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Research Article

Dynamic Ride Height Adjusting Controller of ECAS Vehicle with Random Road Disturbances

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The ride height control system is greatly affected by the random road excitation during the ride height adjusting of the driving condition. The structure of ride height adjusting system is first analyzed, and then the mathematical model of the ride height adjusting system with the random disturbance is established as a stochastic nonlinear system. This system is decoupled using the differential geometry theory and stabilized using the Variable Structure Control (VSC) technique. The designed ride height control system converges in probability to be asymptotically stable in the sliding motion band, and the desired control law is solved to ensure the stable adjustment of the ride height system. Simulation results show that the proposed stochastic VSC method is effective for the dynamic adjusting of the ride height. Finally, the semiphysical rig test illustrates the applicability of the proposed scheme.

1. Introduction

Ride height adjustment is one of the advantages for Electronically Controlled Air Suspension (ECAS) [1, 2]. The height adjustment, which contains the aerothermodynamics and vehicle dynamic processes of variable mass system, is accomplished by charging/discharging gas into/from air spring. The ECU of the ride height adjusting system can automatically regulate the ride height (maintaining or switching the ride height of the vehicle) to improve the performance of the suspension, according to the different driving states.

In the past several years, the study of ride height adjusting system attracted the attention of researchers all over the world. A prototype self-leveling active suspension system for road vehicles is presented to analyze the characteristic of the system [3]. In fact, the adjustment of the ride height system, which belongs to multidomain dynamics, is a process where the energy of the compressed air is converted to potential energy of vehicle sprung mass. Since the ride height adjusting system includes the continuous dynamic system state and the discrete logic state of the height mode switch, a novel approach for the verification of hybrid systems based on linear and mixed-integer linear programming for the electronic height control was proposed [4, 5]. Then, the ride height control system based on the model was designed. A multibody dynamic model of an air suspension vehicle by using Lagrange's method was built, and a ride height simulation under the condition of a step input using PID and PD control strategy was performed [6]. Some advanced control algorithms were also used to improve the adjusting performance of the ride height system. Chen et al. used the combined PID and VSC method to control the Hydro-Pneumatic Suspension, which could eliminate the oscillation and improve the control accuracy of the ride height system [7]. Yu et al. studied the fuzzy control of the ride height system, and the proposed control system has good robustness for the case of the changed structure parameters [8]. Yang et al. further studied the charging/discharging gas system of ECAS, designed the inductance integral height measuring system for real-time tracking information of ride height, and tried to improve the stability of the ride height adjustment system by adopting gearshift integral PID/PWM algorithm [9–11]. Feng and Du adopted the Fuzzy/PWM algorithm on the electronic controlled air suspension of semitrailer based on a quarter-car model, and then the phenomenon of overshoot and oscillation can be overcome effectively [12]. Kim and Lee used a sliding mode control algorithm to improve the tracking accuracy of the control and to overcome nonlinearities and uncertainties in the air suspension system [13]. However, the dynamic adjusting, especially the stability

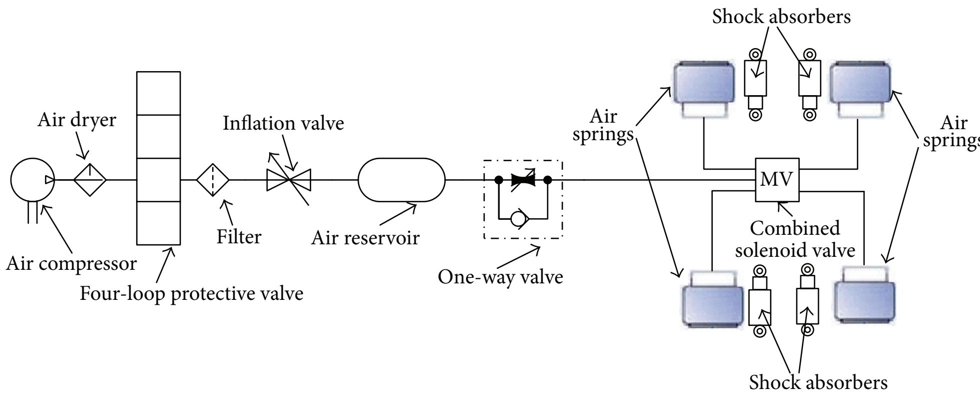


Figure 1: Pneumatic scheme of the ride height system for full vehicle.

control with respect to the random disturbances, has little research, but we can find some theories to apply the nonlinear system with disturbances [14, 15]. According to the characteristics of the nonlinear stochastic adjustment system, the ride height control system is designed by using the stochastic VSC technique in the present paper. The stochastic VSC law is solved by the stabilization in a certain probability, and this may achieve the stable adjustment of the dynamic ride height.

This paper is organized as follows. In Section 2, the ride height adjusting system is described. In Section 3, the dynamic model with random disturbances is built. In Section 4, we design a stochastic variable structure controller to achieve the stable adjusting of ride height, and the simulating results of comparing the algorithm proposed in this paper with PID algorithm are carried out. Experimental results show the effectiveness of the proposed method, as shown in Section 5. Conclusions are provided in Section 6.

2. Structure of Ride Height Adjusting System

The structure of ECAS system is shown in Figure 1. The high pressure air in air springs is exchanged with air reservoir or the atmosphere, which can lead to the state changing of ride height adjusting system. Thus, the considered system is characterized by pneumatic and mechanical coupling.

To further demonstrate the working principle of ride height adjusting system, a quarter ride height system model is used to describe the changing process of the ride height, as shown in Figure 2. Supposing that the sprung mass of suspension is a centralized mass M, the displacement of the sprung mass is changed by charging/discharging compressed air, and the ride height is adjusted to satisfy the vehicle driving performance. In the charging process, air from the air reservoir is supplied into the air spring through the pipeline as shown in Figure 2(a). In the discharging process, air from the air spring is released into the atmosphere through the pipeline as shown in Figure 2(b). In the practical application, the volume change rate and effective area of a diaphragm air spring are constant, and the height of the diaphragm air spring is similar to a piston motion of engine. Therefore, we can see that the characteristics of air springs and compressed gas lead to the nonlinearity of the ride height adjustment system. Additionally, the ride height adjustment system is disturbed by the road excitation when the vehicle was driven at different road conditions and speeds.

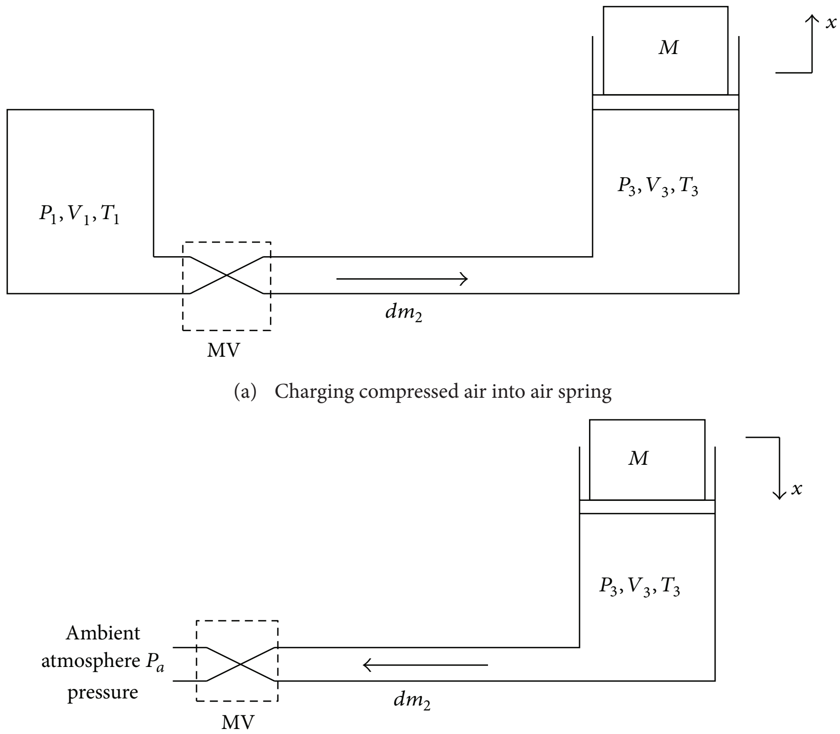
3. Mathematical Model of Ride Height Adjusting System with Random Disturbances

The random disturbance caused by irregularities of the road surface is filtered by the tire system, and it can be unified into the random change of suspension deflection [16]. The ride height adjusting system includes the processes of variable mass thermodynamics and vehicle dynamics, and a quarter-vehicle mathematical model is shown as [17]

$$\begin{aligned} m_s\ddot{Z}_s &= \left(P_3 - P_a\right) A_e - m_s g \\ &\quad - \left(C_3^{(1)}\dot{Z}_s + C_3^{(2)}\dot{Z}_s^2 + C_3^{(3)}\dot{Z}_s^3\right) - k_s\omega, \\ V_3\dot{P}_3 &= -\kappa P_3 \Delta V \dot{Z}_s + \kappa R T_3 q_m, \\ V_3 &= V_{30} + \Delta V Z_s, \end{aligned} \tag{1}$$

where m_s is the sprung mass; Z_s is the absolute displacement of sprung mass; P_3 is the internal absolute pressure of air spring; P_a is the atmospheric pressure; A_e is the effective area of air spring; g is the acceleration of gravity; $C_3^{(i)}$, $i = 1, 2, 3$ are one-degree term, quadratic term, and three-degree term of damping, respectively; k_s is the interference coefficient, relating to the character parameters of tire, air spring, and shock absorber; ω is the Gauss white noise with mean value of zero, relating to the irregularity of road surface and vehicle speed; κ is the adiabatic coefficient; q_m is the mass flow rate of inflow gas (or the outflow gas, which is negative); T_3 is the internal temperature of air spring; V_3 is the volume of air spring (subscript 0 stands for the initial volume of air spring), and ΔV is the volume change rate of air spring.

Choose the state variable of ride height tracking system as $X = \left[X_1 \ \ X_2 \ \ X_3\right]^T = \left[Z_s \ \ \dot{Z}_s \ \ P_3\right]^T$; that is, X_1, X_2, and X_3,



(a) Charging compressed air into air spring

(b) Discharging compressed air from air spring

Figure 2: Structure of ride height adjustment for a quarter vehicle.

separately, are the ride height, the rate of ride height changing, and the pressure of air spring, so we can rewrite (1) as

$$\begin{gathered}\dot{X} = f(X) + g(X)u + q(X)\omega, \\ y = h(X) = X_1,\end{gathered} \tag{2}$$

where

$$\begin{gathered} f(X) \\ = \begin{bmatrix} X_2 \\ \frac{1}{m_s}\left[X_2^3(X_3 - P_a)A_e - m_s g - \left(C_3^{(1)}X_2 + C_3^{(2)}X_2^2 C_3^{(3)}X_2^3\right)\right] \\ -\frac{\kappa \Delta V X_2}{V_{30} + \Delta V X_1} X_3, \end{bmatrix}, \\ g(X) = \begin{bmatrix} 0 \\ 0 \\ \frac{\kappa R T_3}{V_{30} + \Delta V X_1} \end{bmatrix}, \\ q(X) = \begin{bmatrix} 0 \\ -\frac{k_s}{m_s} \\ 0 \end{bmatrix}, \end{gathered} \tag{3}$$

and the control input u is the air mass flow rate q_m.

4. Ride Height Adjusting System via Stochastic VSC Algorithm

4.1. Disturbance Decoupling of Dynamic Ride Height Adjusting System. For Lie derivative $L_q h(X) = 0$ and $L_q L_f h(X) = (-k_S/m_s) \neq 0$, the interference characteristic index ν is 2 [18, 19]. According to the differential geometry theory and $L_g L_f h(X) = L_g h(X) = 0$, $L_f h(X) = X_2$, and $L_f^2 h(X) = X_3$, (2) can be decoupled as

$$\begin{aligned}\dot{X} &= \begin{bmatrix} L_f h(X) + L_g h(X)u + L_q h(X)\omega \\ L_f^2 h(X) + L_g L_f h(X)u + L_q L_f h(X)\omega \\ L_f^3 h(X) + L_g L_f^2 h(X)u + L_q L_f^2 h(X)\omega \end{bmatrix} \\ &= \begin{bmatrix} X_2 \\ X_3 + L_q L_f h(X)\omega \\ L_f^3 h(X) + L_g L_f^2 h(X)u + L_q L_f^2 h(X)\omega \end{bmatrix},\end{aligned} \tag{4}$$

where $L_q L_f^2 h(X) = C_3^{(1)} + 2\ C_3^{(2)}\ X_2 + 3\ C_3^{(3)}\ X_2{}^2 k_s/m_s{}^2$.

4.2. Variable Structure Control Approach to Design the Ride Height Adjusting System. The nonlinearity of the suspension system is composed of air spring and shock absorber, and the disturbance caused by road irregularity is the main characteristic of ride height adjusting system. VSC algorithm can obtain a perfect robustness to the interference and perturbation of the system [20] and will be proposed in this paper. The control input function $u(t)$ is solved by defining the switching function vector $s(t)$. Considering (4), the decoupled system is

$$\dot{X} = \begin{bmatrix} X_2 \\ X_3 \\ L_f^3 h(X) \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ L_g L_f^2 h(X) \end{bmatrix} u + \begin{bmatrix} 0 \\ L_q L_f h(X) \\ L_q L_f^2 h(X) \end{bmatrix} \omega. \quad (5)$$

The height adjusting system belongs to a single-input nonlinear system. Let $a(x) = L_f^3 h(X)$, $b(x) = L_g L_f^2 h(X)$, $\Gamma(X) = \begin{bmatrix} 0 \\ L_q L_f h(X) \\ L_q L_f^2 h(X) \end{bmatrix}$. Then, (5) is defined as $\dot{X} = f(X) + g(X)u + q(X)\omega$. Because the mean value of the normal white noise ω is zero and is relative to the Wiener process [21], (5) is a typically Itô-type stochastic system [22]. It is obvious that the ride height system cannot be globally controlled in the bandwidth region with 100% of total probability. So, the stochastic VSC input $u(t)$ may ensure that the sliding mode of the system could be controlled by a certain probability $1-\delta <$ 100%. We define that the switching function $s(t)$ must be controlled in a determined region by a certain probability, and it helps to solve the control law. The target equation can be represented as

$$P\{|s(t)| \le \mu\} = 1 - \delta. \quad (6)$$

If (6) is satisfied, the Itô-type stochastic system is asymptotically stable as a certain probability at the new balance point, and the control law of VSC input can be solved according to the above.

Firstly, define $e_1 = X_1 - X_d$, $e_2 = \dot{X}_1 - \dot{X}_d$, $e_3 = \ddot{X}_1 - \ddot{X}_d$, switching function $s(t) = c\begin{bmatrix} e_1 \\ e_2 \\ e_3 \end{bmatrix}$, and tracking height X_d, and substituting these into (5) yields

$$\dot{e} = \begin{bmatrix} X_2 \\ X_3 \\ a(x) \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ b(x) \end{bmatrix} u + \Gamma(X)\omega. \quad (7)$$

The part 1.2-Variable Structure Control Strategy in literature [23] can be extended to the nonlinear stochastic system. To get the control law of the ride height adjusting system, we define $m_s = E\{s(t)|X(t)\}$ and $\overline{v} = c\Gamma\omega$. Noting that the variance of ω is σ^2, we can see that $\overline{v}$ is a Gaussian procedure with zero mean and variance $(c\Gamma)^2\sigma^2$. At the same time, the variance can be appropriately identified according to the deflection of suspension. The control law can be solved according to three conditions of the switching function.

(1) Consider $s(t) > \theta^{-1}W$, where θ $(0 < \theta < 1)$ is the regulating parameter of the switching function and W is defined by the equation $\int_{-W}^{W}(1/\sqrt{2\pi}\,\overline{\sigma})\exp(-x^2/2\overline{\sigma}^2)\,dx = 1-\varepsilon$. The equation $\int_{-\theta s(t)}^{\theta s(t)}(1/\sqrt{2\pi}\,\overline{\sigma})\exp(-(x-m^2)/2\overline{\sigma}^2)dx = 1-\varepsilon$ has two solutions of $m_1^+(t)$ and $m_2^+(t)$ which satisfy $m_1^+(t) < m_2^+(t)$; then the control law is

$$u(t) = u^+(t) \in b^{-1}(x)\left[-a(x) - c_1 e_2 - c_2 e_3 + m_1^+(t)(t,x), \right.$$
$$\left. -a(x) - c_1 e_2 - c_2 e_3 + m_2^+(t)(t,x)\right]. \quad (8)$$

(2) Consider $s(t) < -\theta^{-1}W$. The equation $\int_{\theta s(t)}^{-\theta s(t)}(1/\sqrt{2\pi}\,\overline{\sigma})\times\exp(-(x-m)^2/2\overline{\sigma}^2)dx = 1-\varepsilon$ has only two solutions of $m_1^-(t)$ and $m_2^-(t)$ which satisfy $m_1^-(t) < m_2^-(t)$; then the control law is

$$u(t) = u^-(t) \in b^{-1}(x)\left[-a(x) - c_1 e_2 - c_2 e_3 + m_1^-(t)(t,x), \right.$$
$$\left. -a(x) - c_1 e_2 - c_2 e_3 + m_2^-(t)(t,x)\right]. \quad (9)$$

(3) Consider $|s(t)| < \theta^{-1}W$:

$$u(t) = u_{eq}(t) = b^{-1}(x)\left[-a(x) - c_1 e_2 - c_2 e_3\right]. \quad (10)$$

The ideal design objective is that the confidence interval $1-\varepsilon$ is as large as possible, and the bandwidth $\theta^{-1}W_c$ of sliding motion is as small as possible, but these conditions are contradictory. The parameter of ε and the sliding motion band can be determined in the practical application.

4.3. Simulation of Dynamic Ride Height Control System. Control strategies such as stochastic VSC and PID control were compared by means of computational simulations with the help of the software MATLAB/Simulink. Simulation results were conducted to validate the accuracy and effectiveness of the proposed control algorithm. The simulation model consists of the variable mass thermodynamics system model of air spring, the quarter vehicle model, and the controller, as shown in Figure 3. The program of control algorithm is realized by using S-function, and this may be coded to make dSPACE controller acquaint (see Section 5). Since the disturbance magnitude is determined by the irregularity of road surface and the vehicle speed, the road model is built by the integral white-noise as shown in Figure 4, and the disturbance data may be the equipment of road simulator by format changing. Taking B level typical road and the speed 50 km/h as example, the disturbance magnitude is calculated after a low-pass filter of the tire and suspension damping, as shown in Figure 5.

For the comparison of stochastic VSC and PID control algorithm, the same adjusting time needs to be ensured, and the control parameters of K_P for PID [24, 25] and c_1 for VSC are predetermined according to the height adjusting time. Table 1 shows the major parameters of the ride height adjusting system used in the simulation. The ride height adjustment of ECAS has three switchmodes of "High Mode," "Normal Mode," and "Low Mode" in this study. "Normal Mode" is the normal ride height, and other modes are applied in special conditions. The height changing distance between "Normal Mode" and "High Mode" is 20 mm, and the height changing distance between "Normal Mode" and "Low Mode"

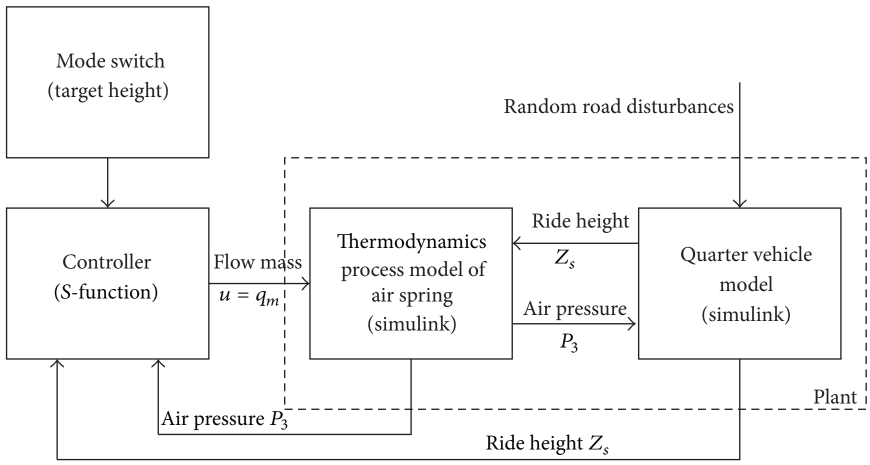


FIGURE 3: Simulation scheme.

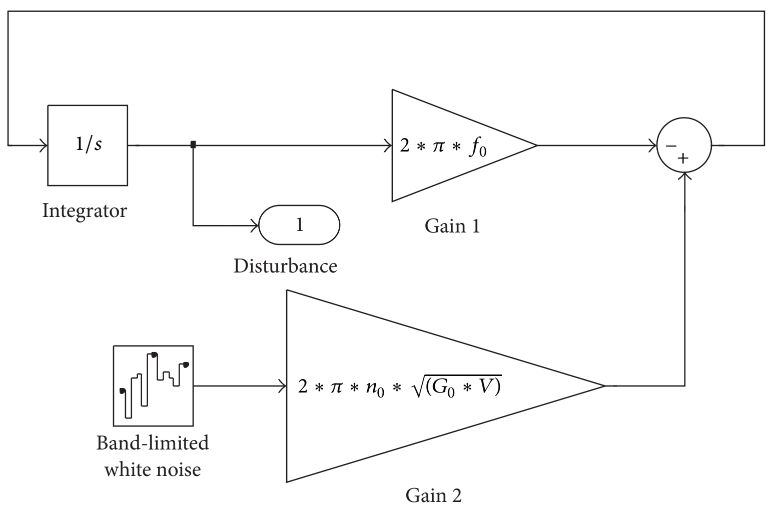


FIGURE 4: Road simulink model based on the integral white-noise.

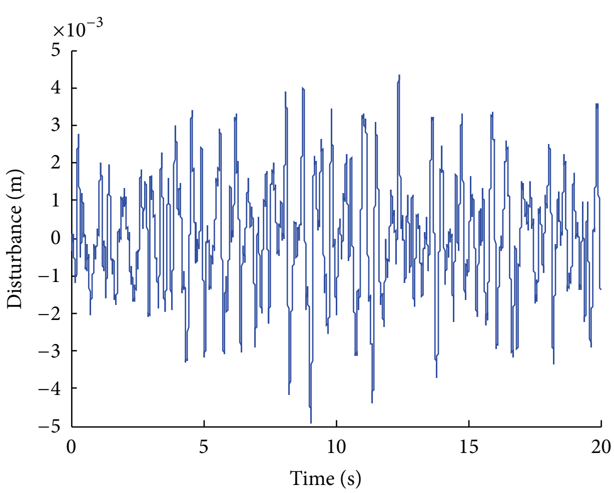


FIGURE 5: Disturbance magnitude of the B level typical road and the speed 50 km/h.

TABLE 1: Values of the ride height adjusting system parameters.

Parameters	Value
Sprung mass M (kg)	1074
First degree term of damping coefficient $C_3^{(1)}$ (N·s/m)	8832
Quadratic term of damping coefficient $C_3^{(2)}$ ((N·s/m)^2)	6245
Third degree term of damping coefficient $C_3^{(3)}$ ((N·s/m)^3)	–1568
Effective area A_e (m^2)	0.019
Volume changing rate ΔV (m^3/m)	0.025
Initial effective volume V_{30} (m^3)	0.0048
Volume of air reservoir V_1 (m^3)	0.06
Pressure of air reservoir P_1 (MPa)	1.0

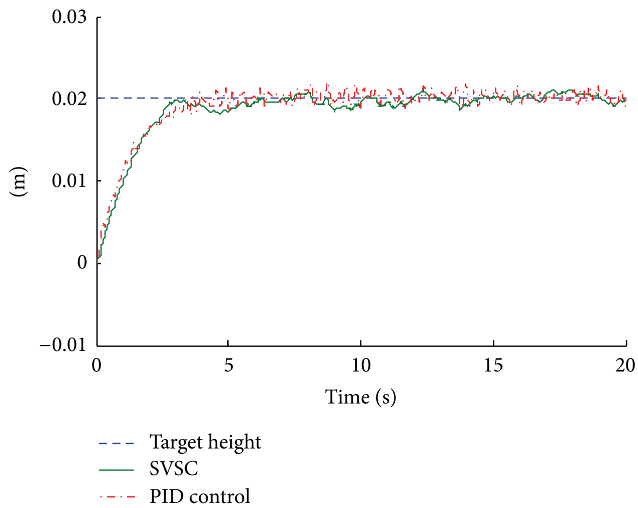


Figure 6: Lifting of the ride height.

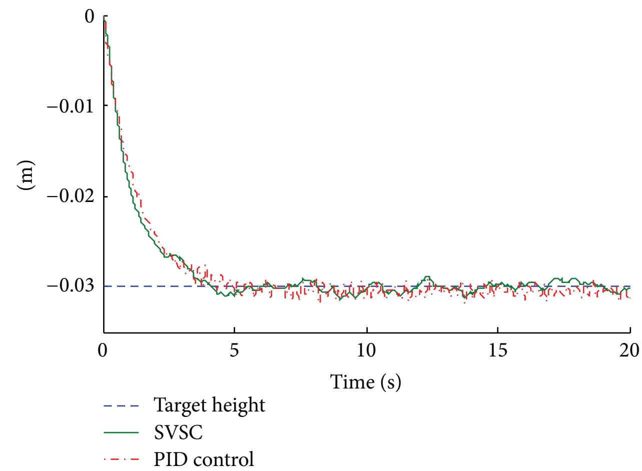


Figure 8: Lowering of the ride height.

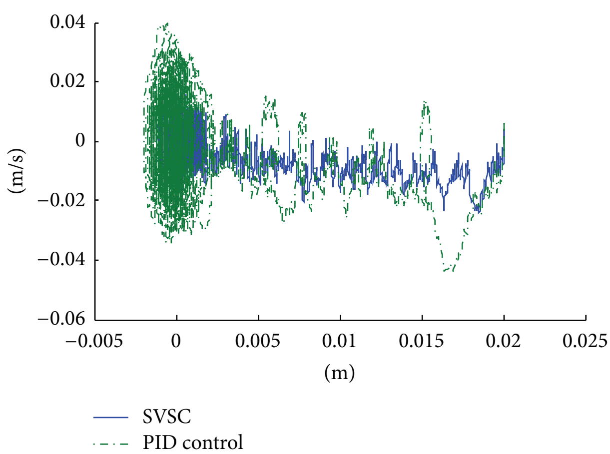


Figure 7: Lifting trajectory of height errors.

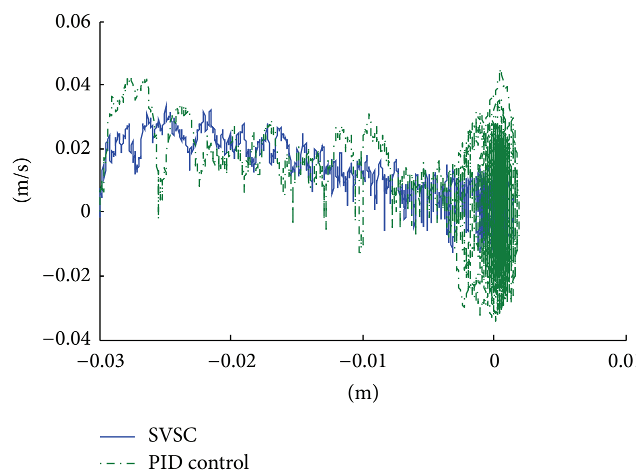


Figure 9: Lowing trajectory of height errors.

is 30 mm. So, we choose the control parameters $K_P = 0.8$, $K_I = 0.2$, and $K_D = 0.5$ for PID control and $c_1 = 15$ and $c_2 = 10$ for VSC.

The experimental results are obtained by applying the stochastic VSC and PID control techniques. Figures 6 and 7 show the results of the ride height lifting condition for the simulations. With the same adjusting time 4 s of both control methods, we can see from Figure 6 that the standard deviation using VSC technique is 3.4 mm, and the one using PID control technique is 3.6 mm. Figures 8 and 9 show the results of the ride height lowing condition for the simulations. By using the same analyzing method, it is observed from Figure 8 that the standard deviation using VSC technique is 4.8 mm and the one using PID control technique is 5.2 mm, under the same adjusting time 5 s of both control methods. Moreover, it is known from the trajectory of height errors in Figures 7 and 9 that the adjusting process of VSC system is more stable. Therefore, the simulation results show that the controller can greatly improve the adjusting stability and the system oscillation by using the stochastic VSC technique. Some performance comparison is shown in Table 2.

5. Test and Validation

The actual adjusting test was conducted with a semiphysical rig equipped with a ride height control system, where the full character was equivalent to six coil springs. Payload of the ride height system can be changed by increasing or decreasing the amount of the iron-sand bags. Random road disturbances created by the simulink model were input into the system of the Digital Hydraulic Servo Test Machine of INSTRON 8800. Meanwhile, the proposed stochastic VSC algorithm was programmed by means of Matlab/Simulink and directly downloaded into the dSPACE/RapidPro platform. In addition, a compressor was used to supply the high pressure air for the ride height system. In current testing applications, the control input calculated by stochastic SVC technique is the mass flow rate u, but the ON-OFF solenoid valve has just two states which cannot continuously adjust the mass flow rate.

Table 2: Performance index comparison of VSC and PID technique.

Performance index	SVSC		PID	
	Lifting	Lowering	Lifting	Lowering
Height deviation (mm)	3.4	4.8	3.6	5.2
Acceleration amplitude of vehicle body (m/s^2)	5.61	5.63	5.96	6.24
Acceleration of vehicle body r.m.s (m/s^2)	1.08	1.09	1.14	1.17
Height adjusting time (s)	4	5	4	5

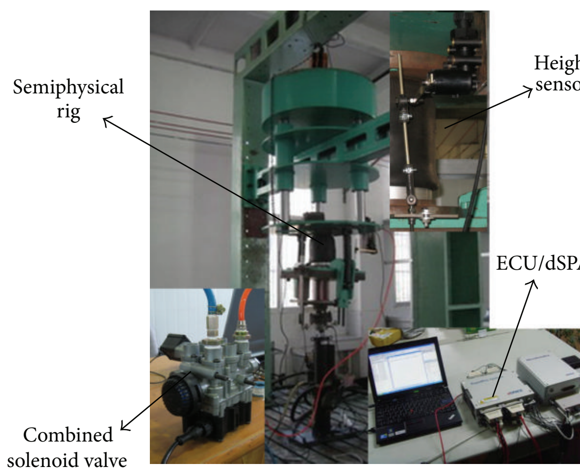


Figure 10: Testing rig of the ride height adjustment system.

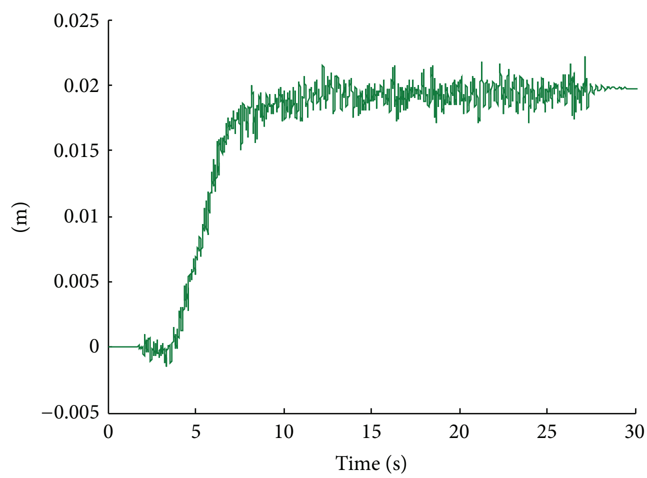


Figure 11: Height lifting testing.

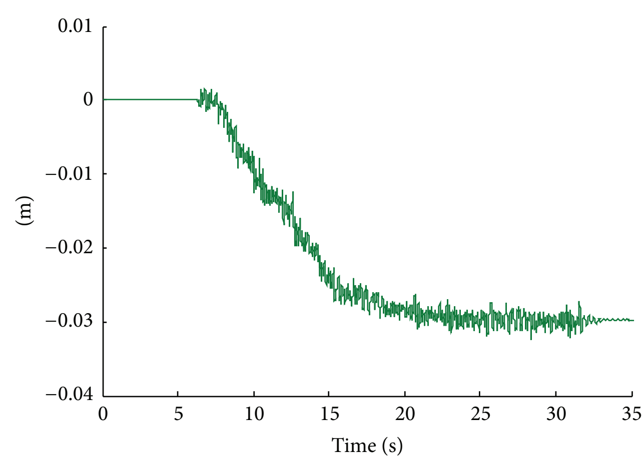


Figure 12: Height lowering testing.

So, the average mass flow rate during 0.062 seconds of the pulse period is controlled by the PWM duty cycle. Since the response speed of solenoid valve is limited, a working dead-zone of solenoid valve should be no less than 0.025 seconds. In addition, the solenoid valve for charging and discharging the compressed gas does not allow opening simultaneously which can reduce energy consumption. Figure 10 shows the configuration of the semi-physical rig test platform. The pressure of air spring is measured by an installed pressure sensor, and the ride height changing is measured by an installed height sensor.

Figures 11, 12, 13, and 14 show the testing results for the proposed control system. The adjusting time of both height lifting and lowering is over 5 s, because the route loss of the pipeline, the pressure decreasing of the air reservoir, and the saturation of control input jointly contribute to the more adjusting time than that of simulations. Nevertheless, the whole height adjusting process has no significant overshoot, and the proposed control system can stably switch the height mode and weaken the effect of disturbances. This result shows the robustness of the proposed controller.

6. Conclusions

This paper focuses on the ride height control system under the random road disturbances. The nonlinear model of ride height system, which contains the aerothermodynamics and vehicle dynamic processes, is established. On the basis of the present simulations and test, the following conclusion can be made.

(i) The ride height adjusting system is modeled as an Itô-type stochastic nonlinear system. Zero stability of the ride adjusting system will not be obtained by the control algorithm. The control law is obtained by using Gauss normal distribution in a certain probability, which can be carried out to weaken the random disturbance of the road irregularities.

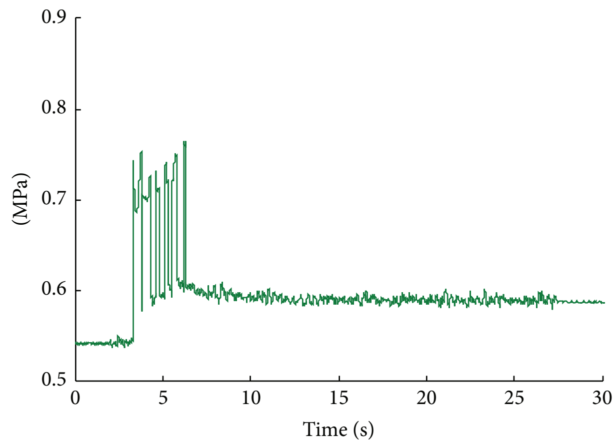


Figure 13: Pressure changing of air spring of ride height lifting with random disturbances.

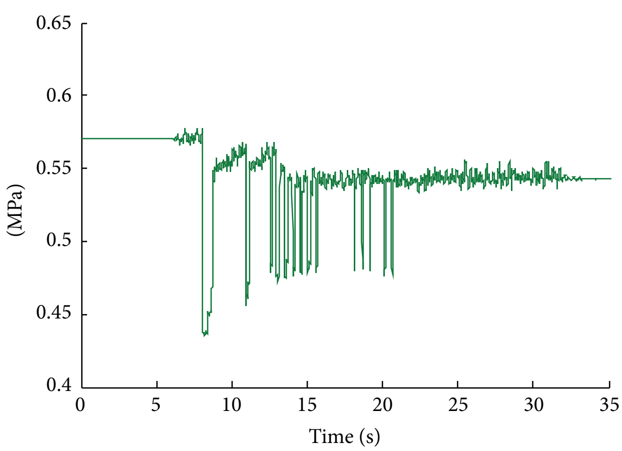


Figure 14: Pressure changing of air spring of ride height lowering with random disturbances.

(ii) Under the same adjusting time, the proposed controller and PID controller both can achieve the same height accuracy, but the proposed controller has a better ride performance than that of the PID controller during the height adjusting process, which shows that the proposed controller is suitable for the current system.

(iii) Rig tests show that the proposed control method is feasible and can satisfy the stability performance of the ride height adjusting system.

Conflict of Interests

No conflict of interests exists in the submission of this paper, and the paper is approved by all authors for publication.

Disclosure

The authors would like to declare that the work described was an original research that has not been published previously and is not under consideration for publication elsewhere, in whole or in part.

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