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# Nonlinear Active Suspension System Control using Fuzzy Model Predictive Controller

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**Key words:** Active suspension system, fuzzy model predictive control, nonlinear dynamical

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**Abstract:** Recent years, active suspension system has been widely used in automobiles to improve the road holding ability and the riding comfort. This study presents a new fuzzy model predictive control for a nonlinear quarter car active suspension system. A nonlinear dynamical model of active suspension is established, where the nonlinear dynamical characteristic of the spring and damper are considered. Based on the proposed fuzzy model predictive control method is presented to stabilize the displacement of the active suspension in the presence of different road profiles. Parameters of the model predictive and fuzzy logic control laws are designed to estimate the (Bump and Sinusoidal)road profile input in the active suspension. At last, the reliability of the fuzzy model predictive control method is evaluated by the MATLAB simulation tool. Simulation result shows that the fuzzy model predictive control method obtained the satisfactory control performance for the active suspension system.

## INTRODUCTION

When we refer to a traditional or conventional suspension system, we mean a system that comes “as is”. In other words, a conventional system is a passive system. Once installed in the car, its character hardly changes. This has certain advantages and disadvantages. On the positive side, the system is very predictable over time and over time you will develop a familiarity with the suspension of your car. You will understand your abilities and your limits. On the other hand, once the system has reached these limits, it no longer has the ability to compensate for situations that go beyond its design parameters. Springs react slowly, torsion bars appear. An active suspension system, on the other hand can continuously adapt to changing road conditions.

It “artificially” expands the design parameters of the system by constantly monitoring and adapting itself, thus, continuously changing its character. With advanced sensors and microprocessors that keep you constantly informed. their identity remains fluid, contextual, amorphous. By changing character to respond to different road conditions, the active suspension provides superior handling, feel, responsiveness and safety. Before we dive into active suspension systems though, a word on why this should be the case. It is true that this type of technology is often expressed in very expensive cars. But as with any new technology, there is a "trickle-down" effect. Rapid advances in microprocessor research will soon make these functions available for an entirely new range of vehicles. This includes family sedans, minivans, pickups, SUVs and even small cars[1, 2].

Active suspension systems (also known as computerized driving control) consist of the following components: one or two computers (sometimes called an electronic control unit or ECU for short), adjustable shock absorbers and springs, a number of sensors in every wheel and everywhere in the car, and an actuator or Servo over each shock absorber and spring. Components can vary slightly from manufacturer to manufacturer but these are the basic parts of an active suspension system.

An active suspension is a sort of automobile suspension on an automobile. It makes use of an onboard gadget to manage the vertical motion of the automobile's wheels relative to the chassis or automobile frame in place of the passive suspension furnished via. way of means of huge springs where the motion is decided absolutely via way of means of the street surface. So-known as active suspensions is divided into 2 classes: actual active suspensions and adaptive or semi-active suspensions. While adaptive suspensions most effective range surprise absorber firmness to suit converting street or dynamic conditions, active suspensions use a few sorts of actuator to elevate and decrease the chassis independently at each wheel[3].

These technologies allow vehicle producers to reap an extra degree of trip pleasant and vehicle handling via. way of means of retaining the tires perpendicular to the street in corners, permitting better traction and manage. An onboard PC detects frame motion from sensors during the automobile and the use of that data, controls the movement of the active and semi- active suspensions. The gadget truly gets rid of frame roll and pitch version in lots of riding conditions inclusive of cornering, accelerating and braking.

Active suspensions, the primary to be introduced, use separate actuators which will exert a freelance force on the suspension to boost the riding characteristics. The drawbacks of this style are high cost, intercalary complication and mass of the apparatus and therefore the want for frequent maintenance on some implementations. Maintenance can need specialized tools and a few issues will be troublesome to diagnose[4].

Adaptive or semi-active systems can solely amendment the viscous damping constant of the shock absorber and don't add energy to the suspension system. whereas adaptive suspensions have usually a slow time response and a restricted range of damping coefficient values, semi-active suspensions have time response on the brink of a couple of milliseconds and may offer a large vary of damping values. Therefore, adaptative suspensions usually only propose completely different riding modes (comfort, normal, sport) similar to different damping coefficients while semi-active suspensions modify the damping in real time, counting on the road conditions and therefore the dynamics of the car. tho' limited in their intervention (for example, the management force will ne'er have completely different direction than the present vector of rate of the suspension), semi-active suspensions are less costly to style and consume so much less energy. In recent times, analysis in semi-active suspensions has continuing to advance with regard to their capabilities, narrowing the gap between semi-active and absolutely active suspension systems.

## MATERIALS AND METHODS

### Mathematical models

**Mathematical modelling of nonlinear active suspension system:** The quarter car model of nonlinear active suspension system is shown in Fig. 1. The nonlinear active suspension system has the extra advantages which a terrible damping can be produced and producing the huge variety of force into the system at low velocities. Besides, this condition potentially will increase the overall performance of the suspension system. The derivations of mathematical equation of nonlinear active suspension system of quarter vehicle system are given through Eq. 1 and 2:

$$\begin{aligned}M_1\ddot{c}_1 &= k_1^l(c_2-c_1)+k_1^{nl}(c_2-c_1)^3+\\ &B_1^l(\dot{c}_2-\dot{c}_1)-B_1^{sym}|\dot{c}_2-\dot{c}_1|+\\ &B_1^{nl}\sqrt{|\dot{c}_2-\dot{c}_1|\operatorname{sgn}(\dot{c}_2-\dot{c}_1)}-F\end{aligned} \quad (1)$$

$$\begin{aligned}M_2\ddot{c}_1 &= -k_1^l(c_2-c_1)-k_1^{nl}(c_2-c_1)^3+B_1^l(\dot{c}_2-\dot{c}_1)-\\ &B_1^{sym}|\dot{c}_2-\dot{c}_1|B_1^{sym}|\dot{c}_2-\dot{c}_1|-B_1^{nl}\sqrt{|\dot{c}_2-\dot{c}_1|\operatorname{sgn}(\dot{c}_2-\dot{c}_1)}+\\ &k_2(c_2-\dot{z})+B_2(c_2-\dot{z})+F\end{aligned} \quad (2)$$

The parameters of the Nonlinear quarter car active suspension system is shown in Table 1.

**Hydraulic actuator:** The hydraulic actuator consists of cylinder or fluid motor that uses hydraulic power to facilitate mechanical operation. The mechanical motion offers associate output in terms of linear, turn or oscillatory motion. As liquids are nearly not possible to compress, a hydraulic actuator will exert an oversized force. the disadvantage of this approach is its restricted acceleration[5, 6].

The hydraulic cylinder consists of a hollow cylindrical tube on that a piston can slide. The term single acting is used once the fluid pressure is applied to simply one aspect of the piston. The piston can move in exactly one direction, a spring being ofttimes accustomed offer the piston a come back stroke. The term double acting is used once pressure is applied on both sides of the piston; any distinction operative between the 2 sides of the piston moves the piston to 1 side or the other. In this study, the nominal model for the hydraulic actuator is modeled as a first order system transfer function as:

$$G(s)=\frac{3}{s+10}$$

Table 1: Parameters of nonlinear quarter vehicle model

| Model parameters | Symbol | Values |
|---|---|---|
| Vehicle body mass | M 1 | 550 kg |
| Wheel assembly mass | M 2 | 63 kg |
| Tire stiffness | k 2 | 165,000 N/m |
| Suspension stiffness (linear) | k1 | 36,000 N/m |
| Suspension stiffness (nonlinear) | $k^{nl}_1$ | 3,600,000 N/m |
| Suspension damping (linear) | B1 | 1,200 N-s/m |
| Suspension damping (nonlinear) | $B^{nl}_1$ | 800 N-s/m |
| Suspension damping (asymmetrical) | $B^{sys}_1$ | 800 N-s/m |
| Tire damping | B2 | 1,800 N-s/m |

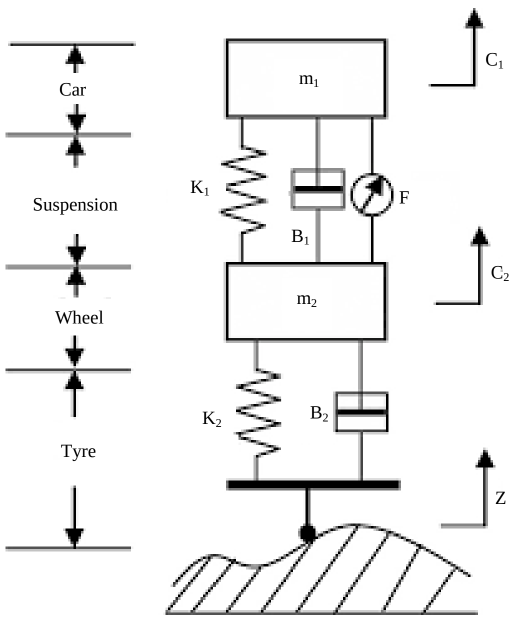


Fig. 1: Quarter model of nonlinear active suspension system

## Proposed controller design

**Fuzzy model predictive control:** A fuzzy model predictive control (FMPC) approach is introduced to style an impact system for an extremely nonlinear process. The two-layered computing theme avoids in depth on-line nonlinear optimization and permits the look of a controller supported linear control theory. The Formal Logic Management (FLC) has been extensively researched, since, Zadeh revealed the famous paper on fuzzy sets. Its control rules are linguistic and intuitive ones that are close to means knowledge. It is applicable to use fuzzy controller once the process is non-linear having time delay or is tough to get precise knowledge of the Model Predictive Control (MPC) has additionally developed significantly in research and industry.

The basic ideas of most MPC strategies are that victimization a model to predict the future process output, calculating the management sequence to minimize the target function and victimization the receding strategy[7].

Table 2: Fuzzy rule base

| u | Δe NVB | NB | NM | NS | Z | PS | PM | PB | PVB |
|---|---|---|---|---|---|---|---|---|---|
| NVB | PVB | PVB | PVB | PB | PM | PM | PS | Z | Z |
| NB | PVB | PVB | PB | PM | PS | PS | PS | Z | Z |
| NM | PVB | PB | PM | PS | PS | Z | Z | Z | NS |
| NS | PB | PM | PM | PS | PS | Z | Z | NS | NS |
| Z | PM | PM | PS | Z | Z | Z | NS | NS | NM |
| PS | PM | PS | PS | Z | NS | NS | NM | NM | NB |
| PM | PS | PS | Z | NS | NS | NM | NB | NB | NB |
| PB | PS | Z | Z | NS | NM | NM | NB | NVB | NVB |
| PVB | Z | Z | NS | NM | NM | NB | NB | NVB | NVB |

Table 3: Neural network parameters

| Network architecture | Values | Parameters | Values |
|---|---|---|---|
| Size of hidden layer | 6 | Delayed plant input | 2 |
| Sample interval(sec) | 0.1 | Delayed plant output | 2 |
| **Training data** | | | |
| Training sample | 65 | Maximum Plant output | 2 |
| Maximum Plant input | 2 | Minimum Plant output | 1 |
| Minimum Plant input | 1 | Max interval value (sec) | 30 |
| Min interval value (sec) | | | 15 |
| **Training parameters** | | | |
| Training epochs | 65 | | |

Both the FLC and MPC have their benefits and disadvantages. There exist some processes that not so precise model of them will be got or these processes are settled by the external noises. In such cases, using the non-model-based FLC strategy might lose some helpful info about the processes, using MPC strategy might result a complex management law and need a long calculation to come up with the manipulate variable. The block diagram of fuzzy model predictive control is shown in Fig. 2[8].

**Fuzzy logic controller:** In closed loop dominion systems, the classical controller has been replaced by the FLC. This quantity that the IF-THEN rules and fuzzy membership functions replaces the mathematical rule to experiment the system[5]. For the fuzzy logic mechanism, the signal variables are error (e) and derivative of error (de/dt) and the output Sus_def (suspension deflection) (u). Gaussian membership functions utilized for inputs variables and the output. Error has 9 membership functions as shown in Fig. 3, derivative of error has 9 membership functions as shown in Fig. 4 and output has nine membership functions as shown in Fig. 5 and 6[9].

**Fuzzy rule base:** The fuzzy input variable e has nine membership functions and fuzzy input variable Δe has nine membership functions, and the output variable has nine membership functions. There are 81 rules generated as shown in Table 2.

**Model predictive controller:** The MPC may be wont to control a good selection of processes reminiscent of processes with long delay time or non-minimum section systems or unstable systems. Table 3 illustrates the network architecture, training data and training parameters of the proposed controllers[10].

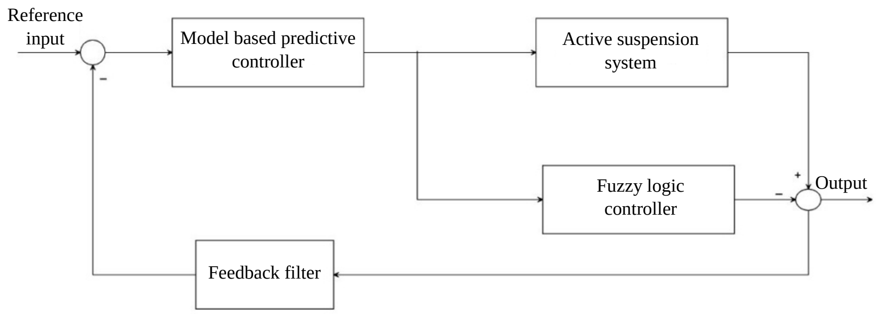


Fig. 2: Block diagram of fuzzy model predictive control

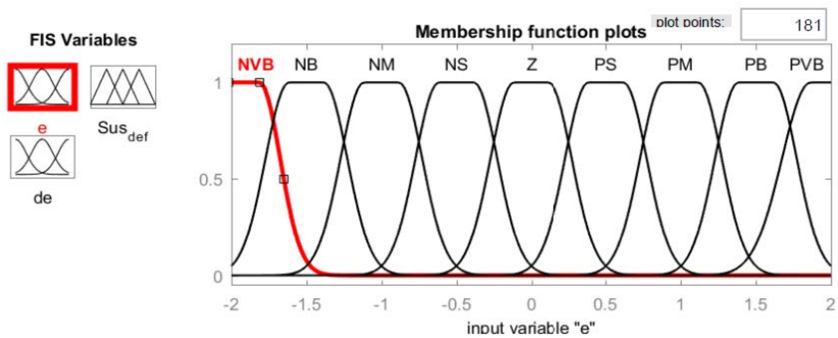


Fig. 3: Error membership function

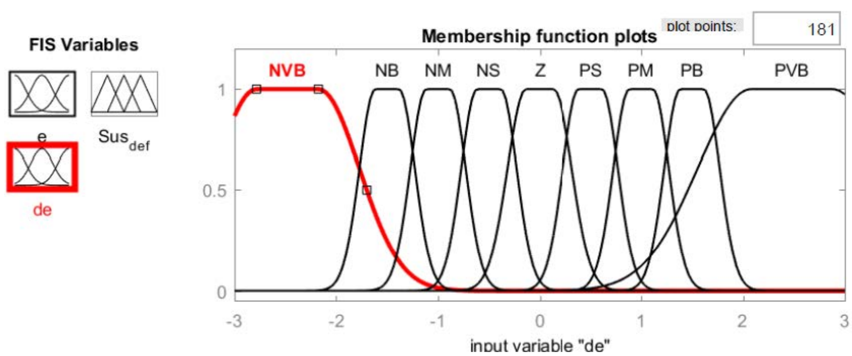


Fig. 4: Change of error membership function

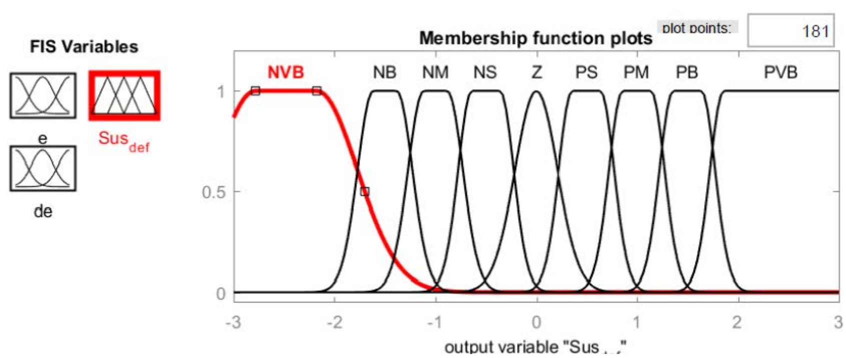


Fig. 5: Output membership function

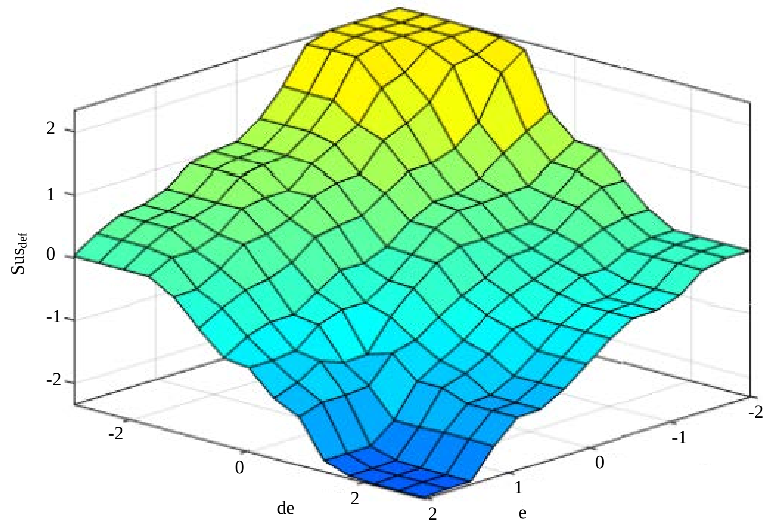


Fig. 6: Surface membership function

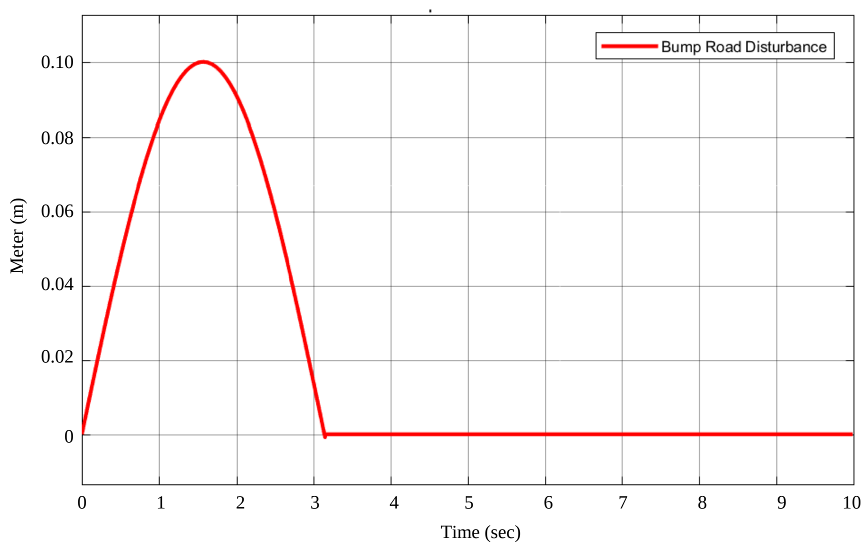


Fig. 7: Bump road profile

## RESULTS AND DISCUSSION

**Road profiles:** The profile is the vertical facet of the road, as well as crest and sag curves, and also the straight grade lines connecting them. The cross section shows the position and variety of car and bicycle lanes and sidewalks, beside their cross slope or banking. In this paper, Bump and Sinusoidal road profiles has been used to test the performance of the nonlinear quarter car active suspension system with fuzzy model predictive controller as shown in Fig. 7 and Fig. 8, respectively[11].

**Suspension deflection response to bump road profile input:** The simulation of suspension deflection response of the nonlinear active suspension system with fuzzy model predictive controller for a bump road profile with comparison of semi-active and passive suspension systems is shown in Fig. 9[12].

The simulation result shows that the nonlinear active suspension system suspension deflects almost exactly like the road profile with a 3.5% error while the semi-active suspension system suspension deflects with an error of 18% and delay error of 37.5% and the passive suspension system suspension deflects with an error of 30%.

**Suspension deflection response to sinusoidal road profile input:** The simulation of suspension deflection

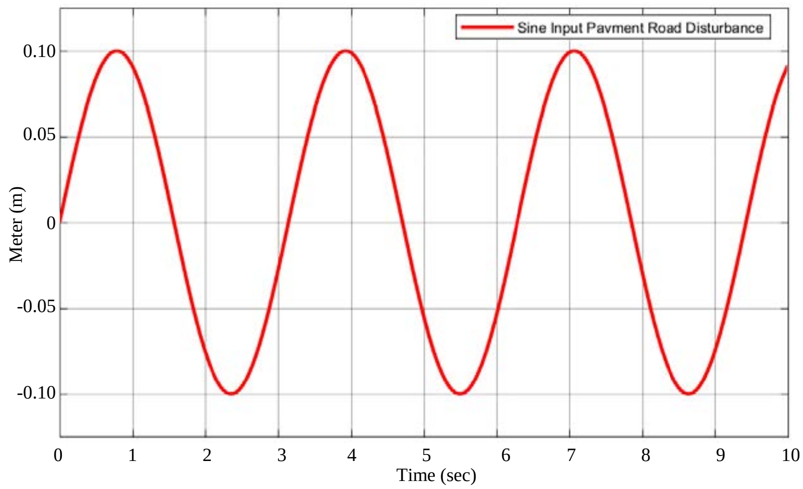


Fig. 8: Sinusoidal road profile

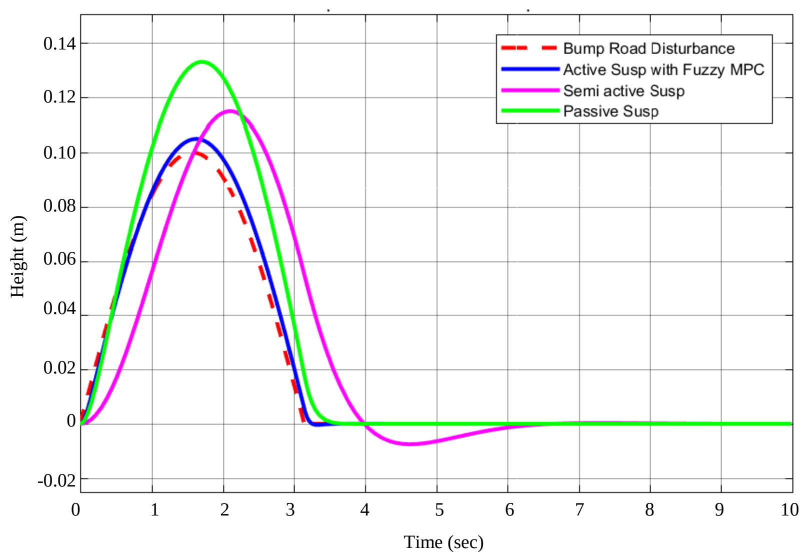


Fig. 9: Suspension deflection response to bump road profile

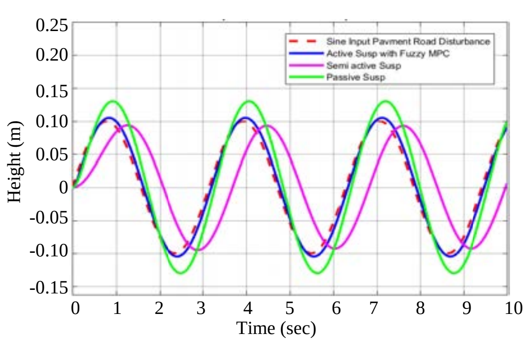


Fig. 10: Suspension deflection response to sinusoidal road profile

response of the nonlinear active suspension system with fuzzy model predictive controller for a sinusoidal road profile with comparison of semi-active and passive suspension systems is shown in Fig. 10. The simulation result shows that the nonlinear active suspension system suspension deflects almost exactly like the road profile with a 0.95% error while the semi-active suspension system suspension deflects with 80% of the road profile and delay error of 47.5% and the passive suspension system suspension deflects with an error of 30%[13].

## CONCLUSION

The nonlinear dynamical model of nonlinear quarter car active suspension system is proposed in this study.

The nonlinear characteristic of the spring and damper are introduced in the proposed nonlinear model. Using the nonlinear model, a fuzzy model predictive controller with the parameter of the MPC and FLC laws are designed as the active control for nonlinear quarter car active suspension system. Stability analysis of the suspension deflection is done using MATLAB simulation tool. According to simulation case results, the proposed fuzzy model predictive control method obtained a satisfactory performance improvement for the nonlinear quarter car active suspension system[14].

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