HYBRID PIEZOELECTRIC VEHICLES (HPEV™) and MOTORS (HPEM™)

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The paper describes a new class of a hybrid vehicle that uses piezoelectric devices for powering an electric motor while still using conventional fuels, such as gas, diesel, or oil. The installed piezoelectric devices can transform the mechanical energy of the moving pistons or crankshafts into electrical energy, which can be stored in the capacitor or the battery charger. Consequently, the stored electrical energy powers an electric motor, which can supplement the conventional gasoline or diesel engine or work independently. The solution to the problem can significantly reduce the consumption of the conventional fuel, diversify transportation fuel supply, and reduce the air pollution. Use of piezoelectric devices for powering a supplemental electric motor will lead to the development of a new generation of hybrid vehicles, where the mechanical energy of the existing conventional gasoline engine will be converted to electrical energy without significant changes in the design of the existing automobile engine and generator. Using piezoelectric elements for powering the motor will significantly increase the cost-effectiveness of the hybrid vehicles and simplify the currently used charging system of the electric vehicles. The principle of operation is based on the unique properties of piezoelectric materials, which are able to generate an electrical voltage when they are mechanically stressed. The preliminary experimental results demonstrate that a single piezoelectric element under transient dynamic mechanical load can generate a pulse of an electrical voltage in the range of tens or even hundreds of kilovolts.

Keywords: power harvesting, piezoelectricity, hybrid vehicles

1. Introduction

The main goal of this work is to develop and demonstrate a new class of a hybrid vehicle, which uses piezoelectric devices for powering an electric motor while still using conventional fuels, such as gas, diesel, or oil. The installed piezoelectric devices will transform the mechanical energy of the moving pistons or crankshafts into electrical energy, which will be stored in the capacitor or the battery charger. Consequently, the stored electrical energy will power an electric motor, which can supplement the conventional gasoline or diesel engine or work independently. The solution to the problem can significantly reduce the consumption of the conventional fuel, diversify transportation fuel supply, and reduce the air pollution. Use of piezoelectric devices for powering a supplemental electric motor will lead to the development of a new generation of hybrid vehicles, where the mechanical energy of the existing conventional gasoline engine will be converted to electrical energy without significant changes in the design of the existing automobile engine and generator. Using piezoelectric elements for powering the motor will significantly increase the cost-effectiveness of the hybrid vehicles and simplify the currently used charging system of the electric vehicles. The results of this work could be used for developing a new class of safe, cost and environmentally efficient hybrid vehicles, which will
lead to the reduction of the consumed fuel, and subsequently the dependence on the foreign oil. The principle of operation is based on the unique properties of piezoelectric materials, which can generate a high electric voltage when they are mechanically stressed. The preliminary experimental results demonstrate that a single piezoelectric element can generate a pulse of the electrical voltage on the order of tens or even hundreds of kilovolts. The novel technology is based on the phenomenon of the direct piezoelectric effect. The source of the electrical energy is a piezoelectric element made of a special type of piezoelectric ceramic with high electromechanical coefficient (piezoelectric pressure constant $g_{33}$), which generates a high voltage electrical signal upon the application of a mechanical stress [1]. The source of the mechanical stress will be investigated. One of the possible sources of the mechanical stress is the energy of the moving pistons and crankshafts. Another source of the mechanical stress could be the energy of the compressed gas in the cylinders during the explosion when a spark plug emits a spark to ignite the fuel. The final decision about delivery of the mechanical energy to the piezoelectric elements and the optimal characteristics of the piezoelectric elements (dimensions and shapes) will be determined experimentally.

2. Technical limitation of existing alternative fuels

The proposed use of piezoelectrics to convert waste mechanical energy into electrical energy is a new technology with significant promise to supplement and quickly surpass other alternative energy recovery technologies, such as the use of thermoelectrics and solar power generation. The principal technologies used by hybrid gasoline-electric vehicles include regenerative braking for electric power production and battery charging [2–13]. In addition, thermoelectric power generation holds promise, yet suffers from limited efficiencies, while solar power generation is expensive and limited by the incident solar flux and cell efficiency. Also, the use of renewable bio-derived fuels to reduce undesirable emissions and dependence on foreign oil has recently received much attention [14], yet the overall energy balance including farming, processing, and storage is negative (more energy is needed to produce the biofuel than is extracted from it in the combustion process) or only slightly positive depending on the feedstock. The use of these complimentary energy recovery technologies and fuel feedstocks are discussed below.

2.1. Regenerative Braking to Recover Waste Heat

Regenerative braking is the process by which a vehicle's kinetic energy can be retained while decelerating. When a vehicle brakes, friction converts the vehicle's kinetic energy into waste heat. Commercial hybrid gasoline-electric cars recover a portion of this kinetic energy using generators to convert the kinetic energy into electrical energy that is then used to charge a battery or generate DC power. Regenerative braking technology recovers about 30% of the energy otherwise to braking in conventional vehicles and accounts for about 20% of the energy to power the electric motor used by the Toyota Prius and thus increase the overall system efficiency. Note that the proposed piezoelectric power generation system is not competing with such technology, yet will compliment it and further increase the overall vehicles system efficiency.
2.2. Recovering Waste Heat from Exhaust and Engine Components

The development of an efficient and practical thermoelectric system [15, 16] that will improve fuel economy by converting waste heat from automobile engine exhaust into electrical power is a long-sought after method to recover waste heat energy produced from gasoline and diesel engines, yet is not a currently cost effective technique. By recovering thermal energy, the effective efficiency of the overall system would increase from efficiencies of roughly 25% for gasoline SI engine and 35% for diesel engines.

Research focused on the development of new thermoelectric materials is ongoing at DOE NREL, NASA JPL, and many corporate research labs (e.g., BSST, Visteon Corporation, Teledyne Energy Systems, BMW of North America, Caterpillar), yet to make a thermoelectric device economically feasible, new materials and micro-manufacturing advances are needed so that the electron performance can be improved or maintained concurrent with a reduction of phonon thermal conductivity. For the past 40 years, Bismuth Telluride (Bi$_2$Te$_3$) has been the most versatile mainstay thermoelectric, yet it's efficiency is limited to 10-13% depending on the temperature range [15, 16]. Other thermoelectric materials include Lead Telluride PbTe, Silicon Germanium Si-Ge, Bismuth Antimony Bi-Sb depending on the temperature regimes, yet suffer from efficiencies on the same order as that associated with Bi$_2$Te$_3$. Additionally, a measure of the temperature-electricity conversion performance is given by a figure-of-merit, i.e., "ZT" rating, which for all thermoelectrics is less than 2 (see Figure 1 below for different materials in different temperature ranges). However, a rating of 4-5 is generally accepted to be the economical limit, below which it is impractical to use thermoelectrics except in limited applications.

![ZT for p-type thermoelectric materials](image1.png) ![ZT for n-type thermoelectric materials](image2.png)

Figure 1. ZT thermoelectric materials [17].

2.3. Solar Energy Generation

Solar radiation incident on the Earth's disk is 1370 W/m$^2$. Multiplying by a factor of $1/4$ – the ratio of the area of the Earth's disk ($\pi R^2$) to the Earth's surface area ($4\pi R^2$), the incident solar radiation if assumed uniformly distributed over the Earth's surface is 342.5 W/m$^2$. If roughly 30% of the incident solar radiation is reflected by clouds, snow, ice, etc., the average incident flux is $342.5 \times 0.7 = 239.7$ W/m$^2$. With advanced Gallium-Arsenide (GaAs) solar cells, which have an efficiency as high as 25%, the average amount of electricity that can be generated is limited to 60 W/m$^2$. Large surface areas and the use of solar collectors are therefore required to generate significant power. In addition, solar cells are susceptible to cracks from debris and are
also prohibitively expensive. Solar power generation is also susceptible to the weather and therefore has limited application.

2.4. The Use of Bio-derived fuels to Reduce Dependence on Imported Oil and Undesirable Emissions.

The use of bio-derived, renewable fuels [14] (e.g., ethanol produced primarily from corn in the U.S. and sugar cane in Brazil) have been hailed by many as part of the solution to climate change (CO₂ and emission reduction), yet only recent attention has been given to the controversy surrounding the total energy balance associated with the complete life cycle (production and utilization) of bio-derived fuels and the obvious need for significant agricultural land that could otherwise be used to grow food or other high value agricultural products. Varying amounts of energy are used and emissions generated due to farming, fertilizer use, transportation, processing (the distillation process is energy intensive), and storage of biofuel. For lignocellulosic feedstocks (hay, straw) the overall energy balance for bio-ethanol is negative, while for corn and wheat feedstocks, the energy balance is only slightly positive.

Biofuels due however offer reduced CO₂ since the CO₂ produced by combustion process can be cycled back into the plant by photosynthesis, and no net CO₂ is produced, with the exception of the emissions produced by cultivating, harvesting and processing biomass [14]. Distribution and refining centers are, however, limited.

3. Hybrid Piezoelectric Vehicles (HPEV™)

The HPEV™ principle of operation is based on the phenomenon of the direct piezoelectric effect [18, 19]. The source of electrical energy is a piezoelectric element, which generates a short electrical pulse upon application of the mechanical stress. This short pulse is applied to the electrical underdamped oscillating circuit, which generates attenuated periodic signal for about 0.5 – 1 s. The rotational velocity of modern automobile engines is typically 2000–3000 rpm, which corresponds to 30 – 50 revolutions per second. So, at least one electrical pulse is generated every 20-30 milliseconds. During this time interval, the amplitude of the generated voltage can reach tens and even hundreds of kilovolts (see some relevant experimental results below). The installed piezoelectric devices will transform the mechanical energy of the moving pistons or crankshafts into electrical energy, which will be stored in the capacitor or the battery charger. Consequently, the stored electrical energy will power a motor, which can supplement the conventional gasoline or diesel engine or work independently. The simplified schematic of the hybrid piezoelectric vehicle is presented in Figure 2.

One or several plates (hammers) made of metal or any other rigid material attached to each piston or crank shaft of the car’s engine. When the pistons move in the cylinders and reach the top or the bottom of its stroke, the metal plates hit the piezoelectric elements. The mechanical stress in the piezoelectric element is transformed into high electrical voltage, which is applied to the capacitor or the battery charger. The stored electrical energy is used to power the electric motor (Figure 2). Please note that no additional energy from the engine is required to move metal plates and consequently to hit the piezoelectric elements.
Piezoelectric elements could also be installed in the body of the combustion chamber. When the piston moves in the cylinder to compress the fuel and a spark plug emits a spark to ignite the fuel, the explosion in the cylinder occurs. The mechanical stress is then applied to the piezoelectric elements. The piezoelectric elements convert mechanical stress into a high electrical voltage. Then, the electrical energy can be stored in the capacitor or battery pack with the help of the associated electronics.

As a result of the explosion or shocks from the hammers, the piezoelectric element is stretched and compressed under severe mechanical stress, which leads to generation of the high voltage electrical signal. Preliminary estimation allows for the conclusion that the required output voltage could be generated by the piezoelectric elements made of the typical piezoelectric material. For example, the total force instantaneously applied to the top of the piston in a combustion is around 6300 pounds, which corresponds to approximately 28,640 N [20]. If this force is applied to a cylinder made of PZT5A piezoceramic of 1 cm diameter and 1 cm high, this would correspond to a pressure of \( p = 37.87 \cdot 10^7 \text{ N/m}^2 \). PZT5A material has the piezoelectric pressure constant \( g_{33} = 22 \cdot 10^{-3} \text{ V/m/N} \). The generated voltage can be calculated from the following formula:

\[
V = g_{33} \cdot l \cdot p = 22 \cdot 10^{-3} \text{ V/m/N} \cdot 10^{-2} \text{ m} \cdot 37.87 \cdot 10^7 \text{ Pa} = 83.16 \text{ kV},
\]
where \( l \) is the height of the piezoelectric cylinder and \( p \) is the pressure applied to the piezoelectric cylinder.

Of course, additional work is needed to evaluate various piezoelectric materials to be used for producing the piezoelectric elements, which will be suitable for our applications.

To prove the concept of the proposed project [1], the following experiments were carried out (Figure 3).

![Schematic diagram of the experimental setup.](image)

Figure 3. Schematic diagram of the experimental setup.


The 5.313 kg object was dropped on two circular piezoelectric disks consequently. Both disks were mounted into a holder between two metal plates (Figure 4).

![Piezoelectric disk mounted into a holder between two metal plates.](image)

Figure 4. Piezoelectric disk mounted into a holder between two metal plates.

Each time, the voltage was recorded between two parallel surfaces of the piezoelectric disk by the oscilloscope using a voltage divider and an attenuator 10:1 (Figure 3). The first piezoelectric element had a diameter of 9.56 mm and a height of 1 mm. The second one had a diameter of 6.96
mm and a height of 8.86 mm. In the first experiment, the object was dropped from the altitude of 1.08 m and the voltage divider was constructed of two resistors, $R_1 = 100 \, \text{k}\Omega$ and $R_2 = 3.3 \, \text{k}\Omega$. In the second experiment, the object was dropped from the altitude of 1.75 m and the voltage divider was constructed of two resistors, $R_1 = 100 \, \text{k}\Omega$ and $R_2 = 1.5 \, \text{k}\Omega$. Recorded voltages for both experiments are presented in Figure 5 and Figure 6, respectively. To obtain the actual generated voltage in kilovolts in the first experiment, the number on the vertical axis of the Figure 5 should be multiplied by 0.313. To obtain the actual generated voltage in kilovolts in the second experiment, the number on the vertical axis of the Figure 6 should be multiplied by 0.677. Units of the horizontal axis in both figures are seconds.

![Figure 5. Voltage oscillogram in the first experiment.](image)

![Figure 6. Voltage oscillogram in the second experiment.](image)

Based on the values of the resistors $R_1$ and $R_2$, their tolerance, and the attenuation coefficient of the attenuator (10:1), the voltage amplitudes in both experiments were 16.7 kV and 44.7 kV, respectively. We suggest that using several piezoelectric elements connected in series or in parallel will allow creating the stable high voltage electrical signal on the order of tens of kilovolts. Other shapes of piezoelectric elements should be also investigated to optimize their dimensions and the shape. The preliminary experimental results will be carefully evaluated for developing a prototype of the piezoelectric hybrid vehicle.

**Summary**

The energy harvesting using piezoelectric materials in hybrid vehicles is described in this work. The installed piezoelectric devices would transform the mechanical strain energy into electrical energy and consequently power an electric motor, which can supplement the conventional gasoline or diesel engine or work independently. The solution to the problem can significantly reduce the consumption of the conventional fuel, diversify transportation fuel supply, and reduce the air pollution. Use of piezoelectric devices for powering a supplemental electric motor will lead to the development of a new generation of hybrid vehicles, where the mechanical energy of the existing conventional gasoline engine will be converted to electrical energy without significant changes in the design of the existing automobile engine and generator. Using piezoelectric elements for powering the motor can significantly increase the cost-effectiveness of the hybrid vehicles and simplify the currently used charging system of the electric vehicles. The
experimental results demonstrate that a single piezoelectric element under transient dynamic mechanical load can generate a pulse of an electrical voltage in the range of tens or even hundreds of kilovolts. The final decision about delivery of the mechanical energy to the piezoelectric elements, optimal characteristics of the piezoelectric elements (dimensions and shapes), and the harvested energy should be determined experimentally.

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