures [4-5]. Gibson et al. [6] studied the vibration response of carbon nano tubes composite structures. Yeh et al. [7] investigated, numerically the effect of weight fraction of nano particles on the natural frequencies and mode shapes of beams. Pol et al. [8] investigated experimentally the mechanical properties of composite structures reinforced with nano particles. According to the existing literature, the effects of nano particles on the dynamic response of non-uniform laminated beams has not been well explored. In the present work, a passive initial stiffness control of the MR tapered beam has been studied. The effects of adding nano particles (from 0% to 3%) on the dynamic response of MR tapered beam has been investigated. Typical tapered laminated composite beams are shown in Fig. 1 [9].

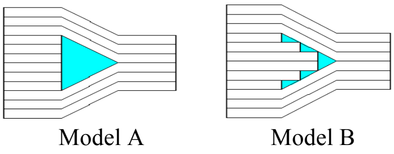

Fig. 1. The arrangement of different tapered laminated composite beams.

2. FEM OF MR-TAPERED BEAM

The MR tapered beam of Model A is consist of two sections, and illustrated in Fig. 2.

The displacement of laminated composite beam based on Classical Laminated Plate Theory (CLPT) is defined as:

$$u(x,z,t) = u_0(x,t) + z\frac{\partial w_0}{\partial x}, \tag{1}$$

$$w(x,z,t) = w_0(x,t), \tag{2}$$

where *u* and *w* are displacements along the *x* and *z*-axis, and *t* is the time.

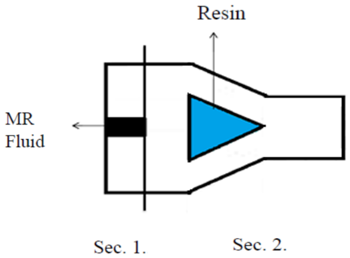

Fig. 2. Schematic drawing of the MR tapered beam of Model A.

The force and moment of the laminated composite beams are obtained and described in full details in Ref. [9].

The equation of motion of tapered laminated composite beam (section two) is defined as:

$$\frac{d^2}{dx^2}\left(k(x)\frac{d^2w}{dx^2}\right) - b(x)q(x) + b(x)\rho_s\frac{d^2w}{dt^2} = 0 \tag{3}$$

where *b*, *q*, and ρ_s denotes the width, force, and density of the structure, respectively. Following a finite element approach, one may achieve the matrix equation of motion of tapered laminated beams as:

$$[M_t]\{\ddot{w}\} + [K_t]\{w\} = \{F(t)\} \tag{4}$$

$$[M_t] = [M_{s1}] + [M_{s2}], \qquad [K_t] = [K_{s1}] + [K_{s2}] \tag{5}$$

where M_t, K_t, F and w are the global mass matrix, stiffness matrix, force vector and deflection of MR tapered beam reinforced with nano particles.

In Fig. 2, one may realize that MR tapered beam is composed of two main sections, a uniform section with MR fluid layer (section 1), and a section with tapered laminated beam (section 2). In Eq. 4, M_{s1}, K_{s1} and M_{s2}, K_{s2} are mass matrix, stiffness matrix of section one and mass matrix, stiffness matrix of section two, respectively.

To determine the global element matrices, one needs to compute element matrices for each section of MR tapered beam and then assemble them. The element matrices of section one are calculated using the procedure similar to the model developed by Eshghi et al. [10] and that of section 2 using a similar approach as given by Zabihollah et al. [1].

The free vibration response of MR tapered beam is defined as:

$$([K_t] - \omega^2[M_t])\{w\} = 0 \tag{6}$$

where ω is the natural frequency of MR tapered beam.

To compute the stiffness matrix of section 1, the estimation of complex shear modulus is essential. The complex shear modulus of structure is defined as:

$$G^* = G' + G'' \tag{7}$$

where G' is the storage shear modulus, G'' is the loss shear modulus and G^* is complex shear modulus.

3. FABRICATION OF MR-TAPERED BEAM

In order to fabricate the MR-tapered beam, tapered laminated composite beam was made of model A, and having a taper angle of 3.5°. The first step, 16 layers of plain woven E-Glass fibers with density of 200 gr/m^3, have been prepared to make section one. A cavity is considered in the middle of the beam and has been filled with MR fluid (MRF-132DG manufactured by Lord Company) as presented in Fig. 3 (b). For section two, as shown in Fig. 3(a), 24 and 12 layers of plain woven E-Glass fibers in thick and thin sections have been prepared, respectively. The resin mixture was prepared using epoxy; hardener and percentage of nano clay particles in an ultrasonic mixer for 25 minutes. The suspension was stirred with resin at 80 $^\circ$C for 10 minutes in speed of 1000 rpm. Fig. 3(c) shows that the prepared laminated plate and placed in an autoclave for 160 minutes at 85 $^\circ$C. Finally, the plate has been cut into strips.

Fig. 4 shows tapered laminated composite beam. In addition, the modulus of elasticity and density of the stripes without MR fluid is determined as 38.16 GPa and 1668 $Kg/m^{3,}$ respectively.

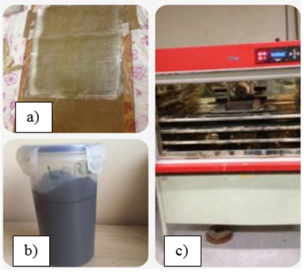

Fig. 3. (a). Laminated beams composed of plain woven E-glass and resin; (b) MR fluid 132-DG; (c) The curing process of E-glass plate.

4. NUMERICAL EXAMPLE

MR tapered beam described in the previous section with clamped-free condition is considered to study the dynamic behavior. The dimensions are 60mm*30mm*5.5mm. In section two, the length is 180mm (60mm thick section, 60mm thin section and 60mm tapered section), the width is 30mm and height for thin section is 3.4mm and for thick section is 5.5mm. MR taper beam are made as the taper configuration Models, namely, A and B. The storage shear modulus and loss shear modulus of MR-Fluid based on the experimental test ASTM-E756 is calculated as:

$$G'(B) = 7.2213\times10^{-2}B^2 - 2.043\times10^2B + 23.049\times10^4 \tag{8}$$

$$G''(B) = 403.8\times10^4B^2 + 21.4\ B + 3.498\times10^4 \tag{9}$$

where B is the magnetic flux density of MR tapered beam.

Fig. 4. MR tapered beam was made of Model A.

5. EFFECTS OF MR FLUIDS AND NANO PARTICLES ON NATURAL FREQUENCIES

Table 1. Theoretical and Experimental natural frequencies (Hz) of taper laminated beams and MR tapered beams in Clamped-Free condition.

Tapered laminated beam Model	Mode 1	Mode 2	Mode 3	Exp of Mode 1	Exp of Mode 2	Exp of Mode 3
A	15.93	60.56	175.34	18	66	219
B	19.44	73.19	199.06	-	-	-
MR tapered A	13.45	53.18	153.36	13	51	171
MR tapered B	16.15	55.67	174.58	-	-	-

The structures described in previous section have been considered to study the effects of adding nano particles on natural frequencies of MR tapered beam. It is understood that the optimum weight fraction of nano particles in the resin, during the manufacturing of laminated composite beam is about 3.5% [9]. Therefore, in this work, 2% and 3% of nano particles have been added to MR tapered beams and the results are given in Table 2. One may realize that, adding just 2% of nano particles to the resin during the manufacturing, reduces the difference between natural frequencies from 2.36 to 0.56 Hz for model A. Similarly, for tapered Model B, adding 2% of nano particles may reduce the natural frequency up to 60%. When the weight fraction of nano particles increases up to 3%, the differences of natural frequencies reaches to a negligible value of 0.27 Hz for Model A and 1 Hz for Model B.

The improvement in stiffness and natural frequencies of MR tapered beam, by introducing Δf, have defined as:

$$\Delta f = f(t) - f(M \text{ with } 3\% \text{ nano}) \quad (Hz) \tag{10}$$

where f_t and f_M are natural frequencies of tapered laminated beams and natural frequencies of MR tapered beams.

It is worth noting that the purpose of adding nano particles to the MR tapered beam is to mitigate the drawback of adding MR fluid to the structure. Therefore, Eq. 8, is defined to illustrate the differences between the natural frequencies of the taper laminated beam after adding 3% of nano particles on MR tapered beam. As it is shown in Table 3, the differences in first modes of Model A, are negligible and for Model B are approximately 1 Hz. However, the improvements for higher vibration modes are not as good as that of the first mode. For example, the differences in second modes for Models A and B are still in the range of 2-3 Hz which is sufficient enough. At the third modes, the differences for tapered models are in the range of 10-15 Hz. Therefore, one may conclude that the present approach, (i.e. adding nano particles to MR tapered beams) is an efficient technique to mitigate the drawback of adding MR fluid to the tapered laminated beam.

Table 2. Effects of nano particles on the first mode natural frequencies differences of taper beam.

	$\Delta f = f_t - f_M$ (Hz)	
% of nano	Model A	Model B
0	2.48	3.29
2	0.56	1.20
3	0.27	1.08

Table 3. Improvement in natural frequencies of MR tapered beams with 3% of nano particles.

Tapered Model	$\Delta f = f_t - f_{M \text{ with } 3\% \text{ nano}}$ (Hz)		
	Mode 1	Mode 2	Mode 3
A	0.27	2.87	18.95
B	1.08	3.88	15.65

6. CONCLUSION

In the present work, the dynamic behaviors of tapered laminated beams and MR tapered beams reinforced with nano particles have been investigated. The effects of adding nano particles on improvement of the first three natural frequencies of tapered laminated beams and MR tapered beams have been studied. Two types of most common tapered laminated beams, namely, Models A and B have been taken into consideration. One may realize that adding nano particles up to 3% significantly improves the natural frequencies of MR tapered beams. By adding 3% of nano particles, the natural frequencies of MR tapered beams in Models A and B have been negligible compared with the first three natural frequencies of tapered laminated beams. However, for higher vibration modes, these differences are in the range of 10-15 Hz. It is observed that adding nano particles up to 3% may significantly modify the natural frequencies of the structures.

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