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Magnetic Stoppers on Single Beam Piezoelectric Energy Harvesting

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Abstract

The single beam structure has been long used in piezoelectric energy harvesting to harvest the vibrations of the circumstances. One of the critical defects of the structure is its narrow band of operating frequency. Many propose mechanical stoppers, rigid or non-rigid, such as another beam, to create a non-linear broadband effect. Moreover, with a piecewise linear PEG (Piezoelectric Energy Generator), or a simple cantilever beam with one or two mechanical stoppers laid on its sides, the constant driven amplitude of the beam displacement can be enlarged by a perturbation. It is also proposed that the stoppers prevent the piezoelectric pad from cracking due to over deformation. However, from a long-term point of view, the impact of the beam on the stoppers can also cause faster fatigue of the beam body, not to mention the noise that will hinder its practical application which maybe apparatuses nearby human. Therefore, this paper proposes a magnetic pair to serve as the stoppers for piezoelectric beam, so as to perform similar effects of bandwidth enlargement and also the amplification using perturbation. With no actual contacts, the single beam can be well protected, but also eliminated from over bending by the magnets. By placing the magnets on a beam on each side of the main beam. The magnetic force, which is distance dependent, can provide a smoother feedback to the beam, giving a greater displacement in comparison to the mechanical stopper. Moreover, the characteristic of the beam output is altered so that there exists two peaking frequencies, depending on the design of the stopper beams.

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1. Introduction

Many work had been long ago done to strive for broaden bandwidths, so as to broaden the applicable frequency range for the energy harvesters. Stoppers by Lars-Cyril Julin Blystad (2008), beam arrays by Huan, Yuntai, and Qing-Ming (2008); J.-Q. Liu et al. (2008), up converters by Lee, Carman, Murphy, and Schulenburg (2007), and non-linear techniques such as bi-stable structures by Arrieta, Hagedorn, Erturk, and Inman (2010); Y.Y. Chen (2013) are some of the most practical. Magnets, which was also one of the bi-stable sources, was introduced by Vinod et al (2008) to tune the resonance frequency of the beam. Later, Wickenheiser and Garcia (2010) had proposed an up-conversion method using magnets. To provide a non-contact stopper, magnets were used in this work. However magnets do not create nonlinear step changes as conventional stoppers, therefore we propose a new structure which tries to join the merits of these methods. The paper is organized as follow: the second section summarizes the behaviour of the conventional stoppers. In section 3, the behaviour of the proposed spring magnet stoppers is presented. Section 4 present the simulation and experimental results. Finally, the last section concludes the paper.

2. Modeling and Simulation

The magnetic stopper pair was set on two other single beams, up and below the main beam. With a repelling force, which feeds back a magnetic force to the main beam, the three beams possess non-contact connection between them (Figure 1a). The geometric parameters of the beams are as listed in Table 1. The force $F_{mag}(d)$ between cylindrical magnets can be represented as the equation 1, Vinod et al. (2008). The magnetic force can be also expressed as the additional stiffness to the main beam, which can be derived from the equation above, as shown as the following:

$$F_{mag}(d) = \left[\frac{Br^2Am^2(l+r)^2}{\pi\mu_0l^2} \right] \left[\frac{1}{d^2} + \frac{1}{(d+2l)^2} - \frac{2}{(d+l)^2} \right] \dots\dots\dots 1$$

$$k_{mag}(d) = \left[\frac{Br^2Am^2(l+r)^2}{\pi\mu_0l^2} \right] \left[-\frac{2}{d^3} - \frac{2}{(d+2l)^3} + \frac{4}{(d+l)^3} \right] \dots\dots\dots 2$$

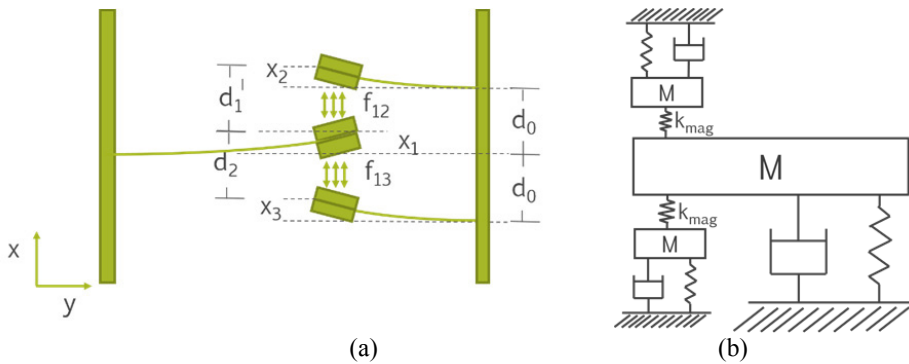


Figure 1 (a) Schematic diagram showing the force and displacement of the configuration (b) Mechanical modelling of the configuration.

Therefore we are able to design the new frequency of the three beams. In this work, the upper and lower beams are designed to have identical, and the tuned resonance frequency of the main beam is twice the frequency of the up and lower beams. It was predicted that the magnetic force will affect each other and create a broader bandwidth on the main beam due to the perturbation of the stopper beams. The stopper beams, on its own can also be an independent piezoelectric output. In the simulation, we use cantilever beams conducted of stainless steel as the substrate, PZT patch, and magnets as proof masses. One of the merit of using magnets is that, it provides easy tuning to the proof mass location on the stainless steel, and therefore the natural frequency can be tuned with ease. The

lump parameters of each beam are shown in Table 2. Here for simplicity of calculation, we assume that the two stopper beams are identical. Table 3 shows the parameters required for the simulation of magnets.

Table 1. Geometric parameters of the applied beams.

	Main Beam	Stopper Beams
Length (mm)	77	46
Width (mm)	15	15
Thickness (mm)	0.3	0.3
Mass w/ proof mass (mg)	3.7	23.6 (Upper) 23 (lower)

Table 2. Parameters of the beams applied in experiment and simulation.

	Middle Beam	Stopper Beams	Units
f_0	18.64	13.02	Hz
f_1	18.69	13.05	Hz
C_0	4.5e-8	9e-9	F
M	4.10e-3	2.36e-2	Kg
K	54.59	158.80	N/m
C	6.74e-3	2.62e-2	N s/m
K_D	187.15	217.75	
K_E	186.15	216.75	
Q_M	71.55	34.13	

Table 3. Parameters of Magnets used in the experiment and simulation.

	Magnet Factors	Units
B_r	0.83	T
A_m	25	mm ²
L	6	mm
R	5	mm
μ_0	1.256e-6	H m ⁻¹

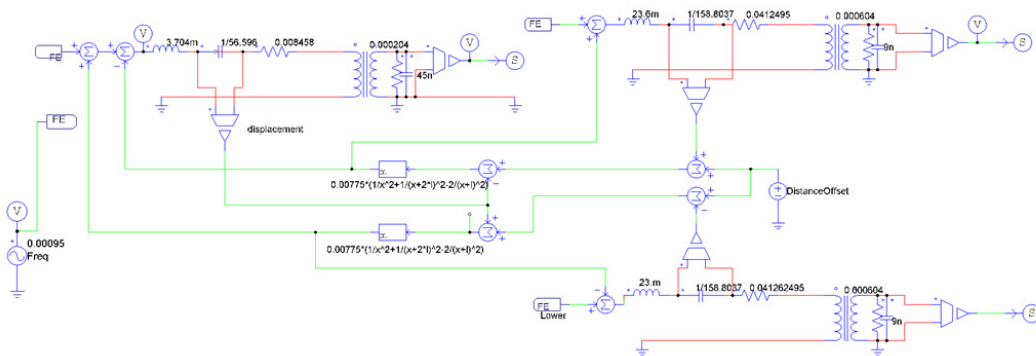


Figure 2 PSIM model used in the experiment

Using the MCK model with magnetic force, we can simulate via PSIM and Matlab Simulink ©, and obtain the theoretical result as shown as figure 3. Despite the depression of the middle beam output after installing the stopper, it creates two peaks, one up converted by the new natural frequency of the upper beam, and the other of its own. On the other hand, the upper beam is slightly enhanced, and also stricken by the resonance frequency of the middle beam. It also shows a non-linear bending effect on the second peak.

As for a dynamic response which is plotted in figure 3(b), a pulse was applied to the beams so that the responses are observed. From the plot, we observe that the ringing of the beam was prolonged in time. By integrating the

power with time, we can get that within the first 10 seconds, the single beam has an output of 1.0907 nJ, whilst installed in the structure, 1.43 nJ, which is a 1.31 fold enhance.

Figure 3 (c) shows the overall stiffness of the middle beam during a period of vibration. The configuration creates a steep curve of stiffness in respond to the displacement.

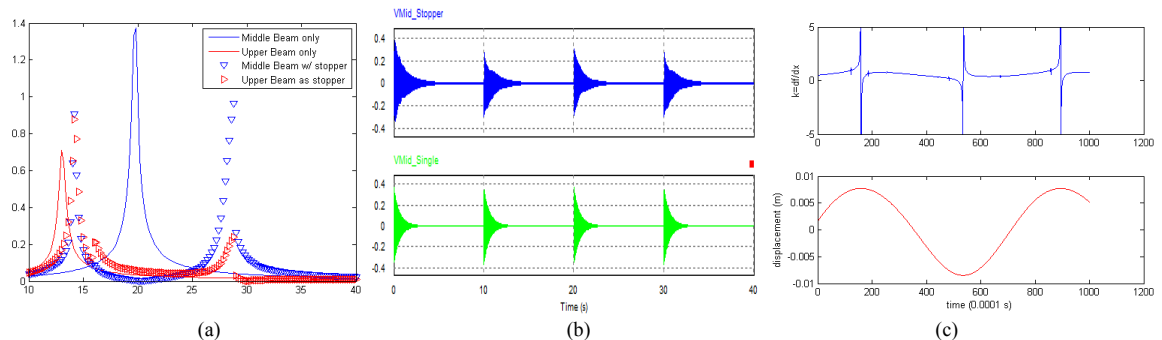


Figure 3. Simulation result of (a) Voltage-Frequency response (b) transient response due to a pulse of force (c) spring constant change during different values of displacements.

3. Experiment Results

3.1. Experiment Setup

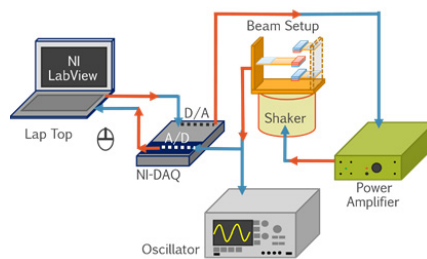


Figure 4. Schematic diagram of experimental setup

The setup of three beams was realized and experiments were conducted using the beams that were mentioned above. A schematic diagram of the set-up is shown as Figure 4. A National Instrument Data Acquisition Card© (NI-DAQ card) is used, as the analogue-digital converter to output-control and obtain the signals. A LabVIEW© program was created to drive and receive signals. With limited power, the DAQ card is then connected to the power amplifier, so that the shaker can be pushed to work. Whilst the beam is vibrated by the shaker, it outputs the resulting energy to the oscillator and, in the same time, the DAQ card. The DAQ card then converts the signal, and offers the LabVIEW Program the collected signal for analysis and information storage.

3.2. Experiment Results

Figure 5 shows that the resonance frequency of the original beam is levered to 26.8 Hz, and is also harmonized on 13.5 Hz, the resonance of the upper and lower beam, which did not change so much as simulated. We also observed the responses of the upper and lower stoppers, unlike the simulation, there were little and not obvious peaks on the resonance frequency of the middle beam since there was found a crack on the patch after a few experiments. The output voltage was greatly reduced and may not show up.

Experiment for prolonged ringing as a result of perturbation was also performed. The pulses were driven by a LabVIEW DAQ card, and the output results were also acquired with the device. Since there were some non-

symmetric properties on the upper and lower beams, the perturbation can be seen to be non-symmetric also. But in overall, it is obvious to see that in comparison to the results without stopper, the amplitude was slightly enlarged, and also the ringing of the signal is much higher. By integration with time, we obtain that within the 38.8 seconds, the power output was $0.1 \mu\text{W}$ and $0.098 \mu\text{W}$ for the stopper structure, and the single beam. It is a multiple of 10.41 times, which is a great enhancement in the transient state.

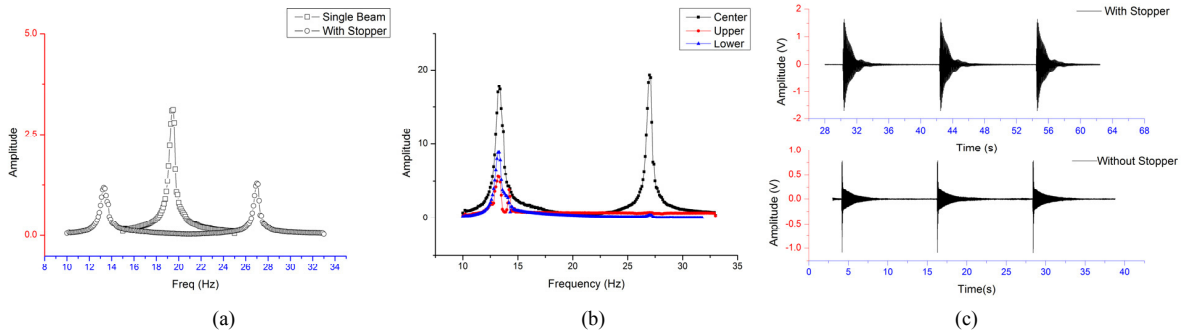


Figure 5. Experimental results of (a) single middle beam with middle beam within the configuration of stopper beams (b) Voltage output responses with respect to a frequency scan (c) the transient response to pulse force inputs, (top) middle beam output

4. Discussions and Conclusions

In this work, a non-colliding structure that is a combination of stopper and up converter is designed and realized. Theoretically, each of the beam can have more than one peak frequency, one of its own and the other perturbed by the coupling beams, thereby extending the usable operating frequencies. In other words, the designed structure provides a non-contact mechanical, other than electrical connections, between the systems. Experimentally, the results are similar to the theoretical prediction. However, it is notable that the second peak of the stopper beam did not show as the simulated results. Moreover, the dynamic response of the designed structure showed prolonged ringing response due to the perturbation of the two additional beams.

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