TECHNOLOGIES OF USING ENERGY HARVESTING SYSTEMS IN MOTOR VEHICLES – ENERGY FROM SUSPENSION SYSTEM

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Abstract. The automotive sector is characterized by a high energy demand related to the use of fuels and maintenance of vehicles in technical readiness. Currently, more and more often solutions are sought that will save energy and cause less losses in the so-called wasted energy. Most of the energy, about 60%, generated from internal combustion engines is dissipated despite the constant efforts of engine manufacturers to improve their economic and ecological properties. In addition, energy is generated in road vehicles from other components, e.g., the suspension system. As a result, systems are being sought to recover some of this energy to power certain sensors and vehicle systems. This study presents energy recovery systems in road vehicles. Based on a literature study of the presented research of various research centres, it was noticed that there is a huge potential in the recovery of energy lost in the vehicle suspension systems. Research shows that it is possible to obtain a regenerative power value of several hundred watts, which depends on the type of vehicle and the road type on which the vehicle is traveling. An area that has been little explored, but also has energy potential, is the recovery of energy from the internal combustion engine suspension system in the engine compartment. This article presents technological solutions for the energy harvesting from the vehicle suspension system and preliminary studies of the potential energy recovery from the suspension of the 4-cylinder in-line diesel engine in an off-road vehicle. It is also important that energy recovery systems have application potential in traditional vehicles powered by internal combustion engines, as well as modern vehicles with hybrid or electric drive.

Keywords: vibration energy, wasted energy, micro sensors, road vehicles.

Introduction

The constantly growing volume of transport performance of individual road transport and the high concentration of transport in general have a very negative effect on environmental pollution and humanity as a whole [1]. Besides, road transport carries certain risks, the most important of which are road accidents [2], the phenomenon of transport congestion [3; 4], noise [5] and exhaust emissions to the environment [6-8]. The transport sector consumes a significant amount of energy and is at the same time a major source of environmental pollution [9]. The energy intensity of transport is a current topic worldwide. The use of alternative fuels is one of the main solutions currently allowing the reduction of pollutant emissions [10]. Literature information on the subject of the research of various alternative fuels was found, e.g., in [11-15], and about reduction in the consumption of lubricating oils and plastic lubricants [16; 17]. Among others, for economic and rural development reasons, there is a growing interest in plant-derived fuels (biodiesel) [18-20] and LPG or CNG gas fuels [9; 10; 15; 21; 22]. The automotive industry is currently undergoing a huge transformation related to the development of new propulsion systems (hybrid and electric), while improving internal combustion engines [23-29]. From a local point of view, the operation of electric vehicles can be considered environmentally friendly, since the operation itself does not produce GHG [26]. Electric car does not supply all the electric energy obtained from the electric network to the wheels in the form of mechanical energy [25]. Unfortunately, during such transformation, a part of this energy is lost, similar to a hybrid system. Nevertheless, it seems that, globally, hybrid and electric drives are more environmentally friendly than internal combustion engines.

The development of piston internal combustion engines manifests itself particularly in the improvement of fuel supply systems [27], exhaust gas treatment systems and diagnostic systems (OBD and OBDII) [30]. Many researchers use methods of vibration signal analysis, such as Fourier transform and wavelet transform [31; 32], and the Hilbert transform [33; 34], or neural networks [35] for detecting defects in rotating systems. In the works [31; 32; 36], a vibration signal was used to analyse the technical condition of the gears of the transmission. In turn, in [37; 38; 39] such signals were used in the diagnostics of vehicle suspension systems. Safety, handling and road stability are guaranteed by appropriate vehicle suspension, consisting of a springing element and a damping element [40].

The automotive sector is characterized by a high energy demand related to the use of fuels and maintenance of vehicles in technical readiness. Therefore, reducing energy losses in individual vehicles

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and the entire transport sector is becoming imperative. For this reason, more and more attention is paid to the management of energy wasted in motor vehicles. It can be thermal energy [41; 42], regenerative braking energy [23; 43; 44], from suspension system or little used vibration energy coming from the suspension of the internal combustion engine [45]. Energy harvesting is a process of capturing these small amounts of wasted or by product energy, which otherwise gets lost and converting it into useful electrical energy [46].

In this article, on the basis of a literature study, possibilities of the damped recovery energy from the vehicle suspension system and combustion engine suspension system are presented. The paper presents preliminary test results for an off-road vehicle powered by a 4-cylinder in-line diesel engine.

Research directions – review of solutions and discussion

Vibration-based energy conversion, called piezoelectric harvesting, has significant advantages over other forms of renewable energy, including low initial investment and less complicated wiring [47]. Piezoelectric energy harvesting has been identified as a candidate for low power devices, such as portable charging devices [48], wireless electronic devices [49] and various types of sensors [50]. Wireless sensors include, e.g., strain gauges, accelerometers and thermocouples equipped with radio transmitting electronics [51]. The recovered energy can be used to power some on-board equipment or electrical sensors that monitor various functions in the vehicle.

Simultaneously with the development of energy management technology in the drive system [52] and braking energy recovery [53] in application, more and more attention is paid to the technology of harvesting energy from vehicle suspension vibrations [54; 55], since only 12–30% of fuel energy is used to drive the car to overcome the resistance from road friction and air drag [56], and one major loss is vibration dissipation in the shock absorber [37]. As demonstrated by Zuo and Zhang [57], 100-400 W average power is available from the suspension at 96.5 km/h on B and C class roads for a middle-sized vehicle. According to Zhang et al. [58], based on the Audi AG tests, it is possible to obtain an average power of approx. 150 W. For a passenger car driving on newly paved German highways, it is 3 W, while 613 W, on a rugged country road. Li et al., [59] show that a maximum of 248.8 W instantaneous power with a mean of 114.1 W can be harvested and a maximum of 38.81% energy harvesting efficiency can be achieved using the optimal load resistance (7.5 Ω) at a harmonic excitation with the amplitude of 8 mm and the frequency of 2 Hz. In automobiles, harvesting the dissipated kinetic energy during the damping events could provide fuel saving by 2–10% of the total automobile fuelling [38]. Fig. 1 shows the fuel saving possibilities as a result of harvesting the kinetic energy during vehicle damping events.

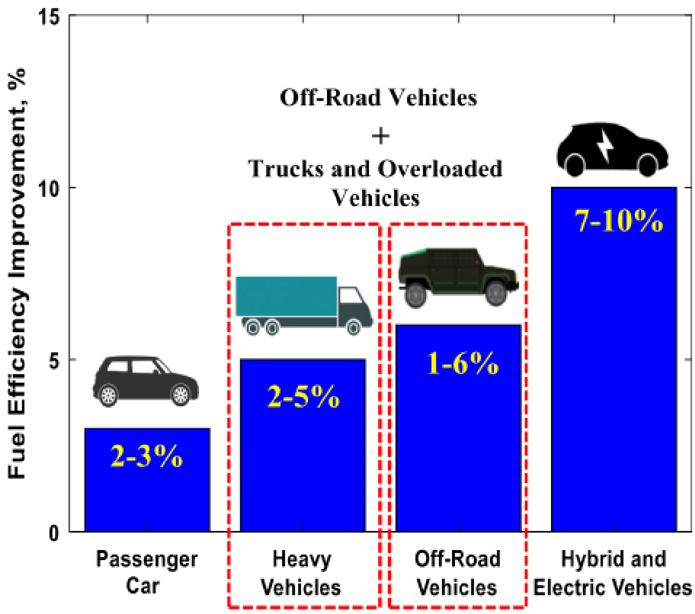

Fig. 1. **Fuel saving from energy-harvesting during vehicle damping events [38; 60]**

As shown in Fig. 1, off-road vehicles, heavy trucks and heavy duty vehicles have a greater potential for fuel savings of up to 6%, while passenger cars may show lower savings to 3%. This is due to higher levels of vibration intensity. Therefore, the energy recovery systems should primarily be of interest to fleet customers.

The key element that converts vibration energy into electricity is the energy receiving shock absorber. It mainly contains two components: energy conversion (a linear or rotary electric motor) and transmission devices (from reciprocation to rotation) [58]. Accordingly, the vibration energy flows into the suspension making the damper moves vertically up and down sequentially. The electrical power could be generated out of these perpendicular oscillations directly by the linear electromagnetic harvesters, or indirectly by the rotary electromagnetic harvesters [54]. The general layout of different electromagnetic regenerative dampers is shown in Fig. 2.

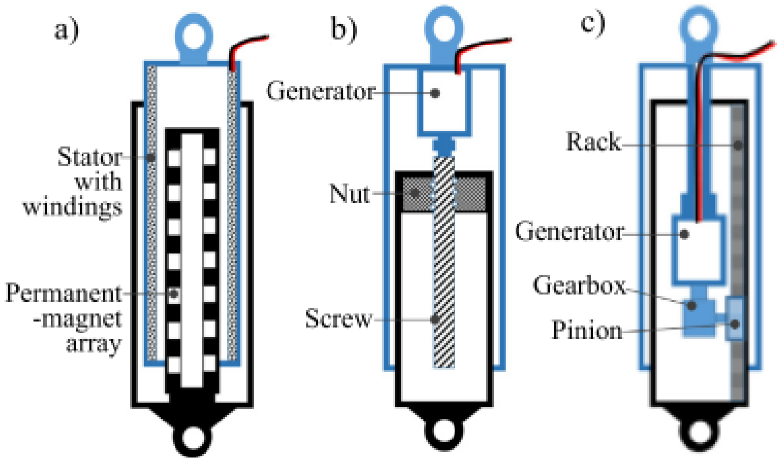

Fig. 2. **General layout of different electromagnetic regenerative dampers [58]:**
a – linear motor; b – ball screw; c – rack-pinion

Zhang et al. [58], obtained an average regenerative power of 110.6 W, used the electro-hydraulic energy harvesting damper on off-road vehicles. However, they showed that a compromise is necessary between energy harvesting and the damping characteristics of a shock absorber. The work of Li et al. [37] presented the design of the energy-receiving shock absorber and optimization of the control circuit, as shown in Fig. 3. The shock absorber architecture mainly consists of a motor and a ball-screw, which is used to convert vibrations between the vehicle body and chassis into rotary motion of the motor. The electric motor acts as a generator to convert the kinetic energy of the suspension into electric energy stored in a battery for further usage, while providing a damping force [37].

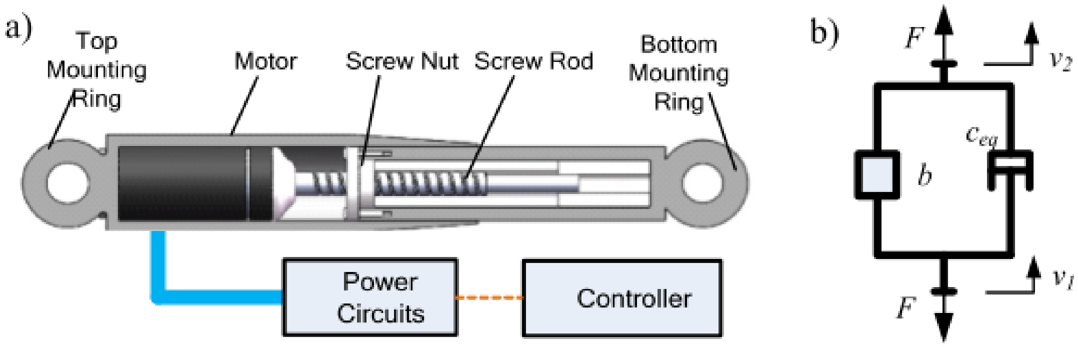

Fig. 3. **Scheme of the shock absorber ball-screw structure (a)**
and the equivalent dynamic model (b) [37]

Due to the impact of the moment of inertia of the motor rotor and screw rod, the energy-harvesting shock absorber can be regarded as a conventional oil damper connected by an inerter in parallel, as shown in Fig. 3. b) [61]. F is the total force of the shock absorber, v_1 and v_2 are the velocities of the vehicle body and chassis respectively, b – the inerter value, c_{eq} is the equivalent damping coefficient. The PMSM generator (permanent magnet synchronous motor) and a buck-boost converter used to collect energy gave positive results. The results showed that the proposed control circuit and control strategy were characterized by a high response speed of 4 Hz and a small tracking error of 6.44%

compared with the pre-set damping coefficient value, which establishes a good foundation for the future study of energy-harvesting semi-active suspension [37]. Additionally, high energy collection efficiency of 40.72% to 70.55% was obtained from the suspension tested with sinusoidal excitation and accidental road excitation.

As shown by Abdelkareem et al. [54], from vehicle vibrations caused by road unevenness, an average power of 350 W can be obtained for a medium-sized sedan (using four energy-absorbing shock absorbers). For larger vehicles, harvesting power can be significantly higher. Electromagnetic regenerative damper has a relative low load carrying capacity, therefore it is more suitable for minivans and passenger cars etc. Electro-hydraulic damper can provide a higher damping force, which is usually required by off-road vehicles. Therefore, there is a great potential to recover the energy lost from vehicles, which can be used to power, e.g., systems that increase the comfort of traveling. More information on the design of waste energy recovery system in the vehicle suspension system can be found in the following literature: [13; 57; 58; 59; 62]. Fig. 4 shows the location of the energy harvesting shock absorber in the rear axle of the vehicle.

Fig. 5. **Place of installation of the energy harvesting shock absorber [57]**

Unlike small-scale energy harvesting, such as wireless sensors and electronic devices, systems based on recovering energy from a car’s internal combustion engine suspension have not been sufficiently researched. Initial research on energy recovery from the displacement of a working compression ignition engine in an off-road passenger vehicle is presented in [45]. The authors believe that there is a potential for partial recovery of energy from a vehicle’s internal combustion engine suspension system during operation with a piezoelectric system. The subject of the research was the following: a passenger all-terrain vehicle UAZ-31512 with a 4-cylinder in-line supercharged diesel engine – 2.5TD with direct injection used in Land Rover Discovery 200 series. Fig 5 shows the measuring circuit for engine displacement and mounted energy piezoelectric harvesting system on the engine block. The results of the output voltage from experiments are present in Fig. 6.

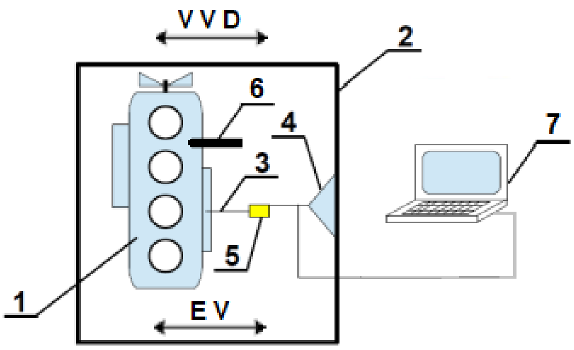

Fig. 5. **Measuring circuit:** 1 – Diesel engine; 2 – vehicle body; 3 – potentiometer arm; 4 – load-bearing structure; 5 – linear potentiometer; 6 – piezoelectric energy harvester; 7 – computer; VVD – vehicle’s vibrations during driving; EV – horizontal engine vibrations

Comparing the linear (with impacts) cases with the non-linear (with impacts), it can be concluded that there is an effect of a higher output voltage in the second case. It is worth noting that by impacts there the damping effect is smaller; the corresponding root mean square of the voltage output is 0.1020 and 0.1325 RMS (voltage) for linear and non-linear energy harvesters, respectively. Impacts of the beam over the amplitude limiter cause oscillations of a higher level, concerning the linear solution there is a dissipation of oscillations [45] (see Fig. 6).

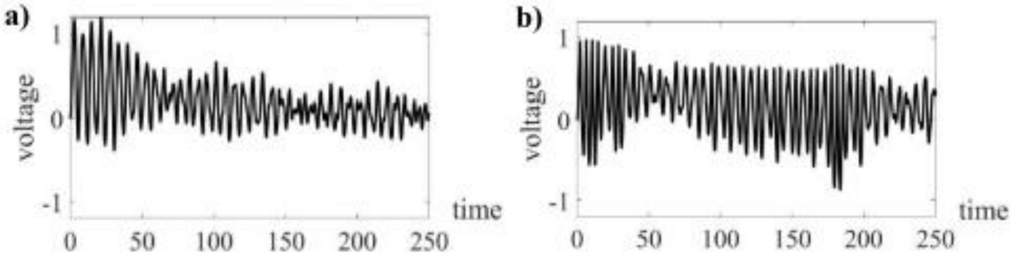

Fig. 6. **Comparison results of output voltage for linear (a) and non-linear (b) case**

Summarized in these experiments, not much difference in performance is found in terms of average induced voltage between the applied duty cycles, but this preliminary study gives the guidelines to prepare further research by changing the design of the energy harvesting system.

Conclusions

1. Based on the presented solutions for energy harvesting from the vehicle suspension systems, it can be concluded that better results were obtained for larger vehicles. Therefore, it is more practical to test electro-hydraulic shock absorbers for SUV's, off-road vehicles, heavy trucks, mining vehicles, military vehicles and engineering machines that are heavy and operated under poor road conditions.
2. As the research shows, it is possible to obtain the value of regenerative power at the level of several hundred watts. The lowest results are obtained for passenger cars driving on good quality roads (3 W). The research shows that it is possible to obtain the value of the recovery power at the level of several hundred watts, on average, about 150 W for passenger cars and from 100 to 400 W for off-road vehicles, depending on the type of the road on which it is traveling. A worse road category results in a greater work of the suspension system and gives better results of the regenerated power.
3. The possibilities of energy recovery from the suspension system of the internal combustion engine in a vehicle are presented. Initial results have shown the potential for energy recovery in this area, but it requires further in-depth research. The author plans further research in this field. Due to the operating characteristics of internal combustion engines in an in-line configuration, it is worth taking an interest in engines with 4 or 3 cylinders.
4. Eenergy harvesting systems should be of particular interest to fleet customers, where a few percent benefits in reducing the fuel consumption lead to specific amounts of savings.

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