Sliding Mode Control for Active Suspension System Using ICA Evolutionary Algorithm

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Abstract: Since suspension system of car plays a major role in reducing transmission of vibrations from the road to car body and passenger comfort, designing suspension system is one of engineers' goals. In this paper, a sliding mode controller for active suspension system is proposed which aims to improve passenger comfort and stability parameters. There is a direct relationship between passenger comfort parameter and vertical acceleration on car passenger. Linear equations based on model ¼ of extraction system and coefficient of sliding mode controller for minimizing maximize of overshoot and settling time for vertical acceleration on a car passenger have been optimized and determined using ICA evolutionary algorithm. Simulation results show that the proposed controller, in addition to improving passenger comfort parameter, has also improved system stability. Comparison of simulation results obtained from proposed controller with the passive mode shows the improvement in passenger comfort and stability parameters.

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1. Introduction

One of the key systems in cars is suspension system that has an essential role in passenger comfort and car stability. According to market needs and developing car technology, passive springs and dampers have replaced by semi-active and active data systems. In the past two decades, many works has been done on active suspension system to improve its functionality. Among the scholars who have worked on the active suspension system, "David Brown" and his colleagues can be noted. In 2008, they proposed an intelligent controller an adaptive control for suspension system [1]. "Zhang Shan Lee" and his colleagues (1995) proposed a nonlinear control algorithm [2]. Also, in 1999, "Supavet" proposed a robust adaptive control for the suspension system [3]. If a suspension system is rigid, passenger comfort parameter and its quality would be undesirable. In this case, the additional vertical force, which is caused by irregularities in the road, will transfer to passenger. When the car is moving with a rigid suspension system, the passengers experience a rough ride. However, this type of suspension system makes the car more stable on the road. Therefore, the designing the suspension system is a compromise between these two parameters. Passive suspension system can improve passenger comfort, but cannot satisfy compromise between these two parameters. But the active suspension system can simultaneously control two parameters. In other words, it can establish a compromise between the two parameters [4]. In this paper, first, linear equations of model ¼ of active suspension system are derived and a sliding mode controller is proposed for the model of suspension system. The coefficient of sliding mode controller has been optimized using ICA evolutionary algorithm and defining a cost function for the algorithm.

2. Model ¼ for suspension system of car

Model ¼ of the active suspension system with two degrees of freedom is shown in Figure 1. Clearly, model ¼ in one of the most efficient models for analyzing the suspension system and is shown based on model ¼ of wheel. It is assumed that the tire is in contact with the road surface and is simulated by a spring and non-spring mass.

Equations 1 and 2 are linear equations for suspension system:

$$m_s\ddot{z}_s = -k_s(z_s - z_u) - b_s(\dot{z}_s - \dot{z}_u) + f_a \quad (1)$$

$$m_u\ddot{z}_u = k_s(z_s - z_u) + b_s(\dot{z}_s - \dot{z}_u) - k_t(z_u - z_r) - f_a \quad (2)$$

Where m_s is body mass of a quarter, m_u is mass of wheel (kg), k_s is rigidity of suspension spring (N/m), k_t is rigidity of tire (N/m), b_s is damper coefficient (Ns / m), z_r is road entrance (m), z_u is wheel displacement (m), z_s is body displacement (m) and f_a is force exerted on the body (N).

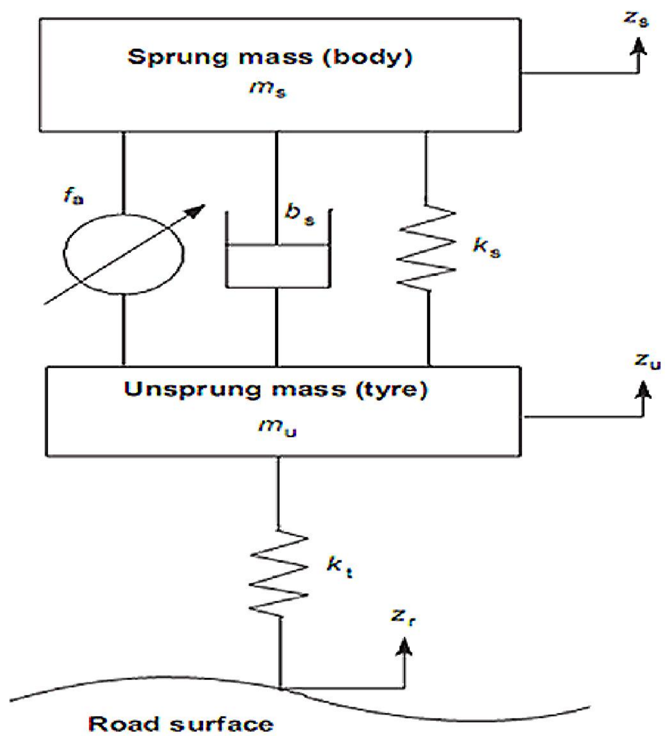


Figure 1: An active suspension system model

State variables
$$\begin{cases} x_1 = z_s \\ x_2 = \dot{z}_s \\ x_3 = z_u \\ x_4 = \dot{z}_u \end{cases} \tag{3}$$

According to definition of state variables as above, and using equations 1 and 2, state space equations can be obtained from equations 3 to 6:

$$\dot{x}_1 = x_2 \tag{4}$$

$$\dot{x}_2 = \frac{F_a}{m_s} + \frac{bs}{m_s}x_4 - \frac{bs}{m_s}x_2 + \frac{K_s}{m_s}x_3 - \frac{K_s}{m_s}x_1 \tag{5}$$

$$\dot{x}_4 = -\frac{F_a}{m_s} - \frac{bs}{m_u}x_4 + \frac{bs}{m_u}x_2 - \frac{K_s}{m_u}x_3 + \frac{K_s}{m_u}x_1 - \frac{K_t}{m_u}x_3 + \frac{K_t}{m_u}zr \tag{6}$$

Using above definitions, state matrices can be determined as follows:

$$\dot{x} = Ax + B\begin{bmatrix} f_a \\ z_0 \end{bmatrix} \tag{7}$$

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 \\ -\frac{K_s}{m_s} & -\frac{bs}{m_s} & \frac{K_s}{m_s} & \frac{bs}{m_s} \\ 0 & 0 & 0 & 1 \\ \frac{K_s}{m_u} & \frac{bs}{m_u} & -\frac{K_s}{m_u} - \frac{K_t}{m_u} & -\frac{bs}{m_u} \end{bmatrix} \tag{8}$$

$$B = \begin{bmatrix} 0 & 0 \\ \frac{1}{m_s} & 0 \\ 0 & 0 \\ -\frac{1}{m_u} & \frac{K_t}{m_u} \end{bmatrix} \tag{9}$$

2.1. Road Model

In the study of active suspension, considered model for the road is very important. Researchers use many models to simulate road model that two common models are as follows:

Model 1:

As shown in Figure 2, the road entrance considered as a half-sine signal that provided in 1997 by "Jung-Shan Lin". Equation 10 is used to simulate and study control system [4].

$$zr = \begin{cases} a(1 - \cos\omega t) & 1.25 \le t \le 1.5 \\ 0 & otherwise \end{cases} \tag{10}$$

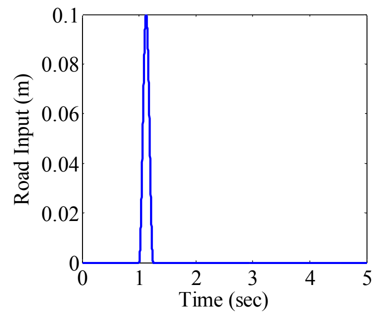


Figure 2: road bumpiness

Model 2: This method is based on Power Spectral Density theory where in road entrance considered as to the state variables according to equation 11 [5].

$$\dot{z}_r = -2\pi f_0 z_r + 2\pi\sqrt{G_0 U_0}\,\omega_0 \qquad (11)$$

Where ω_0 is coefficient of Gaussian white noise, z_r is road entrance, G_0 is road rigidity standard and f_0 is lower cutoff frequency. All entries cannot show all real levels of road. | In this paper, the first method is used to simulate the road.

Colonial rivalry

Optimization algorithms mainly inspired by natural processes and in these algorithms, other aspects of human evolution are not considered. In this paper, a new algorithm was used, which is not inspired by a natural phenomenon but a social-humanity phenomenon. In particular, this algorithm considered colonization process as a stage of social-political evolution of human and by modeling the historical phenomenon, used it as a source of inspiration for a powerful optimization algorithm [6]. Block diagram of the algorithm is shown in Figure 3.

3. Designing Controller

When modeling, inaccuracies in the system model may be due to uncertainties in the system parameters, or be due to the purposeful selection of a simplified view of the dynamics of the system. Therefore, from the control point of view, the lack of accuracy in the modeling can be classified into two main types [8]:

• Structural uncertainty (parametric)

• Non-structural uncertainties (non-modeled dynamics)

The first type of uncertainty is related to inaccuracy in the terms are really are in the model while second type is related to inaccuracy in the order of system. Inaccuracies in modeling can have severe adverse effects on the system and in particular has undesirable effects on the non-linear system. A main and complementary method to deal with the uncertainty of the model is using a robust control that has been explained in this section. In this thesis, the structure of proposed nonlinear sliding mode controller is consisted of a nominal section and a number of additional terms for deal with the uncertainties of the model. Sliding mode controller is used in those systems that are needed in order to keep stability and uniform system performance with approximate model in a legal way [8]. Also, the sliding mode controller is one of optimal controller for systems with uncertainty in parameters and non-modeled dynamics. One problem with this controller is control energy consumption that in this thesis, we minimize it using colonial competitive optimization algorithms (ICA). Figure 4 shows a feedback system with a controller.

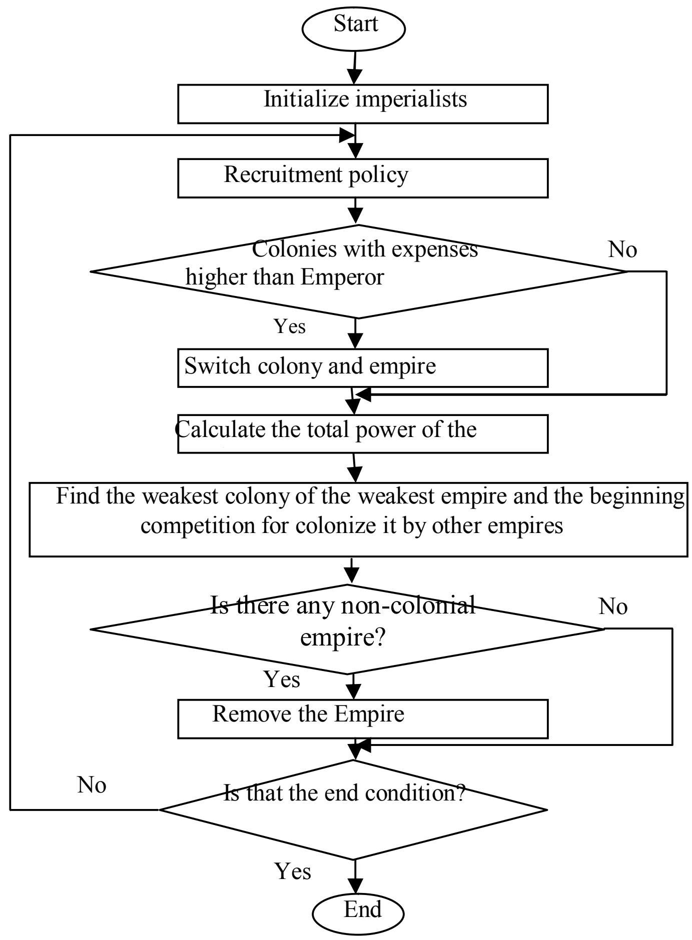


Figure 3- block diagram of Colonial rivalry algorithm

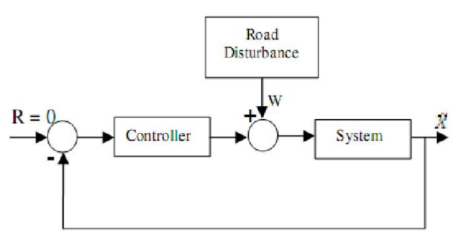


Figure 4- Closed Loop System

The controller consists of two parts: the controller and the switch: control rule and switch rule.
Equivalent control rule:
Sliding surface is defined by the following equation:

$$S(t) = (\frac{d}{dt} + \lambda)^{n-1} \quad (12)$$

Where n is order of system and λ is a positive number.
In this paper, the order of system is 2. So, equation 13 is rewritten based on equation 12:

$$S(t) = (\frac{d}{dt} + \lambda)^{1} e = \dot{e} + \lambda e \quad (13)$$

where e is system error.
By taking the derivative of the sliding surface and replace equations 1 and 4, control rule is obtained as follows:

$$f_{eq}(t) = \ddot{x}_R - b_s x_4 + b_s x_2 - k_s x_3 + k_s x_1 - . \frac{(x_1 - \dot{x}_R)\lambda}{m_s} \quad (14)$$

To make the control rule more robust, sgn function adds to it. Finally, final control rule is obtained as follows:

$$f = f_{eq} - k\,\mathrm{sgn}(S) \quad (15)$$

Based on Lyapunov theory about stability, each system has a Lyapunov function called V that if the derivative of this function is a negative number, the system will be stable.
In sliding mode control, the Lyapanvf function is as follows:

$$V = \frac{1}{2} S^2 \quad (16)$$

$$\dot{V} = \frac{1}{2} S\dot{S} \quad (17)$$

$$\dot{S}(X,t) = \ddot{x}_1 - \ddot{x}_R + \lambda(\dot{x}_1 - \dot{x}_R) \quad (18)$$

Using equation 18 in equation 16:

$$\dot{V} = \frac{1}{2} S(-k\,\mathrm{sgn}(S)) \quad (19)$$

According to equation 9, the system will be stable.

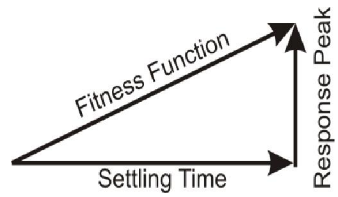
4. Calculating Coefficients

The cost function is considered so that settling time and maximum of overshoot for system response to road entrance, is minimum value. In sliding mode controller design, researchers have used different objective functions in evolutionary algorithms. Usually corresponds to the minimum value of the objective function, the optimal values of design parameters of controller are obtained. The cost function used is based on minimization of Integral Absolute Error (IAE), Integral Time Absolute Error (ITAE) and Integral of the Square of the Error (ISE) for different value [7]. In this paper, as mentioned, the cost function is defined based on the maximum acceleration on car body and its settling time and is considered as equation 21:

$$F = \sqrt{\omega(O_v^2) + S_t^2} \quad (20)$$

where O_v is overshoot maximum and S_t is settling time.

In new idea that provided for the cost function, as showed in Figure 6, the settling time and peak time of response are two perpendicular vectors. The proposed objective function shows the size of sum of these two vectors. In new objective function, in order to give weight to terms of objective function, the parameter ω is multiplied by settling time.



Vector relationship for

$$F = \sqrt{\omega(O_v^2) + S_t^2}$$

Table 1: Parameters of model ¼ for suspension system

Kt(N/m)	bs(Ns/m)	Ks(N/m)	mu(kg)	ms(kg)
101115	1190	66824.2	87.15	225

5. Simulation results

In simulation of model ¼ of active suspension system that has shown in figure 1, system parameters are considered according to Table 1.

In ICA algorithm implementation, number of initial population is considered 10 and number of generation replication is considered 50 that figure 7 shows value of cost function in each decade.

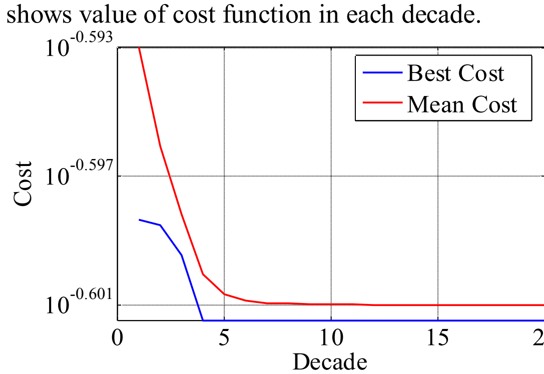


Figure 7: The value of the cost function in each decade

Figures 8 to 10 show comparison of parameters related to the ease of travel with stability of suspension of active and passive system. Table 2 shows statistical comparison of these parameters quantitatively. As is shown in Figure 8, the vertical acceleration on passengers in active system compared to passive system has been shown that is reduced about 7 times.

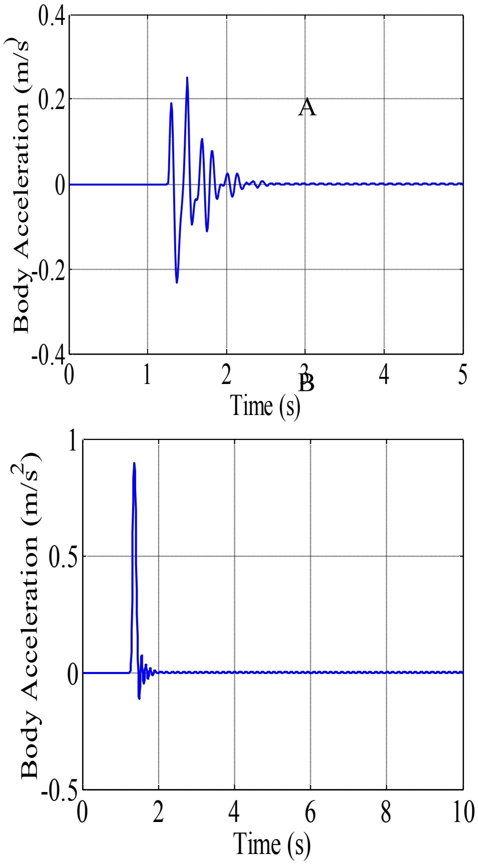


Figure 8- The acceleration on car body. (A) Active (B) Passive

Also, according to Figure 9, the car safety in active suspension system by reducing wheel offset of road is improved. Figure 10 shows the relative displacement that is related to stability of suspension system. As is considered, active mode compared to passive mode has been improved.

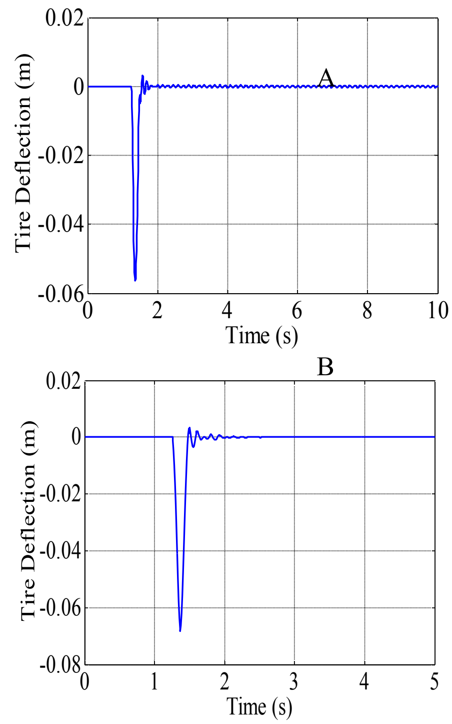


Figure 9: wheel offset from the road surface. (A) Active (B) Passive

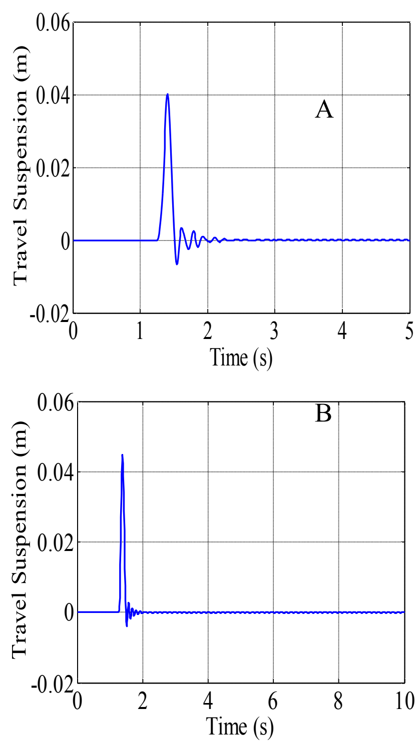


Figure 10: Relative displacement. (A) Active (B) Passive

6. Conclusion

In this paper, a sliding mode controller for linear model ¼ of proposed active suspension system, with good feedback for the vertical acceleration acting on the car body and using ICA evolutionary algorithms for coefficients of controller has been determined. Simulation results show the improvement of parameters of passenger comfort in active mode compared to passive mode. Also, the parameter car stability on the road surface that is directly related to the relative displacement and wheel offset, in active mode using the proposed controller in ICA method is improved compared to the passive state.

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