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Development and evaluation of an MRE-based absorber with two individually controllable natural frequencies

Abstract

Adaptive tuned mass absorbers, which are based on magnetorheological elastomer (MRE) have been widely accepted for vibration absorption due to their frequency shift capability. Wider frequency bandwidth indicates more effectiveness in reducing vibrations. In order to broaden the effective bandwidth of the MRE-based absorber, this study proposes a new design consisting of an eccentric mass. This design enables the absorber to have two natural frequencies: the rotational natural frequency and the translational one. These two natural frequencies can be controlled separately by adjusting the MRE stiffness and the eccentric length. This design not only broadens the effective bandwidth of the absorber, but enables the absorber to suppress vibrations with multiple dominant frequencies. The characterization experiment verifies the existence of the two natural frequencies and draws the conclusion that the translational natural frequency is under the influence of the applied current, while the rotational natural frequency is controlled by both the applied current and the eccentric length. The vibration reduction effectiveness is then evaluated experimentally by mounting the MRE-based absorber on a primary system.

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Development and evaluation of an MRE-based absorber with two individually controllable natural frequencies

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ABSTRACT

Adaptive tuned mass absorbers which are based on magnetorheological elastomer (MRE) have been widely accepted for vibration absorption due to their capability of frequency shift. Wider frequency bandwidth indicates more effectiveness in reducing vibrations. In order to broaden the effective bandwidth of the MRE-based absorber, this study proposes a new design consisting of an eccentric mass. This design enables the absorber to have two natural frequencies: the rotational natural frequency and the translational one. These two natural frequencies can be controlled separately by adjusting the MRE stiffness and the eccentric length. This design not only broadens the effective bandwidth of the absorber, but also enables the absorber to suppress vibrations with multiple dominant frequencies. The characterization experiment verifies the existence of the two natural frequencies and draws the conclusion that the translational natural frequency is under the influence of the applied current while the rotational natural frequency is controlled by both the applied current and the eccentric length. The vibration reduction effectiveness is then evaluated experimentally by mounting the MRE-based absorber on a primary system.

Key words:

Adaptive tuned magnetorheological vibration absorber; vibration control; double natural frequency; individually controllable natural frequencies.

1. Introduction

As a means of overcoming the vibration-caused shortcomings such as ride discomfort, noise, accuracy reduction, and mechanical failure, dynamic vibration absorber (DVA) has already been an attractive option. The first DVA can be dated back to Frahm in 1911 [1], it was a mass spring system and it generally consists of an oscillator and a stiffness component. With the improving DVA technology, damping component was also considered. DVA is generally mounted on the top of the protected structure and its operation principle is transferring the vibration energy of the protected objects to the absorber oscillator. As the DVA has the advantages of simplicity, stability, low cost, and low power consumption, they are widely used to reduce vibrations in areas including building structures, automotive industry, aircraft, generators, and engines [2-4].

DVAs are generally classified into three categories: passive DVAs [3, 5], active DVAs [6], and semi-active DVAs [7-9]. The passive DVA has high stability and is simple to be structured. However, they are normally only effective within a very narrow bandwidth due to their fixed parameters. To overcome this shortcoming, semi-active and active dynamic vibration absorbers have been attractive alternatives. However, the disadvantages of active absorber, i.e. high power consumption, high potential instability and high cost, limit its practical application. In contrast, semi-active absorber can perform comparable performances without these drawbacks.

The composition of the semi-active DVA is similar to that of a conventional dynamic absorber with only an exception that the semi-active DVA consists of a changeable coefficient which can be adjusted in real time according to different requirements. The implementation of a semi-active DVA usually needs smart materials, such as the magnetorheological materials to enable the controllable coefficient. Magnetorheological (MR) materials are smart materials whose viscosity or modulus can be controlled rapidly and have been widely applied in many fields [10-13]. Magnetorheological elastomer (MRE), as a member of the MR materials [14], generally consists of micro-sized magnetic particles dispersed in a non-magnetic matrix. MRE is

popular for developing vibration attenuation devices [15-19], especially a semi-active vibration absorber, due to its variable stiffness, quick response, simple structure, stable property, and its controllability [20]. The incorporation of the MRE into the absorber makes it possible to change the lateral stiffness of the absorber. Following the work of Ginder et. al. relating to the development of an adaptive tuneable vibration absorber using MRE [21], Deng et. al. systematically investigated the performance of MRE absorber both experimentally and theoretically [22]. Xu et. al. used an active force to develop active-adaptive vibration absorbers to overcome the damping of the MRE [23], as another way to further improve the absorption performance. After that Hoang presented a conceptual adaptive tuned vibration absorber (ATVA) with soft MREs to reduce the torsional vibration existed in vehicle power train systems [24, 25] and, Popp et al. analysed the MR effect of the absorber under both shear and squeeze modes based on the experimental studies and simulations [26].

Though the above-mentioned MRE-based absorbers are able to shift their natural frequency when current is applied, a common shortcoming is that they have only one resonance frequency under a certain constant current. That means they can only match one vibration frequency at every moment and become less effective when encountered with vibrations with multiple frequencies. To resolve this challenge, an effective way is to increase the number of natural frequencies. Variable inertia technology is a effective method to develop adaptive DVA [27, 28] and it is promising to develop the second resonance for the MRE absorber. In this regard, an MRE-based absorber with two natural frequencies is designed, tested, and evaluated in our previous work by combining the variable inertia and MRE technologies [29]. However, the previously presented absorber has a limitation that its two resonance frequencies cannot be controlled separately. In order to solve this problem this research innovatively designed a new absorber which is able to control the two resonance frequencies separately. With this property, the designed MRE-based absorber will be able to trace two dominant excitation frequencies and will be more effective on reducing vibrations. Following the introduction, section 2 introduces the structure and the working mechanism of the

absorber. Section 3 investigates the frequency shift performances and Section 4 evaluates its vibration absorption effectiveness. Section 5 draws the conclusion.

2. Structure and working mechanism

Figure 1 shows the schematic diagram and the prototype picture of the designed MRE-based absorber. This absorber is mainly constructed by a multilayer MRE pillar, a permanent magnet, a set of solenoid, an outer steel cylinder, a top plate, a bottom plate, and a step motor serving as an eccentric mass. 5 MRE layers are used to build the MRE pillar in this research. The MRE pillar is always under the action of a permanent magnetic field because of the permanent magnet involvement. The solenoid and the outer steel cylinder then surround this MRE and magnet structure. Once the solenoid is energized, there are a total of two magnetic fields, i.e. the permanent magnetic field and the electromagnetic field, working on the MRE pillar. Then the strength of the overall magnetic field can be not only increased but also decreased by changing the direction of the electromagnetic field (or the applied current) to be the same or opposite to that of the permanent magnetic field. In this way, the effective bandwidth of the absorber can be further broadened. The other essential component of the absorber is the eccentric mass which is a linear stepping motor (17HD40005-300N) in this design. The motor sits in a linear track groove which is fixed to the top plate. The motor will, once started, move along the screw and thus the eccentric length of the eccentric mass can be controlled.

The combination of the MRE structure and the controllable eccentric length enables this proposed absorber have two vibration modes: one is induced by the translational motion and the other is induced by rotational motion. Correspondingly, each mode has a natural frequency. We name them the translational natural frequency and the rotational natural frequency, respectively.

Figure 1 Prototype picture and schematic diagram of the designed MRE-based absorber

The theoretical analysis and calculation in terms of the translational natural frequency and the rotational natural frequency have been introduced in our previously published paper [29]. The mathematical expression for the translational natural frequency of the MRE-based absorber is described as:

$$f_t = \frac{1}{2\pi} \sqrt{\frac{\left(G_0 + 36\phi\mu_0\mu_l\beta^2\vec{H}_0^2\left(\frac{a}{d}\right)^3\zeta\right)A}{5mL}} \quad (1)$$

where G_0 is the initial shear modulus of the MRE, ϕ is the volume fraction, μ_0 is the vacuum permeability, $\beta = (\mu_p - \mu_l)(\mu_p + 2\mu_l) \approx 1$, $\mu_p \approx 1000$ and $\mu_l \approx 1$ are the relative permeability of the particles and silicon rubber, respectively. a is the average particle radius, d is the particle distance before deflection, $\zeta = \sum_{j=1}^n \frac{1}{j^3} \approx 1.202$, A is the effective area of an MRE sheet, L is the thickness of the MRE sheets, and m is the oscillator mass of the MRE-based absorber. $\vec{H}_0$ is the intensity of the applied magnetic field and its relationship with the applied current I can be expressed as:

$$NI + M = \vec{H}_0 S_{MRE} R_m \mu_{MRE} \mu_0 \quad (2)$$

where R_m is the overall magnetic resistance, M is the magnetomotive force of the permanent magnet, S_{MRE} is the area of the MRE layers, μ_{MRE} is the relative permeability of MRE, N is the coil turns.

The natural frequency of the MRE-based absorber in rotational direction can be written as:

$$f_r = \frac{1}{2\pi} \sqrt{\frac{(G_0 + 36\phi\mu_0\mu_1\beta^2\bar{H}_0^2 \left(\frac{a}{d}\right)^3 \zeta) I_p}{5LJ}} \quad (3)$$

$$J = J_1 + J_2 \quad (4)$$

where J is the overall moment of inertia of the oscillator, $J_1 = 0.002$ is the constant moment of inertia of the oscillator, $J_2 = m_1 d_1^2$ is the controllable moment of inertia of the oscillator, m_1 is the eccentric mass, d_1 is the eccentric length, and I_p is the polar moment of inertia of the MRE layer.

According to the above theoretical expressions, the variations of the applied current (i.e. the magnetic field) will induce changes to both the translational natural frequency and the rotational natural frequency. Alternatively, the rotational natural frequency is also influenced by the eccentric length (i.e. the moment of inertia). In this case, two control variables (i.e. current and eccentric length) can adjust/manipulate two controlled variables (i.e. rotational and translational resonance frequencies); therefore, the translational frequency and the rotational frequency can be separately controlled.

3. Evaluation of the frequency shift performance

3.1 Experimental setup

This section is to investigate the frequency shift performance of the proposed absorber under the control of the applied current and the eccentric length. Frequency shift performance is an important index to indicate the absorber's ability for vibration reduction. It is generally characterized by the transmissibility (defined as the ratio of the response to the excitation) by subjecting the absorber to excitations. Each transmissibility has at least one resonance, of which the abscissa is the natural frequency under that condition. Figure 2 shows the experimental setup. It can be seen that the absorber was fixed to the vibration platform and excited by the shaker (VTS, VC100-8). Two accelerometers were installed on the excitation table and the absorber

oscillator to measure their accelerations, respectively. A DC power (THURLBY-THANDAR, INSTRUMENTS LTD) was used to supply current to the solenoid of the absorber. The eccentric length of the stepper motor was controlled by a stepper motor driver and the myRIO control board. The myRIO control board is also used to transfer the measured accelerations to the computer. LabVIEW programming was used for this experiment to collect data, record and display responses, and develop control unit.

A harmonic excitation signal with sweeping frequency was used to excite the absorber to obtain the transmissibility performances under different current levels and eccentric length. In order to enable the direction changing of the electromagnetic field, positive current and negative current were defined here: positive current means under which the electromagnetic field is in the same direction as the permanent magnetic field, otherwise, it is defined as the negative current. The DC signal was changed from -2A to 2A with a step of 1A. The eccentricity changes from 80mm to 110 mm with a step of 10mm.

Figure 2 Experimental setup for absorber characterization

3.2 Effect of the current on the two resonances

Figure 3 shows the testing results under varying current with a constant eccentricity (100mm). It can be seen that each transmissibility response has two resonances. Compared with the absorbers with only one natural frequency, this absorber is more capable of dealing with multiple frequency vibrations. It can be seen from Figure 3 that the variations of the applied current shift both the rotational and the translational natural

frequencies. Both of them increase as the applied current increases from -2A to 2A. This means that between these current intervals, the superposition of the two magnetic fields is increasing as the current increases. It should also be noted that the variations of the applied current pose more obvious influence to the translational natural frequency than to the rotational natural frequency. Specifically, the translation natural frequency varies from 4.8Hz to 9.5Hz when the current increase from -2A to 2A, producing a change rate of 97.9% while the change rate of the rotational natural frequency is 62.9% under the same experimental condition. Table 1 lists the natural frequencies under different current levels.

Table 1 Rotational natural frequency and translational natural frequency under various current with constant eccentric length of 100mm

Current Values	-2A	-1A	0A	1A	2A
Rotational natural frequency (Hz)	2.99	3.15	3.51	3.93	4.45
Translational natural frequency (Hz)	4.81	5.04	6.99	9.14	9.66

Figure 3 Transmissibility performance of the absorber under constant eccentric length and various current.

3.3 Effect of the eccentricity on the resonances

This experiment used a linear stepper motor (17HD40005-300N) as the eccentric mass.

Figure 4 shows the frequency shift performance of the absorber when the eccentricity changes from 80mm to 110mm with a step of 10mm with the current fixed at 2A. It can be seen that the rotational natural frequency decreases as the eccentric length increases. This is because the increasing eccentric length induces the increase of the moment of inertia and thus reduces rotational natural frequency. It can also be seen that the translational natural frequency is irrelevant to the eccentric length as it remains almost unchanged.

It can be concluded from Figure 3 and Figure 4 that the variations of current (magnetic field) lead to the changes of both rotational natural frequency and translational natural frequency, while the eccentric length only has influence on the rotational natural frequency. Therefore, the rotational natural frequency and the translational natural frequency can be individually controlled by these two control variables.

Figure 4 Transmissibility performance of the absorber under various eccentric length with constant current

According to the equations (1) and (2), the calculated rotational natural frequency and translational natural frequency under different current levels and different eccentric lengths can be calculated. The calculated resonance frequencies are compared with the experimentally obtained natural frequencies in Figures 5 and 6. It can be seen that the theoretical natural frequencies match well with the experimentally obtained results under both varied current and varied eccentricity.

Figure 5. Comparison between the theoretical and experimental natural frequencies under different current.

Figure 6. Comparison between the theoretical and experimental natural frequencies under different eccentricity.

4. The verification of the absorption effectiveness

4.1 Absorption effectiveness analysis without control algorithm

This section investigates the vibration absorption performance of the MRE-based absorber. Figure 7 shows the experimental setup. It mainly consists of a power amplifier, accelerometers, excitation table, myRIO controllers, motor driver, stepper motor

(17HD40005-300N), the proposed absorber, and the primary system. The absorber is mounted on the top of the primary system. In this case, no control algorithm was used. We only collected the accelerations of the primary system and the excitation signal to obtain the absorption transmissibility.

Figure 7 Experimental setup for the absorption evaluation

In this experiment, a sweep harmonic excitation was used. Figure 8 presents the vibration absorption effectiveness of the absorber when it has a constant eccentricity of 70mm and varying currents. It can be seen that each transmissibility has two pits (indicated by small circles in Fig. 8 and Fig.9) and we name them the rotational absorption point and the translational absorption point, respectively. The reason for the appearance of the pits is that the amplitude of the transmissibility is reduced at the points where the rotational natural frequency and the translational natural frequency match the dominant frequencies of excitations. Therefore, the pits indicate the frequencies where the resonances happen and the vibration absorptions occur. Additionally, it can also be seen that the rotational pit and the translational pit both show the shift characteristics. This is because the rotational and translational natural frequencies are sensitive to the changes of the applied current.

Figure 8 Absorption performance of the absorber under the constant eccentric length and various current

Figure 9 shows the absorption effectiveness of the absorber under the constant current of 2A and varying eccentric length. It can be seen that there are also two absorption points in each transmissibility curve. For all the transmissibility, the rotational absorption points shift to the left of the x axis when the eccentric length increases while the translational absorption point remained unchanged. This is because the increasing eccentric length induces reduction of rotational natural frequency while pose no impact on the translational natural frequency.

These experimental results, on one hand, verify the conclusion that the current signal influences both the rotational and translational natural frequencies while the eccentric length only influences the rotational natural frequency, on the other hand, give a preview of the absorption effectiveness of the proposed absorber.

Figure 9 Absorption performance of the absorber under constant current and various eccentric length.

4.2 Absorption effectiveness analysis with real time control

This experiment verifies the absorption capability of the MRE-based absorber under different excitations with the designed control algorithm. Figure 10 shows the control flow of the whole process. We would evaluate the absorption capability of the absorber under both real-time controlled current and eccentric length. The rotational natural frequency would be used to trace the lower dominant frequency of the excitation signal and the translational natural frequency traces the higher one. Therefore, it is necessary to identify the two dominant excitation frequencies from the collected responses of the primary system. In order to detect the two dominant frequencies, both filters and short time Fourier transform (STFT) method will be applied in the controller. As shown in Figure 10, the control flow shows that after the acceleration response of the primary system was collected, it will pass through two filters: a low-pass filter and a high-pass filter. The thresholds for the two filters are set as 5.5Hz. In this way, two control routes are needed to transform the collected signal into the desired outputs. In each control route, a short time Fourier transform method was used to identify the dominant frequency. For the purpose of brevity, the details of the STFT control algorithm can be referred to our previous work in [29] and will not be presented here. According to the

STFT, the two dominant frequencies within the range of effective rotational bandwidth (lower than 5.5Hz) as well as the translational bandwidth (higher than 5.5Hz) can be obtained. Then according to the relationships given in Equations (1)-(4), the desired current and the desired eccentric length can be calculated by the detected dominant frequencies. The details of the calculation are shown as following:

$$I = \frac{S_{MRE} R_m \mu_{MRE} \mu_0 \sqrt{\frac{20 f_t^2 \pi^2 m L - A G_0}{A \phi \mu_0 \mu_l \left(\frac{a}{d}\right)^3 \zeta}} - 6 \beta M}{6 \beta N} \quad (5)$$

$$d_1 = \sqrt{\frac{\left(G_0 + 36 \phi \mu_0 \mu_l \beta^2 \left(\frac{N I}{S_{MRE} R_m \mu_{MRE} \mu_0}\right)^2 \left(\frac{a}{d}\right)^3 \zeta\right) I_p - 20 f_r^2 \pi^2 L m_1 J_1}{20 f_r^2 \pi^2 L m_1}} \quad (6)$$

From these two equations it can be seen that the current I is controlled solely by the natural translational frequency f_t and it will be determined as the first step. On the contrast, the eccentric length d_1 is affected by both current I and rotary natural frequency f_r and it will be controlled after the current I being determined in the first step. Upon receiving the desired current and the desired eccentric length, the absorber would perform the desired translational natural frequency and the desired rotational natural frequency.

Figure 10 Control flow

In order to obtain a closer observation of the absorption effectiveness of the MRE-based absorber, we analyzed the performances of the primary system in time domain by subjecting the whole system to three cases: the first case is with only current control, the second case is with only eccentric length control, and the third case is with both current and eccentric length control.

Case 1:

Case 1 is to evaluate the absorption effectiveness of the absorber in translational direction by setting the eccentric length as constant 70mm. The applied current would be controlled according to the real time acceleration of the primary system. In this case, the harmonic excitation frequency is 10Hz.

Figure 11 shows the time history of the acceleration of the primary system. It can be seen that the amplitude of the acceleration is very large when the current and eccentricity controllers are off and then it decreases to the minimum and maintains unchanged after the current controller is turned on at 4s. It can be seen that when the desired current is obtained and the excitation frequency is matched by the translational natural frequency, the acceleration of the primary system is reduced and maintained at the minimum value. The acceleration reduction can also be demonstrated by the RMS value which is reduced from 0.48 m/s² to 0.22 m/s² with a relative change of 55.1%. Therefore, the results demonstrate that the properly controlled translational motion of the proposed MRE-based absorber is effective on reducing the vibration.

Figure 11 Response of the primary system acceleration before and after current control.

Case 2:

Case 2 is to investigate the absorption effectiveness of the MRE-based absorber by only

adjusting the eccentric length with constant 0A current. The harmonic excitation frequency is 5.5Hz.

Figure 12 shows the control performance in terms of the acceleration of the primary system. It can be seen that the amplitude of the acceleration is reduced from about 13s when the eccentric length controller is turned on. It means that from 13s the desired eccentric length is obtained and that the excitation frequency is traced by the rotational natural frequency. Likewise, the RMS value is also shown in the figure. It is reduced by 20.3%. This demonstrates that the rotational motion of the absorber can be well controlled to suppress the vibration.

Figure 12 Response of the primary system acceleration before and after eccentric length control

Case 3:

Case 3 combines case 1 and case 2 by exciting the system using a composite harmonic excitation which contains 5.5Hz and 10Hz frequency. In this case, we investigated the synergized absorption effectiveness by turning on the current controller and the eccentric length controller in sequence. Specifically, both current control and eccentric length control are off before 11s and then the current controller is turned on at 11s while

the eccentric length controller still remains off; at 22s, the eccentric length controller is also turned on. Figure 13 shows the gradient change of the acceleration of the primary system. It can be seen that the first change occurs at about 11s and the second time change occurs at about 22s. The RMS values for the three intervals are 0.74 m/s^2 , 0.57 m/s^2 , and 0.43 m/s^2 , respectively, bring a final reduction by 42.4%. These results indicate that the translational motion of the absorber is effective on absorbing the 10Hz vibration component from 11s. After 22s both the current and the eccentric length are controlled in real time and the vibration is further reduced. This means that the rotational motion of the absorber is also properly controlled to absorb the 5.5Hz vibration component. These testing results verified that the absorber with two individually controllable resonances can trace two vibration frequencies and improve the vibration absorption performance.

Figure 13 Response of the primary system acceleration with current control and eccentric length control turned on in sequence

5. Conclusion

This paper investigates the frequency shift performance and the absorption capability

of the designed MRE-based absorber which includes an eccentric mass and an MRE multilayered structure. The combination of MRE and eccentric mass enables the absorber to have both translational natural frequency and rotational natural frequency. The characterization experiment indicates that the two natural frequencies are both controllable and they can be controlled separately. The vibration absorption experiment demonstrates comprehensive evaluation and verification in terms of the absorption capability of the proposed MRE-based absorber in either the translational direction or the rotational direction. The evaluation results proved that the proposed absorber with two individually controllable resonances is able to trace two vibration frequencies.

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