Dynamic characteristics analysis of nonlinear suspension system of automobile with seven degree of freedom

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Abstract. The application of MATLAB/SIMULINK to establish the mechanical simulation model of seven-degree-of-freedom vehicle linear and non-linear suspension system. Realization of system response under simulated road excitation, the dynamic characteristics of the non-linear suspension are studied, the non-linear spring and damping are simulated, and the parameter $\varepsilon$ is introduced to change the degree of nonlinearity. The root mean square values of acceleration and displacement of linear suspension, non-linear stiffness suspension and non-linear damping suspension are analyzed and compared under different pavement conditions. The results show that: The mean square root of the acceleration of the body mass center and the pitch angle of the non-linear suspension are reduced by 14.3% and 17.0% respectively compared with the linear acceleration of the body mass center and the pitch angle; The root mean square value of pitch acceleration of non-linear suspension damping is 31.2% less than that of linear acceleration, which improves ride comfort and safety to a certain extent.

1. Introduction

This paper studies the vertical motion of the centroid, the pitch and inclinate motion of the body, and the vertical motion of the mass of four wheels. The car suspension system is composed of elastic elements, guide mechanism and shock absorber [1]. Vehicle will bump on uneven road surface, body suspension will vibrate, suspension has an important Influence on vehicle ride comfort and operation stability [2]. In addition to satisfying the driving, steering and braking performance of automobiles, driving safety and ride comfort are also the top priorities of automotive research, the automotive industry is also developing toward three high levels (high added value, high energy and high quality) [3]. Spring and damping are very important in the non-linear characteristics of suspension, the expressions of linear and non-linear spring and linear and non-linear damping are selected in this paper. A seven-degree-of-freedom model of automobile is established by means of dynamic equation [4]. Main Excitation and Vibration Sources of Vehicle Driving is road roughness, according to international standard ISO/DIS 8608 and national standard GB7031-86 [5], road roughness is divided into eight grades (A, B, C, D, E, F, G, H) [6]. In this paper, the response of grade D pavement is studied. The linear and non-linear models of automobile with seven degrees of freedom are established by MATLAB/SIMULINK, the root mean square value is introduced, the root mean square values of displacement and acceleration responses of each degree of freedom in vehicle suspension model are output, through comparative analysis, this paper studies the impact on vehicle ride comfort and driving safety.
2. Nonlinear suspension characteristics

Spring and damping are very important in the non-linear characteristics of suspension, which are discussed in this paper. For the simulation of non-linear spring, the linear expression is as follows:

\[ F_s = K \cdot \Delta x \]  

(1)

The non-linear expression is as follows (The simulation curve is shown in Figure 1.):

\[ F_s = K \cdot \Delta x + \varepsilon \cdot K \cdot \log(\Delta x + 1) \]  

(2)

In the formula \( F_s \) is a spring force, \( K \) is spring stiffness, \( \Delta x \) is Spring displacement. We can adjust the size and change the degree of non-linearity by parameters.

Figure 1. Nonlinear spring force simulation curve Coordinate diagram.

Figure 2. Nonlinear damping force simulation curve coordinate diagram.
The nonlinear damping is simulated and the linear damping expression is as follows:

\[ F_d = c \cdot \Delta x \]  

(3)

The non-linear expression is as follows (The simulation curve is shown in Figure 2.):

\[ F_d' = c \cdot \Delta \dot{x} + \varepsilon \cdot c \cdot e^{\Delta x - 1} \]  

(4)

\( F_d \) is damping force, \( C \) is linear damping, \( \Delta \dot{x} \) is relative velocity, We can adjust the size and change the degree of nonlinearity by parameters.

3. Suspension simulation and response

According to the Dynamic Equation of Seven-degree-of-freedom Vehicle Suspension System [7], anda seven-degree-of-freedom linear vehicle suspension model is established by using MATLAB/SIMULINK (Figure 3. Centroid Model Diagram of Vehicle Suspension.), other degrees of freedom are coupled with the centroid model. Based on the linear model, the nonlinear damping and stiffness models can be obtained by adding different Gain modules.

![Figure 3. Centroid Model Diagram of Vehicle Suspension.](image)

When car speed \( u = 40 \text{m/s} \), the response curve of automobile suspension can be obtained by driving on grade D road (Response output is shown in Figures 4 to 7.) :

![Figure 4. Body center of mass displacement time domain change curve.](image)
Figure 5. The time-domain variation curve of body elevation Angle displacement.

Figure 6. Time domain variation curve of body mass center acceleration.

Figure 7. Time domain curve of body pitch acceleration.
4. Analysis of simulation data
In the data analysis of this paper, the calculation of root mean square value is mainly used, and the root mean square value is compared to draw a conclusion. In MATLAB, we use sqrt (mean (simout. ^) program to calculate the root mean square value, and input different simout numbers according to the required root mean square value.

In this paper, the linear and non-linear comparative analysis of seven-degree-of-freedom suspension is carried out. Vehicle ride comfort is measured by five indicators: centroid acceleration, pitch acceleration, roll acceleration, tire travel and tire dynamic load.

Table 1. Comparison of root mean squared acceleration of linear and nonlinear suspension stiffness.

|         | Centroid acceleration (m/s²) | Pitch angular acceleration (rad/s²) | Inclination acceleration (rad/s²) |
|---------|------------------------------|------------------------------------|----------------------------------|
| Linear  | 0.9976                       | 0.4311                             | 0.0956                           |
| Nonlinear | 0.8548                      | 0.3580                             | 0.1013                           |
| Amount of change(%) | -14.3                        | -17.0                              | +6.0                             |

As can be seen from Table 1: Compared with the linear acceleration of the centroid and the pitch angle, the acceleration of the centroid and the pitch angle of the non-linear suspension are significantly respective reduced by 14.3% and 17.0%. The ride comfort of the vehicle is improved to a certain extent, so the ride comfort of the vehicle is also improved. However, the RMS of the roll acceleration of the stiffness of the non-linear suspension is higher than that of the linear one, but it can be neglected relative to the centroid acceleration and pitch acceleration of the body. Overall, vehicle ride comfort and safety have been improved.

Table 2. Contrast of the root mean square of acceleration between linear and non-linear suspension damping.

|         | Centroid acceleration (m/s²) | Pitch angular acceleration (rad/s²) | Inclination acceleration (rad/s²) |
|---------|------------------------------|------------------------------------|----------------------------------|
| Linear  | 0.9976                       | 0.4311                             | 0.0956                           |
| Nonlinear | 1.0000                      | 0.2965                             | 0.0971                           |
| Amount of change(%) | 0                            | -31.2                              | +1.6                             |

From the Table 2, it can be seen that the root mean square value of pitch acceleration of non-linear suspension damping is smaller than that of linear pitch acceleration, which decreases by 31.2%. It can be seen that the ride comfort of the vehicle has been improved very well.

Table 3 compares the effects of linear suspension stiffness and non-linear suspension stiffness on body acceleration under C, D, E three-level road surface. From Table 3, it can be seen that with the increase of road roughness, the mean square root of the road roughness of the next level is always twice as much as that of the first level, and the mean square root of the road roughness of the non-linear and linear suspensions is almost invariable regardless of the level of road roughness. Surface roughness, body centroid acceleration and pitch acceleration of non-linear suspension improve vehicle ride comfort, while roll acceleration has almost no effect on vehicle ride comfort.
Table 3. Effect of Suspension Stiffness on Vehicle Acceleration.

|                  | Centroid acceleration (m/s²) | Pitch angular acceleration (rad/s²) | Inclination acceleration (rad/s²) |
|------------------|------------------------------|----------------------------------|----------------------------------|
| linear           | 0.4999                       | 0.2160                           | 0.0499                           |
| C pavement       | 0.4259                       | 0.1787                           | 0.0505                           |
| Amount of change(%) | -14.8                       | -17.3                            | +1.2                             |
| linear           | 0.9976                       | 0.4311                           | 0.0956                           |
| D pavement       | 0.8548                       | 0.3580                           | 0.1013                           |
| Amount of change(%) | -14.3                       | -17.0                            | +6.0                             |
| linear           | 1.9972                       | 0.8643                           | 0.1915                           |
| E pavement       | 1.7022                       | 0.7139                           | 0.2001                           |
| Amount of change(%) | -14.7                       | -17.4                            | +0.4                             |

5. Conclusions
Through the analysis of the mean square root values of acceleration and the comparison under different pavement conditions, the following conclusions are drawn:

1) The pitch acceleration of non-linear stiffness suspension and non-linear damping suspension can improve vehicle ride comfort. The non-linearity is 17.0% lower than the linear root mean square value. The roll acceleration has little effect on vehicle ride comfort.

2) The centroid acceleration of the non-linear stiffness suspension improves the ride comfort of the vehicle, and the non-linearity decreases by 14.3% compared with the linear root mean square value. The centroid acceleration of the non-linear damping suspension has no effect on it.

3) The root mean square value of pitch acceleration of non-linear suspension damping is 31.2% less than that of linear pitch acceleration, which greatly improves vehicle ride comfort.

4) Under the C, D and E three-level pavement, the root mean square of the next-level pavement is always twice the root mean square of the upper-level pavement, and the variation of each level pavement is almost the same.

Acknowledgments
Research supported by the Natural Science Foundation of Inner Mongolia (Grant No:2018LH01006).

Reference
[1] Li M 2010 Study on ride comfort and road friendliness of semi-active suspension of heavy haul semi-trailer train ShanXi: Taiyuan University of Science and Technology
[2] Zhou X B, Jiang Y B, Zhou Y F, et al. 2014 Journal of Changchun University of Technology (Natural Science Edition) 7(02):46-48
[3] Wang W D 2004 The Latest Development of Automobile Safety Technology in the World Research on Automobile Industry 04:36-37
[4] Jiang P 2006 The simulation study and parameter optimization on vehicle suspension system Zhejiang University
[5] Lin M C and Zhao J H 1987 Vehicle Vibration Input-Road Roughness Representation Method GB7031-1987 Beijing: China Standards Publishing House
[6] Wang P 2017 Light industry technology 33(04):69-70
[7] Chen X W, Liu W C, Yang W Y, et al. 2016 Time-domain response and simulation of the automobile active suspension with seven DOF Machine Design 33(11):88-93