Decreasing Vibration of Vehicle Using Combined Suspension System

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***Abstract*—A kind of active suspension system combined with passive suspensions and active components is addressed. Suspension dynamics are modeled using a two degree-of-freedom, linear and time-invariant vehicle model. The Least Means Squares adaptive algorithm that guarantees system optimal control, is presented and used to find the optimal suspension system design. For two-DOF vehicle suspension model, LMS adaptive controller is designed. The acceleration of the sprung mass, dynamic tyre load between wheels and road and dynamic deflection between the sprung mass and the unsprung mass are determined as the evaluation targets of suspension performance. For the combined suspension, compared with passive suspension, acceleration of sprung mass acceleration under the road input model has all decreased largely as 8-10 times in high frequency resonance band or low frequency resonance band. The design exhibits superior performance compared to passive suspension.**

***Keywords*—combined suspension system, vehicle vibration, adaptive controller, least means square**

I. INTRODUCTION

In automotive industry, the conception of active and semi-active suspension has been advanced, which give a new way to improve the performance of suspension system [1-5]. The parameters of the passive suspension system cannot change according to the road excitation, and the system can only store or exhaust the body vibration energy. So the nonlinear and adjustable rigidity spring and body's height adjustable plant are respectively applied in order to resolve the difficulties between the riding comfort and handing safety in various operation conditions. The methods get some good results, but can not eliminate the deficiencies of passive suspension system at all.

The adoption of active suspension system overcomes many defects of passive suspension, which makes suspension system get adaptive capacity to variable working condition to maximum extent. But there are some problems on actuator's responsive speed and fast realization of control strategy such as structural complexity, expensive price, big volume and heavy weight [6-7]. In this paper, it emphasizes on the design of combined suspension system and the research of adaptive control method.

II. COMBINED SUSPENSION SYSTEM MODEL

A kind of active suspension system combined with passive suspensions and active components. are designed in this paper, as shown in fig. 1. Suspension dynamics are modeled using a two degree-of-freedom, linear and time-invariant vehicle model. and the dynamic differential equations of suspension system are set up as follows

$$\begin{cases} m_1\ddot{z}_1 - c_2(\dot{z}_2 - \dot{z}_1) - k_2(z_2 - z_1) + k_1(z_1 - z_0) = -u \\ m_2\ddot{z}_2 + c_2(\dot{z}_2 - \dot{z}_1) + k_2(z_2 - z_1) = u \end{cases} \tag{1}$$

where m_1 and m_2 are the sprung mass and the unsprung mass of vehicle system, k_1 is the suspension rigidity, k_2 is the tyre rigidity, C_2 is the suspension damper, z_1 and z_2 are the displacements of the sprung mass and the unsprung mass.

Let $x_1= z_1$, $x_2= z_2$, $x_3=\dot{z}_1$, $x_4=\dot{z}_2$, the state equation of system can be expressed

$$\dot{X} = AX + BU \tag{2}$$

where the state vector $X=[x_1, x_2, x_3, x_4]^T$;

$$A = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -\frac{k_1+k_2}{m_1} & \frac{k_2}{m_1} & -\frac{c_2}{m_1} & \frac{c_2}{m_1} \\ \frac{k_2}{m_2} & -\frac{k_2}{m_2} & \frac{c_2}{m_2} & -\frac{c_2}{m_2} \end{bmatrix} \quad B = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ \frac{k_1}{m_1} & \frac{1}{m_1} \\ 0 & -\frac{1}{m_2} \end{bmatrix}$$

The output equation of active suspension system is, respectively, presented by

$$Y = CX + DU \tag{3}$$

$$C = \begin{bmatrix} -k & 0 & 0 & 0 \\ \frac{k_2}{m_2} & -\frac{k_2}{m_2} & \frac{c_2}{m_2} & -\frac{c_2}{m_2} \\ 1 & -1 & 0 & 0 \end{bmatrix} \quad D = \begin{bmatrix} k_1 & 0 \\ 0 & -\frac{1}{m_2} \\ 0 & 0 \end{bmatrix}$$

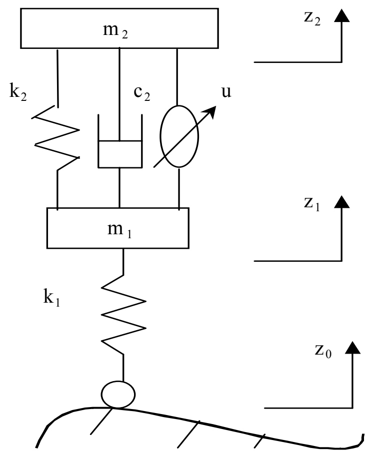

Fig. 1 Combined suspension system

Table I shows values of suspension system model parameters.

TABLE I
VALUES OF 1/4 SUSPENSION SYSTEM MODEL'S PARAMETERS

PARAMETER	Value
m_1	36 kg
m_2	145 kg
k_1	176 N/mm
k_2	13.72 N/mm
c_2	282 Ns/m

III. ADAPTIVE CONTROLLER DESIGN OF COMBINED SUSPENSION SYSTEM

A filter with LMS adaptive algorithm is widely applied in the field of digital signal process. In practice unrecursive transverse structure an adaptive filter is an adaptive linear composer. The x_0, x_1, ⋯⋯, x_L are signal vectors, and w_0, w_1, ⋯⋯, w_L is a set of adjustable weight. If the weight becomes the constant in case, output of the filter is linear composing of the filter's input. So the structure is linear. If system is single input and single output, input vector is considered as the temporal series of input signal at different moment. This adaptive structure can be implemented by adaptive linear composer and unit delay, shown in fig. 2.

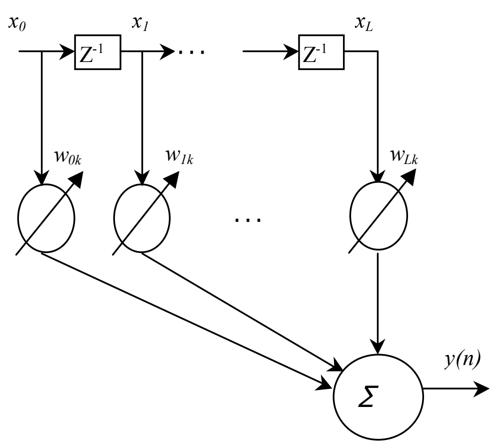

Fig. 2 Adaptive transversal filter

In the LMS adaptive algorithm, Quadratic index can reach minimum by adjusting filter's weight coefficients according to negative gradient of single sample mean square.

Let input vector is

$$X^T(n)=[x(n), x(n-1), \cdots\cdots, x(n-L+1)]$$

Weight vector is

$$W^T=[w_1, , w_2\cdots\cdots, w_L]$$

Where L is the length of filter, input vector X(n)is composed by present samples and sample delay signals before. So output of adaptive transverse filter is

$$y(n)=\sum_{j=1}^{L} w_j x(n-j+1)=W^T X(n) \qquad (4)$$

In addition, error signal e(n) is used to adjust weight vector, supposing

$$e(n)=d(n)\ y(n) \qquad (5)$$

Where d(n) is respondent signal of sprung mass.

The mean square of error signal is

$$E[e^2(n)]=E[d^2(n)]2R^T_{xd}W+W^TR_{xx}W \qquad (6)$$

Where R_{xd} is cross correlative function of x(n) and d(n), R_{xx} is auto correlative function of x(n).

Realization of gradient descent algorithm is that when gradient is zero, the mean square of is the error minimum and weight coefficient is optimum at the same time. Weight value w(n+1) at next moment equals weight value w(n) adding gradient $\nabla(n)$ of proportion to negative mean square of error, namely

$$W(n+1)=W(n)-\mu\nabla e^2(n) \qquad (7)$$

Where μ ——gain constant which controls adaptive speed and stability

In practice, the gradient $\hat{\nabla}(n)$ of single error sample square e^2(n) is generally used as approximation of the gradient of error mean square function $E[e^2(n)]$. From formula (6), we get

$$\hat{\nabla}e^2(n)=-2e(n)x(n) \qquad (8)$$

Thus LMS adaptive control algorithm is attained as below:

$$\left.\begin{aligned} y(n)&=W^TX(n)\\ e(n)&=d(n)-W^TX(n)\\ W(n+1)&=W(n)+2\mu\, e(n)X(n)\end{aligned}\right\} \qquad (9)$$

Because of no mean, there is bigger noise in the calculation. The adaptive course plays the role of a lowpass filter and the noise will be attenuated with advancing of this adaptive course.

IV. EVALUATION INDEX AND SIMULATION RESULTS

A. Evaluation Index

International Standard Organization (ISO) has published ISO2631-1: 1997(E) Mechanical vibration and shock—Evaluation of human exposure to whole-body vibration-Part 1: General requirements in 1997. Accordingly China has established GB/T4970-1996 experimental method for the riding comfort of automobile under random input. The former recommends two evaluation methods [8-9].

B. Simulation Research

Generally overall acceleration mean square root of vibration which human body supports, or acceleration mean square root of vehicle's vibration, is adopted as evaluation index for the riding comfort of vehicle. The vertical acceleration is main index which effect on the riding comfort in vehicle engineering, so in this paper vertical vibration acceleration of vehicle body is an important evaluation target in research [10-12].

In addition to considering the handing safety of vehicle, dynamic load, between wheels and road, and dynamic deflection of suspension system are also used to contrast research.

According to the response of system in the road input model, the results give theoretical base for further experiment and application research.

Generally power spectral density (PSD) of road can be defined as below

$$S_q(n) = S_q(n_0)(\frac{n}{n_0})^{-2} \tag{10}$$

Where n_0—space reference frequency （$0.1m^{-1}$）

$S_q(n_0)$ —value of road PSD when space reference frequency is n_0 .

In the course of analyzing control, the combined suspension system is simulated by road exciting signal. For two kinds of vehicle suspension system, PSD curves of system evaluation index are shown in fig. 3-fig.8.

As shown in fig.3-fig.4, for combined suspension with LMS adaptive control, compared with passive suspension, acceleration PSD of sprung mass acceleration has all decreased largely as 8-10 times in high frequency resonance band or low frequency resonance band.

The investigation of vehicle's dynamic load between wheels and ground focuses on the PSD of high frequency resonance band. As shown in fig.5-fig.6, compared with

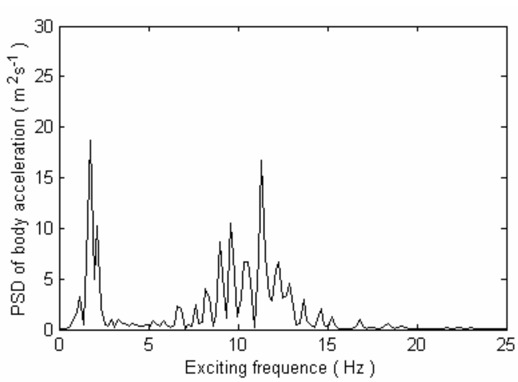

Fig. 3 Sprung mass acceleration PSD of passive suspension

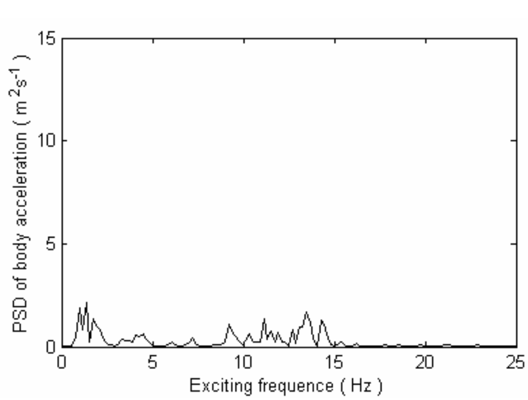

Fig. 4 Sprung mass acceleration PSD of combined suspension

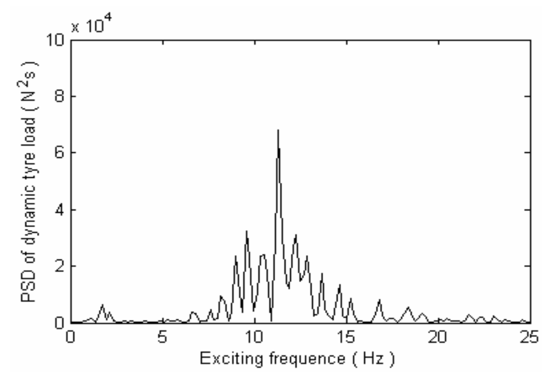

Fig. 5 Dynamic tyre load PSD of passive suspension

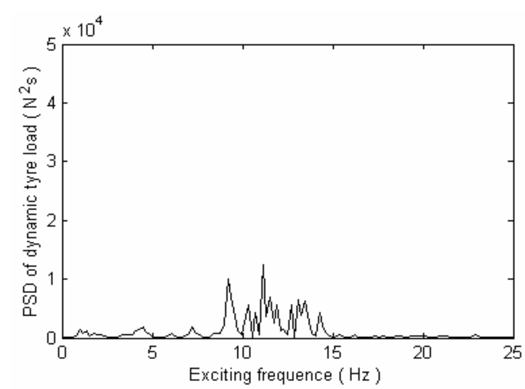

Fig. 6 Dynamic tyre load PSD of combined suspension

passive suspension, in combined suspension with LMS adaptive control, the dynamic tyre load descends 7-8 times, and the result is prominent.

If the index of dynamic deflection is high, it will not only affect the riding comfort but also destroy the handing safety. From fig. 7 to fig. 8, for the combined suspension with LMS adaptive control, the PSD of the suspension system's dynamic deflection descends prominently.

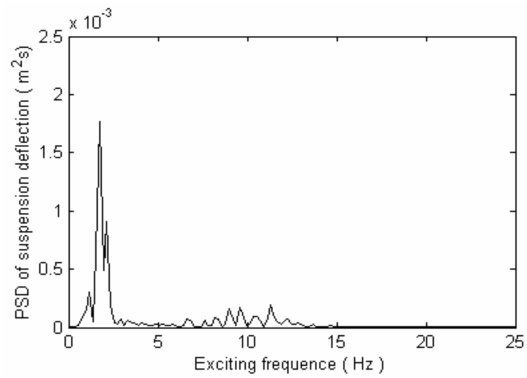

Fig. 7 Dynamic deflection PSD of passive suspension

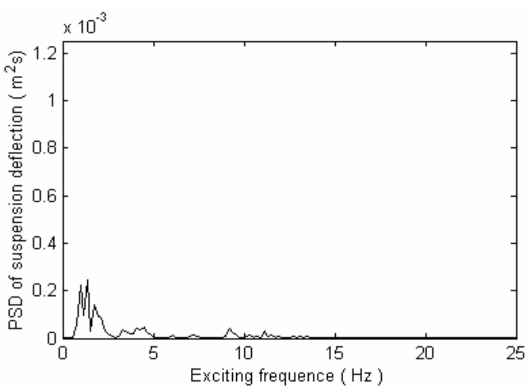

Fig. 8 Dynamic deflection PSD of combined suspension

V. CONCLUSION

In this paper, a kind of active suspension system combined with passive suspensions and active components is addressed. Suspension dynamics are modeled using a two degree-of-freedom, linear and time-invariant vehicle model. The Least Means Squares adaptive algorithm that guarantees system optimal control, is presented and used to find the optimal suspension system design.

For two-DOF vehicle suspension model, LMS adaptive controller is designed. For the combined suspension, compared with passive suspension, acceleration of sprung mass acceleration under the road input model has all decreased largely in high frequency resonance band or low frequency resonance band.

The simulation calculation results of the three evaluation indexes in the stimulation of random road signal verify that the combined suspension system and LMS adaptive control strategy may largely improve the performances of the suspension system.

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