VIBRATION ENERGY HARVESTING IN THE TRANSPORTATION SYSTEM: A REVIEW

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Summary

This review presents different approaches of kinematic energy harvesting. Energy harvesting is the conversion at ambient energy present in the transportation system into electrical energy. Most vibration energy harvesters are based on spring-mass-damper systems which generate maximum power when the frequency of the ambient vibration fits the resonant frequency of harvester. The strategy of the reduction of this limitation is discussed in the paper. At first the periodic tuning of the resonant frequency is explained. Additionally the method of continuous tuning is presented. The emphasis is placed on maximizing the power transferred from the energy harvester to the output load. It is consider the possibility of using a dynamic magnifier in order to amplify the harvested electrical power. It is showed that the proper parameter selection of the magnifier the power can be enhanced and the effective frequency bandwidth of the generator can be improved. Next is presented a comprehensive review of the principles mechanisms of transformation the kinematic energy into electrical energy. The three main transduction methods are based on piezoelectric, electromagnetic and electrostatic phenomena. Piezoelectric harvesters use active materials that generate an electric charge when stressed mechanically.

Electromagnetic generators change the relative motion of conduction in magnetic field, on the principle at electromagnetic inductions. Electrostatic generators convert the relative movements between charged capacitor plates into electrical energy.

The advantages and disadvantages of each are described and evaluated and the relevant merits of each approach are concluded.

Keywords: energy harvesting, inertial generators dynamic magnifier, transolution mechanisms, frequency tuning.

ODZYSKIWANIE ENERGII Z DRGAŃ W SYSTEMIE TRANSPORTOWYM: PRZEGLĄD

Streszczenie

Publikacja prezentuje różne podejścia w odzyskiwaniu energii ruchu. Odzysk energii rozumiany jest jako konwersja otaczającej energii obecnej w systemie transportowym w energię elektryczną. Większość systemów (urządzeń) dokonujących tej transformacji bazuje na układzie sprężyna-masa-tłumik, które generują największą moc jeśli częstotliwość istniejących drgań odpowiada częstotliwości rezonansowej układu transformującego. W pracy została omówiona strategia zlikwidowania przytoczonego ograniczenia. Jako pierwszy został wyjaśniony mechanizm okresowego dostrajania częstotliwości rezonansowej. Fakultatywnie przedstawiono metodę ciągłego jej strojenia. Jednak głównie położono nacisk na maksymalizację mocy przekazywanej z układu odzyskującego energię do obciążenia wyjściowego. Rozważono możliwość zastosowania wzmacniacza dynamicznego, którego zadaniem jest zwiększenie odzyskanej energii elektrycznej. Zostało wykazane, że właściwy wybór parametrów takiego wzmacniacza, zwiększa wydajność energetyczną, jak również szerokość efektywnego pasma częstotliwości generatora. Kolejno przedstawiono obszerny przegląd zasad mechanizmów transformacji energii kinematycznej w energię elektryczną. Opisano trzy główne metody transdukcji, które opierają się na następujących zjawiskach: piezoelektrycznym, elektromagnetycznym i elektrostatycznym. System odzyskujący bazujący na efekcie piezoelektrycznym, wykorzystuje aktywne materiały, które generują ładunek elektryczny pod wpływem występowania naprężeń mechanicznych.

Generatory elektromagnetyczne transformują ruch względny przewodnika w polu magnetycznym, na zasadzie indukcji elektromagnetycznej. Natomiast generatory elektrostatyczne zamieniają względne przesunięcia pomiędzy naładowanymi okładkami kondensatora w energię elektryczną.

Zalety i wady każdego ze sposobów odzyskiwania energii zostały opisane i ocenione a dodatkowo wyszczególniono zalety każdego z podejść.

Słowa kluczowe: odzysk energii, wzmacniający generator dynamiczny, mechanizmy działania, strojenie częstotliwościowe

1. INTRODUCTION

21st century, apart from being the time of intensive development of science and technology, has also brought four crises, growing population, decrease of available natural resources, degradation of natural environment and economic instability. These developments have led to further attempts of finding new ways out of this situation. It has become particularly important to find solutions which would help satisfy energy-related needs. According to the U.S. administration [1], crude oil, coal and natural gas were in 84% the original sources of the energy consumed in 2011.

These developments are accompanied by the growing excavation costs, expressed as the ratio of the energy consumed for excavation and construction of devices and infrastructure to the energy obtained in the process (EROI–Energy return on energy investment).

The above mentioned indicator fell from 30 in 1970 down to 10 now for crude oil and gas. It is forecasted that decrease of EROI down to the range of 3 to 5 could mean occurrence of substantial shortage of energy supply and disturb development of contemporary civilization. Hence, the research and development work, regardless of whether it concerns conventional, natural oil or renewable fuels, should focus on the technologies enabling reaching EROI > 5.

According to the data presented in [2], global demand for power is currently around 16TW. At the same time let us note that the power of the radiation emitted by the Sun in the direction of the Earth is 10^4 times bigger. Assuming that half of the solar energy reaches the surface of the globe, then even its small percentage, when transformed into electrical energy, could substantially contribute to solving mankind's growing energy problems.

On the other hand, the EU climatic package obligates Polish energy producers to buy 100% CO_2 emission rights from 2020 onwards. At that time, according to the experts a ton of CO_2 could reach the price of 63.5 Euro. Attention is drawn to the fact that it is only then that nuclear power plants will become profitable, in the same way as wind power plants. This could result in substantial growth of energy prices, both for the economy and for households. Hence the growth of interest in diversified energy production methods and prosumer system in power engineering. It is already in 2016 that the prices of fotovoltanic cells could be around 1000 Euro. Such cells, upon relevant modification of the energy law, could start generating profit already after 1000 hours of energy generation. Such solutions entail the necessity of development of intelligent power grids, which would help make use of energy recovery systems profitable also in households.

As a result, the issue of efficient use of energy has recently become central to the society and the economic-and-social organizations. The environmental protection requirements, growing prices of fossilized fuel, high prices of implementation of renewable sources of energy are yet further factors leading to growth of interest in these issues. Yet another element is the increasingly growing use of autonomous monitoring and management systems which enable equipment to operate without the need for any additional power modules to be installed.

Though in the case of monitoring systems the main problem is how to deliver power at the level of micro- and milliwatts while using such means as wind, water, solar energy and vibration, still in the case of vehicles it will be the lost heat and the kinetic energy that will continue to be the major sources of energy. It is the development of intelligent power grids that could contribute implementation of such solutions in vehicles, where electrical and hybrid vehicles will not only receive but also store and send electrical power back to the grid.

At present, while we are in the transition period, there is continuous search for new energy sources and technologies, with the search for the solutions which will improve the energy efficiency of the engines and drives used in transport systems being an additional task.

Hence the research and the analyses of the possibilities of increasing the power and the energy efficiency of the kinematic, thermoelectric and thermoacoustic process of energy recovery as well as the process of increasing the density of the energy accumulated in vehicles stir such high interest.

The central issues are those relating to energy harvesting from the vibration caused by a vehicle moving on an uneven surface, especially energy harvesting from the power transmission system and the suspension as well as from the sprung masses. The search includes a method of effective transformation of the kinetic energy of the mass of a mechanical vehicle's driver and his/her seat into electrical energy, efficient use of thermal-cells in the exhaust and cooling systems of a combustion engine as well as examination of the conditions for implementing thermoacoustic generators in vehicles.

Still another issue is that of positioning of solar panels in vehicles depending on the Sun's position, relevant location and shape of a fotovoltaic panel's surface.

Improvement of a power unit's efficiency calls for research in the field of modeling of hybrid, hydraulic-and-electrical power transmission systems which will harvest energy during braking. The research in this area is of key importance due to the need for constructing modern and ecological means of transport as well as development of modern energy processing solutions in mechanical-electrical-and-hydraulic systems. The research on energy recovery in vehicles should be supplemented by the research on increasing the density of the accumulated energy. E.g. use of electrolyte with lower solidification ratio should improve a cell's efficiency at low temperatures.

2. EXISTING STATE OF KNOWLEDGE

While analyzing the state of knowledge, attention should be drawn to two essential, diverse trends: development of energy harvesting methods for use in big industry as well as development of energy harvesting and accumulation methods for miniature, or even microscopic devices. The second trend enables development of energy-harvesting units for increasingly small devices.

The other factor which leads to minimization of energy-harvesting devices is the necessity of ensuring power supply to these devices without their connection to the electrical grid. In such cases batteries are used as a source of electrical power. The main drawback of a battery is the undefined operating time. Once a battery is dead, it has to be replaced, which is connected, at times, with the difficulties related to reaching the place where a battery has been installed. One must not forget about the costs of such an operation. The new techniques of energy harvesting include use of kinetic energy as well as use of the energy of the human body.

Examples include harvesting of energy from human motion (e.g. during sleep or a walk), from the heat generated by human body or even from the contractions of the heart.

Human motion is quite characteristic – it is characterized by high amplitudes and small frequency. For this reason design of a miniature generator which will operate while installed on a human body is quite difficult.

So far several devices have been manufactured which exploit the above methods, including:

- a watch which uses the heat of the human body to drive the mechanism and charge the battery,
- a ring with installed thermoelement which converts the heat of the human body into the electric energy needed to charge the battery [3],
- a heart pacer which will be powered by the movement of the heart.

One of more interesting ideas is a shoe which contains a generator. According to the research done, a man weighing 68 kg is capable of generating 67J of energy this way while walking. [4].

Unfortunately the devices used for these purposes allow for recovery of only several millijoules of energy, which reduces the possibility of powering any bigger devices this way. In the future the range of devices powered this way could be much bigger. There are plans for powering or charging mobile phones and portable computers this way.

The method which uses mechanical vibration is one of the most effective methods of energy harvesting. Electrical energy harvesting requires a mechanism which will generate electrical energy from motion. It is possible thanks to connecting a moving mechanism to a device which can generate electricity from the movement. In other words the device for energy harvesting from vibration consists of a device which converts kinetic energy into electrical energy.[5].

Thanks to this method we are able to generate electricity from deformation, e.g. of piezoelectric materials, from movement of a magnet (core) in a coil, etc. The power which generates mechanical vibration is usually acquired from the environment. Energy coming from vibration is converted into electrical energy and then stored e.g. in batteries.

At present there exist several methods which enable acquisition of energy from vibration. These include:

- the electromagnetic method
- the electrostatic method
- the piezoelectric method
- the magnetostriction method

The diagram showing the methods which harvest energy from vibration is presented in Fig.1.

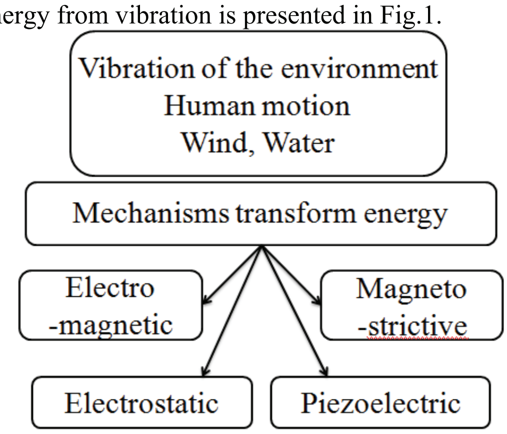

Fig. 1. A diagram showing conversion of kinetic energy into electrical energy and its examples

The piezoelectric method of energy harvesting is the method which currently draws most attention. The goal of the research related to this method of energy harvesting is the attempt to reduce the power required by small electrical devices, e.g. wireless sensors used for monitoring a man's condition (health). The main purpose of the research related to this method is to ensure power supply for the devices while using the vibration energy which is available from the environment.

Magnetostrictive materials are characterized by high coefficient of magnetic and mechanical coupling. The advantage of these materials is their high flexibility and high Curie temperature. Use of these materials involves change of the intensity of the magnetic field thanks to mechanical forces applied to the material which introduce flexible tension. The device for energy harvesting which relies on magnetostrictive materials is composed of: an energy converter, an energy regulator, a high capacity capacitor.

The electromagnetic method uses the kinetic energy of a vibrating mass to generate electrical energy. Electromagnetic devices for energy consumption exist in two configurations: standard and reverse.

The standard configuration: a magnet, whose task is to generate the magnetic field, is moving while the coil is fixed [6]. The reverse configuration: the magnet is fixed while the coil vibrates.

The electrostatic method consists of conversion of the kinetic energy of vibration into electric energy by means of a variable condenser which is polarized by an electrets (a dielectric which generates a permanent external electric field is an equivalent of permanent magnets [7]). The electrostatic generator contains two wires which are separated by a dielectric material which moves from one wire to the other.

The method is widely used but it is not as universal as the method which uses piezoelectric materials.

3. KINETIC SYSTEMS FOR ENERGY RECOVERY

3.1 Use of linear models

Harvesting of kinetic energy means use of a mechanism for electrical energy generation by coupling the vibrating system located in a vehicle with the input caused by a vehicle's vibration. Thus the analysis of the possibility of increasing the power density could be reduced to maximization of the effect of coupling between the source of kinetic energy and the mechanism which generates electrical energy based on a vehicle's motion. The inertial generator, whose elements are connected to a vehicle's structure, would be the most relevant electrical energy generator when the phenomenon of vibration is exploited.

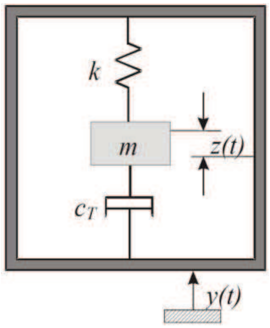

Fig. 2. A dynamic system with one degree of freedom subjected to a kinematic input [8]

Hence a supported mass can be subjected to vibration, leading to relative shift between these elements of the system.

Relevant selection of the vibrating system's parameters is required so that the frequency of proper vibration and the frequency of kinematic inputs are identical, or do not differ much from each other. Thus the mechanism of electrical energy generation could be used, as an outcome of damping in the resonant zone. The theory of inertial generators is well documented and it will be shortly presented here.

Assuming that a kinematic input can be described by means of a trigonometric function, the mean energy which is dispersed during forced vibration is described by the following formula:

$$P_{tr} = \frac{m\xi_T Y^2 \left(\frac{\omega}{\omega_n}\right)^3 \omega^3}{\left[1-\left(\frac{\omega}{\omega_n}\right)^2\right]^2 + \left[2\xi_T\left(\frac{\omega}{\omega_n}\right)\right]^2} \tag{1}$$

Where: ξ_T is a damping coefficient.

The maximum level of dissipated energy is reached when the density of the input is equal to the frequency of proper vibration $\omega = \omega_n$, and hence:

$$P_{av} = \frac{mY^2\omega_n^3}{4\xi_T} \tag{2}$$

Equation (2) shows that the generated power is directly proportional to the mass, it increases at the rate of value of frequency to the power of three and depends on the power of the input signal. The above equations demonstrate that use of resonant systems requires the input frequency to be tuned to resonant frequency. For this reason, as well as due to the broadband inputs occurring in vehicles, the project will focus on the research on non-resonant generators which rely on dynamic non-linear system.

3.2 Non-linear model of vibroacoustic signal

Let us contemplate the possibility of generating a signal which would contain a non-linear component. Let us assume that the generated signal is multiplied by an additional value which is defined by the kinematic properties and that is transmitted to the measuring point via a linear transmission channel, which corresponds to a process with linear elements and multiplying factors which can be described by a Volterra series [9]. Examples of such a description can be found in [10, 11, 12].

After including the linear part of the signal, which in this case will be generated by the dynamic part of the system, as well as upon including the non-linear part of the process, which was defined earlier (Fig. 3), and while acting in accordance with the procedure proposed by [13], we have obtained the following relationship:

$$z(t)=\int_0^t h_1(\tau_1)x(t-\tau_1)\mathrm{d}\tau_1+\int_0^t\int_0^t h2(\tau_1,\tau_2)x(t-\tau_1)x(t-\tau_2)\mathrm{d}\tau_1\mathrm{d}\tau_2 \qquad (3)$$

where:

$$h_1(\tau_1)=h_{Q_1}(\tau_1)*h_{p_1}(\tau_1) \qquad (4)$$

$$h_2(\tau_1,\tau_2)=h_{Q_{22}}(\tau_1-\tau_3)\cdot h_{Q_{21}}(\tau_2-\tau_3)*h_{p_2}(\tau_3) \qquad (5)$$

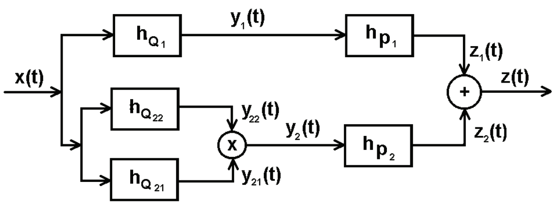

Fig. 3. Diagram showing generation of the linear and non-linear parts of the process.

Let us note that the complex mechanism of influence of non-linearity on the response of the system was reduced to generation of a signal by a system with relatively simple components which are easy to model.

While assuming, after Schetzen (1980), that the relationship (7) which defines the *n-th* element of the series is a function of variables $z_n(t_1,t_2,\ldots,t_n)$, we can apply the n-dimensional Fourier transform:

$$Z_n(\omega_1,\omega_2,\ldots,\omega_n)=\int_{-\infty}^{\infty}\ldots\int_{-\infty}^{\infty}(\int_{-\infty}^{\infty}\ldots\int_{-\infty}^{\infty}h_n(\tau_1,\tau_2,\ldots,\tau_n)\cdot \cdot x(t-\tau_1)x(t-\tau_2)\ldots x(t-\tau_n)\mathrm{d}\tau_1\mathrm{d}\tau_2\ldots\mathrm{d}\tau_n)\cdot \cdot\exp[-j\omega_1 t-j\omega_2 t\ldots-j\omega_n t]\mathrm{d}t_1\mathrm{d}t_2\ldots\mathrm{d}t_n \qquad (6)$$

or

$$Z_n(\omega_1,\omega_2,\ldots,\omega_n)=H_n(\omega_1,\omega_2,\ldots,\omega_n)\cdot X(\omega_1)\cdot X(\omega_2)\cdot\ldots\cdot X(\omega_n) \qquad (7)$$

where:

$H_n(\omega_1,\omega_2,\ldots,\omega_n)$ - transmittance of the *n-th* rank.

The last assumption, reducing the issue of Volterra series resolution down to determination of the higher order transmittance, enables extension of the methods used in linear systems to non-linear systems. While analyzing this issue, Storer and Tomlinson [14] point to calculation and interpretation-related issues in the case of higher order transmittance. Also the experimental methods are subject to relevant revaluation.

The literature on the topic presents methods of measurement of higher order transmittance for a sinusoid input [15]. Attempts are made at the same time to identify the Volterra series' terms. For example, publications [16, 17] take up the issue of estimation of the second order transmittance. The issue of identification of the third order transmittance is tackled by Liu and Vinh [18]. In that publication, the *n-th* order transmittance is determined from the following relationship:

$$H_n(\omega_1,\omega_2,\ldots,\omega_n)=\frac{S_{yx,\ldots,x}(\omega_1,\omega_2,\ldots,\omega_n)}{S_{xx}(\omega_1)\cdot S_{xx}(\omega_2)\ldots S_{xx}(\omega_n)} \qquad (8)$$

where:

S_{xx} - the autospectrum of the input signal,

$$S_{yx,\ldots,x}(\omega_1,\omega_2,\ldots,\omega_n)=\Im\{R_{yx,\ldots,x}(\tau_1,\tau_2,\ldots,\tau_n)\}= =X(\omega_1)\cdot X(\omega_2)\ldots X(\omega_n)\cdot Y_n^*(\omega_1,\omega_2,\ldots,\omega_n) \qquad (9)$$

Recent publications present results of non-linear systems analyses using simplified Volterra series [19].

4. CONCLUSIONS

Use of combustion engines for co-generation purposes is one of the elements of rational use of available energy carriers, which fits in with the tasks realized as part of energy security programs of countries and their systems. The most important feature of co-generation systems built while relying on combustion engines is the simultaneous production of mechanical or electrical energy (in the electrical power generator propelled by the combustion engine) as well as use of waste heat from the engine's systems. A serious drawback, which makes broader use of co-generation systems difficult, is the necessity of employing of efficient solutions for transforming the heat to mechanical or electrical energy .

The paper demonstrates that recovery of energy from mechanical vibration should hold a special place in the research.

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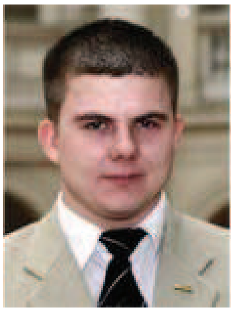

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