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A novel approach to energy harvesting from vehicle suspension system: Half-vehicle model

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ABSTRACT

Vehicles are subject to a variety of road unevenness and random road excitations that potentially cause the vehicle to undergo a significant amount of energy dissipation. The energy loss due to vibration can be harvested/recaptured from the vehicle suspension system and the present paper aims to assess the energy harvesting potential from vehicle suspension under harmonic and random road excitations. In this manner, a mathematical model of half vehicle model was developed and different parameters such as magnitude, frequency, vehicle velocity and the relative velocity between the sprung mass and front and rear unsprung masses were included for harmonic based road type. For random excitations, two typical roads of highway with gravels and smooth runway were used and the results of average power were analysed. It was concluded that for the average harvested power versus vehicle velocity, the greatest value of 57.84 W is obtained at 13 km/h. Also, the average power increases by road amplitude with the minimum and maximum values of 51.54 and 1289 W. For the random excitations, the amount of instantaneous power that corresponds to highway with gravels is much greater than that of smooth highway and by the increase of vehicle velocity from 10 to 50 km/h, there is an increase of average power for the both of tested randomly distributed irregular road types.

1. Introduction

Vehicles are responsible for a great portion of energy loss such as the energy dissipation due to rolling resistance phenomenon [1]. Analyses have revealed that should all light truck tires in California were changed to low-rolling resistance tires about 1135623.53 m^3/y of gasoline, or approximately one thousand million US dollar could be saved [2].

Energy harvesting is used to define the scavenging of ambient energy in the environment that would otherwise be dissipated. One important source of energy harvesting is the vehicle vibrations that could be used to feed the needed energy for vehicle active suspension system or batteries for later use. Mechanical vibration is a result of the continuous transformation of kinetic energy to potential energy and a periodic fluctuation of kinetic energy appears as a result of the aperiodic motion of a massive body. There is also a mechanical element (i.e. damper) that dissipates energy when the total amount of mechanical energy decreases during. Ref. [3] indicates that the full-active suspension consumes 10%–30% engine power, which takes 68%–72% of the total energy losses. Dimitrova and Marechal [4] showed the losses due to the rolling resistance and the aerodynamic of the vehicle takes about 37% of the total of energy loss. It was also found that the energy recovery system such as a pneumatic short-term storage system can lead to 20% of fuel improvement.

A typical vehicle suspension system is comprised of the passive elements of a viscous damper and spring while the vibrational energy is converted into heat energy due to the movement of fluid in the damper. An amount of 3–57 W of power dissipation was reported per damper [5]. It should be noticed that the harvested energy from vehicle suspension system can also be stored as an efficient source of electric energy is batteries or alternatively can be used to run the vehicle active suspension system components.

There are studies documented in the literature concerned with energy harvesting from different vehicles systems. As a prominent type of energy harvesting source from vehicle suspension system, the electromagnetic energy harvester can be mentioned. The

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Nomenclature

m_f	front wheel mass 50 kg
m_r	rear wheel mass 55 kg
m_b	the sprung mass 740 kg
x_f	vertical displacement of the front tire (m)
x_r	vertical displacement of the rear tire (m)
x_b	vertical displacement of the sprung mass (m)
u_f, u_r	road unevenness input at the front tire and the rear tire (m)
k_{sf}	stiffness of the front suspension 32000 N/m
k_{sr}	stiffness of the rear suspension 29000 N/m
k_{tf}	vertical stiffness of the front tire 28000 N/m
k_{tr}	vertical stiffness of the rear tire 28000 N/m
c_{sf}	damping of the front suspension 1200 Ns/m
c_{sr}	damping of the rear suspension 1100 Ns/m
c_{tf}, c_{tr}	vertical damping of the front tire and the rear tire 350 Ns/m
I_b	moment of inertia of the sprung mass kgm^2
θ	pitch angle of the sprung mass (°)

theory behind the electromagnetic method is based on the relative linear movement of an electrical coil attached to a mass with respect to a stable magnet (Fig. 1) [6]. The source to the linear relative movement of the coil-mass component with respect to the magnet is provided by the tire cyclic deformation and the vibration to generate electric current in the coil based on the Faraday's law of electromagnetic induction [6]. In Ref. [7], the feasibility study of the development of electromagnetic dampers for automotive suspension system application was conducted and they presented the concept, design, and modelling of a novel hybrid electromagnetic damper for automotive suspension applications. It was also indicated in Ref. [8] that the coupling of active/passive systems has the advantage of power consumption in active systems but with the saving of cost. A comparison of vehicle vibration energy harvesting between rotary and linear electromagnetic generators in terms of energy harvesting and ride comfort was presented in Ref. [9]. In order to assess the hybrid electromagnetic suspension system, the electromagnetic component was modelled as a 2DOF quarter-car model where three criteria were considered for evaluating the performance of the suspension system: ride comfort, road holding and regenerated power [10]. In Ref. [11], fabrication and testing of energy regenerative suspension for the energy harvesting purpose

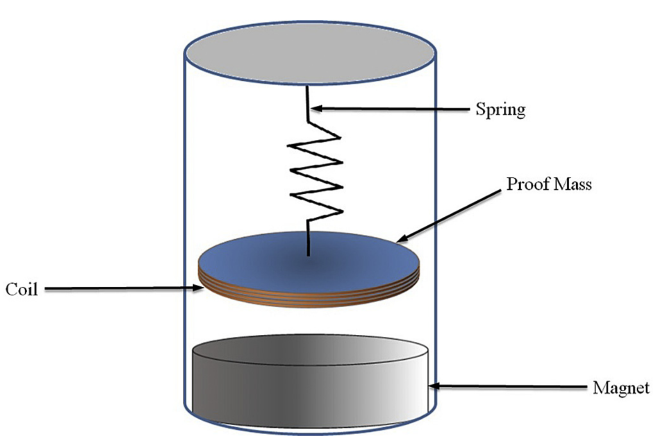

Fig. 1. A typical electromagnetic based energy harvester [6].

was presented based on the vertical motion of vehicle sprung mass relative to the unsprung masses. An analysis of the available power for being harvested through vehicle suspension system was implemented to compromise among energy harvesting, ride comfort, and road handling during the three phases of analysis, simulations, and experiments [12]. It was concluded that at the speed of 26.8 m/s on good and average roads, 100–400 W average power is harvestable in the suspensions of a vehicle with an average size.

Energy harvesting from suspension was investigated theoretically and experimentally concerned with harmonic excitation. Experimental analysis of the harvested energy was carried out using vehicle road apparatus [13]. The road frequency of 0.5 Hz–20 Hz was used to observe the behaviour of vehicle suspension and the maximum power of 984.4 W at frequency of 20 Hz was recorded.

In order to enhance ride comfort and handling as well as energy harvesting, a hydraulic pumping regenerative suspension based on an energy recovery unit and a hydraulic actuator was proposed [14]. It was revealed that an optimal regenerative power 33.4 W can be attained from regenerative suspension through the genetic algorithm optimization.

A hydraulic-electricity energy regenerative suspension was proposed to recapture the vibration based energy dissipation caused by irregular road. In this manner, a mathematical model of two degrees of freedom (DOF) was developed at a frequency of 1.67 Hz on a harmonic road [15].

The energy use from active suspension of railway vehicles was developed and the conditions for self-powered active suspension control was analysed. Linear quadratic regulator (LQR) algorithm was used to assess the effect of the performance index weighting factors to both the ride quality and the energy consumption. It was reported that with low energy harvesting restriction, the self-powered condition can be achieved [16].

A dual-mass piezoelectric based energy harvesting from ambient vibrations of a vehicle suspension system using the road roughness was modelled using mathematical calculations while the dual-mass piezoelectric bar harvester was considered to store energy for the later use in an electric charge [17]. Piezoelectric device has also shown a good potential in energy harvesting from tires as a part of vehicle suspension system with satisfactory performance [18]. There are also studies well documented in the literature that use the vibration from tire (as an important part of vehicle suspension system) to recapture energy or store it in batteries for a later application such as tire pressure monitoring systems TPMS. The background information about the application as well as requirements for an energy harvesting system from the inherent sources of vibrations was presented for the later purpose of Tire Pressure Monitoring System (TPMS) application in the tire/wheel assembly [19] while some designing considerations were presented for an energy harvesting device that is purposed for storing energy for running tire pressure monitoring system [20]. Harvesting the ambient energy of the deflected tire and converting it to electricity was assessed while the dependency of this energy to some important parameters such as the tire air pressure, vehicle speed and tire geometry and forces were further covered [21]. Similarly, a vibration energy harvesting device for tire pressure monitoring application based on a novel asymmetric air-spaced piezoelectric cantilever was documented in Ref. [22] and a battery-less tire pressure monitoring system with piezoceramics mode energy harvesting was further investigated [23].

The energy harvester for vehicle suspension vibration can be both piezoelectric transducer [24] and electromagnetic transducer [12]. For energy harvesting system with electromagnetic conversion, the damper of the suspension can be replaced with an electromagnetic energy transducer, which is composed of an