Available online at www.sciencedirect.com

ScienceDirect

Journal of the Franklin Institute 352 (2015) 485–499

Journal of The Franklin Institute

www.elsevier.com/locate/jfranklin

Study on a novel hydraulic pumping regenerative suspension for vehicles

Yuxin Zhang[a], Xinjie Zhang[a,b,*], Min Zhan[a], Konghui Guo[a,b], Fuquan Zhao[c], Zongwei Liu[c]

[a]State Key Laboratory of Automotive Simulation and Control, Jilin University, Changchun, Jilin 130022, China
[b]State Key Laboratory of Advanced Design and Manufacture for Vehicle Body, Hunan University, Changsha, Hunan 410082, China
[c]Tsinghua Automotive Strategy Research Institute, Tsinghua University, Beijing 10084, China

Received 28 January 2014; received in revised form 20 April 2014; accepted 11 June 2014
Available online 21 July 2014

Abstract

In order to improve the vehicle fuel economy, ride comfort and handling, this paper presents the design, modeling, and performance study of a novel hydraulic pumping regenerative suspension based on an energy recovery unit and a hydraulic actuator. It can harvest energy from suspension vibration and lessen damping oil temperature rising. In addition, variable damping force can be achieved by controlling the electrical load of the energy recovery unit, and proper asymmetric ratio of compression/extension damping force needed by traditional vehicles can be obtained via the special layout of this suspension. It shows that an optimal regenerative power 33.4 W can be obtained from each regenerative suspension via the GA optimization. The physical based model and parameter study in this paper can be used in the regenerative suspension semi-active controller design and the development of this novel hydraulic pumping regenerative suspension in the future.

Keywords: Regenerative suspension; Asymmetric damping forces; Unidirectional pumping oil; Optimization

*Corresponding author at: State Key Laboratory of Automotive Simulation and Control, Jilin University, Changchun, Jilin 130022, China. Tel.: +86 13844843214.
E-mail address: xjzhang5885@gmail.com (X. Zhang).

http://dx.doi.org/10.1016/j.jfranklin.2014.06.005
0016-0032/

1. Introduction

Suspension system plays an important role in the vertical force restriction, is used to improve the vehicle ride comfort and handling, and the vertical force between the vehicle body and wheel which comes from irregular road surfaces and internal disturbances created by dynamic roll and pitch which can be resisted, as well as vertical body acceleration, roll and pitch movement and dynamic wheel load [1]. The damping force created by shock absorbers in traditional suspension is mainly based on orifice compensation, which transfers the vibration energy into the damper oil heat, then dissipating into surroundings through the tubes [2]. Such dissipated heat energy, which originates from the fuel consumption of the engine, affects the vehicle power performance and fuel efficiency [3], and causes the following problems: leading to the damping oil viscosity change which influences the damping characteristic [4], accelerating seal parts aging, and bringing the damping fluid cavitation [5].

With fixing the mentioned issues, energy harvesting and storing attract wide attention. At present, piezoelectric crystals or smart materials are widely used in vibration energy harvesting [6], and the electromagnetic and electrohydraulic are two main types of regenerative shock absorber for a vehicle suspension. Suda et al. [7] developed a self-powered active suspension via a linear DC motor which can be used as an actuator and an energy regenerative damper. Kawamoto et al. [8] proposed an electro-mechanical suspension system (EMS), which consists of a DC motor and a ball screw mechanism, and discussed the energy consumption and vibration isolation through the contour maps. Zhang et al. [9] designed active and energy regenerative controllers based on $H\infty$ control for a similar EMS suspension, which contains a restriction strategy for realizing energy regeneration. Meanwhile, effects of uncertainties were also investigated. Pires et al. [10] conducted a study on the power extraction efficiency and its effect on vehicle dynamics and control. A passive electrical controller was proposed and optimized for a vehicle vibration isolation and energy efficiency. Singal et al. [11] also proposed a zero-energy active suspension based on a ball screw mechanism and electrical motor–generator. With an adaptive sky-hook damping control, this system performed as a passive system for full frequencies, and was equivalent to an active system for a broad range of frequencies including both the sprung mass and unsprung mass resonant frequencies. Zuo et al. [12] developed a linear electromagnetic shock absorber, which was essentially a four-phase linear generator via rare-earth permanent magnets and high permeable magnetic loops. A 1:2 scale prototype was developed and could harvest 16–64 W power at 0.25–0.5 m/s RMS suspension velocity. With combining a permanent magnetic generator and a rack–pinion mechanism, Li et al. [13] designed a regenerative shock absorber, with variable damping coefficients and asymmetric feature in jounce/rebound motions by controlling the electricity of the shock absorber. Song et al. [14] patented an energy harvesting suspension system, which generally included at least one regenerative damper, a module, an electric switch, and a battery, could switch between the passive mode and semi-active mode and convert the mechanical vibration energy into a voltage.

Some patents [15–18] unfolded several electrohydraulic energy harvesting suspensions, which use the oil fluid to drive a hydraulic motor and then drive an electric generator to generate electricity. Some of them involved active control by using the electric generator as an electric motor which drives the hydraulic motor to provide an active damping force. However, all of these patents are still in the conceptualization stage and there are no quantitative study disclosed about the suspension performance and regenerative efficiency.

In the above studies, the electric generators need to switch rotation direction frequently under irregular road surfaces, which reduces the regenerative efficiency and the system reliability.