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Study of dynamics and efficiency of hybrid power harvesting system from mechanical vibrations

***Abstract**. The main goal of this research was to exam and compare dynamics and efficiency of hybrid power harvesting system with piezoelectric and magnetostrictive transducers. We investigated the voltage frequency response of both subsystems to periodic external forcing for different amplitude of the excitation. Although, the beams are linear there are nonlinear magnetoelastic effects that we wanted to identify and strength by adding moving mass into the pipe at the end of the substructure beam.*

Streszczenie.**Głównym celem pracy była ocena i porównanie dynamiki i efektywności hybrydowego układu odzyskiwania energii z przetwornikami piezoelektrycznymi i magnetostrykcyjnymi. Zbadaliśmy odpowiedź częstotliwościową napięcia obydwu podukładów na okresowe zewnętrzne wymuszenie dla różnych amplitud pobudzania. Mimo, że belki są układami liniowymi, istnieją nieliniowe efekty magnetoelastyczne, które chcieliśmy zidentyfikować i wzmocnić przez dodanie ruchomej masy do rurki na końcu belki podtrzymującej.* ***Badania dynamiki i efektywności hybrydowego układu odzyskiwania energii z drgań mechanicznych

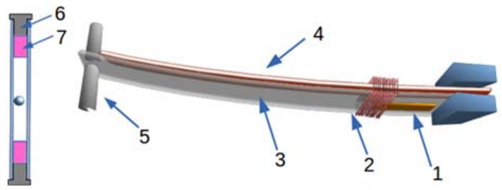
Keywords: energy harvesting, piezoelectric and magnetostrictive effects.
Słowa kluczowe: odzyskiwanie energii, efekty piezoelektryczne i magnetostrykcyjne.

Introduction

The energy harvesting phenomena is based on the concept of gaining energy from a surrounding vibrations. The main goal is to power small sensors or actuators [1,2,3]. In many applications the piezoelectric or the magnetostrictive materials are integrated in simply dynamical systems (like beams) and are used successfully [4,5]. These simple harvesters work optimally in a resonant frequency region that is not easy to tune in real conditions. Because of their complexity, nonlinear dynamic systems have the ability to overcome these drawbacks by widening the resonant frequency spectrum (so called broadband effect) [6,7]. In this work we examined this effect and nonlinear effects in hybrid multi degrees of freedom system based on two layer beam (magnetostrictiveGalfenol and aluminum).

Experimental stand

The basic element of the hybrid system studied consists of two glued beams: longer - aluminum and shorter – magnetostrictive. Tip-mass in the form of a tube is attached to the end of the aluminum beam. The tube is closed with caps each sticked with 10 mm long elastic bumpers. The piezoelectric patch and the coil located near the clamped end of the hybrid cantilever help to compare the measured voltage efficiency of both subsystems and investigate influence of nonlinear effects involved by moving additional masses. These bouncing balls inside the tube can increase the number of degrees of freedom and reinforce the nonlinear effects occurring in the beam itself. The design of the hybrid system is shown on the right in Fig. 1. The cross-section of the tip-mass tube is shown on the left of this figure. In order to avoid the impact of the shaker magnetic field on the test results, the hybrid system was raised by mounting on a longitudinal aluminum cantilever.



ig. 1. The pipe (left) and double beam structure (right) with piezo (1) and electromagnetic (2) transducers. (3) – alumina beam, (4) magnetostrictive beam, (5) – alumina pipe as tip mass. (6) – closing cap, (7) – flexible bumper (top).

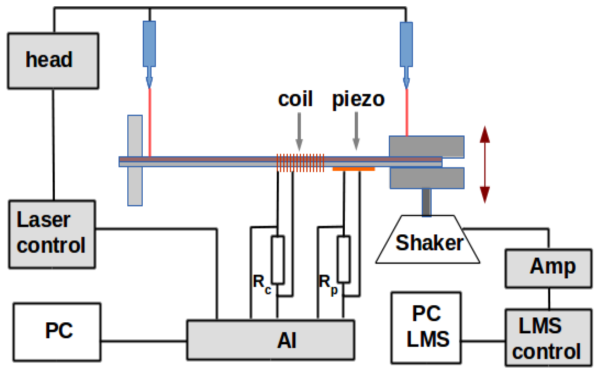


Fig. 2. The experimental stand scheme.

All important information about the configuration of the system, its parameters and the characteristics of the components are listed in Table 1.

The scheme of the experimental stand is presented in Fig. 2. The laser system measures the velocity of the beam end relative to the shaker's handle. The shaker is controlled by the independent system (LSM) managed by software operating on separate computer system. The laser signal and both voltages generated by transducers are recorded in parallel by the DAQ measurement card installed in the main computer unit.

Results

In the first stage of our work we focused on influence of the forcing amplitude and additional nonlinearities on the system response. We investigated the collection of different configurations of free-moving masses in the tip-mass pipe, ie: without mass, with mass M1, with mass M2, and finally with both masses M1 + M2. The comparison of the voltage system response on frequency sweep from 30 Hz to 60 Hz and two amplitudes of the base excitation (a=0.8 g and a=1.5 g) is presented in Fig. 3.
With the increase in acceleration of the system a significant increase in voltage U2 occurs for all configurations. For a system undisturbed by a moving mass (Fig. 3 - blue) the voltage increase is most pronounced. In parallel, its frequency response becomes clearly nonlinear, showing the system hardening. Perturbations provided by balls moving freely in the tube does not improve the energy efficiency of themagnetostrictive subsystem, nor extend significantly the

band of efficient energy harvesting. As can be observed, they result in decreasing the peaks of the voltages amplitude. However, it is worth to notice that both masses acting simultaneously (purple) at a higher level of excitation (right) increase the noise level throughout the whole investigated range. In addition, two broad peaks at lower frequencies (36 Hz and 43 Hz) appear on the frequency response. It is worth to note, that configuration without additional moving mass is most efficient.

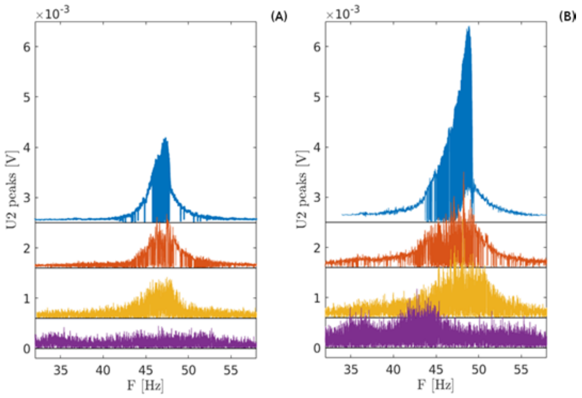


Fig. 3. Voltage output response of magnetostrictive subsystem (U2) for frequency sweep and amplitude of the excitation a = 0.8 g (A) and a = 1.5 g (B). The blue color corresponds to no moving mass, orange - M1, yellow - M2 and purple - M1+M2, respectively.

In Fig 4. one can observe almost two times increase of the voltage with increase of the base excitation. Furthermore, the nonlinear effects seen in the additional peak before the main resonance occur for higher amplitude of external forcing. The additive beats in piezoelectric subsystem (both cases) do not appear in the magnetostrictive subsystem. The source of their occurrence may be nonlinearity in both the mechanical and piezoelectric subsystems.

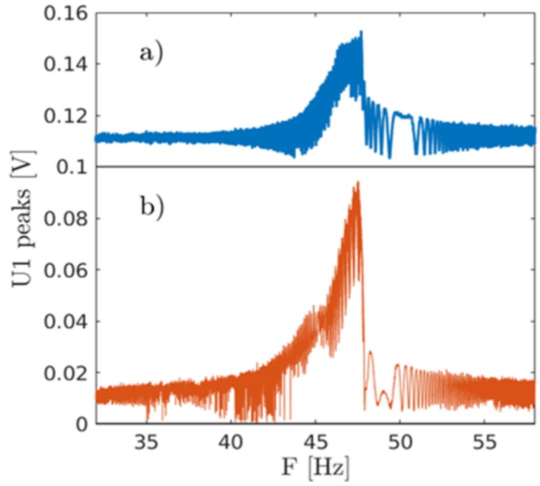


Fig. 4. Voltage output response of piezoelctric (U1) subsystem without the moving ball for frequency sweep and amplitude of the excitation a = 0.8 g (a) and a = 1.5 g (b).

Table 1: Summary of parameters of the mechanical resonator and electrical circuit.

Description	Symbol and value	Description	Symbol and value
Aluminum beam:		Piezoceramic layer:	
length width thickness Young modulus density of the beam material	183 mm 20 mm 1.55 mm 69 GPa ρ = 2.7 g/cm3	length width number of parallel fibers in the piezoceramic layer dimensions of the piezoceramic fibers (PZT) capacity of the piezoceramic layer	20 mm 6 mm N = 10 11.5 mm × 0.24 mm × 0.26 mm 4.9 nF
Magnetostrictive layer (Galfenol):		Moving steel balls:	
length width thickness	163 mm 20 mm 1.75 mm	radius weight	M1: 2.99 mm M2: 4.76 mm M1: 0.87 g M2: 3.54 g
Tip mass:		Measurement:	
outer radius wall thickness height mass	6 mm 1 mm 72 mm 11.5 g	internal impedance of DAQ load of the piezoelectric circuit R load of the coil circuit acceleration amplitude	1 GΩ 550 kΩ 8.3 Ω 0.8 g and 1.5 g

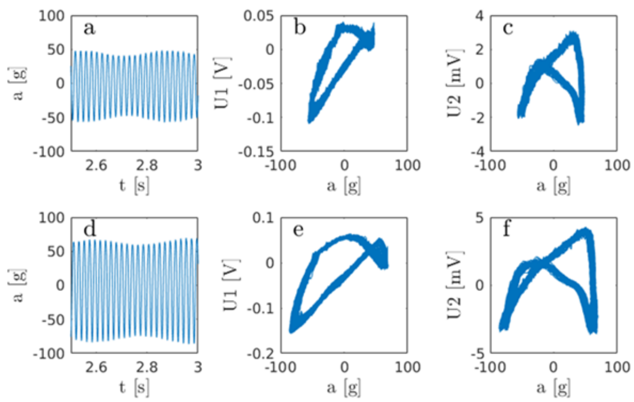


Figure 5. The acceleration measured by laser and the voltage hysteresis loops of both subsystems for different level of external forcing: a = 0.8 g (a, b ,c) and a = 1.5 g (d, e, f).

We also observed nonlinear effects in both subsystems by identifying hysteresis loops for U1 and U2 signals (Fig. 5). Occurrence and shape of those hysteresis loops (Fig 5. b, c, e, f) clearly identify nonlinear response of both transducers. In part, the hysteresis effects are introduced by the mechanical imbalance of the potential caused by the force of gravity. However, to investigate influence of material structure on hysteresis further detailed analysis are required.

The hysteresis of both piezoelectric (Fig. 5 b, d) and magnetostrictive subsystems (Fig. 5 c, f) differ in shape. However, increase of the external forcing doesn't not change them qualitatively. This means that when changing the level of excitation, the physical processes responsible for the energy generation in both transducers remain unchanged.

These results are particularly important for U2 coil voltage. In the absence of the magnetic field, the magnetostrictive beam tension causes random reorientation of magnetic moments in directions perpendicular to the stress axis. This should result in a zero average magnetization of the sample. The non-zero voltage U2 indicates the existence inside the magnetostrictive beam some mechanism for organizing magnetic moments even in the absence of an external magnetic field. By proper integrating of the U2 voltage one can calculate change of the magnetization with respect to time. This may be an interesting source of information about the dynamics of magnetic domains in magnetostrictive material, complementary to dynamic characteristics performed in the presence of an external magnetic field.

Conclusions

In this work we have investigated nonlinear effects and compared the efficiency of the electrical energy harvesting system from mechanical vibration by two different phenomena: piezoelectricity and magnetostriction. Comparing the results of U2 measurements in different configurations and excitations (Fig. 3), it can be inferred that under certain conditions and configuration the disturbances introduced by the moving elements of the tip-mass cansignificantly increase the broadband efficiency of the magnetostrictive subsystem. This is influenced by two co-operating effects: noise growth and extra peaks appearing in different points of the frequency characteristics. It can be assumed that this effect will be exacerbated by increasing amplitude of the external forcing. It has also been shown that the dynamics of the piezoelectric subsystem reflects the dynamics of the mechanical system unlike the magnetostrictive subsystem. In this subsystem there are additional internal magnetic nonlinear effects that influence its dynamics. It is worth to note, that we did not use external magnetic field to reorient the magnetic domains in the magnetostrictive beam.

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REFERENCES

[1] Mitcheson, P.D., Yeatman, E.M., Rao, G.K., Holmes, A.S., Green, T.C. (2008):Energy harvesting from human and machine motion for wireless electronic devices, *Proceedings of the IEEE* 96, 1457-1486

[2] Litak, G., Manoach, E. (2013): Dynamics of composite nonlinear systems and materials for engineering applications and energy harvesting – The role of nonlinear dynamics and complexity in new developments,*European Physical Journal Special Topics*222, 1479-1482

[3] Yildirim, T., Ghayesh, M.H., Li, W., Alici, G. (2017): A review on performance enhancement techniques for ambient vibration energy harvesters,*Renewable and Sustainable Energy Reviews*71, 435-449

[4] Beeby S.P., Tudor M.J., White N.M. (2006): Energy harvesting vibration sources for microsystems applications,*Measurement science and technology*17, R175-R195.

[5] Yoo, J.-H., Flatau, A.B. (2012): A bending-mode galfenol electric power harvester,*Journal of Intelligent Material Systems and Structures*23, 647-654

[6] Daqaq, M.F., Masana, R., A. Erturk, A., D.D. Quinn, D.D. (2014): On the role of nonlinearities in vibratory energy harvesting: a critical review and discussion,*Applied Mechanics Reviews* 66, 040801

[7] Friswell, M.I., Ali, S.F., Adhikari, S., Lees, A.W., Bilgen, O., Litak, G. (2012): Nonlinear piezoelectric vibration energy harvesting from a vertical cantilever beam with tip mass,*Journal of Intelligent Material Systems and Structures*23, 1505-1521