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Performance-oriented controls of a novel rocker-pushrod electromagnetic active vehicle suspension

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ABSTRACT

This paper presents a novel active vehicle suspension rocker-pushrod electromagnetic actuator (EMA) that has the features of easy manufacturing and modular design. Considering the nonlinear influence of the reducer on unsprung mass and the nonvertical arrangement of the spring, parameter perturbation bounds are determined through analysis. To provide drivers with more choices and driving pleasure, performance-oriented controllers are designed by frequency shaping in the sense of H_∞ norm, generating comfort mode, sport mode and hybrid mode respectively. Vehicle suspension performances under different modes are compared in both frequency and time domains, while the system robustness against parametric variations is verified by 81 perturbed systems. To verify the improvement of ride comfort and handling stability, a quarter-vehicle prototype is constructed. Test results show that when driving over certain bumps at speed of 1.4 m s^{-1}, the average regenerated power of the designed EMA is 50.11 W with the system efficiency of 60%–70%.

1. Introduction

Performing the function of vibration isolation between the vehicle body and wheel with constant spring stiffness and damping coefficient, a passive vehicle suspension may not achieve optimal performances over all frequencies [1]. Comparing with the semi-active suspension actuated by magnetorheological fluid or electrorheological fluid damper, an active suspension offers an effective solution for improvements in both vehicle ride comfort and handling stability in a high bandwidth. In particular, an electromagnetic active suspension presents a promising prospect with several advantages. First, electromagnetic actuator (EMA) responds much faster than hydraulic damper without considering time delay influence in control [2]. Further, such a system is more environmentally friendly because of the absence of fluids and the harvesting of vibration energy that would be otherwise dissipated as heat in a passive suspension [3].

Gysen proposed a tubular permanent magnet actuator (TPMA) based on a McPherson suspension whose dynamic performance is proved by the measurements of the frequency response [4–6]. To achieve vibration attenuation, Bose Corporation developed a linear motored actuator integrating an amplifier on each wheel, but it brings disadvantages of large volume occupation and mass increase [7]. In contrast, the rotary motor is more suitable as a power supplier with its higher power

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density and efficiency [8]. Therefore, considerable efforts on the mechanisms transforming the motor rotary motion into suspension linear motion are devoted in the literature. Yu proposed a ball-screw EMA that possesses the advantages of compact structure and high efficiency, but also inherits the disadvantages of complicated structure and manufacturing challenges [9,10]. Li designed an EMA based on the rack-pinion mechanism. Modeling, bench experiment, and road test are carried out, and the result shows that average power of 19 W is attained at 48 km h^{-1} [11]. To improve the system efficiency, another pair of bevel gears is introduced to achieve variable transmission ratio according to working conditions [12]. Maravandi proposed a ‘‘two-leg" mechanism, whose efficiency is proved to be higher than both ball-screw and rack-pinion mechanisms [13]. But common difficulties of the current EMAs lie in the adaption to different suspensions of uniquely manufactured structures.

On the other hand, different controllers are contributed to the improvements in suspension performances. Particularly, robust control is recognized to be appropriate in stabilizing the system with parameter uncertainties and disturbances [14,15]. Both ride comfort and handling stability are highly emphasized performance indices. Further, the suspension deflection should be in the permitted range to avoid strong nonlinearity. It is quite challenging to optimize all the suspension performances in the controller design. Significant efforts of trade-off among the conflicting performances are devoted in the framework of robust H_∞ control. Gao and Chen minimized the body acceleration while taking the suspension deflection and tire deformation as hard requirements [16,17]. Wang constructed a linear matrix inequality (LMI) formulation of design specifications with mixed $GL_2/H_2/GH_2$ control [18]. In real situations, drivers may prefer different driving feelings under different conditions. As a result, the typical method of compromise between suspension performances may not be satisfying for all drivers and operating conditions.

To address the aforementioned concerns, a novel rocker-pushrod EMA based on a double wishbone suspension is proposed in this paper. After matching parameters, a prototype is manufactured, and nonlinearities and perturbation bounds are characterized. In Section 2, regarding vehicle ride comfort and handling stability, performance-oriented controllers are designed in the sense of H_∞ norm in perturbation ranges. Performance comparisons are carried out in both frequency and time domains. Furthermore, a test bench based on a quarter-vehicle is established to verify the feasibility of energy regeneration and effectiveness of robust control.

2. Design of the rocker-pushrod electromagnetic actuator

2.1. Architecture of the rocker-pushrod EMA

A novel rocker-pushrod EMA based on a double wishbone suspension is proposed in this section, which is mainly composed of a permanent magnet synchronous motor (PMSM), a reducer, a rocker, and a pushrod, as depicted in Fig. 1. Designed as an integrated part, the motor and reducer are mounted on the vehicle body. The rocker is fixed with the output shaft of reducer, while the two ends of the pushrod are connected with the rocker and lower arm by revolute pairs respectively. With a higher power density, the rotary motor is preferred to the linear motor with motion conversion achieved by the rocker and pushrod. As the proposed rocker-pushrod EMA can achieve both functions of damping and energy regeneration, the traditional damper in a passive suspension has been substituted, while other components and positions remain unchanged.

Taking the vehicle body as a frame of reference, when the wheel is shocked by a bump on the road without active control, the pushrod would drive the rocker to rotate around the reducer output shaft in a certain range. And meanwhile, the spring is suppressed under the influence of suspension guide mechanism. To actively attenuate the wheel vibration, with the aid of rocker and pushrod, an output torque multiplied by the transmission ratio would be transformed into a vertical force on the wheel. When the torque direction differs with the rotor motion, the EMA would be in the generation mode to harvest vibration energy.

Comparing with the common ball-screw EMA, the rocker-pushrod EMA proposed in this paper features simple structure and easy manufacturing. Besides, modular designs of the components are convenient to adapt to different suspension types and parameters.

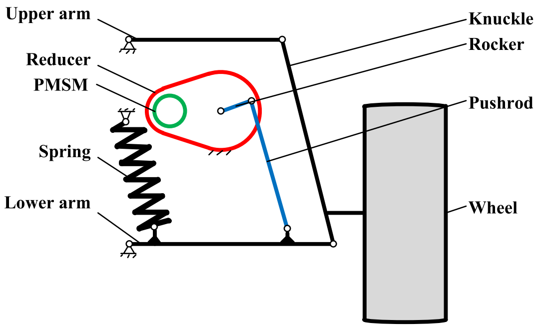

Fig. 1. Architecture of the pushrod-rocker electromagnetic active suspension.