

SIMULATIONS OF PIEZOELECTRIC ENERGY HARVESTING SYSTEM FOR DIESEL ENGINE

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Abstract. The ever-increasing demand for energy, particularly in the transportation sector, is leading to the search for new solutions for more efficient energy use or alternative sources. Currently, there is significant development in drive systems, including hybrid and electric systems, as well as piston combustion engines. Reducing energy losses in transportation stems from the desire to save fuel and reduce harmful emissions, but also to meet the needs of other vehicle systems with electricity. The recovery of energy lost in vehicles depends on the method used for its conversion and can include thermal energy generated from combustion engine exhaust systems or the cooling system, regenerative braking energy, or ground vibration damping energy in the suspension system. Another research direction is energy harvesting from combustion engine vibrations, but interest in this research area is less significant than in the previously mentioned systems. In this paper, we focus on investigating a piezoelectric energy harvesting system (PEH's) mounted on a steel beam and excited by the vibrations of a compression-ignition engine. A beam with a piezoelectric energy harvesting system was installed perpendicular to the axis of the combustion engine in the vehicle's engine compartment. The input data for the numerical study were the results of experimental tests conducted on a compression-ignition combustion engine. Modelling tests were conducted using Matlab/Simulink software. This model allows us to predict the behaviour of the piezoelectric energy harvesting system due to vibrations generated by the engine. Based on this model, the energy yield from the system can be determined under various engine operating conditions related to vehicle operation. This work constitutes a preliminary step towards further research on the PEH system in a vehicle operating environment similar to the Worldwide Harmonised Light Vehicle Test Procedure (WLTP) test.

Keywords: diesel engine, energy harvesting, engine vibration, piezoelectric harvester, numerical modelling.

Introduction

The constantly growing demand for energy, especially in the transport sector, leads to the search for new solutions for more efficient use or alternative sources. Therefore, there is a huge development of drive systems, including hybrid systems [1; 2] or fully electric [3-5] not forgetting the continuous improvement of internal combustion piston engines [6-8]. A very large area of activity is the development of alternative fuels for internal combustion engines [9; 10], including fuels of plant and animal origin (first and second generation biodiesel) [11; 12], gaseous fuels such as LPG (Liquefied Petroleum Gas) [13-15] or CNG (Compressed Natural Gas) [16-18], which is popular in Poland, and increasingly LNG [19; 20] or hydrogen [21-23].

Another very important direction is the development of vehicle emission reduction systems. For this purpose, the efficiency of fuel supply systems is improved, and modern exhaust gas treatment systems are developed and introduced [24-26]. For diagnostic purposes of various vehicle assemblies and engine systems, vibration signal analysis is used. Many researchers use methods such as Fourier and wavelet transforms [27; 28] and Hilbert transform (HT) [29; 30], recurrence graphs, or analyses using artificial neural networks [31-33] to detect faults and operating parameters of machine parts and engines [34].

The main goal of reducing energy losses is to save fuel and reduce harmful emissions [35; 36]. The recovery of energy lost in vehicles depends on the method used for its processing and may include thermal energy from combustion engines [37; 38], regenerative braking energy [39; 40], and ground vibration damping energy in the suspension system [41-43]. There are several alternative methods for recovering waste heat energy in combustion engines [44], and one of the technologies currently being developed is thermoelectric generators (TEG). TEG modules are typically placed in the engine exhaust system, using the exhaust gas as a heat source and outside air [37] or cooling system water as a heat sink [45]. One of the biggest advantages of hybrid and electric vehicles is their function of regenerating braking energy [46], which allows them to increase energy efficiency [39; 47]. This system allows hybrid vehicles to reduce fuel consumption, extend their electric driving range, and also reduce exhaust emissions [48]. In the case of a suspension system, energy harvesting can range from several tens to several hundred watts depending on the vehicle type and the type of the road on which it is driven, which

constitutes a significant share of the vehicle's electricity demand. An interesting research direction is energy harvesting from combustion engine vibrations [35; 49-51], but this area is less explored.

As is known, a diesel engine is characterized by relatively high vibration amplitudes compared to a spark-ignition engine, which gives it slightly greater energy processing capabilities. Diesel engines are used in many larger vehicles, such as vans, trucks, tractor-trailers, buses, agricultural tractors, and construction machinery. This work focused on investigating a piezoelectric energy harvester driven by vibrations from an internal combustion engine installed in an off-road vehicle. Preliminary numerical studies were conducted using the Matlab/Simulink environment.

Materials and methods

Experimental studies were conducted on a four-cylinder 2.5TD direct-injection diesel engine installed in a UAZ-31512 off-road vehicle. The engine was sourced from a Land Rover Discovery 200 series vehicle, and its main specifications are shown in Table 1.

Table 1

Engine main technical data [52]

No.	Engine parameter	Value and unite, type
1	Configuration	In line 4 cylinder
2	Displacement	2,495 cc
3	Cylinder bore/piston stroke	90.47 mm/97 mm
4	Cylinder block material	Cast iron
5	Cylinder head material	Aluminium alloy
6	Compression ratio	19.0:1
7	Power	81 kW at 3,900 rpm
8	Torque	255 Nm at 1,800 rpm
9	Turbocharger	Garrett T2

The tests were conducted with the engine warmed up to normal operating temperature at constant crankshaft speeds of 800 and 1000 rpm. The measurement system (Fig. 1) consisted of a specially designed arm with a potentiometer that converted the voltage and transmitted the value to a DSO-2902 256K oscilloscope. The potentiometer transducer was of the A-linear type with a resistance of 22 k Ω and a linear tolerance of 0.5%. A steel beam with two QP15N piezoelectric generators was mounted to the vehicle frame in the engine compartment.

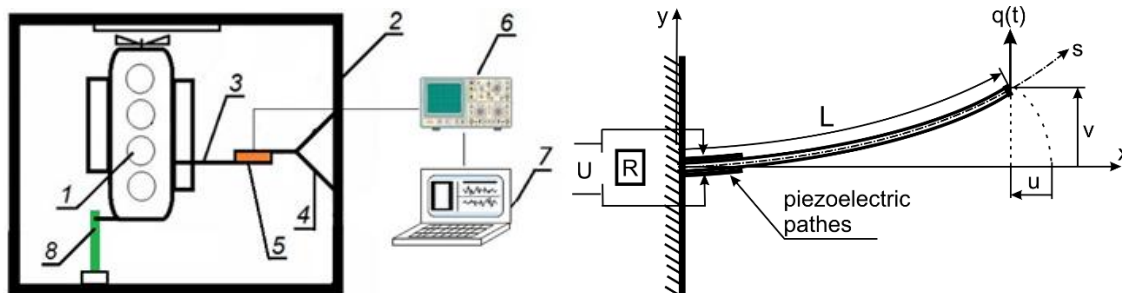


Fig. 1. Diagram of the measurement system in the engine compartment, and PEH scheme:

1 – combustion engine; 2 – vehicle body; 3 – potentiometer arm; 4 – potentiometer mounting element; 5 – potentiometer; 6 – oscilloscope; 7 – recording computer; 8 – PEH's

The proposed system can be divided into an electrical part (PE with external electrical circuits) and a mechanical part with a cantilever beam [53; 54], forced by the displacement of the motor. The Lagrange method was used to derive the equation of motion of the piezoelectric beam system (equation 1):

$$\frac{d}{dt} \left(\frac{\partial L}{\partial \dot{v}} \right) - \frac{\partial L}{\partial v} = 0, \quad (1)$$

where $L = T - \Pi$ is the Lagrangian;
 T – kinetic energy of the system;

Π – potential energy;

v – deflection mm.

Corresponding parts of Eq. (1):

$$T = \frac{1}{2} \rho A \int_0^L [u_p(s,t)^2 + v_p(s,t)^2] ds,$$

$$\Pi = \frac{1}{2} EI \int_0^L \kappa(s,t)^2 ds. \quad (2)$$

The symbols appearing in the energy expressions are defined as follows: ρ denotes the mass density of the beam, A is the cross-sectional area of the beam, $\kappa(s,t)$ is the curvature of the beam and the term EI denotes the flexural rigidity of the beam, N_{1-3} are constants dependent on the shape function. After introducing Eq. (2) into Eq. (1), the equations of the beam motion and electrical current become:

$$\rho A(N_1 + N_2 v^2) \ddot{v} + \rho A N_2 v \dot{v}^2 + \beta \dot{v} + E I N_3 v - D_1 U = q,$$

$$C_p \dot{U} + \frac{U}{R} + D_1 \dot{v} = 0. \quad (3)$$

Here in Eq. (3), R denotes the load resistance, C_p is the capacitance of the piezoelectric patches, and U represents the voltage across the load resistor connected to the patches. The beam is fitted with piezoelectric patches that are connected in parallel. To couple the mechanical and electrical subsystems, the electromechanical constant D_1 is introduced.

Results and discussion

Figs. 2-3 show the results of experimental tests of the engine displacement as an element forcing the PEH beam for 800 rpm and 1000 rpm, respectively.

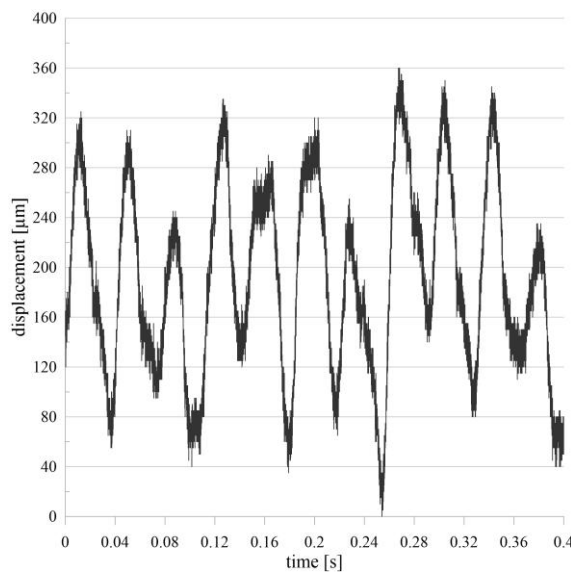


Fig. 2. Displacement at 800 rpm

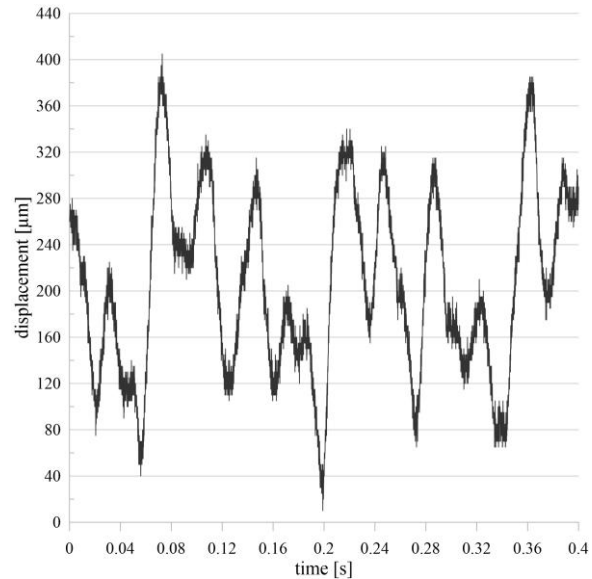


Fig. 3. Displacement at 1000 rpm

Figs 4-5 present data obtained from numerical simulations corresponding to specific engine speeds. The engine model was not simulated as a separate module in Matlab, but only took into account the output data in the form of excitation caused by the engine displacement and the impact on the PEH cantilever beam. As it can be seen, time courses plotted for a time range of 0.4 s based on experiments and simulations are in a good agreement and correspond well. This proves that the model applied was prepared properly and could form the basis for further investigation. Results of simulations for the PEH system are given in Table 2. Voltage emitted by piezoelectric elements as well as the corresponding instant power were registered. It was conducted based on simulated motor deflections forcing the PEH

beam which finally resulted in the PEH system response. Significant differences were observed for different rotational speeds of the motor.

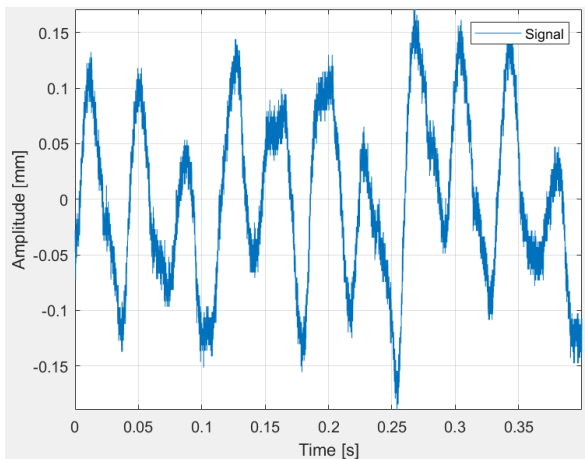


Fig. 4. Simulated result at 800 rpm

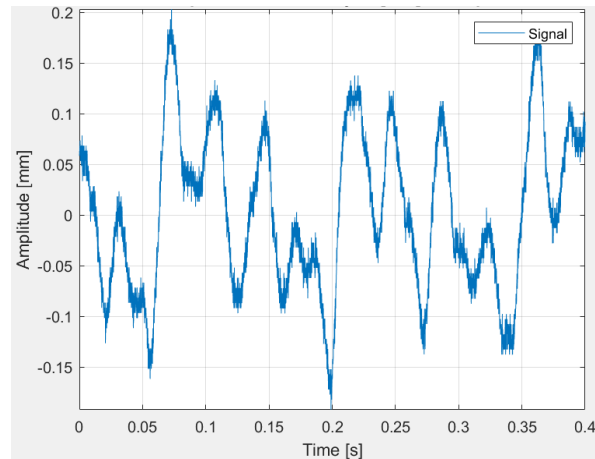


Fig. 5. Simulated result at 1000 rpm

Table 2

Simulation results for the investigated PEH system

Speed of motor	Voltage	Instant power
800 rpm	0.55 V	1.25 μ W
1000 rpm	1.30 V	6.80 μ W

Better piezoelectric performance was observed in the case of 1000 rpm than 800 rpm. This was found interesting because in general higher rotational speed of the motor relates to improved refinement of the diesel engine and lower beam deflections. Therefore, PEH performance is not related to the speed of the motor in that way. Moreover, displacement plots presented in Figures 2-5 show that in the case of 1000 rpm signals actually seem to be more regular. However, single peaks for both cases are at a comparable level. Furthermore, at a higher speed of the motor the cantilever beam probably moved faster which resulted in better performance of the piezoelectric element. In the case of 1000 rpm the PEH voltage registered was over two times greater than in the case of 800 rpm, 1.30 V comparing to 0.55 V, respectively. This influences the instant power results. Hence, the power registered for 800 rpm was equal to 1.25 μ W whereas the power registered for 1000 rpm was a few times higher and equalled 6.80 μ W. It can be concluded that increasing the speed by 25% resulted in significant improvement of the PEH system performance.

The goal of further research could be investigation of PEH performance at speeds higher than 1000 rpm. An engine speed of around 1000 rpm is often the idle speed for small stationary engines or generators [55-57] or maritime engines [58]. Further research at higher speeds could provide new data to determine its impact on the PEH system efficiency. Furthermore, further road testing using driving cycles, such as WLTP (Worldwide Harmonised Light Vehicle Test Procedure), is warranted.

Conclusions

1. This study analyzed the application of a PEH system driven by vibrations from an off-road vehicle’s internal combustion engine.
2. It is possible to use a simple energy harvesting system in a motor vehicle driven by vibrations from its engine.
3. In the case of 1000 rpm, a higher piezoelectric performance level was registered than in the case of 800 rpm, even though improved operating refinement of the diesel engine where engine displacements and therefore the excitation forces acting on the cantilever beam are smaller. However, higher speed of a beam probably resulted in better performance of the PEH system in that specific case.
4. Continuation of research will consist in further improvement of the system towards increasing the recovered energy and in mapping the operation of the system in one of the vehicle operating cycles,

e.g. WLTP. In addition, other speeds of the motor could be considered to investigate if higher values will result in continuous improvement of the PEH performance.

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Author contributions

Conceptualization, J.C.; methodology, J.C. and J.S.; software, M.W.; validation, J.S. and P.J.; formal analysis, J.C. and J.S.; investigation, J.C.; data curation, J.C. and M.W.; writing – original draft preparation, J.C., J.S., M.W. and P.J.; writing – review and editing, J.C., J.S. and P.J.; visualization, P.J.; project administration, J.C.; funding acquisition, J.C. All authors have read and agreed to the published version of the manuscript.

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