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Self-powered suspension criterion and energy regeneration implementation scheme of motor-driven active suspension ☆

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ABSTRACT

Active suspension systems have advantages on mitigating the effects of vehicle vibration caused by road roughness, which are one of the most important component parts in influencing the performances of vehicles. However, high amount of energy consumption restricts the application of active suspension systems. From the point of energy saving, this paper presents a self-powered criterion of the active suspension system to judge whether a motor-driven suspension can be self-powered or not, and then a motor parameter condition is developed as a reference to design a self-powered suspension. An energy regeneration implementation scheme is subsequently proposed to make the active suspension which has the potential to be self-powered achieve energy-saving target in the real application. In this implementation scheme, operating electric circuits are designed based on different working status of the actuator and power source and it is realizable to accumulate energy from road vibration and supply energy to the actuator by switching corresponding electric circuits. To apply the self-powered suspension criterion and energy regeneration implementation scheme, an active suspension system is designed with a constrained H_∞ controller and calculation results indicate that it has the capability to be self-powered. Simulation results show that the performances of the self-powered active suspension are nearly the same as those of the active suspension with an external energy source and can achieve energy regeneration at the same time.

1. Introduction

In the past decades, active suspension systems have become a hot topic both in automotive industrial and academic area, and an immense development has been made based on various mechanical designs and control technologies [1–4]. Most of scholarly studies about active suspensions are focused on the actuator and control scheme, and lots of remarkable results have been proposed to improve the ride comfort and/or ensure the safety based on various control technologies, such as adaptive control [5–8], robust control [9–11], and intelligent control [12,13]. A complete analytical solution of the *LQ* problem is developed to realize optimal active suspension control based on a half-car model in [14]. To adapt to uncertainties and

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parameter variances of the active suspension system, the model reference adaptive control approach is presented [15], which prevents much performance degradation caused by changes in suspension characteristics. A constrained H_∞ control scheme is proposed [16] to deal with the suspension system with time-domain constraints and manage a trade-off between conflicting performances. Further, a finite frequency H_∞ control approach is presented due to the fact that human body is sensitive to vibration in a specific frequency range [17]. The Takagi-Sugeno (T-S) fuzzy controller is applied to the active suspension system to handle nonlinearity and uncertainty [18].

Despite employing advanced control algorithms and actuators, high energy consumption, complex mechanism, and low reliability still limit the application of the active suspension in practical industrial applications. In recent years, researchers pay much attention to reducing energy consumption of active suspensions to make them widely used. Literature [19] presents a principle to select characteristic parameters of the elastic constant of the spring and damper to minimize power consumption. The damper and the spring should be designed to dissipate and exchange the same amount of energy as an ideal actuator would do in order to reduce the energy required by the irreversible actuator. In [20], an electro-dynamic actuator is applied to a single degree-of-freedom active suspension which can regenerate vibration energy when the disturbance is at a high speed. The active suspension system can achieve the self-powered goal by making use of road vibration with an electric actuator and a practical system is demonstrated concretely in [21]. With the controller based on model predictive control, two suspension control modes, consumptive full active control mode and regenerative semi-active mode, are designed in order to reduce energy consumption in [22]. Consumptive full active control mode aims at improving vehicle ride comfort, while regenerative semi-active mode emphasizes energy regeneration by virtue of vibration energy caused by the uneven road, and simulation results show that the design can realize good vibration control of vehicle body and make the battery charged by regenerated energy. On the basis of the researches mentioned above, we can see that by recycling vibration energy excited by the rough road, it is attainable to consume less energy, and even to achieve a self-powered suspension while ensuring good vehicle performances at the same time. According to the review above, these researches provide us plenty of knowledge about energy regenerative suspensions. However, in existing researches, an active controller is first to be designed and then energy consumption is discussed based on this specific active suspension. These studies lack a judgement standard about energy regeneration capability which is applicable to all the active suspensions using different control methods. Therefore, it is meaningful to establish a systematic design framework of energy regenerative active suspensions to promote the use value of active suspensions. In this paper, in the light of energy balance of the motor actuator, a self-powered suspension criterion and detailed energy regeneration implementation scheme are presented in the first place, and then both the active control approach and the motor parameters can be designed in order to meet the proposed self-powered suspension criterion, achieving the energy regeneration of active suspensions. Performances compared with those of the original active suspension will be displayed via simulation.

The rest of the paper is organized as follows. In Section 2, energy flow in the simplified electric circuit of the actuator is analyzed and the working state of the motor is categorized into three operating zones based on combinations of different working status of the motor and power supply. The criterion to realize a self-powered suspension is presented from the perspective of energy balance to judge whether a certain active suspension can be self-powered or not, and a motor parameter condition is given which can be referred to when selecting the DC motor for an active suspension system. An energy regeneration implementation scheme is designed for physical realization of a self-powered suspension in Section 3. In this scheme, there are three working modes of the suspension: drive mode, brake mode, and regeneration mode, corresponding to the three operating zones of the motor. Operating electric circuits applied to different working states are illustrated at the same time to realize commands of energy reclaim and supply. In Section 4, a quarter-car model of suspension is established and a constrained H_∞ approach is applied to build an active suspension system. In Section 5, simulation is carried out between the self-powered suspension and the active suspension with the same controller, and results are compared in terms of performances and properties of the two suspensions.

2. Analysis of energy flow and criterion of self-powered suspension

In this paper, linear DC motors are used as actuators of active suspensions to realize potential energy recovery. Analyzing the simplified armature circuit, the operating state of the motor can be divided into 3 zones [23]. Based on the energy consumption and regeneration of the motor, theoretical analysis about energy-saving efficiency of an energy regenerative suspension is made. Further, the criterion to achieve a self-powered suspension is obtained and the value ranges of motor parameters are given based on the self-powered criterion.

2.1. Energy balance of DC motor

In motor-driven active suspensions, allowing for the voltage of battery, the working states of the DC motor can be divided into 4 types, and relevant working circuits are demonstrated in Figs. 1–4, where U_s is supply voltage of the circuit, R is resistance of the armature, E is induced voltage, i is armature current, and armature inductance is neglected. The sizes and directions of the voltage and current, relationship between electromagnetic force and motor motion, and energy conversion about these four working states are illustrated first, which lays the foundation of the subsequent analysis of energy flow in the DC motor.