Mechanical Systems and Signal Processing 106 (2018) 94–113

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

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

Vibration control of an energy regenerative seat suspension with variable external resistance

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ARTICLE INFO

Article history:
Received 28 September 2017
Received in revised form 22 December 2017
Accepted 26 December 2017

Keywords:
Semi-active control
Energy harvesting
Energy regenerative
Vibration control
Seat suspension

ABSTRACT

In this paper, an energy regenerative seat suspension with a variable external resistance is proposed and built, and a semi-active controller for its vibration control is also designed and validated. The energy regenerative seat suspension is built with a three-phase generator and a gear reducer, which are installed in the scissors structure centre of the seat suspension, and the vibration energy is directly harvested from the rotary movement of suspension's scissors structure. The electromagnetic torque of the semi-active seat suspension actuator is controlled by an external variable resistor. An integrated model including the seat suspension's kinematics and the generator is built and proven to match the test result very well. A simplified experimental phenomenon model is also built based on the test results for the controller design. A state feedback H_∞ controller is proposed for the regenerative seat suspension's semi-active vibration control. The proposed regenerative seat suspension and its controller are validated with both simulations and experiments. A well-tuned passive seat suspension is applied to evaluate the regenerative seat's performance. Based on ISO 2631-1, the frequency-weighted root mean square (FW-RMS) acceleration of the proposed seat suspension has a 22.84% reduction when compared with the passive one, which indicates the improvement of ride comfort. At the same time, the generated RMS power is 1.21 W. The proposed regenerative seat suspension can greatly improve the driver's ride comfort and has the potential to be developed to a self-powered semi-active system.

1. Introduction

As the demands for the driver's ride comfort and health are increasing, the vehicle seat suspension design and control are widely studied in recent years. Semi-active and active seat suspensions are proposed to replace the conventional passive seat suspension [1–4]. There is no doubt that the active seat suspension has best performance in improving ride comfort, however, the high energy consumption is still the main issue for its practical application. On the contrary, the semi-active seat suspension consumes less energy and provides acceptable performance; but the conventional semi-active seat suspension, for example, the magnetorheological (MR) damper seat suspension, still needs considerable extra energy to control its

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https://doi.org/10.1016/j.ymssp.2017.12.036
0888-3270/

damping variation. So, an energy regenerative seat suspension will be a good option for future vehicles, especially for electrical vehicles.

The regenerative vehicle suspensions, which can harvest energy from the road vibration, are being studied recently [5–9]. Two kinds of motors or generators are applied, namely the rotary one and the linear one. Generally, the regenerative vehicle suspension with rotary motor needs a mechanism, such as rack and pinion, to transfer the linear suspension movement to rotary movement [10,11]. On the contrary, the linear generator can directly harvest the vibration energy [12–14]; but, with a given space, the rotary generator is capable of generating more power [15]. A regenerative mechatronic damper is proposed for vehicular applications [9]; it applied a three-phase full-bridge boost converter which has been widely applied in motor applications to control the current [16]. It is believed that the regenerative suspensions should be combined with the energy harvesting and vibration control for their promising prospect [17]. Shi et al. [18] proposed a semi-active energy regenerative suspension and studied the ride comfort improvement with experiment; but an additional adjustable shock absorber is needed. For providing enough damping force, the MR and electrorheological (ER) fluid based regenerative vehicle suspensions are proposed [19,20]. Because the seat suspension requires less damping force than the vehicle suspension, with a careful design, the electromagnetic force will be enough for vibration isolation [21].

In this paper, the vibration control of a regenerative seat suspension with variable resistance is studied. The contributions of this paper are listed as following:

- An energy regenerative seat suspension is designed and built with a three-phase AC motor (generator) and a gear reducer, which are installed in the centre of the scissors structure of a seat suspension. The rotary torque of the generator can be transformed to a vertical force with the original seat structure instead of using additional transmission devices.
- A semi-active control system prototype is built for the proposed regenerative seat suspension. The suspension's damping and stiffness are controllable by controlling a variable external resistance. Rotating a rheostat requires few energy consumption to overcome its very small friction torque and considering the energy regenerative characteristic, the proposed system has the potential to be a self-powered system.
- The regenerative seat suspension is comprehensively tested and the result is fitted with an integrated model including the seat suspension's kinematics and the generator.
- A simplified phenomenon model is built based on tests for controller design. Then, a semi-active state feedback H_∞ controller is proposed for the regenerative seat suspension, and it is validated with both numerical simulations and practical experiments.

The rest of the paper is organized as following: Section 2 presented the semi-active regenerative seat suspension system; Section 3 proposed a controller for the seat suspension; the simulation and experimental results are presented in Section 4; Finally, Section 5 presents the conclusions of this research.

2. Semi-active regenerative seat suspension system

2.1. System design and prototype building

A regenerative seat suspension system schematic diagram is shown in Fig. 1, where the vibration energy is stored in a battery by an energy storage circuit. The regenerative shock absorber produces electromagnetic force when it harvests energy from vibration. In this paper, the electromagnetic force can be controlled for isolating vibration and the regenerative shock absorber can be taken as a semi-active actuator. Generally, a rectifier is applied to transform the induced alternating current (AC) to direct current (DC) for the easy storage of energy. The principle of this semi-active system is shown in Fig. 2, where the regenerative shock absorber is working as an electromagnetic generator which has internal resistance and internal inductance. The electromagnetic force can be controlled by varying the external resistance of the circuit.

A regenerative seat suspension prototype is designed and built based on a modification of a normal passive seat suspension (GARPEN GSSC7) for heavy duty vehicles (see Fig. 3). The proposed regenerative seat suspension removed the original damper in Fig. 3(c), and installed an electromagnetic generator on the centre of left side scissors structure instead. With this modification, the rotary torque generated by the generator is transformed to a vertical force without additional transmission

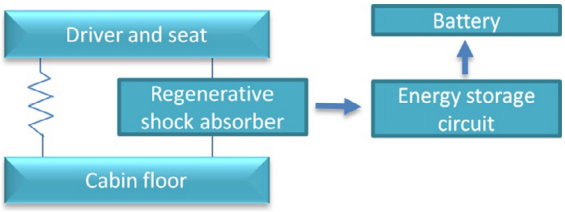

Fig. 1. Schematic of the regenerative seat suspension system.