Energy xxx (2016) 1–10

Contents lists available at ScienceDirect

Energy

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

Energy conversion mechanism and regenerative potential of vehicle suspensions

Yuxin Zhang [a, b, *], Konghui Guo [a], Dai Wang [c], Chao Chen [d, **], Xuefei Li [d]

[a] State Key Laboratory of Automotive Simulation and Control, Jilin University, Changchun, Jilin 130022, China
[b] Department of Control Science and Engineering, Jilin University, Changchun, Jilin 130022, China
[c] Energy Storage and Distributed Resources Division, Lawrence Berkeley National Lab, Berkeley, CA 94720, USA
[d] College of Mechanical Science and Engineering, Jilin University, Changchun, Jilin 130022, China

ARTICLE INFO

Article history:
Received 7 July 2016
Received in revised form
12 September 2016
Accepted 8 November 2016
Available online xxx

Keywords:
Vehicle suspensions
Vibration energy
Oil temperature-rise
Energy conversion
Energy harvesting

ABSTRACT

Vehicle suspension vibration can cause damping oil temperature-rise, which further effects the suspension performance, rapids the suspension failure, and goes against the vehicle fuel efficiency. This paper focuses on the suspension vibration energy conversion mechanism and energy harvest potential analysis. A mathematical model is developed to characterize the oil temperature-rise and damping force change which is then verified by experimental tests. Both simulation and test results show that the damping oil temperature rises with the excitation time and damping force decreases as the oil temperature rises. The equilibrium temperature almost reaches to 105 °C under sinusoidal excitation with 0.52 m/s maximum speed, and the damping force decreases significantly when the temperature rises from −20 °C to 100 °C. Then the energy flow of regenerative suspension system is analyzed and the suspension energy regenerate potential is explored based on the quarter vehicle model and road roughness model. The model simulation results show that vehicles with large mass, relatively high driving speed, and bad driving conditions have a good application prospect for the regenerative suspension systems.

1. Introduction

Recent research on the energy-saving and low-carbon vehicles has focused on the vehicle energy flow and its relationship with vehicle performance [1–3]. Ref. [1] shows that only about 14%–30% of the energy from the fuel is used to move it in a gasoline vehicle. For hybrid electric vehicles, it is possible to improve fuel efficiency by carefully design its energy management system [2]. What's more, some other advanced technologies, e.g. thermoelectric systems [3], also have potential to improve fuel efficiency. After decades of effort, powertrain energy flow management and braking-energy recovery system have been close to mature and used in vehicle industry [4,5]. However, the research on suspension energy flow and its influences on vehicle performance are still in the initial stage [6]. Suspension system is an important part of the vehicle chassis, which plays a key role in supporting vehicle body and absorbing the vibration caused by road roughness, and has a direct impact on ride comfort and driving safety [7].

The traditional passive suspension system has following problems: (1) its fixed damping characteristics are difficult to meet the different requirements of variable driving conditions; (2) a substantial amount of vibration energy is dissipated as heat, which goes against the vehicle fuel efficiency; (3) the serious temperature-rise of damping oil will lead to attenuation of damping force and acceleration of the suspension system failure [8]. Therefore, it is significant to study the suspension energy conversion mechanism and explore the regenerative mechanism and potential of suspension vibration energy.

Several auto-parts suppliers (such as ZF Sachs, Delphi, MANDO, etc.) carried out researches on damping oil temperature-rise mechanism, suspension parts optimization, and suspension system design. In the meantime, OEMs (such as Volkswagen, GM, Toyota, etc.) conducted the study on the relationship between the damping oil temperature-rise and vehicle performance [9]. The main research works are: (1) description of damping oil

* Corresponding author. State Key Laboratory of Automotive Simulation and Control, Jilin University, Changchun, Jilin 130022, China.
** Corresponding author.
E-mail addresses: zhangyuxin312@163.com (Y. Zhang), jluchenchao@163.com (C. Chen).

http://dx.doi.org/10.1016/j.energy.2016.11.045
0360-5442/

temperature-rise and modelling of shock absorber thermodynamic [10,11]; (2) suspension system thermal - mechanical coupling model based on suspension characteristics analysis [12]; (3) analysis oil temperature-rise influence factors via damper dynamometer tests [13]; (4) design and development of new damping system with temperature compensation function [14]; (5) semi-active or active damping control system considering oil temperature change [15].

It is noteworthy that all above researches, no matter considering the relationship between oil temperature-rise characteristics and vehicle performance, realizing temperature compensation via passive adaptive damper design, or using semi-active/active control methods to compensate the damping force attenuation caused by oil temperature-rise, their damping force generating mechanism has not been changed, which is, all suspension vibration energy is transformed into heat and dissipated into the surrounding environment. Therefore, a new research focus arises: whether there is an energy recovery system, which can harvest the suspension vibration energy into useful energy, e.g. electricity, rather than heat dissipation, avoid various hazards caused by damping oil temperature-rise and at the same time, improve the vehicle fuel efficiency.

Some researchers carried out preliminary studies on vehicle suspension energy recovery potential [16–19], but there is a significant difference in the specific amount of energy recovery, various from 46 W [19] to 7500 W [16] in a full vehicle suspension system.

Audi AG engineers did different road tests to reveal the suspension energy harvesting potential of passenger cars [20]. The results show that the average recovery power is about 150 W when the passenger car is driven on German roads, 3 W on newly paved highways, and 613 W on the rugged country road. In these tests, 3 g CO_2 emission reduction is achieved per kilometer driving.

Levant Power engineers carried out extensive simulations and experiments to invest how their developed GenShock, an electro-hydraulic regenerative shock absorber, influences the fuel efficiency of different vehicle models [21]. As shown in Fig. 1, more than 6% fuel efficiency improvement is achieved in military and off-road vehicles, and 7%–10% for hybrid and electric vehicles. Another analysis from this company shows that 1 kW average power can be harvested from six shock absorbers of a heavy duty truck on general highway, which is enough to replace the high – power generator from heavy trucks or military vehicles.

This paper will focus on the suspension vibration energy conversion mechanism based on a thorough analysis of different parts of suspension energy conversion and different types of heat transfer modes, and then conduct a series of energy harvest potential analysis for different kinds of vehicle suspension system. These researches are significant for the traditional and regenerative suspension design, but rarely appear in current literature. The rest of this paper is organized as follows. In Section 2, the suspension system energy conversion mechanism is analyzed and its mathematical model is introduced. Simulation and experimental verification results of the oil temperature-rise and damping characteristics are given in Section 3. Based on a suspension vibration model and a road roughness model, Section 4 studies the suspension energy regenerative mechanism and potential. This is followed by the concluding remarks in the final section.

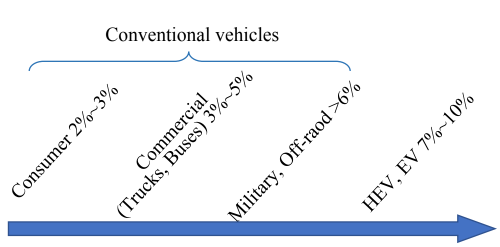

Fig. 1. Fuel efficiency improvement by using GenShock.

2. Suspension energy conversion mechanism

The suspension energy, in this paper, refers to the reciprocating vibration energy of the vehicle suspension system, which is mainly caused by the uneven road surface. Although it is caused by the road roughness excitation, its ultimate source is also from the vehicle powertrain, which is a part of the total engine/motor output energy. Therefore, suspension energy has a certain impact on vehicle fuel efficiency.

According to the energy conversion process of the traditional suspension system shown in Fig. 2, relative movement and related vibration energy between the body and the wheel are caused by the uneven road. A small portion of the vibration energy is dissipated by the tire [22], and most of it is absorbed by the suspension spring, which is used to buffer the impact from the uneven road to vehicle body. However, the spring only dissipates a small part of the absorbed vibration energy, it will release most of the vibration energy. The role of passive shock absorber is to consume this energy by transforming it into thermal energy via damping oil.

2.1. Mechanism analysis and hypothesis

During the vehicle driving process, the micro roughness of the uneven road can be buffered and absorbed by the tire [23]. The tire can be equivalent to a “rigid wheel-spring-damper” system, see Fig. 3(a). Due to the existence of the damping force during the tire deformation process, the released energy is less than the absorbed energy, the difference of energy is dissipated by tire damping via heat, see Fig. 3(c).

During compression/extension process, different types of suspension springs also dissipate vibration energy due to the internal damping effect. There is no energy loss in cylindrical helical springs since it can be considered as without friction, see Fig. 4(a); there is external friction in circular springs, disc springs and leaf springs, see Fig. 4(b); non-metallic springs and air springs are with internal friction, see Fig. 4(c). The springs in the latter two cases will transform and dissipate a part of the vibration energy into heat, and the dissipated energy value equals to the annular area.

Among the entire suspension vibration energy, the percentage of above two parts of energy dissipation (by tire and suspension spring) is very small. Therefore, the following discussion will only focus on the detailed analysis of the shock absorber energy conversion process.

Traditional shock absorber repeats the following energy conversion process during its reciprocating movement: “reciprocating vibration energy transforms into damping oil heat → oil temperature rises → oil heat transfers to cylinders → cylinders heat converts to external environment → oil temperature reduces”, in which, the energy conduction, convective heat transfer, radiative heat transfer, and temperature change are occurring at the same time. In the initial stage, the heat absorbed by the shock absorber is much larger than the dissipated heat, therefore the internal temperature of the shock absorber increases. The whole system will not achieve its thermal equilibrium until the absorbed heat equals to dissipated heat. The damping oil temperature at thermal equilibrium is defined as the thermal equilibrium temperature of the shock absorber under certain condition.

In above heat transfer process, the simultaneous action of heat conduction, convection heat transfer and radiation heat transfer are

Please cite this article in press as: Zhang Y, et al., Energy conversion mechanism and regenerative potential of vehicle suspensions, Energy (2016), http://dx.doi.org/10.1016/j.energy.2016.11.045