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A high-efficiency road energy harvester based on a chessboard sliding plate using semi-metal friction materials for self-powered applications in road traffic

Lingfei Qi[a], Hongye Pan[a], Shehar Bano[a], Miankuan Zhu[b], Jizong Liu[a], Zutao Zhang[a,*], Yujie Liu[a], Yanping Yuan[a]

[a] School of Mechanical Engineering, Southwest Jiaotong University, Chengdu 610031, PR China
[b] School of Information Science & Technology, Southwest Jiaotong University, Chengdu 610031, China

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ABSTRACT

To explore the alternative resources of traditional energy, ambient-energy scavenging technologies have attracted worldwide attention. In particular, the roadways contain a significant potential for environmental energy harvesting (EEH). In this study, we proposed an innovative road energy harvesting system based on a chessboard sliding plate by using semi-metal friction materials (SMFMs) for collecting the mechanical energy induced by running vehicles. The SMFMs have good frictional properties that enable them to absorb energy well. The proposed system consists of four main components as follows: chessboard sliding plate module, transmission module, micro-generator module and energy storage module. Acting as the energy input mechanism, the chessboard sliding plate module harvests the kinetic energy produced by the friction between the wheel and chessboard plate. The transmission module converts the linear reciprocating motion of the chessboard sliding plate to unidirectional rotation of the input shaft of generator. The energy storage module stores the electric energy generated by the generator module in a supercapacitor. The performance of the proposed system is evaluated through dynamic simulations; the simulation results demonstrate that the system possesses rapid response. Efficiency of 62.38% and 57% are obtained in the simulation and experiments, respectively, validating that the proposed road energy harvesting system is feasible and practical for self-powered applications in road traffic electrical equipment, such as traffic lights, street lamps and speed measuring radar.

1. Introduction

With the rapid development of China's economy, its industrialization and urbanization process is accelerating significantly. The foregone conclusion is that China will continue to have an increasing demand for energy and exacerbate energy consumption. The transport industry is responsible for a large part of the total fossil energy consumption in China, of which 23.6% is accounted for by road transport [1]. For sure, consumption of traditional energy sources give rise to some disadvantages regarding the energy crisis, environmental pollution and even energy price fluctuations [2]. These negative impacts led the world to increase the use of renewable energy sources, such as mechanical energy [3–7], solar energy [8–12] and thermal energy [13–17] sources, to achieve sustainable development. Besides, due to the improvement of road traffic construction, the power supply for transport facilities is a serious challenge in remote areas of China. Therefore, the development of renewable energy technologies is required to overcome these problems.

Although the road transport industry consumes a large amount of non-renewable energy, it also has a significant potential for renewable energy harvesting. Various forms of ambient energy are widespread in the road transport environment, including solar energy, thermal energy, mechanical energy and so on. Existing road transport EEH types can be classified into two main categories as follows: vehicle energy recovery and roadway energy collecting.

According to the previous literature [18], approximately 85% of the consumed energy by vehicles is dissipated into the ambient atmosphere in the main form of mechanical vibration, heat dissipation and braking. In recent years, to improve the working efficiency and reduce the energy consumption, vehicle energy recovery methods have attracted worldwide attention [19–23]. Taghavifar and Wei [20] presented an innovative method to harvest energy from a vehicle suspension system based on a half-vehicle model. It was concluded that the greatest average power of 57.84 W is acquired at 13 km/h. Zuo et al. developed

* Corresponding author.
E-mail address: zzt@swjtu.edu.cn (Z. Zhang).

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Nomenclature

V_e	back electromotive voltage of the micro-generator (V)
k_e	back electromotive voltage constant
ω	rotational speed of the input shaft of the electromagnetic generator (rad/s)
τ	generator torque (N·m)
k_τ	generator torque constant
i	electric current of the generator coil (A)
τ_m	input mechanical torque on the generator (N·m)
J_m	inertia of the generator shaft (kg·m^2)
L_i	internal inductance of generator (H)
R	electric load resistance (Ω)
R_i	generator internal resistance (Ω)
i_r	transmission ratios of the rack-pinion
i_b	input power (W)
r	radius of the smaller bevel gears
Z_{b1}	tooth numbers of the smaller bevel gears
Z_{b2}	tooth numbers of the larger bevel gears
i_t	total transmission ratio of our proposed road energy harvester
m_s	equivalent mass of the mechanical structure (K$_g$)
J_b	inertia of the larger bevel gear (kg·m^2)
V	source voltage (V)
ω_d	angular velocity of the smaller bevel gear (rad/s)
k_{ee}	gyration resistance (N)
k_m	stiffness of the mechanical structure (N/m)
C	capacitor of the modelling circuit (F)
T_d	time of the vehicle passes over the chessboard sliding plate (s)
s	sliding distance of the chessboard sliding plate (m)
v_d	speed of the vehicle passing over the chessboard sliding plate (m/s)
m	module of the pinion
Z	tooth number of the pinion
n_d	rotational speed of the input shaft in the micro-generator (rpm)
E_{de}	effective electromotive force in the first half movement (V)
N	number of turns in the electromagnetic coil
B	magnetic field strength (A/m)
S	cross-sectional area of the coils (m^2)
P_d	generated power of the micro-generator in the first half movement (W)
R	resistance of the coil (Ω)
a_u	acceleration of the chessboard sliding plate (m/s^2)
n_1	number of the springs
n_2	number of motion transmissions
k	stiffness coefficient of the spring (m/s^2)
m	mass of each motion transmission (kg)
v_u	mean return velocity of the sliding plate (m/s)
T_u	time of the sliding plate returns to the initial state (s)
ω_u	angular velocity of the pinion (rad/s)
n_u	rotational speed of the input shaft of the micro-generator (rpm)
E_{ue}	effective electromotive force in the second half movement (V)
P_u	generated power of the micro-generator in the second half movement (W)
P_{out}	mean output power (W)
W_{out}	energy collected by one vehicle passing over the road energy harvester (J)
P_{in}	input power in the first half movement (W)
F	friction between the tire and the sliding plate (N)
P	output power of the mechanical transmission (W)
M	resistance moment (N·m)
θ	angle of rotation (°)
η_M	energy efficiency of mechanical transmission
η_{sum}	overall energy efficiency
W_{in}	input kinetic energy (J)
η	measured overall energy efficiency

Abbreviations

SMFMs	semi-metal friction materials
RTEGS	road thermoelectric generator system
EMF	Electromotive Force
MTS	Mechanical Testing and Sensing
WPH	wind and photovoltaic hybrid
EEH	environmental energy harvesting
REH	road energy harvester

a novel regenerative shock absorber with a mechanical motion rectifier. The prototype was fabricated, and experiments were conducted to validate the system. The results showed that over 60% efficiency was obtained by the prototype at high vibration frequency [21]. Demir and Dincer [22] proposed a progressive automobile exhaust waste heat recovery system based on a thermoelectric generator. Energy and exergy efficiencies were analysed and assessed with different thermoelectric materials; the assessment results laid the foundation for material selection. Yang et al. [23] proposed a regenerative braking control strategy for application in an electric-hydraulic hybrid vehicle. Simulation models were made to evaluate the effect of the control strategy; the results demonstrated that it could effectively harvest the braking energy. The main problem with vehicle energy recovery approaches is that, they require other structures to be attached to the vehicle; the increased weight of these structures will increase the energy consumption. Little work is reported in the literature on evaluating this part of energy consumption; thus, redundant energy recovery or more energy consumption is uncertain.

An alternative to vehicle energy recovery is roadway energy collecting. Pavement energy harvesting methods primarily include three types as follows: photovoltaic, thermoelectric and piezoelectric. Pascual-Muñoz et al. [24] introduced a new technology involving the use of multilayered asphalt pavements as solar collectors connected to an embedded pipe network. Experimental results showed that excellent thermal efficiency was acquired by the prototype of the proposed solar collectors. In addition, roadways contain huge amounts of thermal energy because of the double impact of solar radiation and vehicle heat dissipation. Some research on the thermal energy scavenging from roadways based on the thermoelectric effect has been reported [25–27]. Jiang et al. [25] studied a road thermoelectric generator system (RTEGS) for harvesting thermal energy from a road. An RTEGS prototype was made to investigate the generation capacity; the results demonstrated that output voltage was approximately 0.4 V and 0.6–0.7 V for different temperature difference in winter and summer, respectively. Wu and Yu [26] conducted a novel system design to harvest thermal energy from a pavement structure. The proposed system was verified by simulated experiments in the laboratory; based on the result, the system showed potential for applications of low power devices, such as sensors. Another primary source of unused ambient energy is the stress and induced vibration caused by running vehicles on the roadways. Currently, road vibration energy acquisition based on piezoelectric technology is a popular research spot [28–31]. Moure et al. [28] presented an innovative piezoelectric cymbals road vibration energy harvesting method. Their results showed that energy densities of