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Influence of Magnetic Repulsion on Vibration Energy Harvesting

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ABSTRACT

The progress in electronic devices, including the wireless sensors, leads to the great demand on powering these devices which utilize wireless sensor systems. Recent researches focused on nonlinear energy harvesters to overcome the limitations of linearity. Magnets are a common method that used to achieve nonlinearity to the system. In this paper the effect of nonlinear magnetic force on the response of the energy harvester proposed. A model of a cantilever beam with tip magnet opposing a fixed magnet is introduced. The mathematical model predicted the response of the cantilever beam with and without the magnet effect. By changing the gap distance between the magnets, the response of the harvester investigated. Experimental work carried out to validate the results of the mathematical approach. The mathematical model shows a good agreement with experimental model results for different gap values. The results prove that repelling magnetic force leads resonance frequency to a larger value. Tip displacement of cantilever beam changed according to gap distance (d). Without magnet, the cantilever moves freely without magnetic force constraint so maximum displacement reaches about 17 mm. In another hand, maximum tip displacement decreases by decreasing the gap distance as the magnetic force restricts free motion of the beam.

Keywords: Nonlinear, Vibration energy harvester, Magnetic coupling, piezoelectric

1. INTRODUCTION

In the recent years, there is a great demand for new energy sources. Various renewable energy sources such as thermal energy, photonic energy, and mechanical energy can be used [1-3]. For many years, batteries were the only method for powering wireless electronic devices and its sensors. Batteries have limitations which make them unsuitable to use in many devices which are used in critical applications. Energy harvesting is an effective alternative to the usage of batteries. Energy harvesters can overcome the problems of maintenance, chemical waste, and replacement for powering wireless electronic systems [4].

While solar energy and thermal energy have limitations in the application, mechanical energy is a reliable source of energy. Mechanical energy comes across different sources such as human movement, air or water flow induced vibration and vibrating structure [5-7].

Vibration energy harvesting is one of the promising fields. It depends on using wasted vibrations to power wireless sensors. To extract energy from vibration sources we need a transduction mechanism or conversion mechanism. Transduction mechanisms vary between electromagnetic [8-11], electrostatic [12, 13], and piezoelectric [14-16] Piezoelectric energy harvester is widely used as a transducer due to ease of application, higher energy density and conversion energy from mechanical to electrical directly [17].

Williams and Yates, 1996 presented the first vibration energy harvester which consists of a mass connected to the housing by a spring and damper[18]. This type of harvesters called linear vibration harvesters (LVEH). It exploits tuning the natural frequency of the host structure to maximize the harvested energy. Ambient vibrations usually are chaotic and nonstationary. When the system vibrates with a frequency out of resonance, the energy harvested dropped swiftly. This makes the linear vibratory energy harvester limited in application [4]. The researchers make every effort to enhance the efficiency of vibration energy harvesters and overcome linear systems limitations. The enhancement techniques confined to power amplification, resonance tuning approach and the nonlinear oscillations and their methods.

Nonlinear oscillators have received a great attention in the recent researches because they have the benefit of broadening the frequency range and increasing the harvested power [19]. Magnetic nonlinearity is one of the effective techniques to increase the operating frequency range. The nonlinear magnetic force causes hardening or softening behavior according to the application. This behavior effects on the stiffness of the structure[20]. Tang et al.,2012 studied the nonlinearity of the harvester in monostable and bistable behaviors. They investigated that both monostable and bistable harvesters can exceed the linear harvesters under low excitations [21]. The frequency bandwidth has broadened and the resonance frequency shifts to a lower value by decreasing the distance between two attractive magnets [22].

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Stanton et.al,2009 presented an experimental and numerical approach to verify that nonlinearity (both hardening and softening) is more convenient to apply to ambient vibration with a steady frequency sweep. Both hardening and softening behavior shows a remarkable increasement of the frequency range [23]. In 2010, Stanton et al, investigated the displacement response of a piezoelectric cantilever with a tip magnet opposing another one with the same polarity. The displacement of the cantilever tip has measured at different acceleration values with a frequency sweep. By increasing the base acceleration, the frequency peak shifts towards higher value [24]. It was observed that the output voltage has increased by 50% when the piezoelectric cantilever coupled with a magnet related to the uncoupled beam. Also, the amplitude of cantilever tip displacement has increased due to the effect of repelling magnetic force [25]. Monostable harvester preferred to use at low to moderate excitations, but bistability is more adequate to use with relatively high excitations [26].

This paper presents the effect of magnetic force indicating nonlinearity. The effect of gap distance on the tip displacement has studied. The response of the harvester with and without magnets has investigated. The vibration energy harvester has analytically modeled and experimentally validated.

This paper divided as follows: In section 2, the mathematical model of the harvester is derived. MATLAB program is used to solve equations. Section 3 presents the experimentation and setup used. Results are discussed in section 4. Finally, the conclusions proposed in section 5.

2. MATHEMATICAL MODELLING

A nonlinear energy harvester has been modeled theoretically using MATLAB. The nonlinearity of the harvester achieved by magnetic repelling force. The model consists of a cantilevered beam with a tip magnet facing another repelling magnet with gap distance (d) as shown in Figure 1.

The model of rectangle beam simplified as mass, spring and damper model as shown in Figure 2. Single degree of freedom equation derived and solved using the MATLAB program. The equation of motion of the model presented as following

$$M\ddot{z} + c\dot{z} + kz = A_F \sin \omega t + F_m \qquad (1)$$

Where z is the relative motion (x-y), c is the Damping coefficient, k, is the cantilever stiffness and M is the effective mass of beam and tip magnet calculated according to Equation (2).

$$M = m_t + 0.23\, m_b \qquad (2)$$

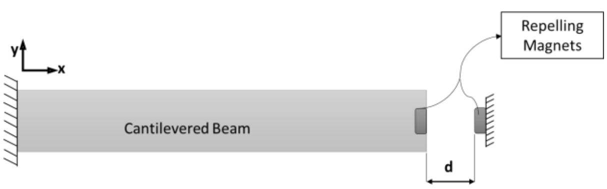


Figure 1 Schematic drawing of the nonlinear energy harvester

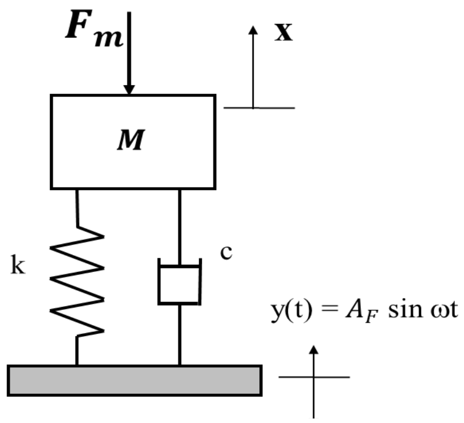


Figure 2 Equivalent model of the cantilever beam harvester.

The right-hand side of the equation represents the equivalent force acting on the structure. Where y(t) is the base excitation calculated from the following equation:

$$y(t) = A_F \sin \omega t \qquad (3)$$

As $A_F = M\omega^2 A$ is the amplitude of forced vibration (as A is the acceleration in (m/s^2)), ω is the operating frequency which swept as following equation:

$$\omega = f_1 + \left(\left(\frac{f_2 - f_1}{2T}\right) * t\right) \qquad (4)$$

Where (f_1) is the start frequency and (f_2) is the final frequency swept with time range (T). The magnetic force (F_m) is interpolated from experimental results conducted in [27]. The magnetic force measured versus different gap distance values Figure 3 illustrates that the magnetic force increases nonlinearly by decreasing the gap distance between two repelling magnets. Three gaps have chosen (7.5mm, 10mm, and 15.5 mm) to study the effect of magnetic nonlinearity on the energy harvester response. The damping coefficient has determined experimentally for three gaps and without magnetic forces. The results show roughly the same value of damping coefficient at different gap values ad shown in Figure 4. Dimensions and material properties of the harvester model listed in Table 1.

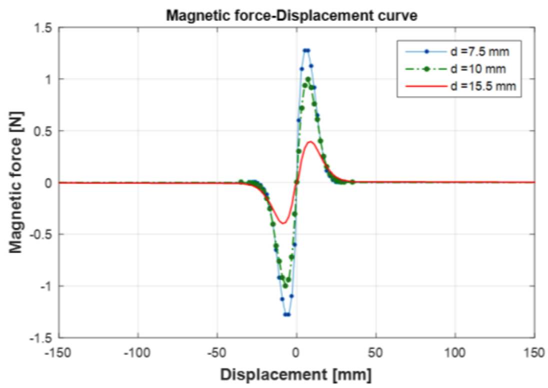


Figure 3 Magnetic force versus displacement at different gaps (d= 7.5 mm , d=10 mm, and d=15.5 mm) measured experimentally by Hadidi et.al [27].

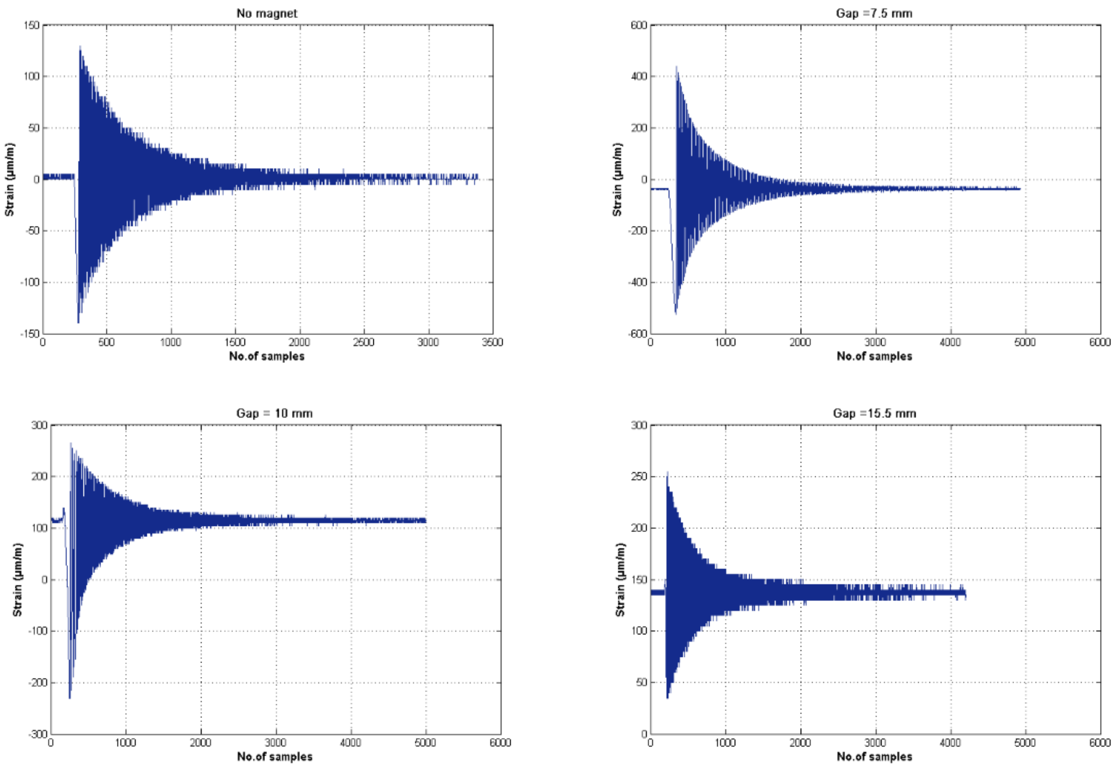


Figure 4 Experimental results of tip displacement used to calculate C value

MATLAB program is used to solve the equation of motion of the system. Conducting all the equation and solving it using Rung Kutta method (ode45). The numerical investigation calculated the tip displacement of the cantilever beam under excitation level of 0.075g. The natural frequency of the model theoretically calculated ($\omega_n \approx 5.32$ Hz) to define the frequency range. The frequency range selected with 4Hz as an initial value and 20 Hz for final value and the sweeping time set to 60 seconds. The model predicted the behaviour of the harvester without magnetic force and with magnetic force at different separation distance value.

Table 1 Dimensions and properties of the model.

Description	**value**
Cantilever beam	
Length of the cantilever (L)	224 mm
Width of cantilever (b)	26.7 mm
Thickness of cantilever (h)	0.55 mm
Density of beam (ρ)	7850 kg/m^3
Poison ratio (υ)	0.32
Modulus of elasticity (E)	200 GPa
Damping coefficient (c)	0.01 N.s/m
Magnet	
Diameter of magsnet (d_m)	10 mm
Thickness of magnet (h_m)	5 mm
Remanence flux density (B_r)	13200 Gauss
Tip mass (m_t)	0.01178 Kg

3. EXPERIMENTAL SETUP

The setup of the experimental work illustrated in **Figure 5** (a). the harvester consists of a rectangle beam. Two Neodymium (grade N42) magnets with dimensions (10mm Dia.*5 mm Thick, first4magnets, UK) attached, one fixed on the tip of the beam using epoxy resin and the other one inserted into L shaped wooden part as shown in Figure 5 (b). A strain gauge pasted on the beam to measure the tip displacement by epoxy resin. A wooden part used as a ruler to measure gap distance between two magnets.

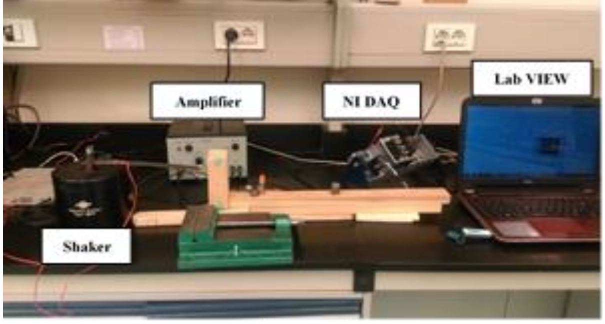
Beam fixed to shaker (Brüel & Kjær type 4809) which connected to a power amplifier (Brüel & Kjær type 2706). The input signal generated using LabVIEW software. The input chirp signal created as a frequency swept from 4 Hz to 20 Hz with a constant acceleration of 0.075 g. A computer connected to the NI9263 module (16-bits resolution, 0.11V accuracy, 100 Ks/s update rate and ±10 voltage range) using a USB cable to the input signal to the amplifier. Strain gauge connected to KYOWA (type PCD-300A) to present strain values. Data from strain gauge collected and converted to displacement according to Equation (5) to validate the tip displacement of the cantilever beam.

$$e_{max} = \frac{2L^3}{3ha} \cdot \varepsilon \qquad (5)$$

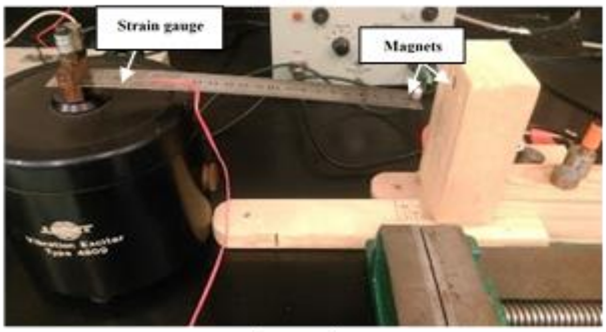
As e_{max} is the tip displacement, h, is thethickness of the cantilever beam and, a, is the distance between strain gauge and the tip [28].

4. RESULTS and DISCUSSION

Experimental results are compared with the mathematical one and show good agreement. The effect of distance between magnets is studied. Figure 6 (a) and (b) show the response of the cantilever beam when it tested without the effect of magnetic force



(a)



(b)

Figure 5 (a) Experiment setup used for validation of the mathematical model (b) The harvester model attached to shaker opposing a magnet.

mathematically and experimentally respectively. It can be noticed that the maximum displacement occurred at the resonance frequency of cantilever (≈ 5.14 Hz for mathematical model approaches to experimental result 7.5 Hz). In this case, the response of the harvester is linear. The maximum displacement of the cantilever tip reaches to 8 mm when the beam tuned at its resonance.
The effect of magnetic force takes place for different gap distances. Figure 6(c) and (d) present the tip displacement of the beam when the fixed magnet located 15.5 mm apart from the tip magnet. The effect of magnetic force appears as peak displacement moves toward a higher frequency value. The value of frequency increased to 9.66 Hz experimentally and 8.47 Hz by mathematical calculations. When the gap distance between two magnets increased to 10 mm, resonance frequency reached to ≈13.3 Hz experimentally and 11.9 Hz mathematically. Maximum displacement decreased from ≈8 mm at gap distance 15.5 mm to 6 mm as shown in Figure 6 (e) and (f). The cantilever beam responds to the effect of the magnetic repelling force and the frequency bandwidth increased. For smaller gap distance reached 7.5 mm, the peak tip displacement is almost 4.5 mm at an experimentally measured frequency of about 15 Hz and 13 Hz calculated mathematically. Figure 6 (g) and (h) shows tip displacement at gap distance equal to 7.5 mm. it found that by decreasing the gap distance between magnets, the frequency bandwidth increases as well. Also, the presence of magnetic repelling force moves the resonance to higher values.

5. CONCLUSIONS

This paper conducted a mathematical and experimental study to investigate the effect of magnetic force on the energy harvesting. A model of a cantilever beam with a tip magnet opposing a fixed magnet is proposed. The effect of the gap distance between the magnets has studied. The mathematical model predicted the response of the cantilever beam with and without the magnet effect. Experimental work carried out to validate the results of the mathematical approach. The mathematical model shows a good agreement with experimental model results for different gap values as shown in Table 2. Differences between resonance value in the experimental and mathematical model are with almost constant value. In otherwise, the experimental and mathematical model results have the same behaviour. It is clear that the magnetic force lead resonance frequency to a larger value. Tip displacement of cantilever beam changed according to gap distance (d). Without magnet, the cantilever moves freely without magnetic force constraint so maximum displacement reaches about 17 mm. In another hand, maximum tip displacement decreases by decreasing gap distance as the magnetic force restricts free motion of the beam. Finally, the magnetic force could enhance the response of the energy harvester under low excitation levels.

Table 2 Values of natural frequency at different gap values.

Gap Distance d (mm)	Experimental ω_n (Hz)	MATLAB ω_n (Hz)
No magnet	7.504438	5.1478768
15.5	9.667375	8.475226
10	13.28116	11.904988
7.5	15.020044	12.105013

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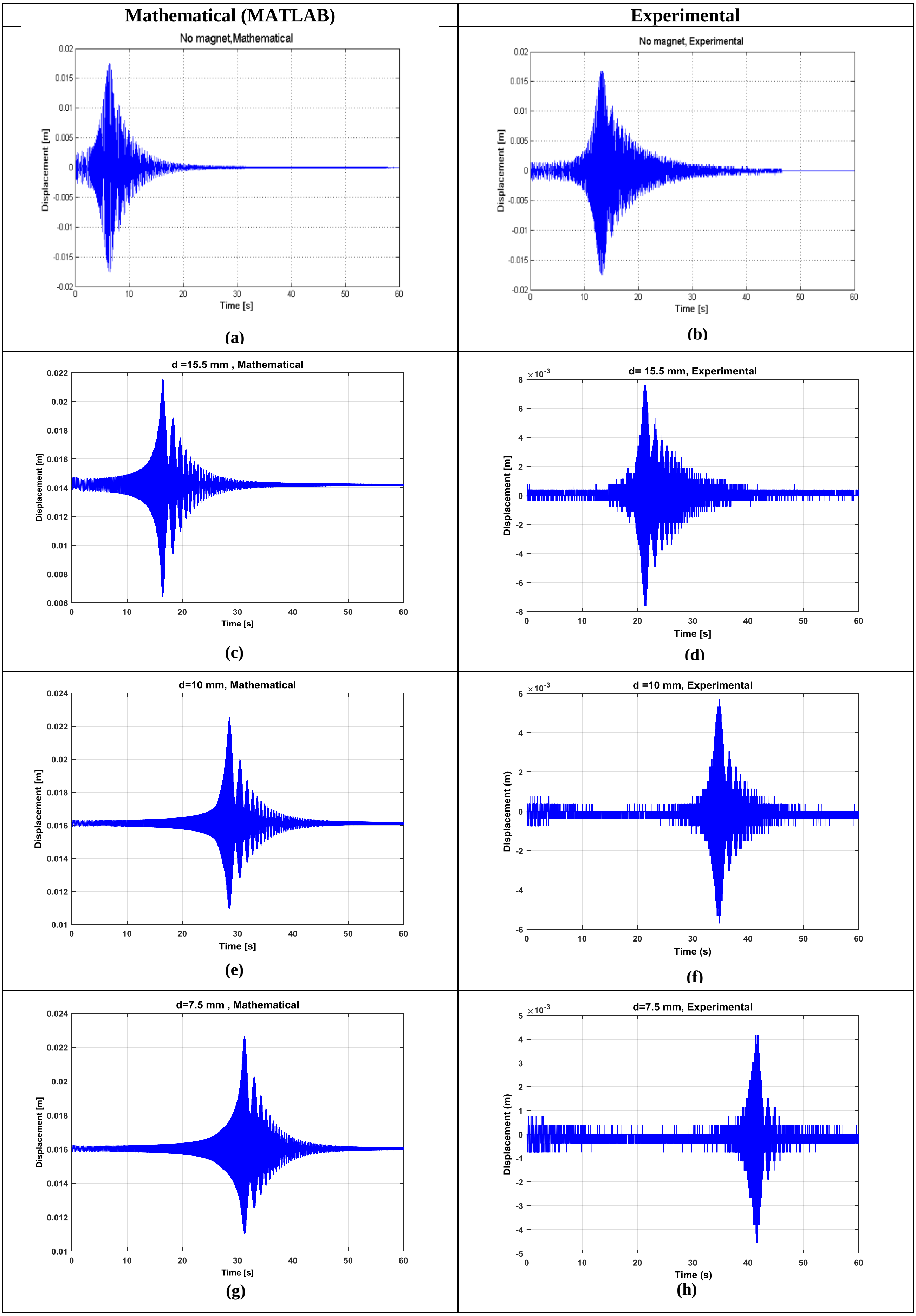

Figure 6 Mathematical and experimental results for the tip displacement of the cantilever beam with frequency sweep from 4 Hz to 20 Hz for different gap distances (a), (b) without magnetic force , (c,d) d=15.5mm, (e,f) d=10mm , (g,h) d=7.5mm

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تأثير التنافر المغناطيسي على حصد الطاقة بالإهتزاز

الملخص

إن التطور في الأجهزة الإلكترونية المتضمنة لحساسات لاسلكية أدي إلى تزايد الطلب على هذه الأجهزة التي تستخدم أنظمة للحساسات اللاسلكية. و مؤخراً ركزت الأبحاث على حاصدات الطاقة اللاخطية للتغلب على عيوب نظيرتها الخطية. المغناطيسات هي الأكثر استخداماً لتحقيق اللاخطية للنظام. هذا البحث يقدم تأثير القوة المغناطيسية اللاخطية على استجابة حاصد الطاقة. حيث تم تقديم نموذج مكون من عارضة مثبتة من إحدى طرفيها و مثبت بالطرف الأخر مغناطيس يتنافرمع مغناطيس ثابت. النموذج الرياضي أُستُخدم للتنبؤ بإستجابة النموذج مع وجود التأثير المغناطيسي و بدونه. تم التحقق من استجابة الحاصد عند تغيير قيمة الفجوة بين المغناطيسين. تم إجراء اختبار معملي للتحقق من النتائج الرياضية. النموذج الرياضي أظهر توافق جيد مع النتائج المعملية لقيم مختلفة للفجوة بين المغناطيسين. أثبتت النتائج أن قوة التنافر المغناطيسي أدت إلى زيادة قيمة التردد الرنيني. إزاحة طرف العارضة تتغير تبعاً لتغير المسافة بين المغناطيسين. فبدون استخدام المغناطيس، العارضة تتحرك بحرية بدون قيود قوى التنافر المغناطيسي حيث تصل أقصى إزاحة إلى 17 مم بينما تقل أقصى إزاحة لطرف العارضة بتقليص الفجوة بين المغناطيسين حيث تتقيد الحركة بوجود قوى التنافر المغناطيسي.