Semi-Active Torsional Vibration Isolation Utilizing Magnetorheological Elastomer

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Abstract

In rotating machinery, unattenuated excessive torsional vibration leads to damage and excessive wear. This type of vibration, which is transferred from one structure to another can be estimated using torsional transmissibility factor (TTF). The value of the TTF describes the ratio of output to input and reaches its peak at the natural frequency. Hence, the ability to vary coupling stiffness of two rotating shafts will allow the control of the TTF towards better performance and preventions from fatigue loading. Traditionally, passive rubbers are used as a flexible coupling in between two shafts. However, the constant passive stiffness of the material limits its performance. To address this issue, an adaptive coupling based on magnetorheological elastomer (MRE) is proposed to achieve better TTF at varying frequencies. Mathematical modelling, simulation study and experimental results of MRE for torsional vibration isolation are presented in this work. Natural frequency obtained from the TTF shows an increase of about 3 Hz when current changed from 1 to 6 A.

Keywords: magnetorheological elastomer (MRE), torsional vibration, vibration isolation, smart materials

1. Introduction

Rotational machines such as turbines, compressors and pumps experience torsional vibrations, especially at low frequencies. Excessive torsional vibrations are one of the reasons for the wear rate which could significantly reduce their durability. In extreme cases, this could lead to machinery breakdowns and structural failure. The aim of this paper is to investigate the efficacy of magnetorheological elastomers (MRE) in semi-active torsional vibrational control.

MRE is a polymer composite that contains magnetizable particles which changes the stiffness of the elastomer based on the intensity of the surrounding magnetic field [1, 2]. As its stiffness property can be tuned, thus, it is capable of isolating vibrations.

In rotational machines, a common type of shaft coupler that utilizes a rubber piece as an intermediary to connect the two shafts is usually used. This rubber is considered passive as it does not require any external power supply. Due to this reason, it has a fixed property and therefore fixed natural frequencies. On the other hand, active vibration control techniques, though requires large external power source, are usually adopted due to its superior performance [3-5].

This paper proposes the use of magnetorheological elastomer (MRE) to replace the passive rubber as a shaft coupler. In addition to that, in comparison with active control systems, MRE requires a lower amount of external energy. The MRE is activated by a magnetic flux that is produced by a solenoid consisting of enamelled copper wire encircling the coupler. MRE is chosen for the benefit of controllable stiffness and quick response time [6-7].

The most common type of magnetic circuit designs utilizes C-shape magnetic core. However, in this paper, the magnetic field is provided by a stationary solenoid surrounding the MRE while separated with a gap to avoid collision if the MRE vibrates significantly.

2. Modelling of magnetorheological elastomer (MRE) transmissibility

The system is modelled based on the base excitation of a single degree of freedom system. Figure 1 is an illustration of a linear motion base excitation, at which the transmissibility equation can be derived as expressed in Eq. (1) [8].

$$T = \left|\frac{X(\omega)}{Y(\omega)}\right| = \left[\frac{(c\omega)^2 + K^2}{(c\omega)^2 + (K - m\omega^2)^2}\right]^{1/2} \tag{1}$$

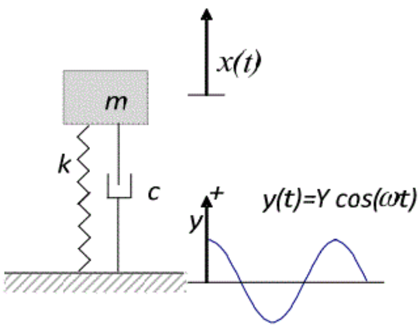

Figure 1. An illustration of the vibration model

In Eq. (1), *c* refers to the damping, *K* is the stiffness, *m* is the mass and ω is the frequency. In addition, *Y* is the input and *X* is the output. By substituting the torsional equivalent parameters in Eq. (1), the equation can be rewritten as

$$T = \left|\frac{X(\omega)}{Y(\omega)}\right| = \left[\frac{(c\omega)^2 + K_{mre}{}^2}{(c\omega)^2 + (K_{mre} - J\omega^2)^2}\right]^{1/2} \tag{2}$$

where *J* is the inertia. Eq. (2) is used throughout this paper, to control excessive torsional vibrations. It is assumed that the most distinctive changes to the MRE system is the stiffness. On the other hand, the changes in the damping property due to the magnetic field do not change significantly [9]. Therefore, in the simulated model of the MRE system, the change in the stiffness due to magnetic field is linearly related to the current in the solenoid, as seen in Figure 2.

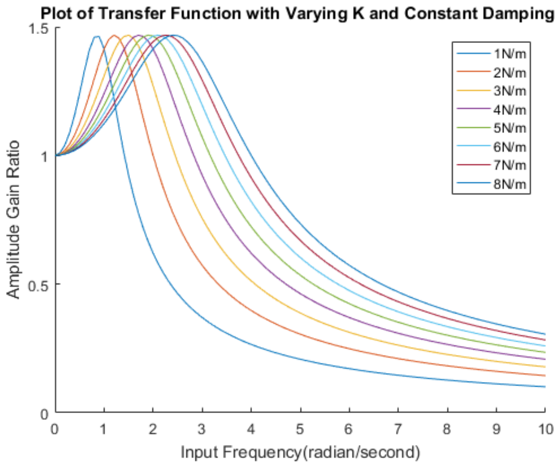

Figure 2. Estimated values of TTF

3. Experimental setup

The schematic diagram of the experimental setup is shown in Figure 3. It consists of a dynamic signal analyser (DSA), a voltage amplifier, a power supply, an inertial shaker and a 40% iron particles by mass magnetorheological elastomer (Figure 4).

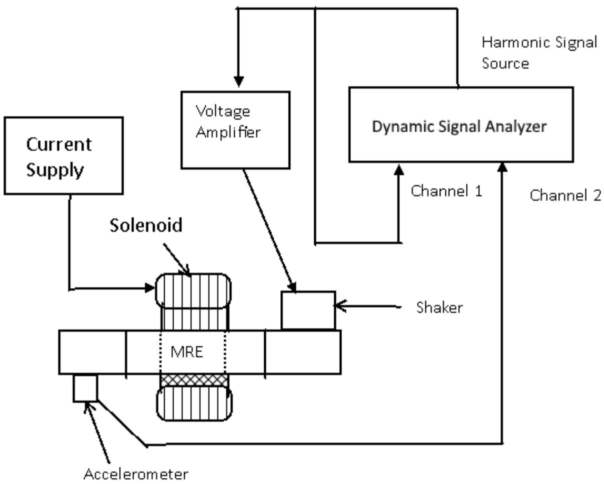

Figure 3. Experimental Diagram

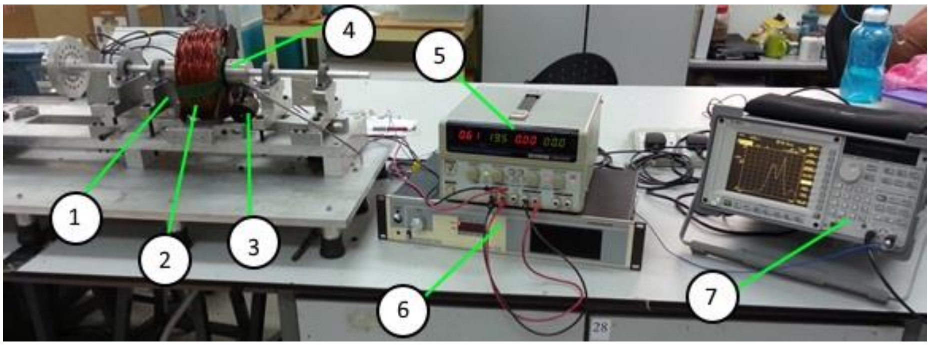

Figure 4. Experimental Setup
1) Accelerometer 2) Solenoid 3) Inertial Shaker 4) MRE and solenoid
5) Power Supply Unit 6) Voltage Amplifier 7) Dynamic Signal Analyser

The DSA provided harmonic sweep signal which was then amplified to supply enough voltage for the FG-142 shaker. The frequency range considered in the experiment was from 0 Hz up to 400 Hz. The MRE was formed to a cylinder which was glued to the rigid couplers, as shown in Figure 5(a). The ends of the shaft coupler were attached to an inertial shaker and accelerometer, respectively. An additional mass was also attached to one of the shaft ends to lower the natural frequency [10]. In this experiment, the stiffness of the MRE was observed at various levels of current. The experiment was first done without the presence of the magnetic field, and increased up to 6A, with 1A increment. The response obtained was captured by the DSA.

(a) MRE shaft coupling (b) Solenoid

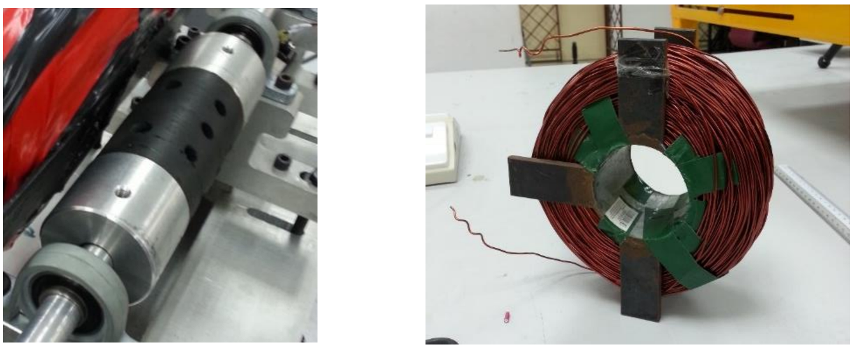

Figure 5. MRE formed in the shape of a cylinder, which was then placed inside a solenoid, as shown in item (4) in Figure 5

4. Results

The torsional transmissibility factor (TTF) obtained in the experiment is shown in Figure 6. It is taken in terms of transfer function, which is accelerometer reading over the input voltage $\left(\frac{g}{V}\right)$. It is seen that the natural frequencies of the system, excited at different value of applied current occur in between 160 Hz and 190 Hz. Thus, this region is then zoomed in so that every natural frequency can be clearly analysed (Figure 7).

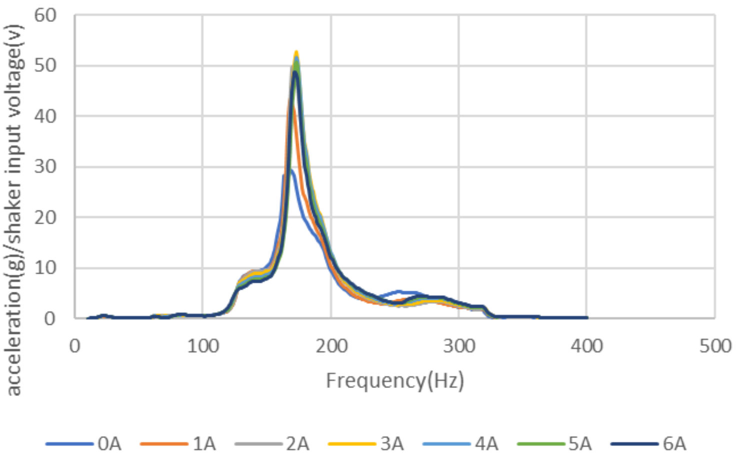

Figure 6. Estimated values of TTF at varying current

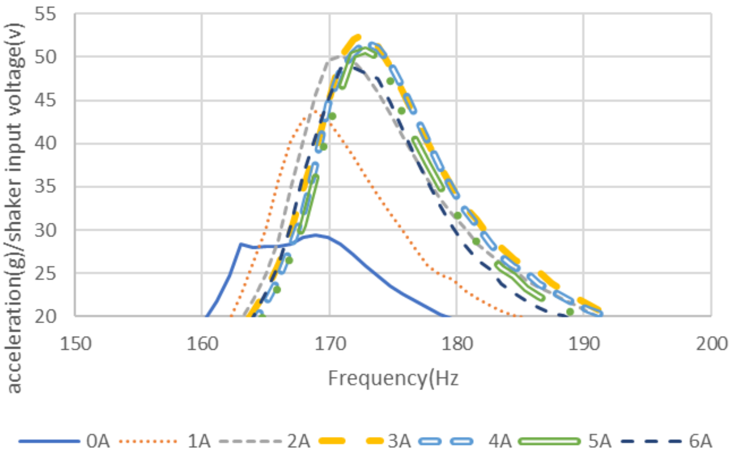

Figure 7. An excerpt of Figure 6, focusing on 160 Hz < freq < 190 Hz

From Figure 7, it is seen that after 3A of current supplied to the solenoid, the TTF reaches a saturation point. Before 3A, the natural frequency increases with increasing current. After saturation, the natural frequency drops. From the plot of frequency response, the determine ratio, ζ can be determined using

$$\zeta = \left[\frac{\omega_2 - \omega_1}{2\omega_n} \right] \tag{3}$$

In Eq. (3), ω_1 and ω_2 are the frequencies at which the response is at $\sqrt{2}$ TTF_{max} [8]. The estimated values of damping ratio are listed in Table 1. Current applied to the coil generates magnetic field that changes the stiffness of the MRE. The value of magnetic field generated were recorded using FW Bell 5100 Series Gaussmeter and is also listed in Table 1. The estimated damping ratio at different magnitude of magnetic field is also shown in Figure 9.

Figure 8. Measuring magnetic field using FW Bell Gaussmeter

Table 1. Damping ratio estimated at different levels of applied current

Current (A)	Magnetic Field Density (Gauss)	ω_n (Hz)	ω_1 (Hz)	ω_2 (Hz)	Damping ratio, ζ
0	0	168.925	161.125	177.7	0.04906
1	38.1	168.925	165.025	174.775	0.028859
2	79.3	170.875	166.975	177.7	0.031383
3	108	172.825	168.925	178.675	0.028208
4	153.6	172.825	168.925	178.675	0.028208
5	214.6	172.825	168.925	178.675	0.028208
6	242.8	171.85	167.95	177.7	0.028368

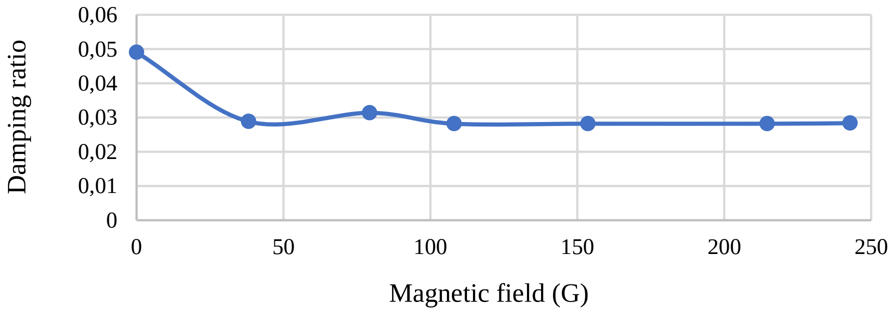

Figure 9. Estimated value of damping ratio at different value of magnetic field

5. Conclusion

Magnetorhelogical elastomer (MRE) is a smart material that is capable of changing its stiffness subjected to the intensity of the magnetic field. Thus, the use of MRE in rotating machineries helps in reducing the effect of torsional vibration to the system. Torsional transmissibility factor (TTF) can be used to evaluate the effectiveness of the material in suppressing the vibration. An experimental setup involving an MRE in a rotating machinery was utilized to study the influence of the MRE to the system, at various levels of magnetic field. It is seen that the calculated damping ratio of the system undergoes a change of value by 0.020853. The natural frequency of the system changes with a maximum range of 3.9 Hz.

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