PID Control for the Vehicle Suspension Optimized by the PSO Algorithm

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Abstract: To solve the problems of the PID controller when it is used for the vehicle suspension, a method using the PSO algorithm is designed. This method utilizes the global searching strategy of the PSO algorithm to design and optimize the parameters of the target function for the suspension performance indexes matrix. And then a simulation experiment is provided. The simulation results show that the performances of the actively controlled vehicle suspension using the PID controller optimized by the PSO algorithm can be greatly improved compared to the suspension controlled by the normal PID controller and the passive one. It means that the problems of defining the weight matrices are well solved and the advantage of the normal PID controller is utilized sufficiently.

1 INTRODUCTION

The suspension system is such an important component of the vehicle, that its performance significantly affects the vehicle ride comfort, operation and stability. The traditional passive suspension is generally composed of the elastic component and damping components with the fixed parameters. Such suspension systems are generally designed to adapt to a certain type of road, so the vehicle performance is restricted obviously. In recent years, with the rapid development of the electronic technology, testing techniques, and system dynamics theories, the semi-active or active vehicle suspension systems have been developed based on the active vibration-isolation theory (Zhang, 2013; Zhao,2011; Zhang, 2013; Chai, 2010; Liu, 2010).

The popular vehicle suspension control strategies include the Neural Networks Fuzzy Control, Optimal Control, Immune Control, PID control, and Fuzzy PID Control and etc.

The PID control is a popular method used in industry due to its advantage. But the control effects greatly depend on the PID parameters. As to the active vehicle suspension, the control objects include the body vertical acceleration, the suspension dynamic travel distance and the tire's dynamic load. And these three often conflict with each other. So, the parameters setting of the PID controller is of greatest significance. The traditional parameters setting method include the Ziegle-Nichols method, the experience piece-try method and etc. But these methods all have great blindness, therefore the good PID parameters can not be achieved and the optimum performances can not be realized.

In 1995, Dr. Eberhart and Dr. Kennedy provided a new theory-Particle Swarm Optimization(PSO) based on the Swarm Intelligence Theory. This method uses the swarm competition and cooperation to produce swarm intelligence which guides and optimize the value search. The PSO algorithm has a quicker rate of convergence compared to the Genetic Algorithm (GA). Meanwhile, its algorithm is simple and it can be realized easily(Wang, 2006).

To solve the problems of the PID control used for the vehicle suspension, the PSO method is adopted to optimize the PID parameters. And the system control model is set up by Matlab/simulink together with simulation experiment. The simulation results show that this active suspension can achieve better vehicle ride compared to the normal PID controller and the passive one.

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2 ESTABLISHMENT OF THE 1/4 ACTIVE SUSPENSION CONTROL SYSTEM

For convenience, a simplified 1/4 vehicle model is set up as research object, as figure 1 shows.

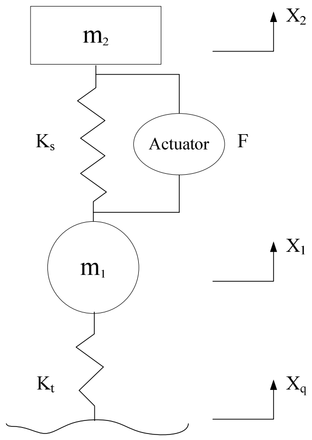

Figure 1:The quarter-vehicle body model of 2 DOEs.

In figure 1, the symbole k_t is the tire stiffness, and k_s is the suspension stiffness. The symbol m_1 means the non-sprung mass and m_2 means the sprung mass. And symbol F is the force of the actuator, and X_q is the road input. X_1 means the displacement of the non-sprung mass and X_2 means the travel of the sprung mass.

The system state variables and the output variables are chosen respectively as shown in formula (1)&(2).

$$X = (\dot{x}_2, \dot{x}_1, x_2, x_1, x_q)^T \tag{1}$$

$$Y = (\ddot{x}_2, x_2 - x_1, x_1 - x_q)^T \tag{2}$$

The control input is the active force F. And the filtering white noise is used to simulate the real road input as follows shown in formula (3),

$$\dot{x}_q(t) = -2\pi f_0 x_q(t) + 2\pi\sqrt{G_0 V}\,\omega(t) \tag{3}$$

In above formula, the symbol G_0 means the pavement roughness coefficient (m^3/cycle). The symbol V is the vehicle speed. The ω(t) represents the Gaussian white noise with zero mathematical expectation. The f_0 means the lower cut-off frequency(Zhou, 2012).

Then the system state-space equation(4) can be achieved as follows,

$$\left.\begin{aligned} \dot{\mathbf{x}} &= \mathbf{Ax} + \mathbf{BU} \\ \mathbf{y} &= \mathbf{Cx} + \mathbf{DU} \end{aligned}\right\} \tag{4}$$

The symbol A,B,C,D are annotated as follows,

$$\mathbf{A} = \begin{bmatrix} 0 & 0 & -\dfrac{K_s}{m_2} & \dfrac{K_s}{m_2} & 0 \\ 0 & 0 & \dfrac{K_s}{m_1} & -\dfrac{K_t + K_s}{m_1} & \dfrac{K_t}{m_1} \\ 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -2\pi f_0 \end{bmatrix}$$

$$\mathbf{B} = \begin{bmatrix} 0 & 1/m_2 \\ 0 & -1/m_1 \\ 0 & 0 \\ 0 & 0 \\ 2\pi\sqrt{G_0 v} & 0 \end{bmatrix}$$

$$\mathbf{C} = \begin{bmatrix} 0 & 0 & -\dfrac{K_s}{m_2} & \dfrac{K_s}{m_2} & 0 \\ 0 & 0 & 1 & -1 & 0 \\ 0 & 0 & 0 & 1 & -1 \end{bmatrix} \mathbf{D} = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}, \mathbf{U} = [\begin{matrix} \omega(t) \\ F \end{matrix}]$$

3 MODEL OF PID CONTROLLER OPTIMIZED BY THE PSO

The main performance indexes for the vehicle suspension design consist of three ones, which are the body vertical vibration acceleration, the suspension dynamic travel, and the dynamic load of the tyre.

The body vertical vibration acceleration represents the car ride. The suspension dynamic travel represents the body posture and the suspension structure. And the he dynamic load of the tyre represents the tire grounding characteristic. So, the three variables are selected as the aim of PID controller.

3.1 Design of PID Controller for the Suspension

PID controller is a linear one. It forms the control deviation $e(t)$ according to the given value $r(t)$ and the actual output value $c(t)$, as following formula (5) shows.

$$e(t) = r(t) - c(t) \tag{5}$$

It combines the proportion, integration and differential of the deviation $e(t)$ to form a control variable, and controls the object.

The body vertical vibration acceleration, the suspension dynamic travel, and the dynamic load of the tire is the representative of the suspension performance. Therefore, they can be set as the control aims. The active force F of the PID controller is shown as follows,

$$F = K_p * e(t) + K_i * \int_0^T e(t)dt + K_d * \frac{de(t)}{dt} \tag{6}$$

Among them, K_p means the proportional coefficient, K_i means the integral coefficient, and K_d is the differential coefficient.

When PID controller is adopted, the three coefficients play decisive roles in control effects. To solve the problems in deciding the three ones, the PSO algorithm is used.

3.2 Optimization Procedure of the PSO Algorithm for the PID Controller

The PSO optimization algorithm is derived from prey behavior of birds. Similar to the GA, the PSO algorithm first initializes a swarm of particles. Every particle represents a possible solution to the optimizing problem, which has its own position and speed. The target function value according to the particle position coordinate is decided as the particle's fitness. On every iteration, each particle memorizes and follows current optimal particle. It renews itself by tracing two extremums. One is the optimal solution pbest found by itself, and the other is the optimal solution found by the whole swarm gbest.

After finding the two optimal values, the particles renew their own speeds and positions according to relative formula. And then the unknown parameters, K_p, K_i and K_d, can find their optimal solutions from the assembly of all possible values by the PSO algorithm. And the fitness function value is the minimum(Wang, 2011; Yan, 2011).

The optimization procedure of the PSO algorithm for the PID controller is shown as figure 2.

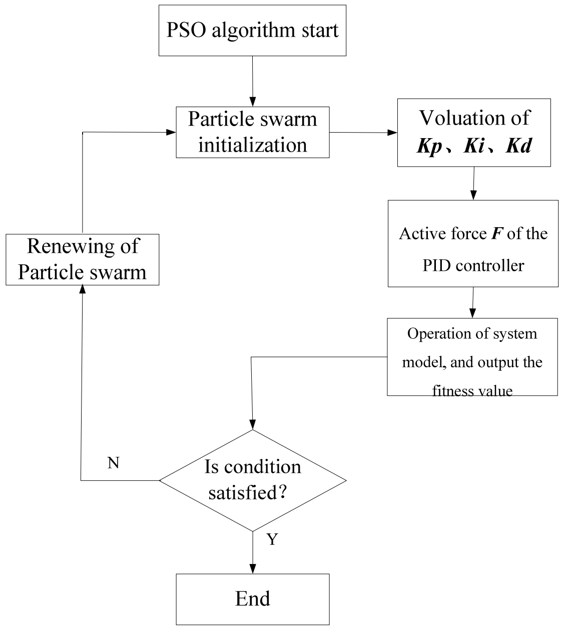

Figure 2: Optimization process of PID controller by PSO algorithm.

1）Renewing of Particle swarm

Since the parameters can not deal with the space parameters directly, the feasible solution must be coded as the particle space unit. And the PID parameters code are the particle code cluster, which is the matrix [K_p, K_i, K_d]. Every variable of the particles is expressed by real number and its value range is decided by specific application background. And then the PSO algorithm is used to search the optimal solutions of above variables. By preliminary setting, the range of the three PID parameters is set to [0, 50].

2）Each particle are evaluated to the three parameters successively, and then the active force F of the PID controller is solved and sent to the 1/4 body model.

3）Fitness function values of every swarm are solved.

Because of the magnitude order of the performance indexes, which are $\ddot{x}_3$,（$x_3 - x_2$）and $(x_1 - x_q)$, the fitness function value L is set as follows.

$$\text{Minimum L} = \frac{RMS[\ddot{x}_3(\mathbf{X})]}{RMS[\ddot{x}_{3pass}(\mathbf{X})]} + \frac{RMS[(x_3 - x_2)(\mathbf{X})]}{RMS[(x_3 - x_2)_{pass}(\mathbf{X})]} + \frac{RMS[(x_1 - x_q)(\mathbf{X})]}{RMS[(x_1 - x_q)_{pass}(\mathbf{X})]}$$

$\mathbf{X} = (Kp, Ki, Kd)$， 1<Xi<50，i=1,2,3

$$s.t. \begin{cases} \dfrac{RMS[\ddot{x}_3(\mathbf{X})]}{RMS[\ddot{x}_{3pass}(\mathbf{X})]} < 1 \\ \dfrac{RMS[(x_3 - x_2)(\mathbf{X})]}{RMS[(x_3 - x_2)_{pass}(\mathbf{X})]} < 1 \\ \dfrac{RMS[(x_1 - x_q)(\mathbf{X})]}{RMS[(x_1 - x_q)_{pass}(\mathbf{X})]} < 1 \end{cases} \quad (7)$$

Among the formula, RMS means the mean square root of the relative data. $\ddot{x}_{3pass}$ means vertical acceleration of passive suspension. $(x_3 - x_2)_{pass}$ means the dynamic travel of passive suspension. $(x_1 - x_q)_{pass}$ means the dynamic displacement of the tire. And X is the PID coefficient matrix.

Fitness function value can be calculated by formula (6) and it is the termination condition for the PSO algorithm. If condition is satisfied, the algorithm will end. If not satisfied, the previous step continues to change the PID parameters.

4）Renewing of the position and speed of the particle.

For every particle, its fitness value is compared to its optimal position-fitness value and whole particles' optimal position-fitness value. If better, the value is set as current optimal position, and the particle's speed and position is renewed.

And the speed and position is decided by following formula (8).

$$\left.\begin{aligned} v_{t+1} &= \omega v_t + c_1 r_1 (P_t - x_t) + c_2 r_2 (G_t - x_t) \\ x_{t+1} &= x_t + v_{t+1} \end{aligned}\right\} \quad (8)$$

Among the formula, x means the particle's position. v means the particle's speed. ω means the inertia factor. c_1、c_2 mean acceleration const. r_1、r_2 are random numbers among [0,1]. P_t is the optimal position-fitness value of the particle. And G_t is the optimal position-fitness value of all particles.

5）If the termination condition is not satisfied, the procedure returns to step 2), or the optimal solution is achieved.

3.3 PID-control Model for Suspension under Matlab/Simulink Circumstance

The PID-control model for active suspension is realized under Matlab/Simulink circumstance, as figure 3 shows. The input signal is the road stimulus. The output signals are the vertical acceleration, vertical body speed, the travel of suspension and the displacement of the tire.

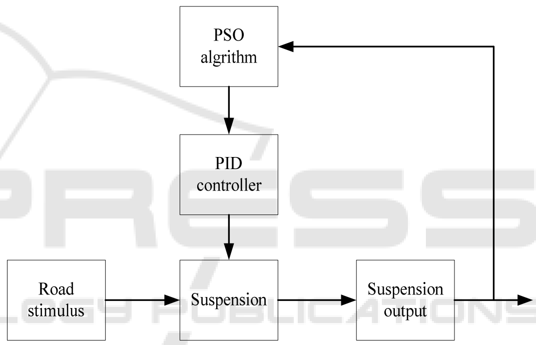

Fig.3 PID controller model for active suspension in simulink

The vertical body speed is selected as the input variable for the PID controller. And the output of the PID controller acts as the active force of the suspension. The suspension output is selected as the input variables for the fitness function value of the PSO.

4 SIMULATION EXPERIMENT AND RESULT ANALYSIS

The initial condition for PSO algorithm is set as follows.

The ranges of the three parameters, K_p, K_i and K_d, are all set in[1,50]. And their deviations are 1×10-6.

The road input model uses the filtered white noise, and made by the WGN（M, N, P） function of MATLAB. M and N are the rows and columns of the generative matrix. And P is the power of the filtered white noise（dB. M, N and P are set to 10001, 1 and 20 accordingly. The sampling time is 0.005s, and the vehicle speed is 20m/s. And the total simulation time is 50 seconds.

The vehicle parameters are set as follows. m_2=300kg. m_1=50kg. k_s=20000N/m. k_t=200000 N/m. The operation distance of the suspension is ±100mm.

After optimization, the three parameters, K_p, K_i and K_d are 11.3617, 0.01 and 49.05.

The simulation results are shown as figure 4-6.

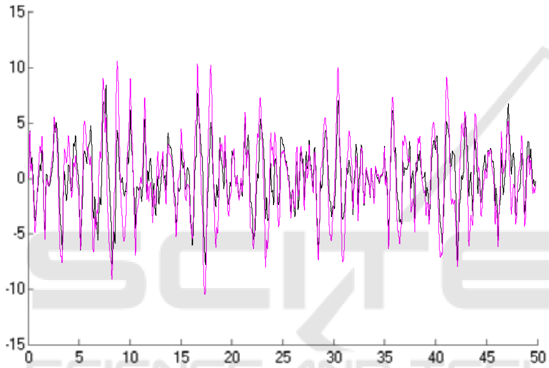

Figure 4: Vertical accelerations of active and passive suspension.

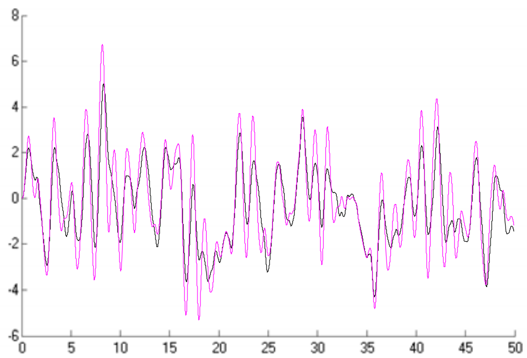

Figure5: Working distances of active and passive suspension.

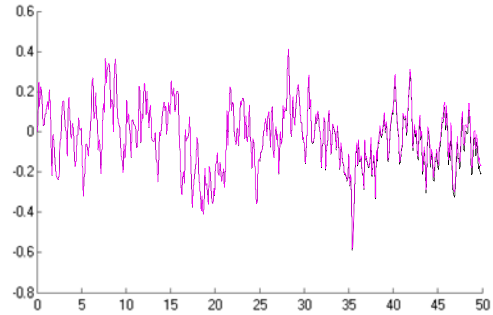

Figure 6: Wheel dynamic travels of active and passive suspension.

Among the figures, the red line represents the passive suspension, and the black line represents the active suspension. To confirm the advantage of the PSO algorithm in optimizing the PID controller (PSO-PID), the control performances of the active suspension are compared to the passive one. The analysis result is shown on table 1.

Table 1: Performance indexes of suspension controlled by different manners.

Performance indexes	unit	Root mean square value (RMS)		
		Passive suspension	Active suspension by normal PID controller	PSO -PID
Vertical acceleration	m/s^{-2}	5.2716	4.5	3.954
dynamic travel of suspension	mm	3.135	2.986	2.467
dynamic displacement of the tyre	mm	0.2190	0.310	0.231

From fig4~6 and table 1, we can see that the suspension performance indexes, especially the suspension dynamic travel and vertical acceleration, are dramatically improved when PSO-PID is used. This means that, the PSO algorithm has a great application effective when used in suspension control. Though the index, dynamic displacement of the tyre, is no better than other control manners, it has no big influence on the suspension performance.

5 CONCLUSIONS

This paper used the global-searching ability of the PSO algorithm to optimize the three parameters of the PID controller in suspension control. The design efficiency and control performance of the PID controller are greatly improved. The advantages can be expressed in two respects.

1）The problems in deciding the three parameters of the PID controller are well solved. Thus the deciding efficiency and control performance are bettered.

2）The three performance indexes of the vehicle suspension are improved.

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