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Effectiveness and nonlinear characterization of energy harvesting absorbers with mechanical and magnetic stoppers

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Abstract

Tuned mass dampers are a common method implemented to control structure's vibrations. Most tuned-mass dampers only transfer the mechanical energy of the primary system to a secondary system, but it is desirable to convert the primary systems' mechanical energy into usable electric energy. This study achieves this by using a piezoelectric energy harvester as a tuned-mass damper. Additionally, this study focuses on improving the amount of energy harvested by including amplitude stoppers. Mechanical stoppers have been investigated to sufficiently widen the response of piezoelectric energy harvesters. Furthermore, magnetic stoppers are compared to the mechanical stopper's response. A nonlinear reduced-order model using Galerkin discretization and Euler-Lagrange equations is developed. The goal of this study is to maximize the energy harvested from the absorber without negatively affecting the control of the primary structure.

I. Introduction

Damaging environmental vibrations, especially harmonic oscillations which occur when the excitation frequency matches the natural frequency of the structure, are aimed to be avoided or controlled when designing systems and structures [1]. A popular way to combat harmonic oscillations is a tuned-mass-damper. Most tuned-mass-dampers dissipate the energy as mechanical energy through a secondary system. However, it is desirable to convert this energy into useful electrical energy. This is especially important in dangerous to reach locations, such as the top suspension bridge towers or remote cell towers because it would be able to power sensors without the need for battery replacements A great way to accomplish this is by using a piezoelectric energy harvester as the tuned-mass-damper [2].

To further improve the capabilities of the harvester, the parameters of the energy harvester are optimized to get the bandwidth as broad as possible. To further the width of the operable range, amplitude stoppers are included in the energy harvesting absorber. Contact with the amplitude stoppers may generate a nonlinear response that is evaluated to improve the energy harvesting absorber's ability to generate power as well as maintain control of the primary structure's oscillations. In addition to mechanical stoppers, magnetic stoppers are also investigated to obtain the optimal design.

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II. System's dynamics and reduced-order modeling

To avoid lengthy computations due to the high nonlinearities of the contact impacts between the absorber and stoppers, a reduced-ordered model is developed. The primary system is represented by a spring-mass-damper system. The reduced-ordered model displacements can be seen in Figure 1, where the primary structure's displacement and the energy harvesting absorber's displacement are represented as w_1 and w_2, respectively. The amplitude stoppers' locations are placed at the end of the beam where it comes into contact with the tip mass and are represented as the cyan hashed blocks.

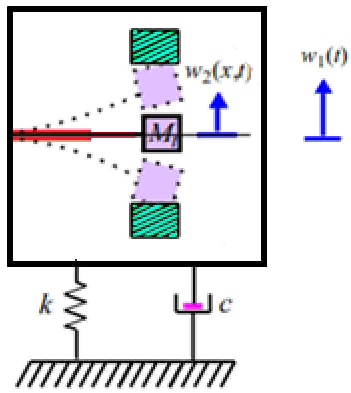


Figure 1. Schematic of the dynamical system subjected to base excitations.

Using similar strategies and model reduction as provided in [3] and [4], the equations of motions and the reduced-order model are derived. The only expressions that are not derived in [3] or [4] are the expressions for the force do to impact with the stoppers. The force due to mechanical stoppers is derived from a trilinear spring model developed by Paidoussis et al. [5], as expressed in equation (1).

$$F_{mechanical} = k\left[\sum_{i=1}^{\infty} \varphi_i(L_f) r_i(t) - \frac{1}{2}\left(\left|\sum_{i=1}^{\infty} \varphi_i(L_f) r_i(t) + d\right| - \left|\sum_{i=1}^{\infty} \varphi_i(L_f) r_i(t) - d\right|\right)\right]^3 \qquad (1)$$

where L_f denotes the distance along the beam where the stoppers are placed and d is the initial distance between the beam and the stoppers.

Previous research involving a magnetic coupled piezoelectric energy harvester used the dipole-dipole representation for the magnetic force [6], as shown in equation (2). However, this representation is only accurate for gaps larger than 7 mm. Due to this, Upadrashta et al. [7] evaluated an accurate forcing representation by utilizing the magnetostatic module in COMSOL Multiphysics, a finite element analysis software. A comparison of the dipole-dipole representation and the COMSOL results can be seen in Figure 2.

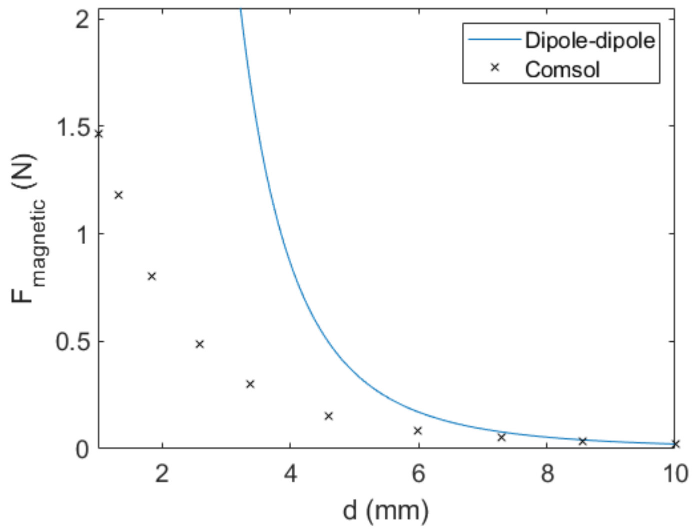


Figure 2: Comparison between the dipole-dipole representation and the data obtained from COMSOL [7].

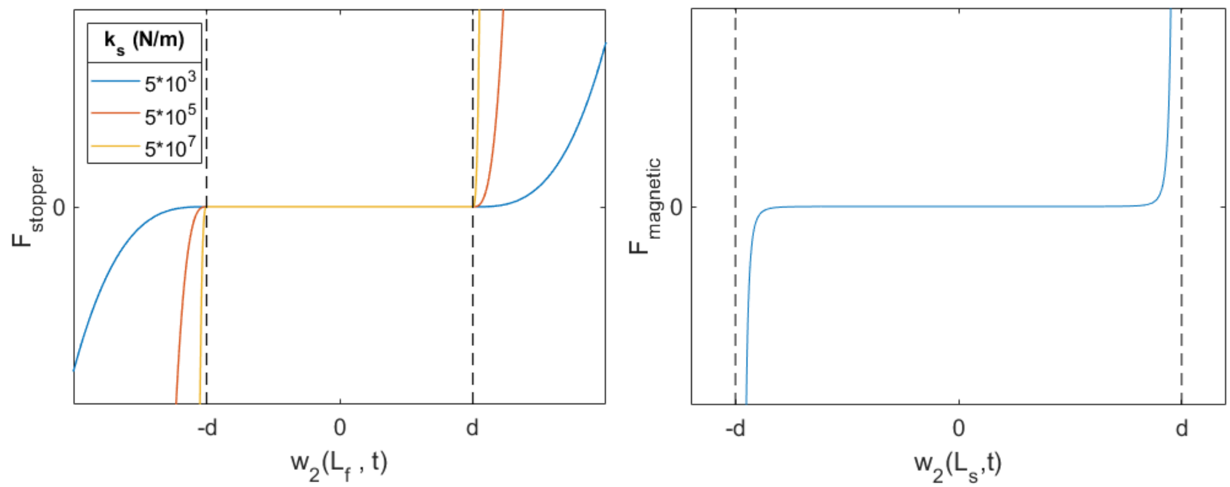
Since the range of data for the COMSOL data is from 1 to 10 mm, a hybrid system is proposed for the magnetic force expression, where the dipole-dipole representation will be used for gaps larger than 10 mm and an 11th order curve fit to the COMSOL data will be used for gaps smaller than 10 mm. The final expression is given as follows:

$$F_{magnetic} = \begin{cases} -\dfrac{3\tau a_1 a_2}{2\pi y^4} & if\ w_2(L_f,t) > 10\ mm \\ b_0 + b_1 y + b_2 y^2 + \dots + b y^{11} & if\ w_2(L_f,t) \leq 10\ mm \end{cases} \tag{2}$$

where τ is the vacuum permeability, a_1 and a_2 are the moment of the magnetic dipoles, the dynamic gap y is expressed as $d - w_{2s} - \sum_{i=1}^{\infty} \varphi_i(L_f) r_i(t)$, w_{2s} represents the static position of the absorber, and the polynomial constants can be seen in Table 1. Additionally, the mechanical and magnetic forces are compared graphically in Figure 3.

Table 1: Polynomial constants for magnetic force representation

b_0	b_1	b_2	b_3	b_4	b_5	b_6	b_7	b_8	b_9	b_{10}	b_{11}
3.2 44	$-2.59 *$	$1.072 *$	$-2.87 *$	$5.33 * 1$	$-7.07 *$	$6.72 * 1$	$-4.52 *$	$2.1 * 1$	$-6.39 *$	$1.14 * 1$	$-9.09 *$



(a) (b)

Figure 3. Impact force versus energy harvesting absorber's displacement at the location of the stoppers for (a) varying mechanical stopper stiffnesses and (b) magnetic stoppers.

Finally, after applying the Galerkin approach and Euler-Lagrange principle, the nonlinear-reduced-order model can be expressed as:

$$M_{S1}\ddot{w}_1 + c\dot{w}_1 + kw_1 + \sum_{i=1}^{\infty} M_{s2i}\ddot{r}_i = Fcos(\omega_f t + \phi) \tag{3}$$

$$\ddot{r}_i + 2\xi_i\omega_i\dot{r}_i + \omega_i r_i + M_{s2i}\ddot{w}_1 - \theta_i V = \varphi_i(L_s)F_{stopper} \tag{4}$$

$$C_p\dot{V} + \frac{1}{R} + \sum_{i=1}^{\infty} \theta_i\dot{r}_i = 0 \tag{5}$$

where the piezoelectric coupling term is $\theta = E_p d_{31} b\left(h_p + h_s\right)\varphi_i'(L_1)$, the capacitance of the harvester is $C_p = 2\frac{\varepsilon_{33} b L_1}{h_p}$, and the two mass sums M_{s1} and M_{s2i} are as follows:

$$M_{s1} = M + M_t + M_{b1}L_1 + M_{b2}(L - L_1)$$

$$M_{s2i} = M_t\varphi_i(L) + M_t L_c \varphi_i'(L) + M_{b1}\int_0^{L_1} \varphi_i(x)dx + M_{b2}\int_{L_1}^{L} \varphi_i(x)dx$$

III. Stoppers' effects on the system's responses and harvester's efficiency: preliminary results

Three different cases are investigated: mechanical stoppers with a soft stiffness of $5 * 10^3 N/m$, mechanical stoppers with a hard stiffness of $5 * 10^5 N/m$, and magnetic stoppers that are both repulsive to the magnets in the tip mass. Figure 4 shows these three cases' effects on the primary structure's amplitude and average energy harvested. Mechanical stoppers with soft stiffness show great control of the primary structure, with a reduction of 62% or greater. Additionally, soft stoppers show an increase of peak energy harvesting when the gap size decreases, where a gap of $0.005\ m$ doubles the peak power compared to the case with no amplitude stoppers. Mechanical stoppers with a hard stiffness show adequate control of the structure with a medium gap of $0.0275\ m$, with a reduction of 53%. However, there is a near-total loss of control of the primary structure's amplitude when there are small gaps. Also, apparent is the onset of aperiodic oscillations where there are large hardening effects in the power with small gaps, and where the peaks of the harmonics deteriorate and appear noisy. This is due to the steady-state response being averaged out. Also, we can see that there is no longer an increase in peak power when there is contact with the stoppers. Magnetic stoppers effects seem to be between the soft and hard mechanical stiffnesses, where medium-size gaps show adequate control of the structure, but small gaps show a loss of control and aperiodic regions. Although, unlike the soft stoppers, there is only a slight increase of power with a medium magnetic stopper gap. With a small gap of $0.01\ m$, there is practically no response. This is due to the shift in natural frequency due to the magnets [8]. With this gap, the energy harvesting absorber's natural frequency is $45\ rad/s$, which is nearly double that of the primary structure. Due to this, the subsystems would not couple and control the primary structure.

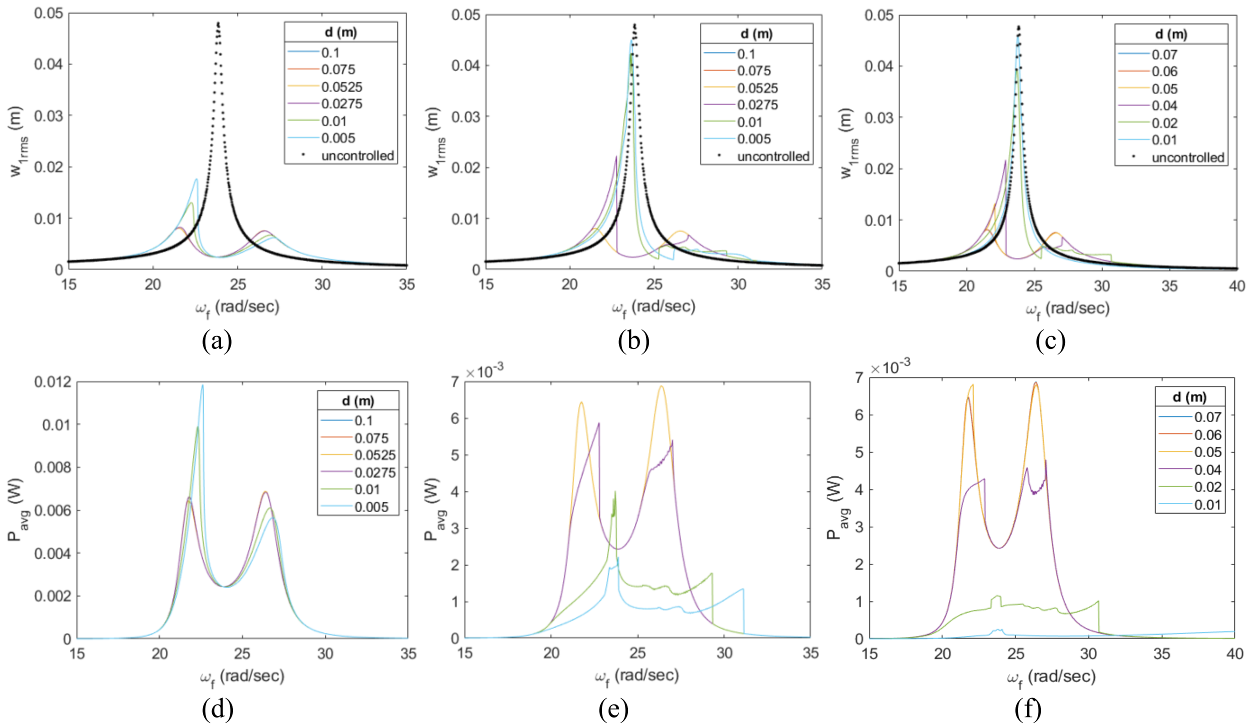


Figure 4: Primary structure response (a, b, c) and average energy harvested (d, e, f) for mechanical stoppers with stiffness $5 * 10^3\ N/m$ (a, d), mechanical stoppers with stiffness $5 * 10^5\ N/m$ (b, e), and magnetic stoppers (c, f).

For the considered design's parameters and dimensions of the energy harvesting absorber, it is clear that a decrease in the distance between the magnets results in inefficient effectiveness of the primary structure as well as the energy harvester. The proposed energy harvesting absorber shows an extreme decrease in peak harvested power due to the effects of the magnetic force when small spacing distances are taking place and due to its coupling to the primary structure. One of the future investigations should be on the optimal design of the energy harvesting absorber by effectively selecting its dimensions and characteristics in such a way the coupled frequencies of the primary structure and absorber can create a broadband resonance region. In this way, the magnetic stoppers could perform substantially better, but the mechanical stoppers are optimal for the current excitation and the geometric and mechanical parameters of the system.

This study also aims to perform the nonlinear characterization of the energy harvesting absorber's behavior, especially in the cases where aperiodic regions are present due to the presence of the mechanical stoppers. This characterization aims to describe why these aperiodic regions occur. Time histories, phase portraits, power spectra, and Poincare maps are utilized. These approaches to characterization are strong when used together, allowing for a clear representation of the system's behavior [9], particularly for optimal designs of the energy harvesting absorber when considering mechanical or magnetic stoppers. Preliminary results for mechanical stoppers with a stiffness of $5 * 10^7\ N/m$ and a gap size of $0.01\ m$ are shown in Figure 5. It is apparent that the system is behaving chaotically. This is apparent in the Poincare map, where there are infinite points that do not form a closed loop. A likely source for this chaotic behavior is grazing bifurcation. Grazing bifurcation is when the system oscillates and comes into contact with the boundary with zero velocity [10]. This can be seen in the time history and phase portrait where some oscillations are tangent with amplitude stoppers, which are represented by the black dashed lines. A more in-depth study is planned to further the investigation, including looking at varying frequencies before and after bifurcation points to aid in pinpointing the source of the bifurcation for both mechanical and magnetic stoppers.

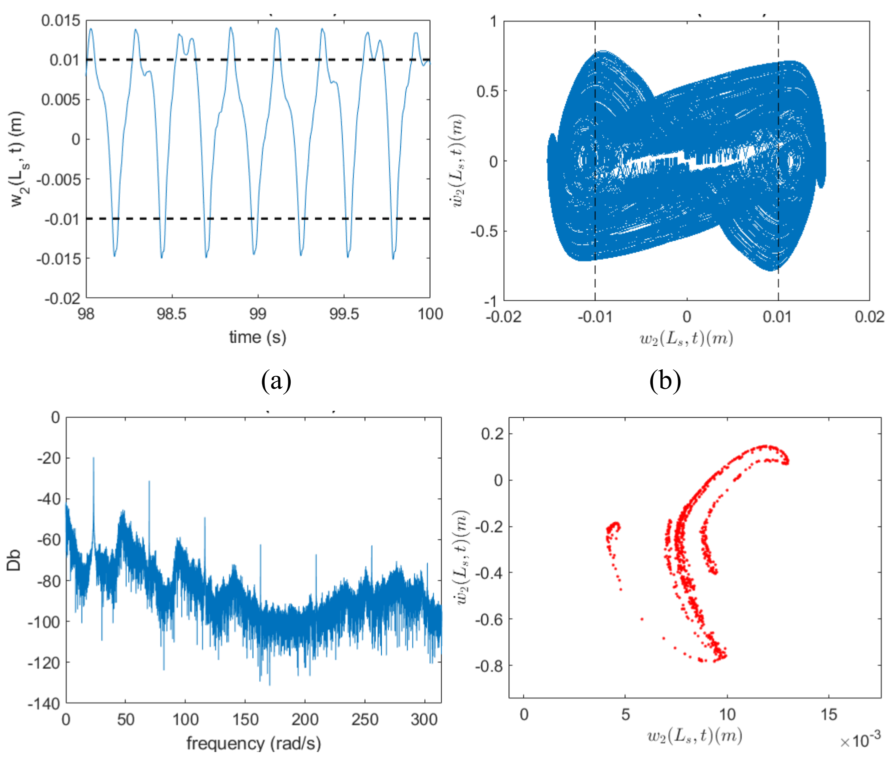


Figure 5: Nonlinear characterization of a mechanical stopper with stiffness $5 * 10^7\ N/m$ and a gap size of $0.01\ m$ using (a) time history, (b) phase portrait, (c) power spectrum, and (d) Poincare map.

IV. Conclusions

The results showed that mechanical stoppers with a soft stiffness are the most promising. The primary structure's amplitude remains controlled while increasing the amount of energy harvested. Mechanical stoppers with a hard stiffness are not desirable. This case loses all control of the primary structure regardless of gap size if there is contact and has a great decrease of energy harvested. Magnetic stoppers with a medium gap are beneficial with regards to control of the primary structure and energy harvested, but smaller gaps show similar results to the hard stiffness case with a change in the coupled frequencies of the system which resulted in the inefficiency of the used design. Due to the non-contact benefit of the magnetic stoppers, the optimal design of the energy harvesting absorber's dimensions and parameters should be considered in future investigations.

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