Microsyst Technol (2016) 22:1767–1779
DOI 10.1007/s00542-016-2832-4

TECHNICAL PAPER

Analysis and efficiency measurement of electromagnetic vibration energy harvesting system

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Received: 7 August 2015 / Accepted: 8 January 2016 / Published online: 18 January 2016

Abstract This paper deals with the efficiency analysis of developed electromagnetic vibration energy harvesting systems. The efficiency analysis of this energy harvesting system is specified and a linear model of the vibration energy harvesting system is simulated to determine theoretical limits. The influence of individual parameters of vibration energy harvesters is evaluated by the simulation model. Three vibration energy harvesting devices, developed at Brno University of Technology, were measured and their efficiencies were consecutively calculated from the measured data. Vibration tests of these harvesters were done with a lightweight vibrating structure of a steel beam where the effect of the vibration energy harvester operation is noticeable. The effects of used electronics and power management circuit for different levels of excited mechanical vibrations are presented. Realized analyses and measurements will be used for future improvement of vibration energy harvester design; mainly in applications of lightweight vibrating structures where the vibration energy harvester can affect mechanical vibrations in feedback.

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1 Introduction

This paper is focused on the efficiency analysis of developed electromagnetic vibration energy harvesting systems. Vibration energy harvesting systems use ambient energy of mechanical vibrations to harvest useful electrical energy. Such systems have limitations in a resonance operation. The level and stability of frequency of mechanical vibrations are fundamental for successful energy harvesting. However, the efficiency improvement could be useful for wider usage of vibration energy harvesting systems in applications with lower level and varied frequency of mechanical vibrations.

Nowadays vibration energy harvesting technologies are used in various engineering applications (automotive, smart buildings, transport and heavy industry, etc.) and the power gain of energy harvesting systems is still improving. Although the levels of ambient mechanical energy are very low, this technology can be used as a power supply for modern ultra-low power electronics and wireless sensing.

The vibration energy harvesting system consists of a resonance energy harvester with an electro-mechanical converter, electronics, power management and an energy storage element (Hadas et al. 2014). The resonance energy harvester is usually the key element of the whole energy harvesting system. The value of efficiency of this autonomous energy source is the most frequently discussed issue of technical public. The efficiencies of power electronics and power management circuits for energy harvesting are well known and these results were published several times (e.g. Amirtharaiah et al. 2006). The efficiency of energy harvesting electronics is usually in the range of 60–95 %. Contrary, the efficiency of separate vibration energy harvesting systems is not widely discussed (Funck 2011). This paper describes the efficiency analysis of vibration energy harvesting system and the linear model of vibration energy harvesting system is simulated to determine the theoretical limits. Furthermore, three vibration energy harvesting products, developed at Brno University of Technology, were measured and their efficiencies were calculated.

2 Efficiency of vibration energy harvesting systems

2.1 Model of vibration energy harvesting system

The fundamental part of the vibration energy harvesting system is a resonance mechanism. It is schematically shown in Fig. 1. This mechanism is based on a spring suspension of moving seismic mass m_1 of tuned up stiffness k_1. This resonance mechanism is excited by ambient mechanical vibrations of a vibrating structure and it provides the relative movement x_1 against fixed frame.

The excited relative movement of the seismic mass inside the mechanism could be converted to electricity by several physical principles of the electro-mechanical conversion. The vibration energy harvesters usually use principles of an electro-magnetic, piezo-electric, electro-static or magnetostriction mechanical conversion (Paradiso and Starner 2005).

The overall harvested power is dissipated from the energy harvesting system by an electro-mechanical converter and energy harvesting provides electro-mechanical damping effect, which is depicted as damper d_e. Maximal electrical power is harvested when dissipated mechanical forces inside the harvester, depicted as damper d_m, and electro-mechanical conversion forces are in equilibrium. Nevertheless the vibration energy harvester has to operate in resonance and a sufficient vibration level (Williams and Yates 1996).

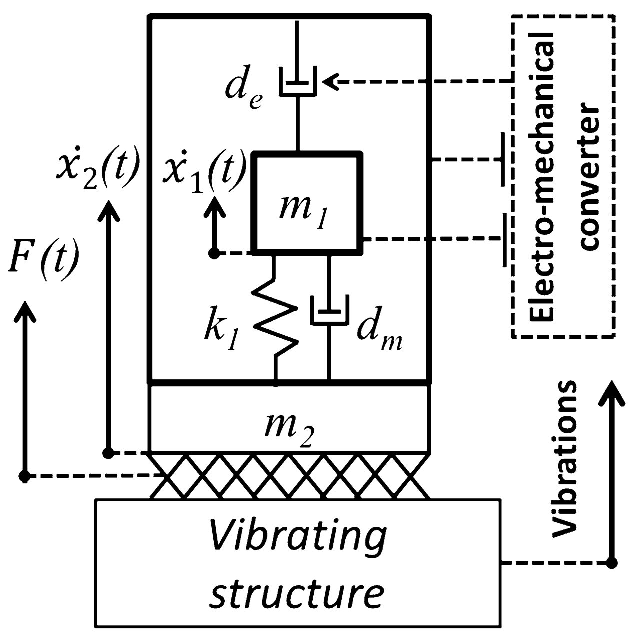


Fig. 1 Schematic diagram of vibration energy harvesting system

The electro-magnetic physical principle of the electro-mechanical converter is used in the developed vibration energy harvesters. Used electro-magnetic converter consists of an oscillating magnetic circuit (seismic mass) and a self-bonded air coil fixed to the frame. As the harvester is excited by the mechanical vibration, the resonance mechanism produces the oscillation of the magnetic circuit with rare earth permanent magnets against the fixed coil. Due to Faraday's law the oscillation movement provides change in magnetic field through the coil and it induces the voltage in the coil. The current flow through the coil causes electromagnetic damping effect, denoted as damper d_e. The amplitude of the excited oscillation movement in the resonance operation depends on the level of vibration and the quality factor of the resonance mechanism. A very high quality factor of the mechanism is fundamental to generate useful energy from mechanical vibrations (Hadas et al. 2010).

2.2 Efficiency of vibration energy harvesting systems

The harvested output power depends on the level and frequency of excited mechanical vibrations, the weight of the moving seismic mass, the quality factor of a resonance mechanism and connected electrical load. The output harvested power $P_{electric}$ is observed on the electrical load as output voltage and current flows through the electrical load (1). This useful electrical power $P_{electric}$ and electrical losses inside the electro-magnetic converter dissipates the energy from oscillating system of the resonance mechanism in damping feedback d_m.

$$p_{electric} = u(t) \cdot i(t) \tag{1}$$

Input mechanical power P_{mech} is transferred to the vibration energy harvesting system through the harvester frame. P_{mech} is defined as a product of the internal mechanical force $F(t)$ in harvester mounting point and the velocity of mechanical vibrations $\dot{x}_2(t)$, see Eq. (2). The vibration velocity and the internal mechanical force $F(t)$ could be calculated or measured. It will be discussed below.

$$p_{mech} = F(t) \cdot \dot{x}_2(t) \tag{2}$$

The efficiency of the vibration energy harvesting system can be calculated for harmonic electrical signals and sinusoidal course of mechanical vibration as follows (3).

$$\eta = \frac{P_{electric}}{P_{mech}} \tag{3}$$

However, common mechanical vibrations and electrical outputs have a character of nonharmonic signals. Therefore the energy harvesting efficiency has to be calculated in the form of electrical and mechanical energy ratio (4). This calculation of the efficiency can be used for the analyses of vibration energy harvesting systems (Kubba and Jiang 2013), which operate in the environment with random moving oscillations or mechanical shocks (Li et al. 2015).

$$\eta = \frac{E_{electric}}{E_{mech}} = \frac{\int_{t_1}^{t_2} u(t) \cdot i(t)dt}{\int_{t_1}^{t_2} F(t) \cdot \dot{x}_2(t)dt} \quad (4)$$

The output voltage and current through the coil are commonly measured. The velocity of mechanical vibrations can be measured by common vibrometers, however, the measurement of the internal mechanical force between the vibration energy harvester frame and the vibrating structure has to be performed using an additional force transducer. The effect of this additional mass inside the vibration energy harvesting system is analysed in following linear model.

3 Efficiency analysis based on vibration energy harvesting simulation

3.1 Mechanical model of vibration energy harvesting system

A linear mechanical model of the whole mechanical system is used for the calculation of internal mechanical force, the model is shown in Fig. 2. The presented linear model consists of the vibrating structure, the source of vibrations, the force sensor, the frame of the harvester and the vibration energy harvesting system. The linear model of electro-magnetic converter is integrated in this mechanical model for calculation of dissipation feedbacks which provide electromagnetic damper to the energy harvesting mass-spring system. Similarly the model of the electro-magnetic converter is used for the calculation of the output voltage and current through the electrical load; it represents the output electrical energy. Calculated internal force and velocity of excited vibrations provide the information about input mechanical energy into the energy harvesting system.

The vibrating structure is depicted as 1 DOF mass-spring-damper system (m_3, k_3, d_3) and it represents the mechanical part where the vibration energy harvesting system is placed (m_1, k_1, d_m, d_e). The resonance frequency of the energy harvesting system is tuned up with respect to the value of the first natural frequency of the vibrating structure. The model of the force sensor is in the form of mass-spring system ($m_{2platform}$, k_2) and it is integrated between the vibrating structure and the frame of the energy harvester m_{2frame}. Consequently the frame of the energy

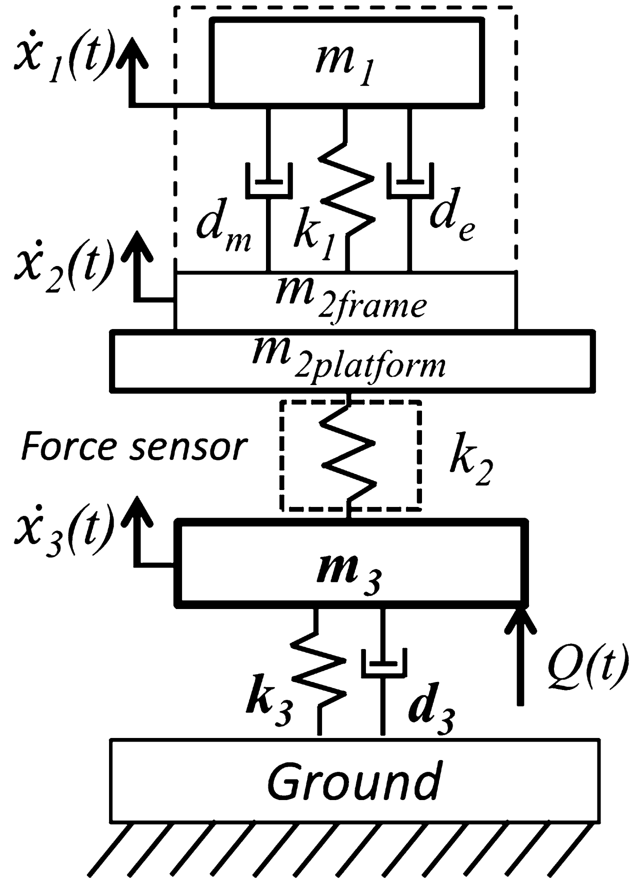


Fig. 2 Linear mechanical system of vibrating structure with energy harvesting system

harvester is fixed to the vibrating structure by the force sensor model. The force sensor model includes the mass of a platform $m_{2platform}$ which is used to fix the energy harvester frame m_{2frame}. We observed the influence of mass m_2 on the harvesting system behaviour and the efficiency calculation. The spring element k_2 of the force sensor model with very high value of the stiffness k_2 can provide information about the input mechanical force into vibration energy harvesting system on the base of Eq. (5).

$$F = k_2(x_2 - x_3) \quad (5)$$

This complex mechanical system is excited by the excitation model of external force $Q(t)$ and it provides mechanical vibrations of the vibrating structure.

3.2 Equivalent RCL circuits of vibration energy harvesting system

The three-mass mechanical system with the vibration energy harvester, Fig. 2, can be expressed in a circuit form using equivalent RCL circuits. Kirchhoff equations will be calculated for each loop (Erismis 2013). This model can be easily

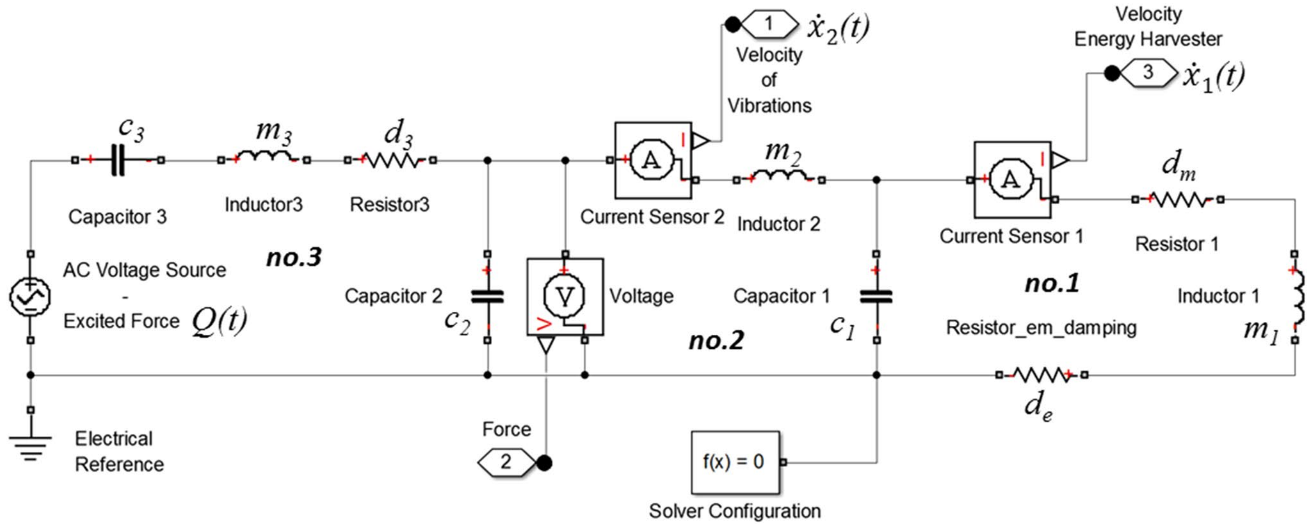


Fig. 3 SIMULINK model of equivalent electrical RCL circuit; electromechanical analogy of three-mass mechanical system

connected to the circuit of the electro-magnetic converter with the electrical load, where output electrical energy is calculated. The electro-mechanical model of equivalent RCL circuits is shown in Fig. 3 and it consists of three equivalent electrical circuits. This model was created in SIMULINK environment. The physical analogy of electro-mechanical elements is depicted below. Currents through individual RCL circuits are equivalent to the velocity of individual mass. The voltage sources are equivalent to mechanical forces. The inductors are equivalent to the masses, resistor to the damper and capacitor to a compliance of mechanical spring. The compliance c of the mechanical spring is inversely proportional with known stiffness k (6) and it is used as capacitance in the equivalent electrical RCL circuit, see Fig. 3.

$$c_i = \frac{1}{k_i} \tag{6}$$

The equivalent RCL circuit no. 3 is excited by the source of an input voltage which is equivalent to the external mechanical force $Q(t)$. The equivalent RCL circuit no. 2 provides information about the force sensor, velocity of the platform and masses of the frame (7). The electrical energy which flows through the equivalent RCL circuit no. 2 presents input mechanical energy to the vibration energy harvester, which is presented as the equivalent RCL circuit no. 1.

$$m_2 = m_{2frame} + m_{2platform} \tag{7}$$

The current in the equivalent RCL circuit no. 1 represents relative velocity of the seismic mass of the harvester. This velocity is used in the linear model of the Faraday's Law and induced voltage (8) is calculated (Hadaš et al. 2007), where N is the number of coil turns, l is active length of the coil, B is magnetic flux density.

$$u_i = N \cdot l \cdot B \cdot \dot{x}_1(t) \tag{8}$$

This induced voltage represents and input to the electrical circuit of the electromagnetic vibration energy harvester, which is shown in Fig. 4, and harvested output power on a resistive electrical load is calculated. The harvesting of

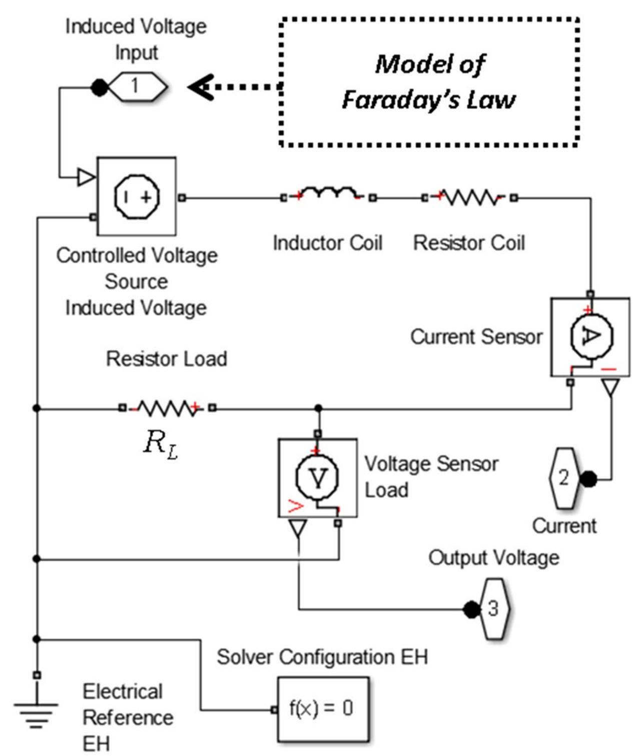


Fig. 4 Electrical circuit of electromagnetic vibration energy harvester

energy provides the linear electromagnetic damping d_e in Fig. 3. Thereafter the harvested electrical energy from the model in Fig. 4 and input mechanical energy to the vibration energy harvester, which flows through the equivalent RCL circuit no. 2, Fig. 3, represent the inputs to the efficiency analysis. The value of efficiency of the linear vibration energy harvesting system is further calculated.

3.3 Results of equivalent RCL circuits

The main aim of this simulation with RCL equivalent circuits is in the identification of parameters affecting the efficiency of the linear vibration energy harvester. The influence of harvester parameters in the resonance operation was investigated using given SIMULINK model. Used parameters follow from our experience with the development of electromagnetic vibration energy harvesters. The model was tuned up to operation frequency of 17 Hz and the quality factor of this system has value 100. The list of parameters used for the equivalent electrical RCL simulation is shown in Table 1. The list of parameters used for the simulation of Faraday's Law is shown in Table 2. The mass m_3 is 200 times higher compared to the seismic mass m_1; it means the harvester operation does not affect input mechanical vibrations.

The energy harvesting model with the optimal resistive load (Khan et al. 2014) was used in simulations. The maximal harvested power on the optimal resistive load R_L does not exactly correspond with equilibrium of both mechanical and electrical damping. Due to electrical losses on the coil resistance the value of optimal resistive load R_L is slightly shifted to achieve the maximal output power. The peak of maximal output power is determined by parameters of energy harvesting system and excited mechanical vibrations. The modern power management electronics includes maximal power point tracking function which guarantees maximal harvesting of electricity during varied input conditions.

At first the influence of the harvester frame mass and force sensor platform was calculated and the mass m_2 has not influence the value of efficiency. The increasing of the mass m_1 mass provides causes decreasing of the efficiency, however, the harvested output power is proportional to the mass and harvested power grows up with the mass. The parameters such as magnetic flux density B, number of coil turns N and active length of the coil l have only a minor impact to calculated efficiency; only several percent only.

Another simulation was focused on the dependence between output harvested power and efficiency. The model was excited with the sinusoidal external mechanical force $Q(t)$ and the vibrating structure m_3 is moving

Table 1 Parameters of equivalent RCL model in SIMULINK environment

Mechanical system		Equivalent electrical system		Value
Parameter	Unit	Parameter	Unit	
Seismic mass m_1	g	Inductor 1	mH	50
Mechanical damping d_m	Ns/mm	Resistor 1	mΩ	53.4
Harvester stiffness k_1	N/m			570
Mechanical compliance $1/k_1$	m/N	Capacitor 1	mF	0.00175
Mass m_2	g	Inductor 2	mH	1070
Force sensor stiffness k_2	N/µm			1050
Mechanical compliance $1/k_2$	µm/N	Capacitor 2	µF	0.00095
Mass m_3	kg	Inductor 1	H	10
Stiffness k_3	N/µm			0.5
Mechanical compliance $1/k_3$	µm/N	Capacitor 3	µF	2
Damping d_3	Ns/m	Resistor 3	Ω	44.7
Frequency of vibration f	Hz	Resonance operation f	Hz	17

Table 2 Parameters of electrical circuit of electromagnetic harvester in SIMULINK environment

Electrical circuit		
Parameter	Unit	Value
Magnetic flux density B	T	0.4
Coil turns N	–	500
Active length of coil l	mm	40
Diameter of wire d	mm	0.1
Inner coil resistance R_C	Ω	180

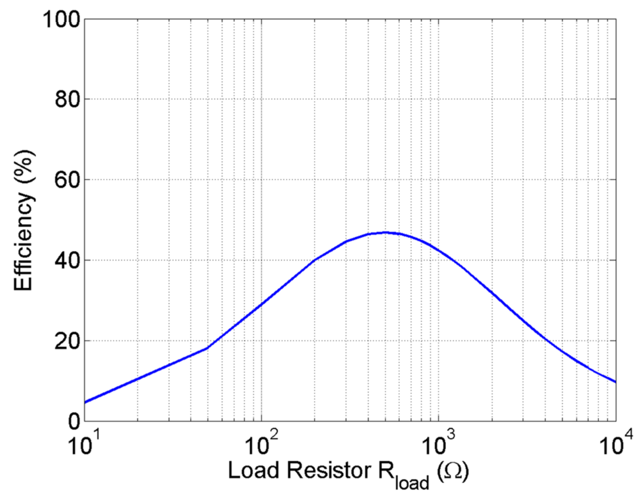


Fig. 5 Simulation results of efficiency vs. resistive load

with sinusoidal vibration with the frequency of 17 Hz and vibration level set to 100 mG RMS. The resistive load was varied in SIMULINK model and the simulation results are presented, in particular the harvested output electrical power, see Fig. 5, and harvester efficiency, see Fig. 6. The output voltage of this harvester model is shown in Fig. 7. The maximal efficiency of the vibration energy harvesting system is 46.82 % for resistive load of 500 Ω. However, the value of maximal harvested power 7.62 mW is in accordance with the published study; the value of the optimal resistive load is around 1.3 kΩ. The value of the efficiency for maximal harvested power is 38.8 %; it means that the seismic mass needs higher kinetic energy in the operation with optimal load compared to the operation with load of 500 Ω, where mechanical and electrical energy ratio is maximal.

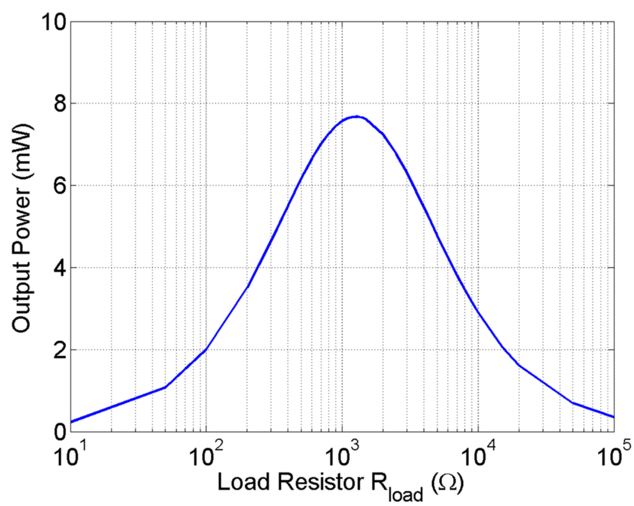


Fig. 6 Simulation results of output power vs. resistive load

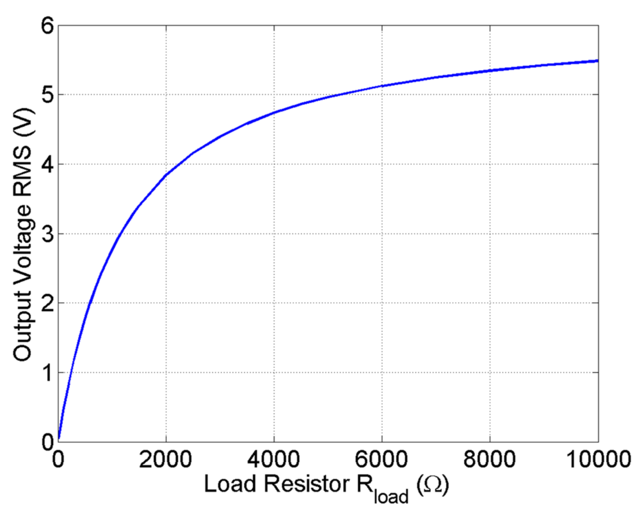


Fig. 7 Simulation results of output voltage vs. resistive load

4 Efficiency measurement apparatus

4.1 Lightweight vibrating structure

The simulation presented above assumed that the vibration energy harvesting system does not affect mechanical vibrations of the vibrating structure. Developed electromagnetic vibration energy harvesters were tested with real mechanical vibrations and lightweight vibration apparatus was developed to test the energy harvesting devices (Hadas and Ksica 2014). The testing vibration apparatus consists of heavy base, flexible steel beam, electromagnetic actuator and control unit. The force, acceleration and velocity measurements are integrated and the response of the vibration energy harvester is measured as well. Consecutively the efficiency is calculated from measured data. The schematic diagram of testing apparatus with the vibration energy harvester is shown in Fig. 8.

The testing apparatus allows to change the geometry and additional masses, therefore the natural frequency of lightweight vibration structure can be tuned up to required dynamics (Brezina et al. 2014). Thereafter the tested energy harvester is fixed on the flexible beam and the electromagnetic actuator provides desired mechanical vibration of the flexible steel beam. The control unit of electromagnetic actuator has no feedback and provides constant pulses of external force, which cause mechanical vibrations (Vetiska and Hadas 2012). The impact of energy harvesting to mechanical vibrations is observed for this reason. The picture in Fig. 9 shows the testing vibration apparatus with the tested energy harvester and power management evaluation board.

The frequency characteristic of the flexible steel beam was measured and it is shown in Fig. 10. The tested vibration energy harvesters have resonance frequency near the first natural frequency of the steel beam and very low pulses of the electromagnetic actuator can cause suitable mechanical vibrations for energy harvesting. However, the vibration energy harvesting device could operate as a shock absorber if both natural frequencies are close together. In such a case the resonance frequencies of the beam and the harvester are shifted. The vibration energy harvesting devices are tested with the new resonance frequency. The simulation model of the vibration energy harvesting system is very useful tool for tuning up the operation frequency.

4.2 Measurement of testing apparatus

The harvester in this assembly is fixed on the force sensor platform. The force sensor works as a fixation joint

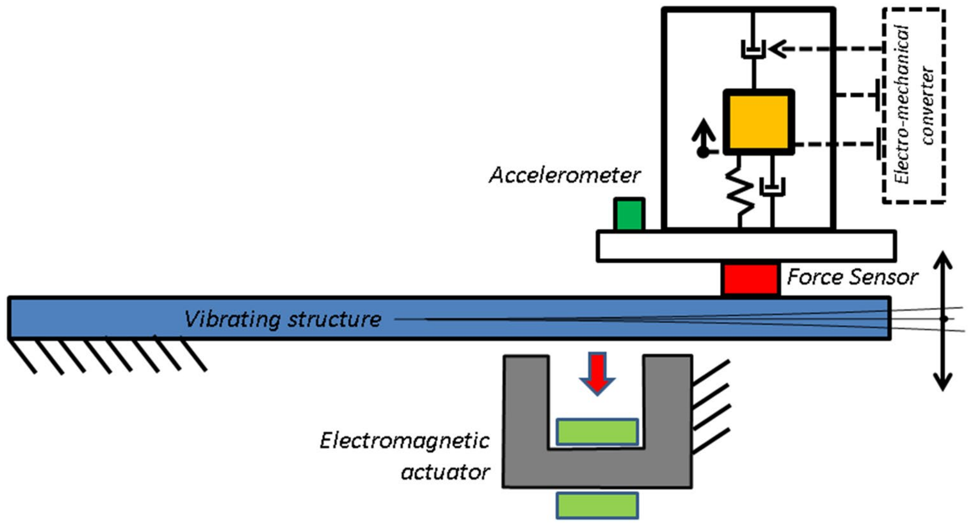


Fig. 8 Schematic diagram of testing apparatus with vibration energy harvesting system

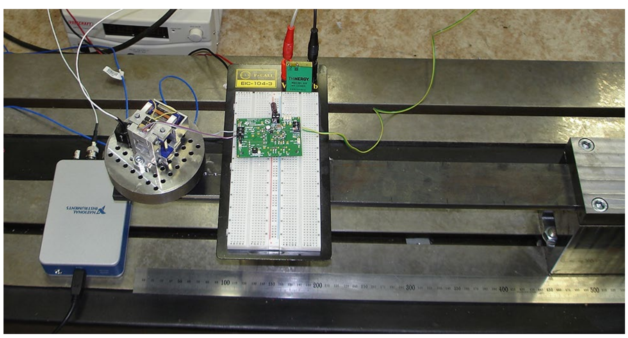


Fig. 9 Picture of testing vibration apparatus with energy harvesting system and power management evaluation board

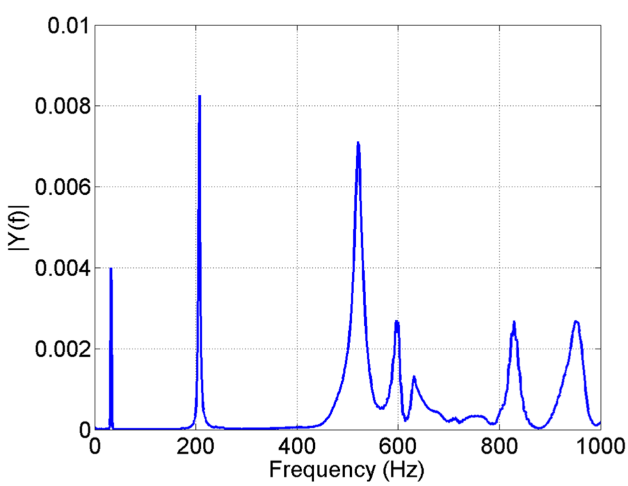


Fig. 10 Measured frequency characteristic of steel beam

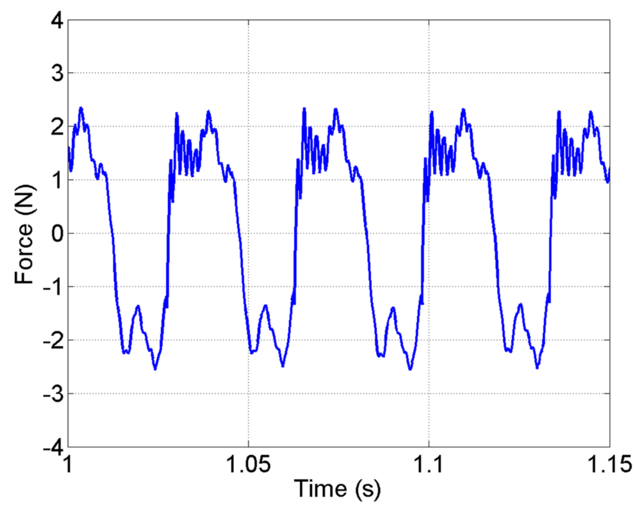


Fig. 11 Force measurement of vibration energy harvester

between the platform with harvester and the vibrating steel beam. The accelerometer is fixed on the platform as well. The signals from the sensors and the signal from the harvester are processed by high-accuracy data acquisition module National Instruments 9234.

The force sensor platform is used for easy mounting of the tested device to the force sensor. The PCB force sensor 208C01 with very high stiffness and measurement range of 44.48 N is used. The simulation results show that the platform mass does not affect efficiency analyses. For that reason the platform with the weight of around 1 kg is used for more accurate force measurement. Due to inertia force the force signal is amplified and the sensor operates in nominal range of the

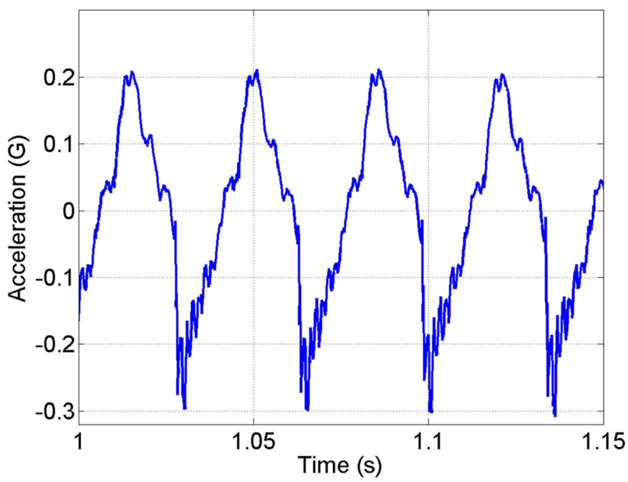


Fig. 12 Acceleration measurement of platform/frame of vibration energy harvester

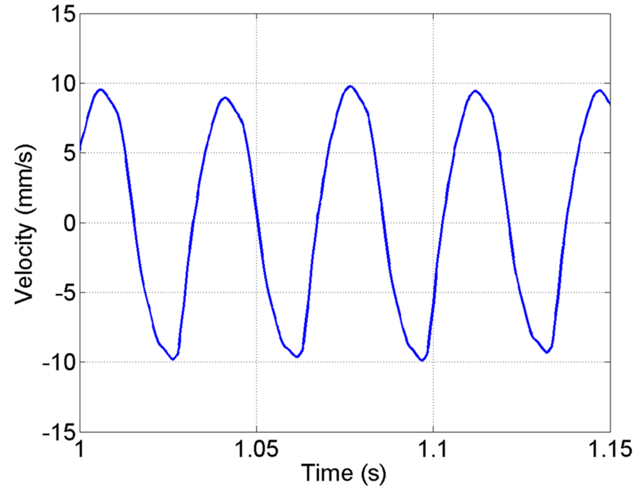


Fig. 13 Velocity of vibrating platform/frame of vibration energy harvester

sensing force. The force sensor was calibrated and an example of the force measurement in time domain is shown in Fig. 11.

The velocity of mechanical vibrations was measured by a vibrometer. However, the process of velocity measurement with the vibrometer is not comfortable and synchronization with the force measurement has to be done. The testing apparatus provides acceleration data, therefore the velocity was calculated from acceleration data. The acceleration measurement, Fig. 12, provides information about the vibration level and the frequency of excited vibration level and furthermore these data are used for additional velocity analysis without direct velocity measurement.

4.3 Velocity analysis

In order to determine the velocity course from acceleration data, the inevitable integration drift has to be corrected. Moreover, the process of zero-mean noise integration leads to an output that increases with integration time, even in the case that the accelerometer is at rest, see Thong et al. (2004). That is why velocity determination based on acceleration sensor measurement requires additional source of information. For the oscillating structures the long-term mean of all kinematic variables tends to zero, therefore a simple DC removal filter can be utilized to correct the drift. The velocity is first calculated by numerical integration of acceleration data and then the DC removal is performed by subtraction of mean computed from the sliding window. The length of the sliding window has to correspond to the period of the signal. Such period determination is essential for correct performance of drift removal, and can be found automatically, see e.g. Estrada et al. (2014), where the period identification is based on the features of the phase portrait or manually, it respects excited period of mechanical vibrations. The velocity of mechanical vibrations, Fig. 12, is analysed and the integrated velocity is shown in Fig. 13.

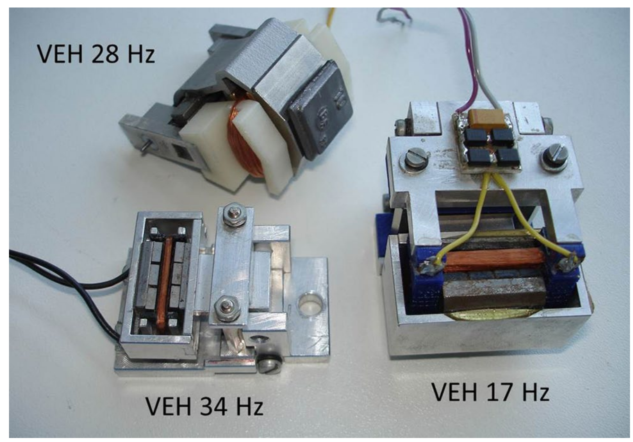


Fig. 14 Tested electromagnetic vibration energy harvesters

5 Measurements and results

5.1 Tested electromagnetic vibration energy harvesters

Several electromagnetic vibration energy harvesters were developed at our department in last 8 years. Three devices were chosen for efficiency analyses in the testing apparatus. Other developed devices cannot be tested due to size limitation or very low response of the force sensor where the measurement accuracy is not guaranteed. Tested vibration energy harvesters are shown in Fig. 14 and the review of harvester parameters is shown in Table 3. The device labelled VEH 28 Hz was developed in 2014, operation

Table 3 Review of tested electromagnetic vibration energy harvesters

Label of harvester	Volume (mm)	Weight (g)	Average quality factor (–)	Inner coil resistance (Ω)	Tested frequency (Hz)	Release (year)
VEH 28 Hz	55 × 45 × 45	116	44	52.5	28.35	2014
VEH 17 Hz	50 × 40 × 42	60	75	210	18.40	2010
VEH 34 Hz	40 × 32 × 27	146	51	273	33.75	2007

frequency is around 28 Hz and maximal harvested power is around 125 mW during very high vibration levels above 1 G. VEH 28 Hz device is described in detail in publication (Rubes et al. 2014). The device labelled VEH 17 Hz is very sensitive and nonlinear vibration energy harvester with operation frequency in range of 16.6–18.5 Hz and maximal harvested power around 40 mW. The VEH 17 Hz is described in publication (Hadas et al. 2012) and it was improved from previous design (Hadas et al. 2008). The device labelled label VEH 34 Hz is the first developed vibration energy harvester with operation frequency of 34 Hz and maximal harvested power around 8 mW. The VEH 34 Hz is described in publication (Hadas et al. 2007). All devices were tested with very low vibration level of around 50–150 mG and the efficiencies were analysed and responses of the lightweight vibrating structure were also observed. These devices were measured with a pure resistance load, with pure rectifier and resistance load and with rectifier, capacitor and resistance load. All devices were measured with the commercial power management evaluation board.

5.2 VEH 28 Hz

The VEH 28 Hz is the newest developed device, see Fig. 15, with most parts printed from ABS plastics and aluminium. The vibration energy harvester was measured with the varied resistance load and the efficiency was calculated.

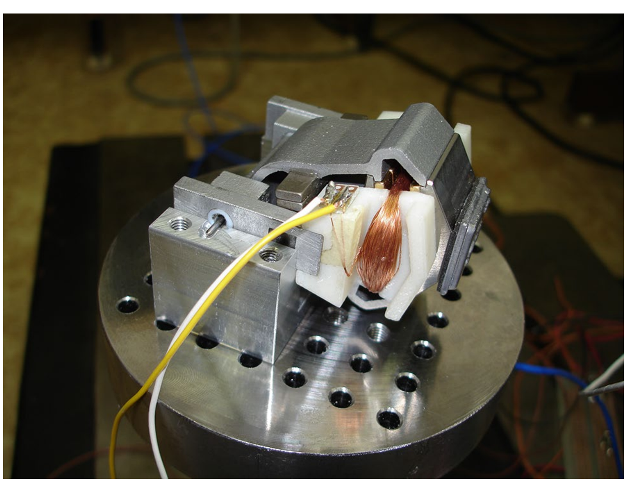


Fig. 15 VEH 28 Hz fixed on force sensor platform

Consecutively the rectifier based on Schottky diodes was used with and without the capacitor of 100 μF. Impacts of used rectifier and capacitor to output power, voltage and efficiency were investigated and results are shown in Figs. 16, 17 and 18. The maximal efficiency is 47.1 % for pure resistance load of 300 Ω. This value degreases with used rectifier and capacitor due to diodes losses. The capacitor provides the extension of maximal peak for wider electrical load. Maximal value of the efficiency with the rectifier and

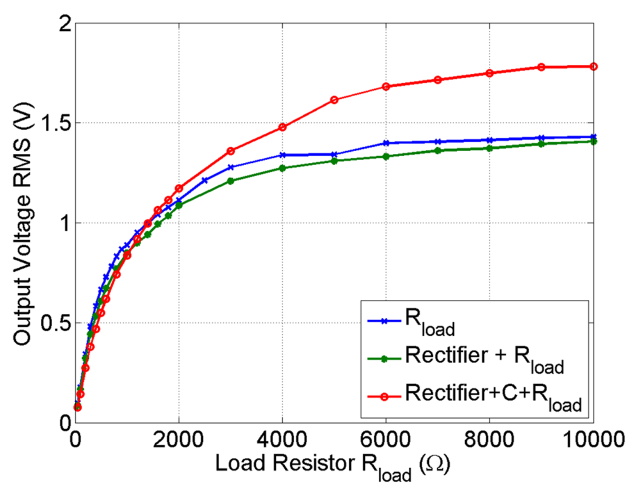


Fig. 16 Output voltage measurement of VEH 28 Hz

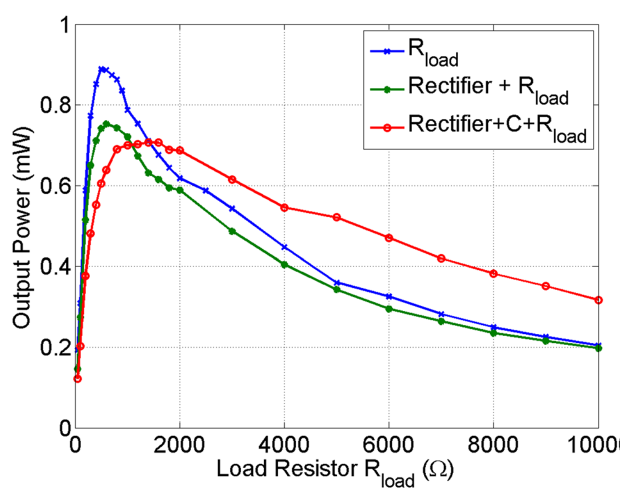


Fig. 17 Output power measurement of VEH 28 Hz

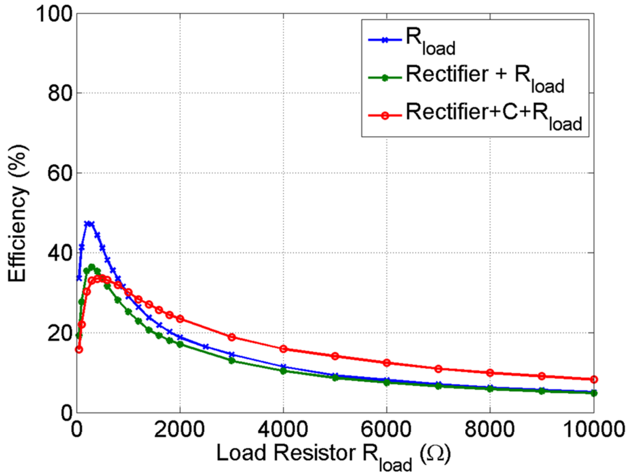


Fig. 18 Efficiency measurement of VEH 28 Hz

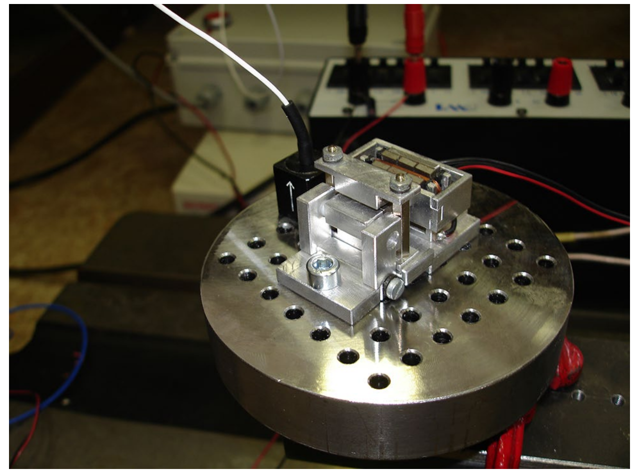


Fig. 20 VEH 34 Hz fixed on platform

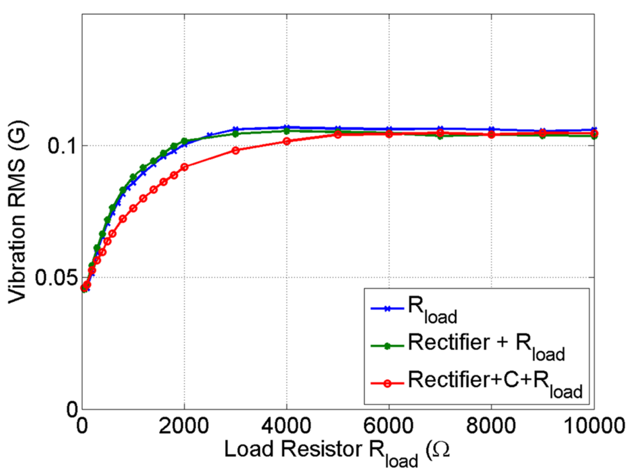


Fig. 19 Influence of vibration level during operation of VEH 28 Hz

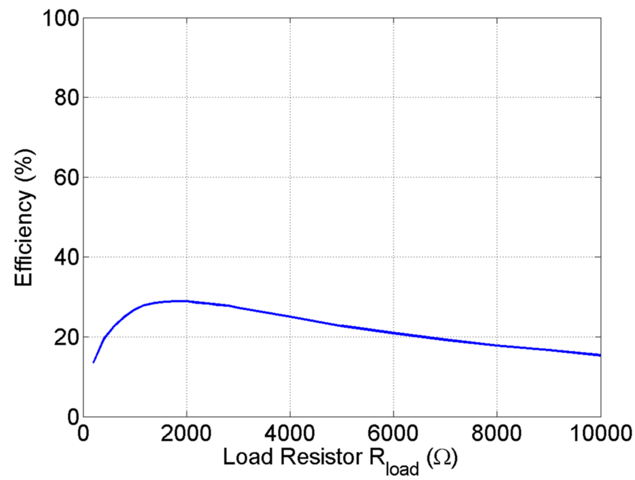


Fig. 21 Efficiency measurement of VEH 34 Hz

capacitor is 33.7 % for the load of 500 Ω. Maximal output power 0.7 mW was generated for the connected electrical load of 1600 Ω.

The level of input vibration is set up to 50 mG and the dynamic operation of the vibration energy harvester in resonance can increase vibration level up to 100 mG. The excited force of the steel beam provides the same pulses during all measurements. It is remarkable that the energy harvesting of power below 1 mW can increase vibrations of this lightweight structure (see Fig. 19).

5.3 VEH 34 Hz

Similar results were achieved during the test of the VEH 34 Hz with connected rectifier based on Schottky diodes and capacitor of 47 μF, VEH 34 Hz is shown in Fig. 20. The maximal value of efficiency with the rectifier and

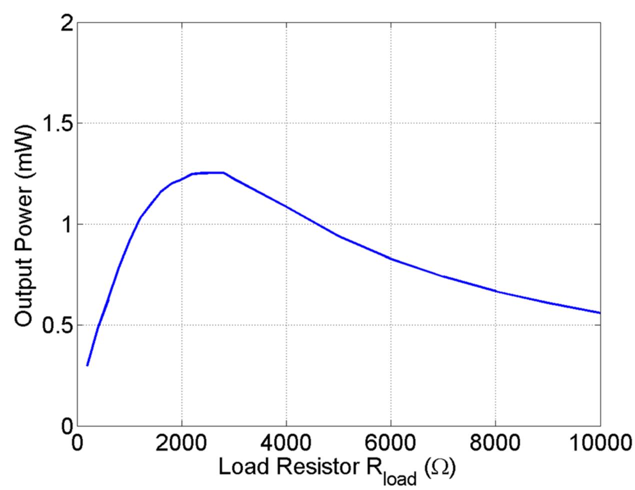


Fig. 22 Output power measurement of VEH 34 Hz

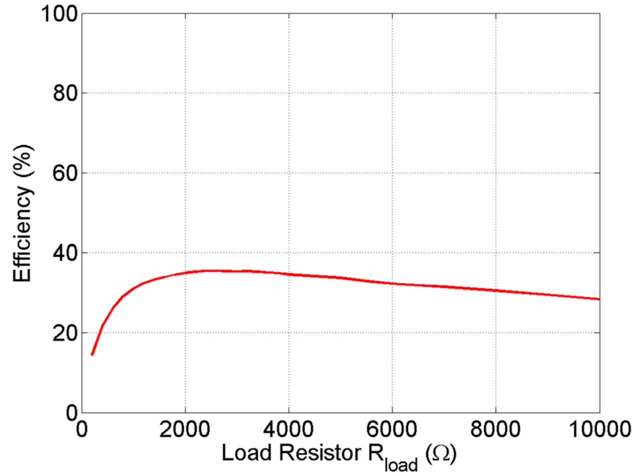


Fig. 23 Efficiency measurement of VEH 17 Hz

capacitor is 28.97 % for the load of 1800 Ω, see Fig. 21. The maximal output power 1.25 mW was generated for the connected electrical load of 2600 Ω, see Fig. 22. However, this vibration energy harvester did not affect the level of mechanical vibrations. The vibration level was shifted in range 120–130 mG during this test. This device has the lowest weight of the seismic mass and the operation frequency is the highest. The lightweight vibrating structure is relatively heavy for this VEH 34 Hz vibration energy harvester and dynamic influence of beam oscillation was not observed; the level of excited vibration was 50 mG during the whole test.

5.4 VEH 17 Hz

The VEH 17 Hz is the most sensitive device developed and it was measured with varied resistance load, connected rectifier with and without capacitor of 100 μF. The measured responses have similar courses as VEH 28 Hz, therefore we only present the numerical values of efficiency and power. The maximal efficiency of VEH 17 Hz measured with the rectifier and the capacitor is 35.48 % for the electrical load of 2400 Ω, see Fig. 23. Without rectifier the maximal efficiency is 43.4 % for the pure resistance load of 1200 Ω. The maximal output power 2.4 mW was generated for the connected electrical load of 9000 Ω; connected rectifier with the capacitor of 100 μF.

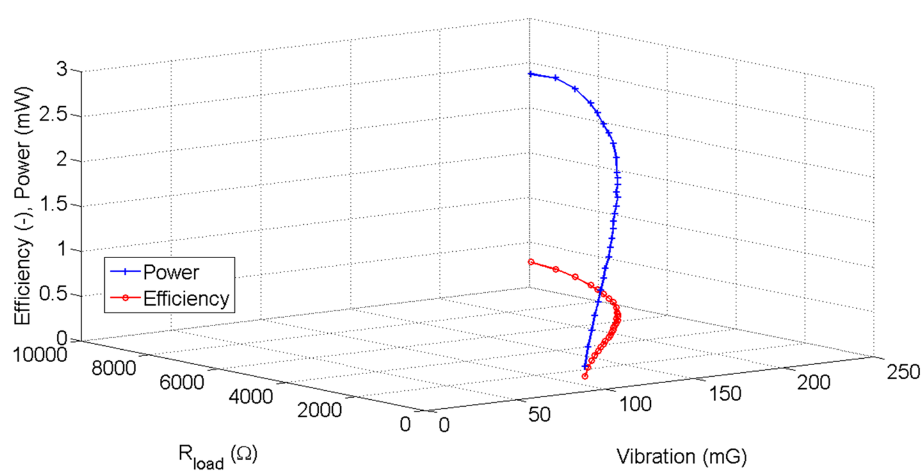
However, the operation frequency of this harvester is very close to the natural frequency of the vibrating structure and the resonance frequency was shifted to 18.4 Hz. The dynamic influence of the beam oscillation was observed; constant force excitation pulses were used during the whole test. The level of the beam vibration started on 50 mG and vibrations grow up to 200 mG during the test. The beam vibrations are affected by the resonance operation of the harvester. The change of electrical damping, which is proportional with the resonance amplitude of the harvester mechanism, is also influential.

The measurements which show that the operation of this VEH 17 Hz vibration energy harvester significantly affects input mechanical vibrations are shown in Fig. 24. The efficiency measurement from Fig. 23 and the output power measurements with maximal value of 2.4 mW are presented in this 3D plot in accordance with measured vibration level.

5.5 Efficiency measurement with power management

The test of the VEH 17 Hz with power management electronics is shown in Fig. 25. The power management circuit bq25504EVM is connected in this case. The bq25504EVM is a commercial ultra-low power boost converter with battery management for energy harvester applications by Texas Instruments. This commercial evaluation module was tested with all harvesters during operation with different vibration levels and the battery charging current was

Fig. 24 Output power and efficiency measurement of VEH 17 Hz vs. load and influence of vibration level



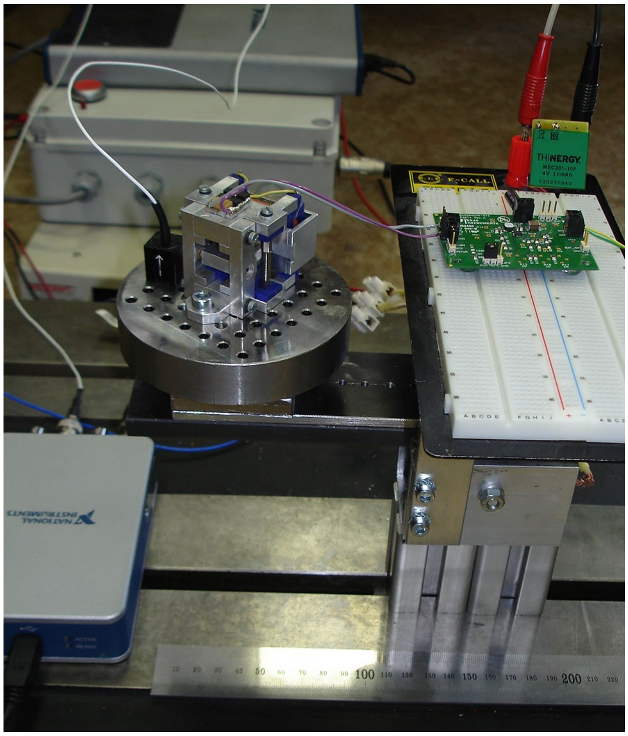


Fig. 25 VEH 17 Hz fixed on platform—power management circuit bq25504EVM is connected

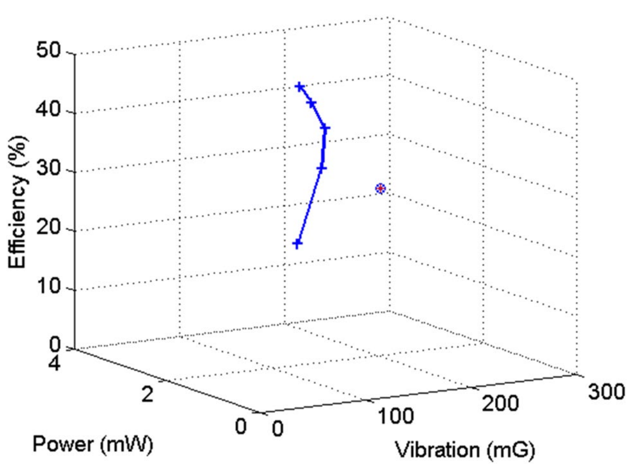


Fig. 26 Efficiency measurement VEH 17 Hz; *line* measurement with 2 kΩ load for different vibration excitation; *dot* operation with power management electronics module bq25504EVM

measured. The efficiency of the VEH 17 Hz was calculated and it is shown as a dot in Fig. 26. This value is compared to other measurements with the 2 kΩ load for growing excitation of the vibration level.

In this case the VEH 17 Hz is excited with higher vibration level and higher output power is harvested; however, the efficiency is only 23.6 % against efficiency of 46 % with the pure electrical load of 2 kΩ. It means that the operation of the power management circuit bq25504EVM can affect the dynamics of the vibration energy harvester in the form of electromechanical damping feedbacks.

Results of efficiency analyses and harvested power measurements for all tested devices are presented in Table 4 and in accordance with expectations the best efficiency is achieved with the most sensitive VEH 17 Hz device.

6 Conclusions

The linear analysis of efficiency of vibration energy harvesting systems and efficiency measurement of three developed electromagnetic vibration energy harvesters are presented in this paper. The efficiency of vibration energy harvesting system provides the information about input mechanical and output electrical ratio and this efficiency analysis is defined in this paper. The linear equivalent electrical RCL circuit with electromagnetic converter is used for analyses of individual parameters of vibration energy harvesting systems. Linear equivalent electrical RCL circuits provide the information that electrical energy is mainly wasted in the mechanical damping (parameter of quality factor) and coil resistance (parameters of electro-mechanical converter). Other parameters have minor influence to energy harvesting system efficiency nevertheless these parameters have a significant impact on harvested output power. The output power depends on the seismic mass and operation frequency and furthermore the vibration energy harvester has to operate at maximal output power point. The mass of the harvester frame does not affect the efficiency due to self-oscillation round equilibrium with no energy transfer.

Mechanical vibrations in industry are commonly observed at the lightweight structures like housing and sheathing. This is the reason the lightweight vibration structure with the independent source of vibration was used for

Table 4 Measurement of harvesters with power management circuit bq25504EVM

Energy harvester	Excited frequency (Hz)	Vibration RMS (G)	Charge current (mA)	Output power (mW)	Efficiency (%)
VEH 28 Hz	28.35	0.236	0.87	2.7	15.1
VEH 17 Hz	18.40	0.266	1.1	3.3	23.6
VEH 34 Hz	33.75	0.254	0.78	2.4	13.5

measurements of three vibration energy harvesting devices developed at our department. Two devices influence the vibrating steel beam (the source of vibrations) during energy harvesting while the third one does not. The electrical and mechanical measurements were analysed and the efficiency was calculated. The efficiency of tested electromagnetic energy harvesters without electronics is in the range of 40–47 %. This range depends on the nonlinear quality factor and the level of vibrations. The rectifier and the capacitor decrease the efficiency to the range of about 30–35 %. The maximal power point does not correspond with maximal efficiency and it is shifted to higher resistance of the electrical load. Finally the harvesters were measured with the commercial power management electronics bq25504EVM, reaching the efficiency in the range of about 13–25 %.

In the future we plan a design improvement of new vibration energy harvesters for higher harvested output power while keeping the volume and weight. The presented results are very important for such process. The simulation model of the energy harvesting efficiency can be helpful in this task and other optimization studies (Hadas et al. 2012). The increased harvesting of electrical energy can be calculated by the simulation model. Furthermore the model can predict an undesirable case when the energy harvesting system influences the input vibrations.

Acknowledgments The research leading to these results has received funding from the Ministry of Education, Youth and Sports, Czech Republic under the National Sustainability Programme I (Project LO1202) and additionally it has been funded by the European Commission within the FP7 project "Efficient Systems and Propulsion for Small Aircraft| ESPOSA", Grant Agreement No. ACP1-GA-2011-284859-ESPOSA.

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