



Pendulum energy harvester with amplifier

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Abstract

This paper presents a new principle of inductive vibration power harvester. Harvester is a pendulum that uses energy capacitor which is the mass. The mass is connected to the pendulum via a gearbox to achieve greater movement of the pendulum that generates an electromagnetic voltage. The harvester is developed at a very low frequency (1 to 10 Hz) which uses the rectified magnetic fluxes. Magnets are statically placed in the harvester case, and relative motion is carried out by the coil. Magnets are static, and the coil moves due to the weight ratio of magnets which the steel leads of the magnetic flux and the coil itself. This paper is focused on a harvester with a mechanical amplifier with the proposed technique is brings the plow harvester access with an auxiliary force. The experimental results indicate that the optimal results of the harvester with an accumulator for the resonant zone are 3.75 Hz, 7 Hz, and 10 Hz.

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Keywords: Pendulum; energy; harvester; amplifier; vibration.

I. Introduction

Today, given the wireless data transmission, sensors are limited by the necessity of electric power supply. When using the cable system to power the devices, the advantages of wireless communication are considerably reduced. Using batteries is not the best solution because of their durability and limited working conditions. To push the limits of the possibilities for technical control and management, the new alternatives based on the inexhaustible energy sources in the close distance around the power system are investigated.

One of the most effective alternative ways to supply power to electronic devices is by utilizing the surrounding vibrations. However, kinetic parameters of the standard environment, including human movement, the vibration of bridges, buildings, machines, and many devices are low frequency. To solve this problem, many solutions were designed, such as utilization of resonance oscillation, mechanical frequency, or rotating movement with eccentric mass [1]. Performance of these systems goes

down out of the appropriate conditions range whenever big static displacement, non-periodic vibrations, and low amplitude exist. The range is usually narrow, which is a huge disadvantage. The opposite approach to this solution is “direct force” where vibrations are transmitted only by transfer multiplying amplitude and frequency [2]. Although these solutions tend to create less energy compared to resonance harvesters, these also have the advantage of a wider excitation band. The However, these solutions might not be applicable everywhere, especially for vehicles and enclosed spaces, where only a relative movement to the earth that can be utilized. Therefore, this paper is focused on the harvester with the mechanical amplifier.

The proposed solution brings the plow harvester access with an auxiliary force. It accumulates in a mechanical condenser. The transformation of the excitation of the excised mass (capacitor) in the translational motion is associated with the pendulum through the constrained accouplement. The layout has proven to be suitable for very low excitation frequencies and further research. There are a large number of physical phenomena combinations that are used to construct the collector. Different ways of storing resonant and power components that have a

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tremendous impact on performance. The proposed harvester is unique due to its solution that offers options for further innovation in its extensive development.

II. Harvester assembly

The principle of capturing vibration energy is the resonant operation of the oscillation mass and the subsequent electromechanical transformation into electrical energy [3]. These devices work correctly only in narrow resonant bandwidth. Therefore, the energy collector structure is tuned into a resonant frequency of operation that is the same as the dominant vibration frequency. The excited oscillation movement inside the mechanism is transformed by a certain physical principle of electromechanical conversion. Vibration energy collecting devices typically use the principles of piezoelectric, electrostatic, electromagnetic, or magnetostrictive conversion [4]. Schematic diagram of the vibration energy harvester principle is shown in Figure 1 [5]. Mechanical vibrations generate the mass of the resonant mechanism, and the relative movement of mass with the magnetic circuit against the solid coil (vice versa) leads to tension due to Faraday's law. The current flows through the connected electronics (electrical load), and then the output power is harvested.

The vibration pickup bandwidth is a key element in gaining energy from mechanical vibrations. Non-linear stiffness is therefore used to extend the working bandwidth of non-linear vibration energy harvesting devices [6][7]. Non-linear behavior can be ensured by several designs of flexible elements, Pendulum architecture [8], MEMS structure of electrostatic collectors [9], resilient spiral structures of polymer resonators [1], or a set of permanent repellent magnets [10]. The combination of magnetic forces and mechanical spring provides another possibility of non-linear operation with extended bandwidth operation [11][12].

An electromechanical power generator is proposed for converting mechanical energy in the form of low-frequency vibrations that available in the measurement environment into electrical energy. The intended applications for the proposed electromechanical power generator described in this paper are for examples mechanical systems with lower frequency vibrations (1 to 10 Hz).

The main mean of the phenomenon explored is an oscillating body which can amplify small amplitude 0.325 R-times because of an amplifying gear connected to a coil on a crank. The system of magnets in the trajectory of the coil multiplies the frequency four times to give a maximum oscillation. The scheme of the oscillating body Harvester is shown in Figure 2. According to the Figure 2, it was shown that a pendulum connected to the base with a mass "m²", and its center of gravity in a distance "R" from the rotation axis and the inertia "I". A gear wheel radius is "r". The gear ratio is 1 mm = 18°. The harvester is performed optimally by the acceleration of the

ambient vibration $A_{(t)}$, k stiffness, d_m mechanical damping and d_e electrical damping. The magnetic field of magnets is paired and connected by steel plates. B is a vector of magnetic flux density. The generator implements a novel configuration of magnets that is proposed and analyzed with the aim to improve the conversion efficiency and increase the spatial variation of magnetic flux.

To create a proper design of individual parts which define its parameters and efficiency, the equations have been assembled to be processed in Matlab and other analytical programs.

The axial stiffness k , which calculated in Equation (1) was purposed to add the measured values obtained during the load test. Meanwhile, F is the load force, and Δy is the difference in which the spring length has changed. In Equation (2), the relation between displacement of the mass m and change in an angle of the pendulum φ is defined, and the respective velocity values are yielded by the derivation. In Equation (3), the kinetic energy has modified, as all of the single variable φ . For simplicity, a gear wheel and a pendulum have been put with a spool into the inertia of the coil. Afterwards, the Equation (4) is generated with potential energy. All elements in the system, containing energy terms are rearranged into the basic

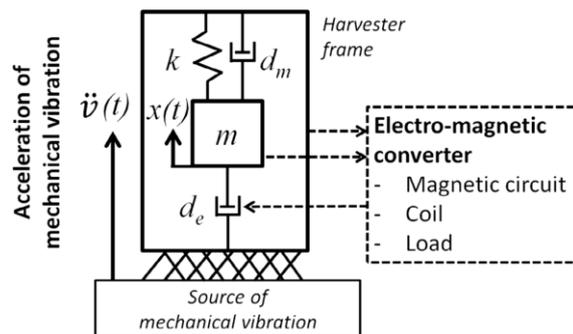


Figure 1. Schematic diagram of vibration energy harvester principle

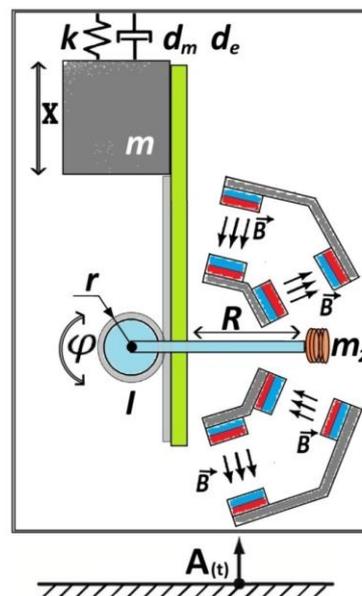


Figure 2. Schematic of the oscillating body harvester

2nd order Lagrangian Equation (5) with D is the dissipative energy, E_p is potential energy, E_k is kinetic energy and Q_j are generalized forces.

$$k = \frac{F}{\Delta y} \quad (1)$$

$$x = r \sin\varphi \rightarrow \dot{x} = \dot{\varphi} r \cos\varphi \quad (2)$$

$$E_k = \frac{1}{2}m\dot{x}^2 + \frac{1}{2}I\dot{\varphi}^2 = \frac{1}{2}mr^2\dot{\varphi}^2\cos^2\varphi + \frac{1}{2}I\dot{\varphi}^2 \quad (3)$$

$$E_p = \frac{1}{2}m_2gR(1 - \cos\varphi) + kr \sin\varphi \quad (4)$$

$$\frac{d}{dt}\left(\frac{\partial E_k}{\partial \dot{\varphi}}\right) - \frac{\partial E_k}{\partial \varphi} + \frac{\partial E_p}{\partial \varphi} + \frac{\partial D}{\partial \dot{\varphi}} = Q_j \quad (5)$$

$$\begin{aligned} \frac{\partial E_k}{\partial \dot{\varphi}} &= \frac{\partial}{\partial \dot{\varphi}}\left(\frac{1}{2}mr^2\dot{\varphi}^2\cos^2\varphi + \frac{1}{2}I\dot{\varphi}^2\right) \\ &= mr^2\dot{\varphi}\cos^2\varphi + I\dot{\varphi} \end{aligned} \quad (6)$$

The kinetic energy is further adjusted by partial derivation in Equation (6) and Equation (7). Then the potential energy of the saturation is expressed in Equation (8) and Equation (9).

$$\begin{aligned} \frac{d}{dt}\left(\frac{\partial E_k}{\partial \dot{\varphi}}\right) &= mr^2\ddot{\varphi}\cos^2\varphi - 2mr^2\dot{\varphi}\cos\varphi\sin\varphi + I\ddot{\varphi} \\ &= mr^2(\ddot{\varphi}\cos^2\varphi - \dot{\varphi}\sin(2\varphi)) + I\ddot{\varphi} \end{aligned} \quad (7)$$

$$\frac{\partial E_p}{\partial \varphi} = \frac{1}{2}kr^2\sin^2\varphi + \frac{1}{2}m_2gR\sin\varphi \quad (8)$$

$$\frac{\partial E_D}{\partial \dot{\varphi}} = \frac{1}{2}R^2b_e\dot{\varphi}^2 + \frac{1}{2}b_mr^2\dot{\varphi}^2\cos^2\varphi \quad (9)$$

All acquired energy is set in Equation (5), from which the Equation (10) is obtained.

$$\begin{aligned} mr^2(\ddot{\varphi}\cos^2\varphi - \dot{\varphi}\sin 2\varphi) + I\ddot{\varphi} + \\ \frac{1}{2}mr^2\dot{\varphi}^2\sin(2\varphi) + \frac{1}{2}m_2gR\sin\varphi + \\ kr\sin\varphi + \frac{1}{2}R^2b_e\dot{\varphi}^2 + \frac{1}{2}b_mr^2\dot{\varphi}^2\cos^2\varphi = 0 \end{aligned} \quad (10)$$

Before finishing the basic description of the system, the Equation (11) is arranged as follow:

$$\begin{aligned} \ddot{\varphi}[mr^2\cos^2\varphi + I] + \dot{\varphi}^2\frac{1}{2}mr^2\sin 2\varphi - \\ \dot{\varphi}mr^2\sin 2\varphi + \frac{1}{2}R^2b_e\dot{\varphi}^2 + \frac{1}{2}b_mr^2\sin^2\varphi + \\ \frac{1}{2}m_2gR\sin\varphi = 0 \end{aligned} \quad (11)$$

The magnetic circuit with permanent magnets is firmly attached to the frame of the harvester. Coil with the oscillated mass is part of the oscillating resonance mechanism. This design provides magnetic fields with a vector of magnetic flux and density B . The velocity of the moving coil against fixed magnetic circuit induced voltage due to Faraday's law in accordance with Equation (12). The induced voltage u_i depends on the velocity of magnetic circuit $x = r \sin\varphi$ and magnetic flux density B through activate the length of the coil l with known number of coil turns N .

$$u_i = N \oint_l^0 (\mathbf{x} \times \vec{B}) d\vec{r} \quad (12)$$

The resonance frequency Ω is determined by the stiffness k and mass m ratio as shown in Equation (13).

$$\Omega = \sqrt{\frac{k}{m}} \quad (13)$$

Periodic excitation optimally transferred and stored into the energy vibration system. Because of this repeated storage and additional energy input, the system swings stronger until its load limit is exceeded.

III. Model of construction

In this study, defining assignments and solving tasks for designing a low frequency harvester were proceeded with a simple model that was tuned by experiments. The overall process of the energy harvesting device development is shown in Figure 3.

The model of the harvester is implemented to Multibody Dynamics (MBD) software, Adams together with Matlab software. Using these types of software, the relatively accurate response of the system to the input parameters is obtained. For a better vision of the total distribution of single particles in the harvester, a view from a slight angle of the profile is shown in Figure 4.

Due to more complicated harvester with several new solutions, the static and supportive parts of the collector are removed as shown in Figure 5. One of the four magnetic pairs on the steel sheet was taken away for the position of a pendulum with a coil. The harvester design is not final, and it is intended for laboratory experiments. Therefore, it is designed spatially without higher claim of the frame.

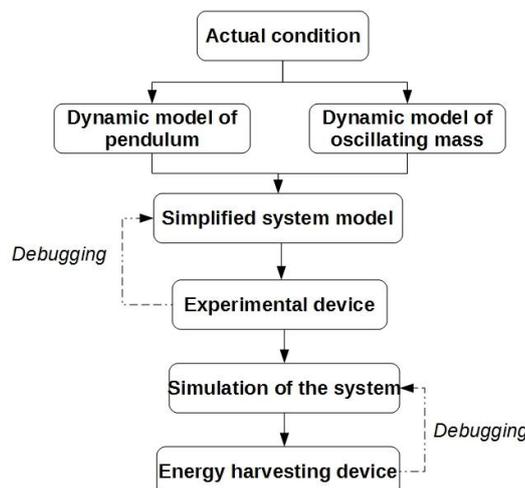


Figure 3. Diagram of the energy harvesting device

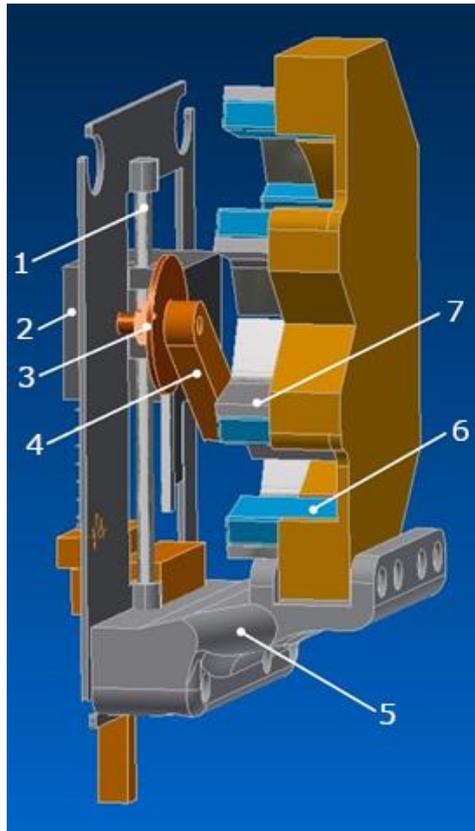


Figure 4. The model of the assembly from the profile: 1) wheel for oscillating mass, 2) oscillate mass, 3) gear wheel, 4) pendulum, 5) adjustable holder for adjusting the position of magnets, 6) NdFeB magnets, and 7) the steel plate

IV. Result and discussion

Based on the model, a prototype was created as shown in Figure 6 which also serves to verify the analytical model. This prototype can be used for tuning the system for further development. Measurements have shown the best results when keeping dynamic parameters of 3 to 7 Hz and excitation amplitude of ± 2 mm, respectively. The asymmetric progress of generating voltage was caused by the incomplete track of the coil between the magnets, and also their non-linear velocity in the given sections between the magnetic pairs. Figure 7 has shown the captured progress of a voltage at the resistance of 240Ω , excitation frequency 3 Hz, amplitude ± 3 , and $U_{Pk-Pk} = 4.04$ V.

In Table 1, dimensions of the energy harvester were recorded with the holder based on the prototype that has been made in laboratory scale. Meanwhile, Table 2 has shown recorded electrical energy from the harvester. The obtained advantage was there were two parts which respond together up to three zones resonance. When comparing to harvester, it was also sized from 3 to 10 Hz, and had the approximately same dimensions.

The harvester with the parameters was shown in Figure 8 [13], a magnetic field between two magnetic materials was served virtual mechanical spring. The harvester is 200 cm high is capable of producing 100 to 200 mV with a voltage of 4,500 mV. Resonance of the given values has reached up from 3.5 to 6.5 Hz and accelerated to 10 m/s. The advantage of the

present harvester was up to 3 times the lesser acceleration needed to achieve resonance.

The overall trend of the generated voltage was shown in Figure 9. There were two resonance curves. The top curve has shown a generated voltage of 240Ω without direction. The lower curve has described the value after the direction of generated voltage. Unidirectional voltage has been measured through a Graetz bridge made of Schottky diode and $220 \mu\text{F}$ smoothing capacitor. Schottky diode opens the circuit from a voltage of 0.3 V and due to the stiffness of the mechanism it is possible to reach the resonant zone.

Table 1.
Dimensions of the harvester laboratory assemblies.

| Parameters | Value |
|------------|-------|
| Height | 100 |
| Width | 50 |
| Depth | 50 |
| Unit | mm |

Table 2.
Summary of optimal performance information.

| Parameters | Value | Unit |
|------------|-------|---------------|
| F | 3 | Hz |
| A | 2 | mm |
| R_L | 240 | Ω |
| R_C | 30 | Ω |
| U_{Pk} | 4 | V |
| U | 1.2 | V |
| P | 440 | μW |

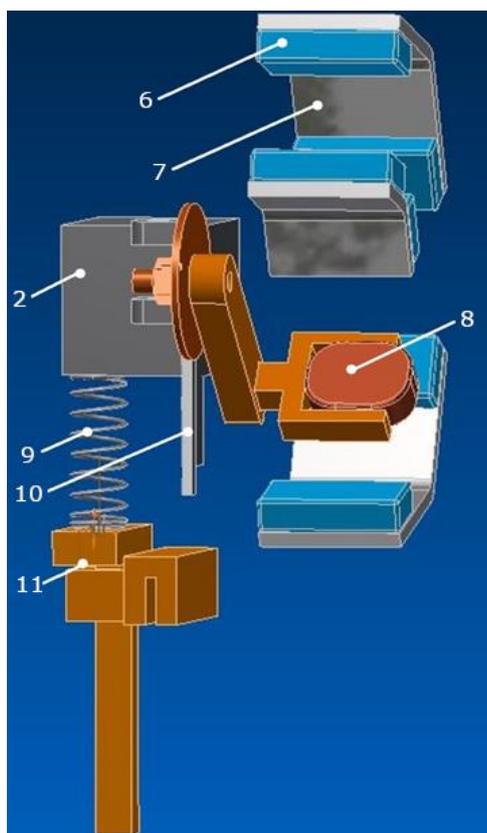


Figure 5. Selected main parts of the model from the profile: 2) oscillate mass, 6) NdFeB magnets, 7) the steel plate, 8) coil, 9) spring, 10) gear rack of mass m , and 11) spacer support of spring

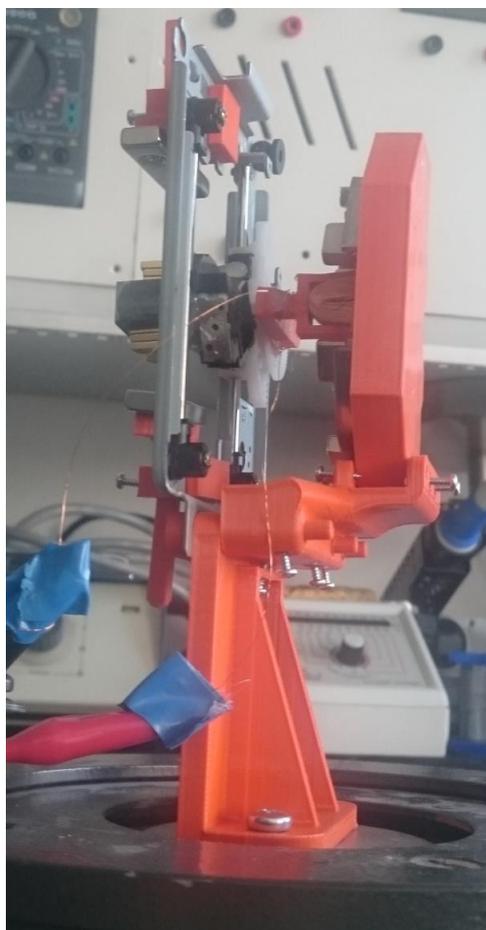


Figure 6. The prototype printed on a 3D printer

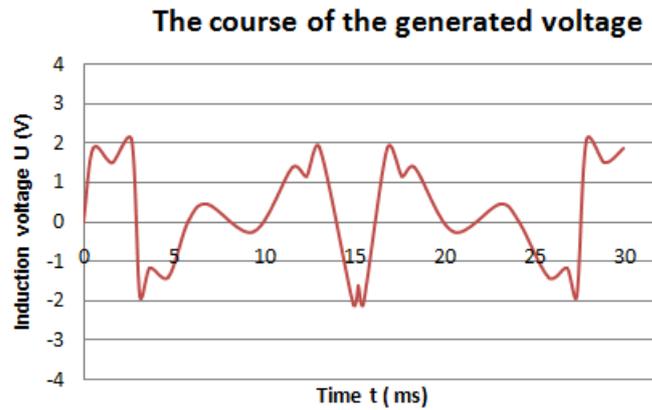


Figure 7. The progress of a voltage at the resistance of 240Ω , excitation frequency 3 Hz, and amplitude ± 3 , $U_{Pk} - P_k = 4.04 \text{ V}$

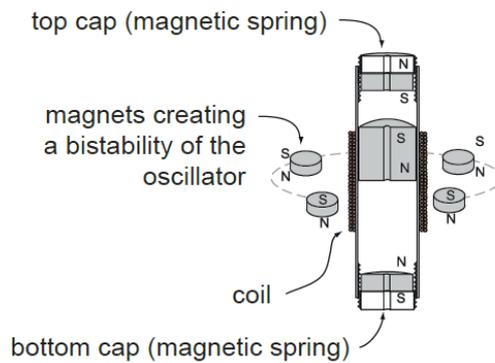


Figure 8. The harvester with the specification: 200 centimeters high, capable of producing 100 to 200 mV with a voltage of 4,500 mV

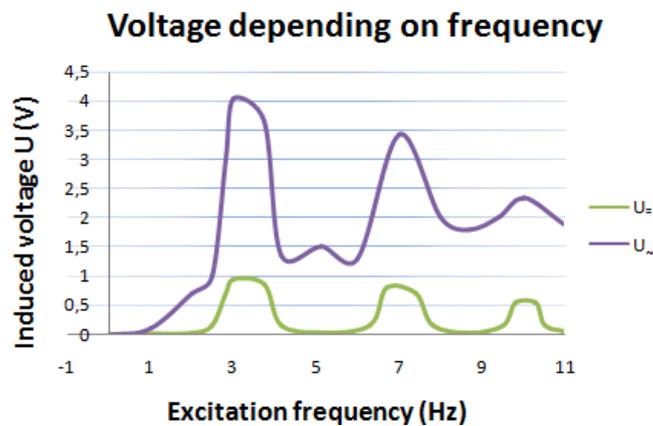


Figure 9. The overall trend of the generated voltage

V. Conclusion

The harvester with an accumulator has shown the optimal results in a wider spectrum of frequencies for resonant zone 3.75 Hz, 7 Hz, and 10 Hz, which allowed non-linear damping by magnets and the addition of an oscillating mass. Measured experimental results were the highest for the frequency of 3.75 Hz with power (P) = 3.6 mW, volume power (P_v) = $14.4 \mu\text{W}/\text{cm}^3$ and DC = 2000 mV. The disadvantage of the harvester was the loss of energy in the toothed gear. Further research should be focused on how to eliminate the energy loss. Great opportunities appear mainly in the alternative folding of magnetic field lines, which can streamline the various non-standard system of oscillating bodies.

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