POSSIBILITIES OF ENERGY HARVESTING FROM THE SUSPENSION SYSTEM OF THE INTERNAL COMBUSTION ENGINE IN A VEHICLE

Jacek Caban¹*, Grzegorz Litak¹, Bartłomiej Ambrożkiewicz¹, Leszek Gardyński², Paweł Stączek¹, Piotr Wolszczak¹

¹Department of Automation, Faculty of Mechanical Engineering, Lublin University of Technology, Lublin, Poland
²Department of Materials Engineering, Faculty of Mechanical Engineering, Lublin University of Technology, Lublin, Poland

*E-mail of corresponding author: j.caban@pollub.pl

Resume
The automotive industry faces a huge challenge in environmental protection by reducing fossil fuels and energy consumption by developing various practical solutions in energy harvesting. The current analysis is related to the diesel engine power supply system in a passenger off-road vehicle for application of the piezoelectric energy harvesting system. Experimental tests were carried out for the three constant rotational speed values - 800, 1000 and 1500 rpm. The results pertained to operational and simulation tests of available power supply options from the engine suspension system in the vehicle, e.g. to power sensors supervising the engine’s operation or other small electrical devices in the vehicle. The simulations of output voltage were conducted by means of a nonlinear model with a resonator coupled to a piezoelectric elastic beam deformed in the magnetic field to improve the band of frequency transducing kinetic mechanic energy into electric energy.

1 Introduction
Pollution of the environment, replenishment of natural supplies and growth in the volume of waste disturb the equilibrium of the natural environment [1]. In addition, the constantly increasing demand for energy and continuous technical development lead to the search for new solutions in use and recovery of energy from various technical systems. This pursuit occurs in numerous sectors of the economy and various technical facilities. Transportation, which is one of the most important parts of development, also contributes to environmental issues and energy waste [2]. Currently, we are witnessing a huge transformation in the transport and automotive industry. In the automotive industry, one can see enormous progress in development of the new propulsion systems (electric and hybrid) and in improvement of piston internal combustion engines with both spark ignition [3-5] and compression ignition engines [6-7]. Development of fuels alternative to crude oil has become another area. There is an increasing interest in the fuels of vegetable origin (bio-diesel) [1, 8] gas fuels from biogas plants and other, e.g. LPG, CNG [9-10].

As far as internal combustion engines are concerned, development of the fuel supply systems, exhaust purification systems and diagnostic systems has been particularly important. Recently, vibration signal analyses have been heavily used for diagnostic purposes of various engine assemblies and systems, as well as other vehicle systems, e.g. suspension or transmission. Many researchers use methods such as Fourier and Wavelet Transforms [11-14] and Hilbert Transform (HT) [15-16], Recurrence Plots [17], Neural Networks [18] in detecting defects and operational parameters in rotating systems. Authors of [8,19] diagnosed the fuel supply systems using vibration signals are noteworthy. Balytskyi et al. [19] investigated degradation of the lock seal ring based upon the loss of combustion engine working gases. In [11, 20-21], authors used a vibration signal to analyze the technical conditions of gears. In [22-25], authors used analysis of the vibration signals to diagnose the vehicle suspension systems.

Reducing vehicle energy losses is necessary in order to improve fuel economy, reduce emissions, and supply other systems’ power demand [9, 26-28]. In addition to improving engine and powertrain efficiency, one may also harvest energy wasted in vehicles including the recovery of wasted heat energy [24, 29], regenerative braking energy [30] and vibrational energy of shock absorbers [25, 31]. As demonstrated by Abdelkareem et al. [25], an average power of 350 W can be obtained from a medium-sized sedan (using four energy-harvesting dampers) from vehicle vibration stimulated by road irregularities. For larger vehicles the harvestable power can be greater.
Energy recovery in the sector of transportation has become an interesting and increasingly undertaken research topic. Obtaining energy from roads as an innovative way to provide green and renewable energy for the needs of sustainable transport is one of the directions [22]. Technologies, which harvest energy from roadways include piezoelectric-based modules [23, 32], asphalt solar collectors [33], thermolectric systems [34], electromagnetic systems [35] and the solar panels installed in the pavement [36]. Another direction of research is harvesting energy from various components of a vehicle and the internal combustion engine. In this way, previously lost energy can be used to power certain on-board devices or electrical sensors supervising various functions in the vehicle.

The vibration-based energy conversion, termed piezoelectric energy harvesting, has significant advantages when compared to other forms of renewable energy, including the low start-up investment and less complex wiring [37]. The piezoelectric energy harvesting has been identified as a candidate for low-power devices such as portable rechargeable devices [38], wireless electronic devices [39] and sensors [40]. In the considered case, the nonlinear bi-stable resonator with a piezoelectric elastic beam is used. The bi-stable system provides broadband frequency transduction [41-44].

Unlike the small-scale energy-harvesting, such as wireless sensors and electronic devices, systems based on energy harvested from a vehicle’s combustion engine suspension have not been sufficiently investigated. However, there is a space to partially recover energy from the suspension system of the internal combustion engine of a vehicle during its operation. This option was tested for aircraft vibrations in multimodal transport [45]. For this purpose, exploratory tests, based on measurements of vibration and displacement of the diesel engine during its operation, were carried out at three different crankshaft rotational speeds (800, 1000 and 1500 rpm).

In this article the focus is on application of the experimental data as the excitation for the piezoelectric energy harvesting system based on the Duffing oscillator. The remainder of this article is following. In the Section 2, the experimental procedure is described, i.e. the experimental setup, the duty cycle and the measuring circuit. In the Section 3, the information is provided on the bi-stability phenomena, proposed piezoelectric EH system and broadband effect. Next, the output results from simulations, after applying the experimental time series to the mathematical model, are shown. Section 5 summarizes the paper.

2 Materials and Methods

The engine suspension study was conducted on a running diesel engine at selected values of the crankshaft rotational speed (800, 1000 and 1500 rpm) as the most frequently obtained speeds during the standard operation of a vehicle. The subject of the research was the following: a passenger all-terrain vehicle UAZ-31512 (earlier 469B type) with a four-cylinder supercharged diesel engine - 2.5TD with direct injection used in Land Rover Discovery vehicles 200 series.

Despite the green revolution in automotive industry and more and more often application of alternative driving systems, the Diesel engine is still widely used in transportation, industry, agriculture and construction, owing to their high efficiency, reliability and durability [46]. The reason of application of the Diesel engine car in the experiment are relatively high amplitudes of vibrations generated by engine comparing to the gasoline engine [47] and possibility to use the terrain vehicle in off-road having additional natural external source of mechanical vibrations. Nevertheless, the engine operation by different rotational velocities will bring diversified response of energy harvesting system. The tests were carried out for the three rotational speeds on an engine warmed up to
transformed it into voltage and transferred the value to the oscilloscope DSO-2902 256K. The potentiometer transducer was a linear type with 22 kΩ resistance and 0.5% linear tolerance. The diagram of the measurement trajectory of engine-to-body displacement is presented in Figure 2.

The engine’s displacement was measured using a specially constructed arm with a potentiometer which transformed it into voltage and transferred the value to the oscilloscope DSO-2902 256K. The potentiometer transducer was a linear type with 22 kΩ resistance and 0.5% linear tolerance. The diagram of the measurement trajectory of engine-to-body displacement is presented in Figure 2.
POSSIBILITIES OF ENERGY HARVESTING FROM THE SUSPENSION SYSTEM OF THE INTERNAL...

Stanton et al. [47] found the greatest strain profile nearest the equilibrium point obtaining the highest response. Masana et al. [48] showed the advantage of a bi-stable energy harvesting (EH) system over the mono-stable, super-harmonics resonances in that it could activate the inter-well dynamics by even a small amplitude of excitation resulting in higher voltage response. Cottone et al. [49-50] proposed a design of a piezoelectric buckled bridge in which the highest voltage response is in the equilibrium point during the beam compression. In previous works by authors of this paper [51-57], the research focused on a different type of excitations acting on the system with the double-well potential both in mathematical and experimental approaches.

In many studies of vibration energy harvesting mathematical models, the Duffing oscillator, characterized by the double-well potential, is applied. Its equation of motion describes the complex dynamics, but the cubic nonlinearity and properly selected perturbation coefficients bring an advantage in the form of hardening or softening response of the system. This results in wider range of operational frequencies. By combining the piezoelectric coupling with the Duffing oscillator, equation of motion and an addition of the Kirchhoff laws to the circuit with a resistive load, one obtains electromechanical equations describing the system dynamics [41]:

\[
\dot{x} + 2\zeta \dot{x} - \frac{1}{\kappa} x (1 - x^2) - \chi v = F \cos(at),
\]

\[
\nu + \lambda \dot{v} + \kappa v = 0,
\]

where \(x\) is the dimensionless displacement of the beam in the transverse direction, \(\zeta\) is the mechanical damping ratio, \(\chi\) is the dimensionless piezoelectric coupling term in the mechanical equation, \(\nu\) is the dimensionless voltage across the load resistance, \(F\) is the dimensionless excitation force, \(\omega\) is the dimensionless excitation frequency, \(\lambda\) is the reciprocal of the dimensionless time constant, \(\kappa\) is the dimensionless piezoelectric coupling term in the electrical circuit equation. Solution of Equation (1) gives three equilibrium points, saddle point \((x, \dot{x}) = (0, 0)\) and two sinks \((x, \dot{x}) = (\pm 1, 0)\).

In the next section of this paper, with regard to the

Figure 4 Potential energy \(V(x)\) of the system in the Duffing oscillator versus displacement, three equilibrium points creates double-potential well, which is consisting of \(x = -1, 1\) for stable and 0 for unstable equilibria (dimensionless model)

The device scale was selected in such a way that the voltage value corresponded to the appropriate displacement value (1 V = 1.6 mm).

Tests measurements of acceleration in the suspension system were performed by means of the experimental setup (Figure 2). The displacement results of the measurements are presented in Figure 3 using the cyan color. In the next sections an energy harvesting system to transform the kinetic inertial excitation energy into electric power is proposed.

Unfortunately, this data is strongly affected by the measurement noise. Therefore, the initial digital signal processing of the experimental signals using the low pass filter is performed (see black curves in Figure 3). These time series are then applied as the source of excitation in the model. The outcomes of the simulation in form of inertial force courses, phase portraits, voltage response are presented in the next sections.

3 The bi-stable energy harvester based on Duffing oscillator

A greater focus is placed on the non-linear behavior in vibratory energy harvesting (VEH) systems and more attention is paid to the bi-stability phenomenon. Such systems are characterized by double-well potential, in which the tested system can get stuck in one of the two equilibrium points with small amplitude oscillations. Alternatively, it can oscillate with a large amplitude going through the potential barrier. One of the main advantages of this type of energy harvesters is the possibility of improving their performance by adjusting the operational frequency to desirable effect in the form of operational frequency or output voltage/power [41]. The design of the proposed system can represent three types of operating modes, i.e. single-well (intra-well) mode, when the system has the tendency to be stuck in one of the wells, chaotic double-well (inter-well) mode or periodic double-well depending on the excitation [46]. However, the strongest effort is placed on the third mode where the system operates in the periodic double-well mode. This constitutes the most desirable behavior.

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which are also useful for energy harvesting. In such cases, the system passes through the potential barrier in a non-periodic (chaotic) way.

Disadvantages of the bi-stable VEH proposal are based on appearance of multiple coexisting solutions, including the optimum solution, with questionable robustness in the presence of disturbances such as uncertainties in source and system parameters.

4 System parameters and configuration of the energy harvesting system

In this energy harvester design, attached to the engine suspension (Figure 1), one starts from the original equation

\[ m \ddot{z} + c \dot{z} + k z = F'(\tau), \]

where, with respect to the model structure (Figure 5), \( z \) is the displacement of the frame / oscillator / harvester, \( m \) is an effective mass of the first mode beam motion, \( c \), \( k \) are effective damping and nonlinear stiffness coefficient, \( V \) is the voltage output and \( \chi' \) is the coupling parameter, \( F'(\tau) \) is the inertial force \( F' = -m \ddot{y} \) is the kinematic excitation force governed by the engine relative displacement \( y \). We transform this equation to the dimensionless by adjusting the parameters as follows: \( k/m = \Omega^2 \), \( c = \zeta \beta \), where \( \beta = \omega \Omega, \Omega t = \omega t \), (to transform to dimensionless time into the band of [1-4] (see Figure 6)). Finally, the beam tip point \( x \) and voltage \( v \) will be changed to \( x \) and \( v \), with respect to the geometrical, material and electrical properties of the system (to fit Equations (1) and (2)).

The power generator is based on the ferromagnetic beam, two PZT-5A piezo-ceramic layers QP16N are attached

deduction of the bi-stability phenomena occurring in the system, is a broadband effect resulting in higher mean output power obtained in a wider range of operational frequency. In contrast to the linear system, which has only one specific value of frequency in the resonance region, the nonlinear bi-stable system is characterized by a broad frequency band composed of inclined resonances of one and multiple period responses (Figure 6). In calculations the initial conditions: the displacement was fixed to 1.0 (one of minima in the potential) while velocity was selected random for each frequency, and the initial voltage was nodal. Note that the single well linearized natural frequency is fixed to 1.0 (see Equation (1)). These results were obtained using the random initial condition for velocity and 1 for displacement. Similar diagrams were discussed in [43-44, 52]. Note that the sub-harmonic responses with a large voltage output cover a large interval of excitation frequencies. These solutions correspond to the inter-well oscillations of the resonator. On the other hand, the small voltage response is related to the intra-well solutions. Those solutions include non-periodic solutions,
the cases (a)-(c) have been estimated as the second order time derivatives of displacements in Figures 3 (a)-(c), respectively and expressed in dimensionless units.

Figure 7 Inertial force time series from the experimental data (dimensionless model Equations (1)-(2)), the cases (a)-(c) have been estimated as the second order time derivatives of displacements in Figures 3 (a)-(c), respectively and expressed in dimensionless units.

onto both faces of the beam at the root using a high shear strength epoxy. The modulation of permanent magnets is adjustable in order to obtain bi-stable configuration of the system.

5 Numerical simulations and results

In this section are presented results of the numerical modelling of the proposed EH system excited with the signal coming from vibrations generated by a diesel engine during its operation. For the numerical simulations three rotational velocities of the crankshaft are taken to observe the change of the inertial force of the beam in the additional magnetic field, the output voltage response from the piezoelectric, with phase portraits instead. The behavior of the system is presented below.

The experimental signals were obtained by the three different rotational velocities, i.e. \( n = \{800; 1000; 1500\} \) [rpm]. In order to obtain the response in the longer period of time, the signals were multiplied a few times still reflecting the engine operation under one specific rotational velocity. The applied Duffing oscillator works as the filter for the vibration signals. The perturbation parameters in its equation of motion and in the equation of electromechanical coupling are the following \( \zeta = 0.01, \chi = 0.05, \lambda = 0.01, \kappa = 0.5 \) (see Equations (1) and (2)). The external force, as presented in Figure 7, is substituted with experimental signals. For all the considered cases the initial conditions are the same at one of the stable equilibrium points \( (x(0) = 1) \) with the zero initial velocity and voltage.

Regarding the obtained time series of the inertial force-acceleration (Figure 7) it can be stated that the excited beam is getting lumped in the stable equilibrium points. Amplitudes of the inertial force in all the cases are almost the same varying in the frequency. The phase portraits (Figure 8) present the situation when the beam is changing its position from one well to another. As a consequence, the engine's vibrations are able to cause the chaotic movement of the beam by various rotational velocities. It is difficult to interpret the phase portraits at once. However, the output voltage time series of the piezoelectric element in all the cases present strongly non-periodic behavior of the beam. Both the characteristic jumps between the wells and oscillating response are observed in all cases. The highest RMS(V) response (Figure 9) was obtained for \( n = 800 \) [rpm], but all the outputs were similar, namely, 0.25, 0.18 and 0.20 in cases (a-c) of Figure 9, respectively. Despite the similar values of obtained voltage response, the character of time courses differs for each case. In general, one has the multi-
Figure 8 Phase portraits of energy harvesting resonator response excited by the Diesel engine vibrations (dimensionless model)

Figure 9 Voltage response of the piezoelectric beam (dimensionless model). The corresponding root mean square of the voltage outputs, RMS(V), were estimated as a) 0.24, b) 0.18 and c) 0.20, respectively
frequency excitation and obtains the periodic response, when the ferromagnetic beam moves between the potential wells and time intervals of beam stuck in wells. The dimensionless model is proposed for the experimental excitation, but the energy system provides possibility to introduce changes in its design within dimensions of the beam and make the system's response adjustable to supply the connected sensor.

6 Conclusions

The main idea in development of the energy harvesting technologies is to apply own concepts in the real environment. In the present paper, application of a piezoelectric EH system, based on the Duffing oscillator in the diesel engine, is proposed. Random vibrations, generated by the engine, caused the movement of the beam with the tip magnet, by different operational velocities of the crankshaft and application of the nonlinear methods (phase portraits and resonance curve) allowed to observe its displacement between the two potential wells. The chaotic character of the beam movement and strong nonlinearity of the system in different duty cycles show the broadband effect in the system. This means that it can be applied in a wider range of operational frequencies than in the linear system. Simulations of the analytical model demonstrated that even the small magnitude of external excitation and proper initial conditions are able to provide the desirable inter-well behavior of the beam. The nonlinear EH system, based on the Duffing oscillator, can adapt to the different source of vibrations generated by the engine still gaining the energy, which can be possibly later used to power up the low self-powered diagnostics sensors mounted in the engine block. The next step in the research would be to build the prototype of the EH system and test it in the engine block by different duty cycles. Subsequently, the comparable results from the test and the mathematical model would lead to the nonlinear system's optimization in order to reach the maximum output power in the wide range.

Note that the general dimensionless model of the EH is proposed. To design the specific device one should re-examine the properties of the excitation sources (amplitude and frequency of excitation) and scale the size and mass of the resonator accordingly.

In general, not much difference in performance is found in terms of average induced voltage between the applied duty cycles in the experiment; however, this gives the idea to prepare the further research by changing the design of the EH system and perform extended experiment considering not only other rotational velocities but the variable road conditions, as well. The strongly nonlinear behavior of the system also gives another direction of research for applying methods for quantification of nonlinearities in the system. As the energy harvesting technology is still developing, this research presented an opportunity to apply the concept in the real environment.

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VOLUME 23  COMMUNICATIONS   2/2021

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