Applied Energy 229 (2018) 672–699

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Vibration energy harvesting in automotive suspension system: A detailed review

Mohamed A.A. Abdelkareem[a,b,*], Lin Xu[a,*], Mohamed Kamal Ahmed Ali[a,b], Ahmed Elagouz[a,b], Jia Mi[a], Sijing Guo[a,c], Yilun Liu[c], Lei Zuo[c,*]

[a] School of Automotive Engineering, Wuhan University of Technology, Wuhan 430070, China
[b] Automotive and Tractors Engineering Department, Faculty of Engineering, Minia University, El-Minia 61111, Egypt
[c] Department of Mechanical Engineering, Virginia Tech, Blacksburg, VA 24060, USA

HIGHLIGHTS

- State-of-the-art of the energy harvesting based vehicle suspension is introduced.
- Different electromagnetic harvesting-based dampers are presented and compared.
- The challenging issues and research gaps that remain unresolved are addressed.
- The given synthesis to regenerative suspensions is helpful for future research.

ARTICLE INFO

Keywords:
Energy harvesting
Vehicle suspension
Regenerative dampers
Electromagnetic harvesters
Vibration

ABSTRACT

Hydraulic shock absorbers have come into widespread use in vehicle suspensions since decades ago to effectively reduce the acceleration of vehicle bodies and maintain good contact between tires and ground under road irregularities. Although energy efficiency has been a major concern in the automotive industry since the mass production in the 1900s, researchers realized that the energy dissipated in traditional hydraulic shock absorbers is worthy of being recovered only in the middle of 1990s. Since then, many different types of energy harvesting based shock absorbers were conceptualized and prototyped. Unlike traditional suspension systems which suppress the vibrations by dissipating the vibration energy into waste heat, the regenerative suspension with energy harvesting shock absorbers can convert the traditionally wasted energy into electricity. This paper is a comprehensive review on energy harvesting based vehicle suspensions. Specifically, it focuses on an analytical and statistical study of the vehicle regenerative suspensions and reviewing the concepts, designs, simulations, test rig experiments and vehicle road tests. The most common energy harvesting systems in vehicle suspensions are compared in terms of advantages and limitations. In addition, the challenging issues and research gaps that remain unresolved are addressed and some recommendations regarding such challenges are stated for further research.

1. Introduction

Traveling on roads, vehicles are subjected to different disturbances such as road irregularities, braking forces, acceleration forces, and centrifugal forces on a curved road which cause discomfort to the driver and passengers and influence maneuverability. Passive suspensions, composed of viscous hydraulic shock absorbers and springs in parallel, have been widely used to suppress the vibration by dissipating the undesired mechanical energy into heat waste. The active and semi-active suspensions have been investigated extensively in the past 40 years showing improved vehicle dynamic performances at the cost of complexity and additional energy consumption [1–3]. However, the passive suspension system is still dominating in the automotive industry because of its simple structure, high reliability, and low cost.

Reducing vehicle energy losses is necessary for improving fuel economy, reducing emissions, and supplying other systems power demand [4–6]. In addition to improving engine and powertrain efficiency, we may also harvest the energy wasted in vehicles including the recovery of wasted heat energy [7–9], regenerative braking energy [10–12], and vibrational energy on shock absorbers [13,14].

* Corresponding authors at: School of Automotive Engineering, Wuhan University of Technology, Wuhan 430070, China (M.A.A. Abdelkareem).
E-mail addresses: mohamed.a.ali@mu.edu.eg (M.A.A. Abdelkareem), xulin508@whut.edu.cn (L. Xu), leizuo@vt.edu (L. Zuo).

https://doi.org/10.1016/j.apenergy.2018.08.030
Received 14 April 2018; Received in revised form 26 July 2018; Accepted 6 August 2018
0306-2619/

Abbreviations

AC	Asphalt Concrete Pavement
AERS	Active and Energy Regenerative Suspension
CAD	Computer Aided Design
CD-EHSA	Cable-Dynamics Energy Harvesting Shock Absorber
EM	Electro-Magnetic
eROT	Electromechanical Rotary Damper Technology
EVDG	Electromagnetic Vibration Driven Generator
FTP	Federal Test Procedure
GA	Genetic Algorithm
HESA	Hydraulic Electromagnetic Shock Absorber
HMR	Hydraulic Motion Rectifier
HWFET	Highway Fuel Economy Test
IRI	International Roughness Index
MMR	Mechanical Motion Rectifier
MMR-EHSA	Mechanical Motion Rectifier-Energy Harvesting Shock Absorbers
NEDC	New European Driving Cycle
NonMMR-EHSA	Non-Mechanical Motion Rectifier-Energy Harvesting Shock Absorbers
PCC	Portland Cement Concrete Pavement
SDOF	Single Degree of Freedom
WLTP	Worldwide Harmonized Light Vehicles Test Procedure

Regenerative suspensions with the energy harvesting shock absorber have gained tremendous attention in the past two decades as promising directions in vehicle research because of its potential to enable the suspension system not only providing enhanced dynamic performance but also converting the wasted vibration energy to electricity. After the early trial in the middle of 1990s [15–17], the number of publications per year on regenerative energy suspensions has been exponentially increased over the last decade, as illustrated in Fig. 1.

Energy harvesting potential based vehicle suspensions and its effect on fuel saving have been estimated extensively by several scholars. Zuo and Zhang [18] demonstrated that the potential energy of a typical passenger car is between 100 and 400 W considering that the car is traveling on good and average roads with a 97 km/h approximately. Consequently, for an energy conversion efficiency of 75%, 300 W of electrical power can be achieved which corresponds to 3% fuel efficiency improvement according to BMW's data on the electricity need in typical passenger cars [19]. Levant Power engineers [20] also emphasized such a positive effect on the fuel saving if such a power loss is partially recovered in which an average power of 1 kW could be captured from a 3-axle truck on a highway which is possibly enough to replace the high-power alternator from heavy-duty trucks or military vehicles. Additionally, Audi Automotive Group (Audi AG.) [21] reported the possibility of reducing carbon dioxide (CO_2) for hybrid vehicles with energy harvesting based suspension in which a 3 g/km of CO_2 emission reduction could be achieved for a hybrid passenger automobile traveled on German roads. Moreover, Audi AG. engineers expected that harvesting this otherwise dissipated energy could improve the fuel economy by 0.7 L per 100 km. Figs. 2 and 3 summarize the energy harvesting potentials and fuel efficiency benefits for different vehicles. The power capacity is related to the vibration intensity levels meaning that the aggressive vibrations can collect more power and save more fuel which manifested obviously in case of heavy trucks and off-road vehicles. For example, as for the fuel cost saving, harvesting the otherwise dissipated energy from small road bumps in Wal-Mart trucks could save $13 million a year [22]. In addition to fuel-saving, several studies have been carried out for achieving better ride quality and road handling using the energy harvesting absorbers through different strategies such as tunable damping and variable inerter [23–25].

Different strategies of regenerative suspension systems have been investigated and proposed to recover the otherwise dissipated energy in vehicle suspension. The energy harvesting mechanisms for suspension systems have also been investigated with an aim to improve the fuel efficiency and thus reduce energy consumption [27–30]. Practically, the harvested energy from suspension vibrations could be used for charging batteries and supplying electrical loads as a supplement to the vehicle alternator [31,32]. Otherwise, it may have the potentiality to provide the energy demand of the semi-active or active suspensions as a self-powered controllable damper to achieve better ride quality and road handling [33–35].

The regenerative based shock absorbers can be classified based on how the perpendicular vibrations are translated into electricity. Among various vibration energy harvesting structures, the electromagnetic harvesters have gained popularity in vehicle regenerative based suspensions because of the high-energy conversion efficiency, quick response, strong controllability, and capability in energy recovery [36–38].

The electromagnetic motors were first proposed to be used as energy harvesting dampers two decades ago since then the electromagnetic shock absorbers have been the main interest of many scholars. Mainly, the energy harvesting suspension mechanisms can be classified as linear electromagnetic harvesters [39,40] and rotary electromagnetic harvesters [41–43]. The linear electromagnetic harvester converts the energy potential of vertical oscillations directly into electricity based on electromagnetic induction with a simple structure. While the rotary electromagnetic harvester translates the linear vertical vibration into rotational oscillation of the generator and produces electrical energy based on linear-to-rotary transmission mechanisms. The rotary electromagnetic harvesters can be more compact and have high energy density than linear harvesters [44].

In rotary based electromagnetic harvesters, there are two common kinds of linear-to-rotary motion transmissions, the mechanical based transmission and the hydraulic based transmission. The mechanical transmission based harvester has been developed rapidly because of its simple construction, greater efficiency, and considerable average power [45]. Many proposed designs of the mechanical regenerative shock absorber have been introduced including ball screw mechanism [46,47], rack-pinion mechanism [48,49] and other mechanisms [50,51]. The second category of the rotary electromagnetic harvesters is the hydraulic regenerative shock absorbers which harvest the

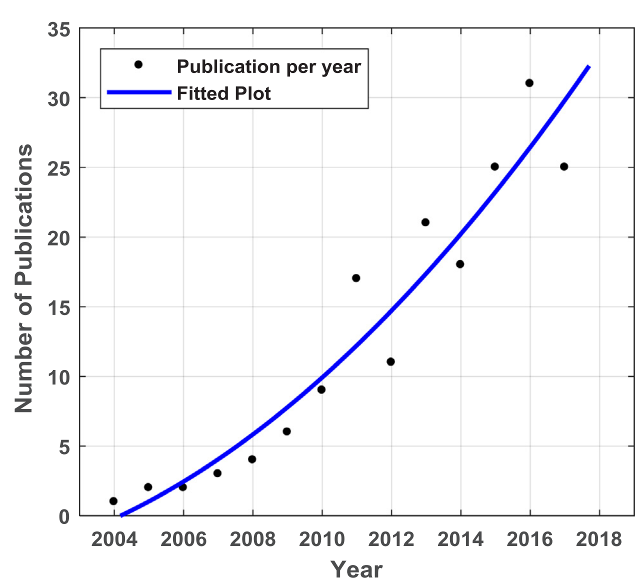

Fig. 1. Publication profile over the last decade regarding energy regenerative suspension. [Drawn according to the literature survey].