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Research on the Use of Multifrequency Excitations for Energy Harvesting in a Combustion Engine

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ABSTRACT

Research conducted around the world shows that energy harvesting (EH) systems can be used in contemporary vehicles powered by combustion engines, hybrid or electric motors. Unfortunately, the efficiency of modern combustion engines is only about 40%, the remaining energy is lost and can be recovered to some extent. Therefore, the search is ongoing for systems that will use this part of the energy to power specific systems or micro-sensors installed in the vehicle. The article presents the possibilities of energy harvesting from four main sources in the vehicle: energy during braking, energy from the damping of the vehicle suspension, from the exhaust system and energy from the vibrations of the combustion engine. Based on the analysis of the literature on the presented research of various scientific centres and the author's experiment, it can be concluded that there is a huge potential for obtaining thermal energy from the engine exhaust system and the vehicle suspension system. A field that has not been explored much, but according to the authors also has energy potential, is the recovery of energy generated during vibrations in the suspension of an internal combustion engine in the engine compartment of the vehicle. For the obtained measurement data from the experiments, initial digital processing of the signal was performed using a low-pass filter, then the fast fourier transform (FFT) and the Hilbert-Huang Transformation (HHT) were used. Preliminary research shows the possibility of mounting the energy recovery system in the engine compartment and the potential possibility of obtaining electricity in certain operating states of the combustion engine.

Keywords: diesel engine, electricity consumption, energy harvesting, mechanical vibrations, waste energy.

INTRODUCTION

The great economic progress that has taken place over the last 50 years has resulted in significant demand for energy in many sectors, including the automotive industry, and unfortunately has contributed to the progressive pollution of the natural environment. This progress was visible primarily in technical areas such as: construction and transport infrastructure [1–3], car design and modelling [4–6], technical objects diagnostics [7–10] in materials engineering [11–13], among alloy materials [14–16], hybrid and composite materials [17–20] and polymer materials [21–23]. In addition, great progress has been made in manufacturing techniques [24–27] and in material technology processes [28–31], as well as recycling of various construction materials [32–34]. As a result of these positive changes in technique and technology, there has been enormous economic [35–37] and social growth [38], as well as progress in the field of medicine [39–42]. Unfortunately, this progress has resulted in extensive exploitation of natural resources, environmental pollution and an increase in waste. The main source of environmental pollution turns out to be the transport sector, which plays a very important role in the economic development of each country and at the same time consumes a significant amount of energy in the economy [43–45].

The issue of environmental pollution from the transport sector is the subject of many scientific studies [46–48]. For example [49, 50], examined the scale of heavy metal contamination in areas along Polish expressways and highways. Skrucany and Gnap [47] studied the impact of transport on air pollution in an urban area. Similar studies were also presented by Skrucany et al, [51], indicating an increase in greenhouse gas emissions from the transport sector.

The first driving force behind changes in the transport sector was the fuel crisis of the 1970s. Since then, work has been intensified on various types of alternative fuels, which are still the subject of many scientific studies [52–55]. The search for alternative fuels is related to economic [56, 57] and environmental [58–60], factors and technical aspects [61, 62]. There are many studies in the literature on the emission of basic exhaust components from fuels alternative to gasoline [63–67] or diesel fuel [68–71].

For many reasons, over the last 2 decades, there has been a growing interest in fuels of plant origin (so-called biodiesel) [55], as well as gas fuels, including: liquefied petroleum gas (LPG) [72, 73], compressed natural gas (CNG) [45, 74] or LNG (liquefied natural gas) [75] or methane [76]. Interesting research was presented by Žvirblis et al., [77] in their work on the reliability of a diesel engine when fueled with hydrogenated vegetable oil (HVO) fuel. The various mixtures of HVO and fatty acid esters (FAE) was investigated in work [78]. Many recent scientific works also concern the possibility of hydrogen production [68, 79, 80] its use in public transport [81, 82] and freight [71, 83]. Based on this overview, it is clear that hydrogen obtained from renewable energy sources will be an important fuel in the future.

Recently, the road transport sector has seen a huge development of drive systems for motor vehicles. It is visible mainly in the continuous improvement of the design of internal combustion engines [84–86] and the processes of fuel combustion in the combustion chamber [87–89], also electric motors for vehicle propulsion [90–92] and hybrid systems [93, 94]. Analyzing the above literature, it can be concluded that the future will belong to electric and battery-powered vehicles, and alternative fuels such as HVO or hydrogen will be constantly used.

Machines, vehicle components, steel structures of buildings, etc. usually generate vibrations that can be an excitation signal for piezoelectric energy harvesters (PEH) [95]. The term energy harvesting (EH), or energy recovery in general, can be defined as the process of converting energy from various sources of mechanical vibrations on a small scale [96]. In the automotive industry, the vibroacoustic signal was usually used to diagnose faults in various vehicle components, for example the transmission [97, 98], fuel supply system and load exchange system [99–101] or lower parts of piston engine assemblies [102, 103] and electric motors [104, 105] or vehicle controllers [106]. In the automotive industry, the main direction of research on EH systems is obtaining energy from various vehicle components and the drive unit (mainly the internal combustion engine). One direction in the analysis of the vibration signal is the application of the Fourier series [107].

In addition to improving the overall efficiency of the vehicle's engine and drive system, we can also recover energy lost in vehicles, e.g. by converting waste thermal energy [108–114], regenerative braking energy [115, 116] or vibration energy converted in special shock absorbers from the damping of the vehicle suspension [3, 117–122]. Research attempts are also being made to recover energy from the air flowing around the vehicle while driving [123]. An area that has so far been little explored, but also shows some energy potential, seems to be energy recovery from engine vibrations and its suspension in the engine compartment. The energy recovered from this system can be used to power some low-energy on-board devices or micro-sensors monitoring various vehicle functions. Among the various energy recovery systems, we can distinguish those based on the following four types of converters [124]:

- piezoelectric,
- ferromagnetic materials,
- electromagnetic,
- thermoelectric.

To obtain more positive results for the broadband use of EH, it is proposed to introduce interactions using the nonlinearity effect of the system. This was confirmed in the following research works [125–127]. In the study of the PEH cantilever beam model by Vijayan et al. [128] it was shown that the contact stiffness and clearance have a significant influence on the obtained power output. In turn, in the work [129] it was shown that introducing an impact into the system allows for obtaining a broadband effect, which makes it possible to achieve a two-linear stiffness characteristic, which results in obtaining energy in a wider frequency range. The mentioned PEH project led to the verification of the physical system tested in an experimental environment and in real conditions. In the following research works: [130, 131] and [132], an air stream was used as the external excitation for the PEH system, which allows for a more efficient use of the EH system. In our case, based on related work, we propose a similar utilitarian approach to this problem, with the difference that the excitation of the energy conversion system will be a random signal obtained from vibrations generated by the vehicle's internal combustion engine.

According to the analysis of the literature, many studies of mathematical models of systems used to obtain vibration energy use a Duffing oscillator, whose characteristic feature is the double-well potential. Thanks to it, the equation of motion describes the complex dynamics of the system under consideration, but cubic nonlinearity and appropriately selected disturbance factors benefit from strengthening or softening the system's response. The result is a wider range of operating frequencies. Therefore, by combining the piezoelectric coupling with the Duffing oscillator, the equation of motion and adding Kirchhoff's laws to the circuit with a resistive load, the electromechanical equations describing the dynamics of the system are obtained [133]:

$$\ddot{x} + 2\zeta\dot{x} - \frac{1}{2}x(1 - x^2) - \chi v = F\cos(\omega t) \quad (1)$$

$$v + \lambda\dot{v} + \kappa\dot{x} = 0 \quad (2)$$

where: x – the dimensionless displacement of the beam in the transverse direction, ζ – the mechanical damping ratio, χ – the dimensionless piezoelectric coupling term in the mechanical equation, v – the dimensionless voltage across the load resistance, F – the dimensionless excitation force, ω – the dimensionless excitation frequency, λ – the reciprocal of the dimensionless time constant, κ – 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 $(x, \dot{x}) = (\pm 1, 0)$.

Based on Equations 1 and 2, calculations of the voltage response were made, and their results are shown in Figure 1.

The effective value root mean square (RMS) of the output voltage from the considered system is plotted as a function of the excitation frequency (angular). In turn, in a nonlinear problem, additional subharmonics are created as a result of the impact (multiple solutions). The calculations are carried out in such a way that different initial conditions correspond to each angular frequency $(x, \dot{x}, v) = (0, \sigma, 0)$, where σ is a random number uniformly distributed in the interval (-1, 1).

A wide frequency band was observed near the linear frequency resonance $\omega0 = 1$ and additionally in the range $\omega \epsilon (2, 3)$, and the resonance curve is strongly inclined to higher frequencies. At the same time, the total amplitude of the excitation is proportional to the square of the excitation frequency, thus causing an increase in the inertial force acting on the considered beam (Equation 1). Moreover, the width is much greater compared to the linear resonance. In turn, in the area of $\omega \epsilon (1.2, 1.5)$ two solutions coexist, including resonant and non-resonant. A solution without resonance is a solution without impact. The situation is similar at higher frequencies, $\omega \epsilon (2, 3)$, where the appropriate resonance solutions are driven by the subharmonic resonance [134–136]. Both resonance solutions, the main harmonic and the subharmonic, create the so-called broadband effect in the considered EH system.

In this article, we focus on the use of random vibrations generated by a diesel engine in a PEH cantilever beam system with an amplitude limiter. The use of interactions in the operating

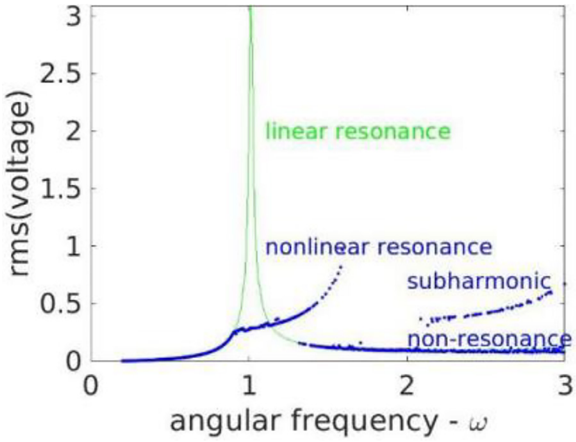

Figure 1. Comparison of two cases of resonance curves of the EH system: linear system (green line), non-linear system (blue line)

system results in a broadband effect, then the lost energy recovery system can operate in a wider range of excitation frequencies. The use of multi-frequency excitations to obtain energy from a running combustion engine is a field that has not been explored much, but it has some energy potential. Experimental research on the vibration spectrum of an off-road vehicle engine was carried out at ambient temperature in the laboratory of the Department of Automation of the Lublin University of Technology.

METHODOLOGY

Experimental tests were carried out on an off-road vehicle UAZ-31512 (formerly type 469 B), with a four-cylinder turbocharged compression-ignition engine with direct fuel injection - 2.5 TD, used as standard in Land Rover Discovery 200 series vehicles. The location of the main elements of the measurement track in the vehicle's engine compartment is shown in Figure 2. The block diagram of measuring circuit with the tested engine is shown in Figure 3.

The engine vibrations from its suspension were carried out on the working diesel engine at the rotational speed of the crankshaft amounting to 1000 rpm. This value of the engine speed is the most frequently obtained speed during the standard operation of a vehicle. The displacement measured using the potentiometer was then converted into voltage and transmitted to the DSO-902 256K oscilloscope. The tests used an A-linear potentiometer with a resistance of 22 kΩ and a linear tolerance of 0.5%. The potentiometer on the vehicle was mounted 540 mm above the engine crankshaft. The potentiometer was scaled so that a displacement of 1.6 mm corresponds to a voltage response of 1 V. In order to ensure proper registration and visualization of the obtained displacement signal, the potentiometer was connected to an oscilloscope and a PC with appropriate software. The best place to install the EH system is the engine block because it is where the pure vibrations of the running engine occur.

The obtained measurement data from the experiments due to the measurement noise occurring, preliminary digital signal processing with the use of a low-pass filter was applied. The results of this analysis in 1000 rpm are shown in Figure 4 (see black curves).

These time series are then used as the excitation source in the model. The following chapter present the simulation results and discussion of the obtain results.

SIMULATION RESULTS AND DISCUSSION

This part presents the obtained simulation test results. Typically, the experimental

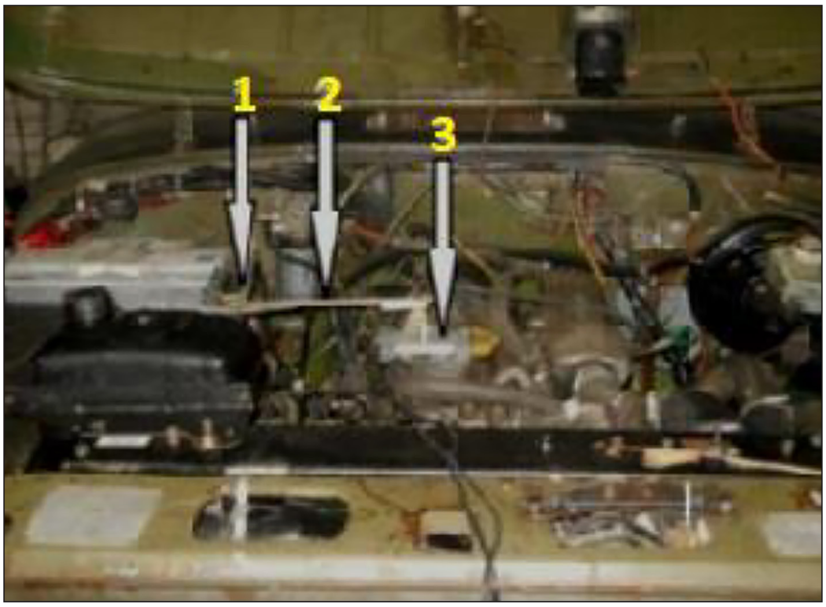

Figure 2. The measuring system mounted on the vehicle, consisting of 1 – clamping arm, 2 – potentiometer arm, 3 – linear potentiometer

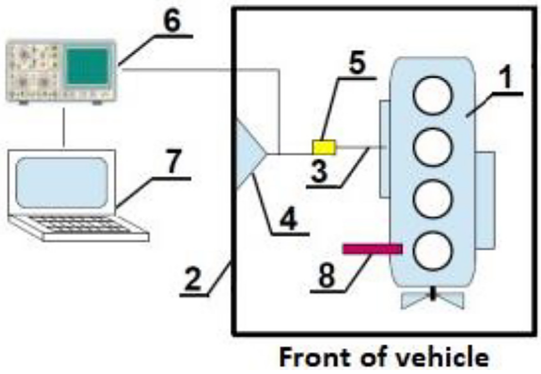

Figure 3. The measuring circuit and mounted EH system: 1 – 2.5TD Diesel engine, 2 – body of the tested vehicle, 3 – potentiometer arm, 4 – supporting structure, 5 – linear potentiometer, 6 – oscilloscope, 7 – computer with data recording software, 8 – PEH mounted on the engine head

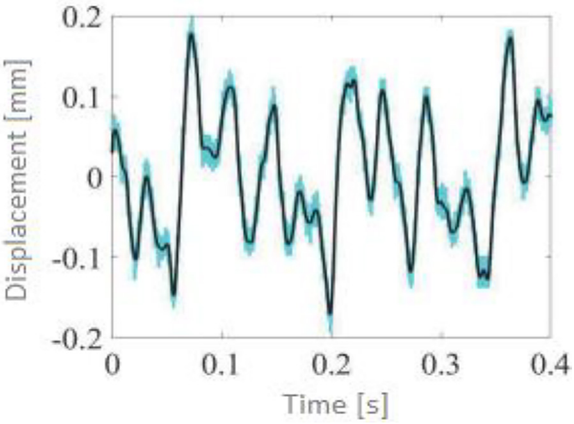

Figure 4. The raw signal (blue) recorded during the rotation of the car engine at the speed of 1000 rpm and low-pass filtered signal (black)

signals are highly non-linear, and the use of the Hilbert-Huang (HHT) transformation allows to extract the characteristic modes of the raw signal. The Fast Fourier Transform (FFT) is a tool that helps identify characteristic frequencies found in vibration spectra. Figure 5 shows the analysis of the engine vibration frequency (displacement time series) of the signal components – left graph: distribution of empirical modes, right graph: FFT of the raw signal and empirical modes in the case of an engine crankshaft speed of 1000 rpm.

The raw signal consists of six modes, and its number is determined by the signal recording period. The analysis shows that there are many higher harmonics in the experimental signal. However, some of them have measurement errors that cannot be used to estimate the inertia force F(t) specified in the equation.

Taking advantage of the repeatability of the measured signal, it was continued for a longer period of time and then fitted to the dimensionless model of Equations 1 and 2. In the case of the inertia force, it is calculated as the second-order derivative of the engine displacement signal relative to the vehicle body (Fig. 6). On the basis of the obtained inertia-acceleration force time series (Fig. 6), it can be concluded that the excited beam becomes concentrated at points of stable equilibrium. The amplitudes of the inertia force in all cases are almost the same, changing the frequency. Figure 7 shows a phase portrait in which the beam changes its position from one well to

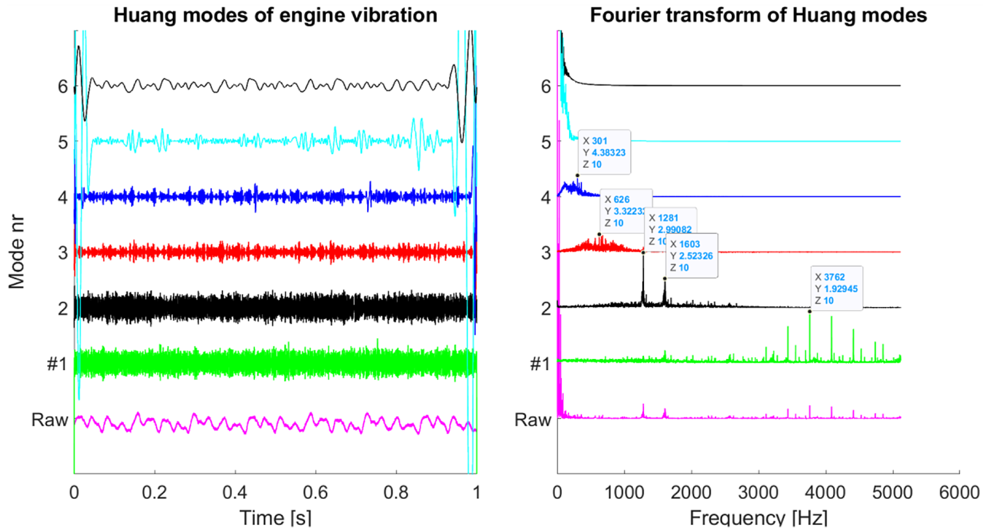

Figure 5. Engine vibration frequency analysis (at 1000 rpm), distribution of empirical modes (left) and FFT of the raw signal and empirical modes (right)

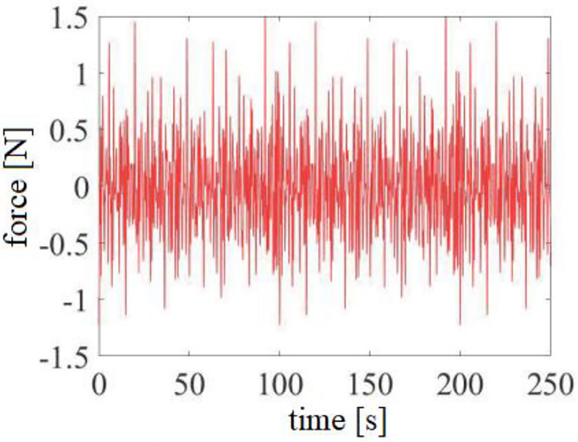

Figure 6. Time series of inertial force from experimental data (dimensionless model of Equation 1 and 2), (at 1000 rpm)

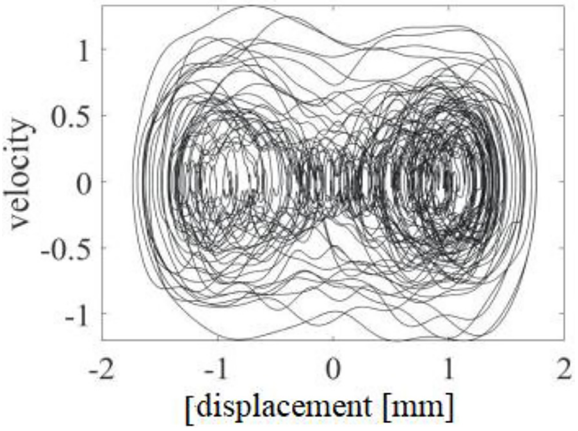

Figure 7. The phase portraits of EH resonator (dimensionless model)

another. As a consequence, engine vibrations may cause chaotic movement of the boom when the rotational speed changes, which is especially common in urban traffic or in off-road conditions. The phase portraits are difficult to interpret right away. In contrast, the time series of the output voltage of the piezoelectric element presents a strongly non-periodic behaviour of the beam. Both the characteristic jumps between the wells and the oscillating reaction.

The Figure 8 shows a phase portrait of the displacement and velocity of the vibration sensor (cylinder head cover). In real conditions, spiral densities form clusters (wells) in several places of the displacement axis, while in the model two clusters are revealed (Figure 7). The displacement of the wells is caused by external disturbances of the experimental system because the measurements were made while driving an off-road vehicle. Figure 8 shows empirical phase portraits of the response of the energy-collecting resonator excited by the vibrations of the 2.5TD engine of the tested vehicle at a crankshaft speed of 1000 rpm. Figure 9 shows the RMS (V) response for n = 1000 rpm, it was 0.18. The waveform also shows the potential ranges around -0.5 V and 0.5 V (adequately 0.8 mm and 0.8 mm).

In summary, we are dealing with multi-frequency excitation and a periodic response is obtained when the ferromagnetic beam moves between the potential wells as well as at time intervals of the beam stuck in the wells. In this study, a dimensionless model was proposed for the experimental excitation. In turn, the energy system provides the possibility of introducing changes to its structure in terms of beam dimensions, which will enable the regulation of the system's response to the power supply of the connected sensor. Multistable PEH configurations have two important features, firstly, broadband frequency response, secondly, large orbital oscillations, which in turn exhibit periodic, multiperiod and chaotic solutions [137].

Depending on the size of the engine and the type of vehicle or other device powered by an internal combustion engine, the generated vibrations may have different energy potential. Even though other vehicle systems provide better energy recovery results (Thermoelectric Generators in exhaust systems, shock absorbers with EH), it is worth paying attention to the engine vibrations themselves. The combustion engine generates vibrations regardless of the type of object it drives and has different energy potential. The vibration energy will be different in passenger cars and trucks, agricultural machines (tractors, combines, etc.), and construction machines. In the case of the latter, vibrations may be generated not only by the engine – drive unit, but also by executive – working elements, such as, for example, an excavator arm or mining heads in crushers. In this particular type of machines, you can also find inspiration for a new direction of research, i.e. obtaining energy from vibrations caused in the actuating elements of machines. As shown on the basis of the literature included in this article, mechanical vibrations can be a good carrier of information about the technical condition of the combustion engine and the drive unit, but they also have energy potential.

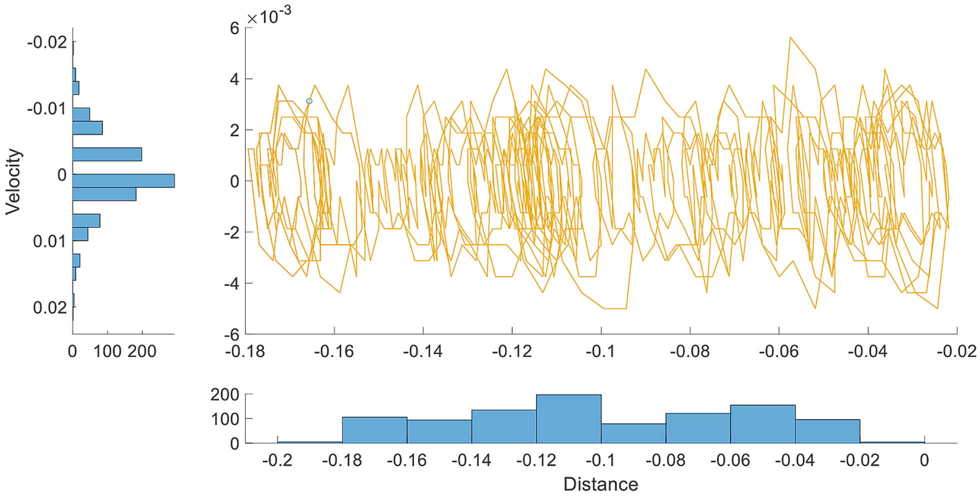

Figure 8. The empiric phase portraits of EH resonator (at 1000 rpm)

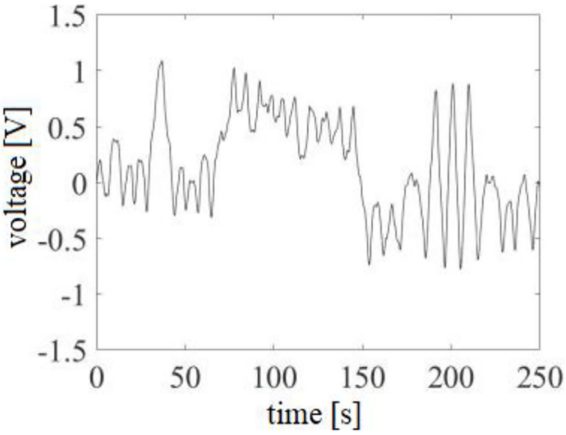

Figure 9. The RMS of the piezoelectric beam in volts (dimensionless model)

CONCLUSIONS

The article presents an analysis using vibratory, PEH, which uses experimental multi-frequency excitations from a 2.5TD compression ignition engine in an off-road vehicle. The main purpose of the work was to present the possibility of recovering energy generated during vibrations from the suspension of an internal combustion engine in the engine compartment of a motor vehicle. It turned out that the introduction of an amplitude limiter to the system had a positive effect on its dynamic characteristics. The use of experimental multi-frequency vibrations improved the broadband effect of the system because it was found that the presence of subharmonic branches could be more easily induced in the resonance curve (see Figure 1, blue line). The chaotic nature of the beam motion and the strong nonlinearity of the system in the engine operating cycle indicate a broadband effect throughout the system. Which means that it can be used in a wider range of operating frequencies than in the case of a linear system. The nonlinear EH system, based on the Duffing oscillator, has the ability to adapt to various sources of vibrations generated by the internal combustion engine, which continues to obtain energy, which can later be used to power diagnostic sensors with low self-power, mounted e.g. in the engine block.

In this study, a general dimensionless model for the system for obtaining energy from vibrations of an internal combustion engine is proposed. To design a specific energy harvesting device, the properties of the excitation sources, such as the excitation amplitude and frequency, must be re-examined and the size and mass of the resonator used must be scaled accordingly. In the next stage of research, a prototype of the EH system should be built and tested in the engine block at various work cycles. In this way, the results from the experiment and the mathematical model can be compared further, which would lead to the optimization of the non-linear system in order to achieve the maximum output power in a wide range of the given system.

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