Fuzzy logic control for active bus suspension system

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Abstract. In this study an active controller is presented for vibration suppression of a full-bus suspension model that use air spring. Since the air spring on the full-bus model may face different working conditions, auxiliary chambers have been designed. The vibrations, caused by the irregularities of the road surfaces, are tried to be suppressed via a multi input-single output fuzzy logic controller. The effect of changes in the number of auxiliary chambers on the vehicle vibrations is also investigated. The numerical results demonstrate that the presented fuzzy logic controller improves both ride comfort and road holding.

1. Introduction
Vibrations, caused by road roughness affect the ride comfort and drive safety negatively. These vibrations can be minimized by using semi-active [1] and active suspension systems [2]. In this study, an active control strategy was applied to the full-bus suspension system. Fuzzy logic controllers were used on this system with a fixed number of auxiliary chambers. Fuzzy logic control was preferred since it has a model-free design methodology.

2. The bus model with seven degrees of freedom
The physical model of the full-bus is presented in Figure 1.

Figure 1. The bus model with two axles
a, b, c and d are the distances from the body inertia of each rear and front axles; z₁, z₂, z₃, z₄ are the front and rear wheel road surface inputs; k₁, k₂, k₃, k₄ are the stiffness of front and rear wheels; m₁, m₂, m₃, m₄ are front and rear unsprung masses; y₁, y₂, y₃, y₄ are front and rear wheel hops; k₁, k₂, k₃, k₄ are front and rear suspension spring constants; b₁, b₂, b₃, b₄ are front and rear suspension damping
coefficients; \( u_1, u_2, u_3, u_4 \) are control inputs to the front and rear of the vehicle; \( y \) is body bounce; \( \theta \) and \( \alpha \) are body pitch and roll angles; \( I_\theta \) and \( I_\alpha \) are body inertias of pitch and roll, respectively.

The air spring model proposed by Bal [3] is used in this study. It can be designed to have different spring constants while carrying the same load. This is achieved by using auxiliary chambers which can be added to or separated from the air spring volume. The air spring model with auxiliary chamber is shown in Figure 2.

![Figure 2. Air spring model with auxiliary chamber](image)

Here \( p \) is the pressure and \( v \) is the volume of air spring at time \( t \); \( V_{ac} \) is volume of auxiliary chamber; \( h \) is height of air spring; \( x \) is displacement of the air spring. Accordingly, the spring constant of the air spring is

\[
k = nMgA_{as} (h_{as} \cdot A_{as} + n_{ac} \cdot V_{ac})^{n}([h_{as} \cdot A_{as} + n_{ac} \cdot V_{ac}] A_{as} x)^{-\frac{1}{n+1}}
\]

- \( n \): Polytropic exponent
- \( M \): Body mass
- \( g \): Acceleration of gravity
- \( A_{as} \): Area of auxiliary chamber
- \( n_{ac} \): Number of auxiliary chamber

3. The fuzzy logic controller

In this section the effects of the fuzzy logic controller on ride comfort and drive safety are investigated. The algorithm of the multi-input single-output fuzzy logic controller for the vehicle suspension system uses the errors of the suspension end velocities, their accelerations and suspension gap velocities as the input variables while the control forces are \( u_1, u_2, u_3 \) and \( u_4 \). The range of membership functions has been chosen as \([-1, 1]\) and scaling factors are used in order to map the crisp input output values to their corresponding fuzzy values. A model of the rule base developed for each suspension is given in Table 1. In this Fuzzy Associative Memory (FAM) table, the rules are given for front right suspension. \( x \) denotes the displacement of the front right suspension vehicle connection. The column of with each (P or N) row stand for two rules using the “or” connector. Therefore, there are 75 rules in this table. Identical FAM tables are valid for the other suspensions as well. P, N, ZE, VB, B, M and S represent Positive, Negative, Zero, Very Big, Big, Medium and Small, respectively.

| \( e(\xi - \hat{\xi}) \) | \( e(\dot{\xi}) \) | \( e(\ddot{\xi}) \) | \( u_1 \) | \( e(\xi - \hat{\xi}) \) | \( e(\dot{\xi}) \) | \( e(\ddot{\xi}) \) | \( u_1 \) |
|---|---|---|---|---|---|---|---|
| PM | PM | ZE | ZE | PM | PM | P or N | PS |
| PS | PM | ZE | PS | PS | PM | P or N | PM |
| ZE | PM | ZE | PM | ZE | PM | P or N | PB |
| NS | PM | ZE | PM | NS | PM | P or N | PB |
| NM | PM | ZE | PB | NM | PM | P or N | PB |
| PM | PS | ZE | ZE | PM | PS | P or N | PS |
| PS | PS | ZE | PS | PS | PS | P or N | PB |
| ZE | PS | ZE | PS | ZE | PS | P or N | PB |
| NS | PS | ZE | PM | NS | PS | P or N | PB |
| NM | PS | ZE | PM | NM | PS | P or N | PB |
| PM | ZE | ZE | NS | PM | ZE | P or N | NM |
| PS | ZE | ZE | ZE | PS | ZE | P or N | NS |
| ZE | ZE | ZE | ZE | ZE | ZE | P or N | ZE |
| NS | ZE | ZE | ZE | NS | ZE | P or N | ZE |
| NM | ZE | ZE | PS | NM | ZE | P or N | PM |
| PM | NS | ZE | NM | PM | NS | P or N | NB |
| PS | NS | ZE | NM | PS | NS | P or N | NB |
| ZE | NS | ZE | NS | ZE | NS | P or N | NM |
4. Numerical results

The bus model is assumed to travel over the bump shown in Figure 4. The road input to the rear wheel is the same but delayed by \( \Delta t \)

\[
\Delta t = \frac{(a + b)}{V}
\]

(2)

![Figure 4. Road disturbance input](image)

The vehicle bounce and pitch motion and their accelerations are shown in Figure 5 for controlled, uncontrolled-without auxiliary chambers and uncontrolled-with 4 auxiliary chambers cases. It is seen that when auxiliary chambers are in effect the ride comfort improves since magnitudes of the displacements are reduced.

![Figure 5. Time responses of the full-bus model](image)

Suspension deflections for the uncontrolled and fuzzy controlled cases are shown in Fig. 6. It is clear from this figure that the maximum suspension deflections for the fuzzy controlled case do not exceed the un-controlled ones with four auxiliary chambers and that there is no permanent deflection, which indicates that the ride comfort is improved without degenerating the suspension working limits.

![Figure 6. Time history of suspension gap](image)
Frequency response is another way to evaluate the behaviour of a dynamic system. The frequency response of main body displacement and its acceleration are given in Figure 7. The resonances of the body motions belonging to body bounce and its acceleration disappear and the amplitude of the motion over the most of the frequency range becomes smaller effectively. The amplitude of the dynamic wheel load is reduced by fuzzy logic controller.

![Figure 7. Frequency response of main body, its acceleration and dynamic wheel load](image)

Figure 7. Frequency response of main body, its acceleration and dynamic wheel load

Figure 8 depicts the time history of the control force. The maximum values of the front and rear control forces are about 1200N and 400N, respectively.

![Figure 8. Controller forces of change over time graphs](image)

Figure 8. Controller forces of change over time graphs

5. Conclusions
In this study, a controller is designed for comfortable and reliable ride for a bus model using an air spring with auxiliary chambers. A fuzzy logic controller was presented in this. The controller is able to protect the suspension working limits. On the other hand ride comfort can be improved while dynamic wheel load improve.

6. References
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