

Study on the Vehicle Dynamic Load Considering the Vehicle-Pavement Coupled Effect

H L Xu¹, L He¹, D An¹

¹School of Civil Engineering, North China University of Technology, Beijing 100144, China

Abstract. The vibration of vehicle-pavement interaction system is sophisticated random vibration process and the vehicle-pavement coupled effect was not considered in the previous study. A new linear elastic model of the vehicle-pavement coupled system was established in the paper. The new model was verified with field measurement which could reflect the real vibration between vehicle and pavement. Using the new model, the study on the vehicle dynamic load considering the vehicle-pavement coupled effect showed that random forces (centralization) between vehicle and pavement were influenced largely by vehicle-pavement coupled effect. Numerical calculation indicated that the maximum of random forces in coupled model was 2.4 times than that in uncoupled model. Inquiring the reason, it was found that the main vibration frequency of the vehicle non-suspension system was similar with that of the vehicle suspension system in the coupled model and the resonance vibration lead to vehicle dynamic load increase significantly.

1. Introduction

The interaction between vehicle and pavement included two research systems: the vehicle system and the pavement system. Existing pavement design methods simplified vehicle load as a constant static load. In fact, the vehicle load was random dynamic load which was excited by the pavement roughness. The vehicle dynamic load caused the pavement deformation caused by dynamic load is larger than the static load, the extra deformation increase the vibration of the vehicle. The study on the vehicle dynamic load should carry out the vehicle and the pavement together as an integrated system. Pavement roughness as a random excitation, the whole system should be studied in the theory of random vibration.

At present, the research on random vibration of the vehicle and the pavement was carried out usually by two ways: (1) Using the simplified vehicle model, the dynamic load of the vehicle was calculated. Then using the dynamic load, the response of the pavement structure was studied [1-3]; (2) Assumed the dynamic load of the vehicle as a fluctuating load, and then the response of the pavement structure was studied [4, 5]. The above methods did not completely reflect the actual situation of the vehicle-pavement coupled vibration.

2. The establishment of vehicle-pavement coupled linear elastic model

2.1. Traditional vehicle-pavement model

Previous research considered that the pavement deformation under the vehicle load was small and the pavement deformation relative to pavement roughness could be neglected in the research. So the 1/4 vehicle model was usually used in the research [3, 6, 7] which was shown in figure 1.



The main ideas of the traditional model research: using the 1/4 vehicle model, the random vibration load of the vehicle caused by the pavement roughness could be obtained; Then using this load as the input for the pavement vibration response research.

In the traditional model, the vehicle and the pavement were considered separately, and the pavement was assumed to be rigid in the random vibration analysis, which was not in conformity with the actual situation. For the random vibration problem, the coupled effect of the vehicle and the pavement would affect the frequency distribution of the freedom degree. The influence of the change of frequency distribution on vibration amplitude can not be ignored. It is necessary to carry out comparative study on the influence of the coupling effect of the vehicle-pavement system, especially on the influence of the vehicle road interaction.

2.2. Vehicle-pavement coupled linear elastic model

In view of the shortcomings of the previous research model, this paper introduced the pavement structure system into the traditional vibration model, and then established a new vehicle-pavement coupled model. In this model, the pavement structure was stimulated by the mass-spring-damping elements, and the influence of the adjacent masses block of the pavement structure was stimulated by the shear spring and the shear damping elements. The vehicle-pavement coupled model was shown in figure 2.

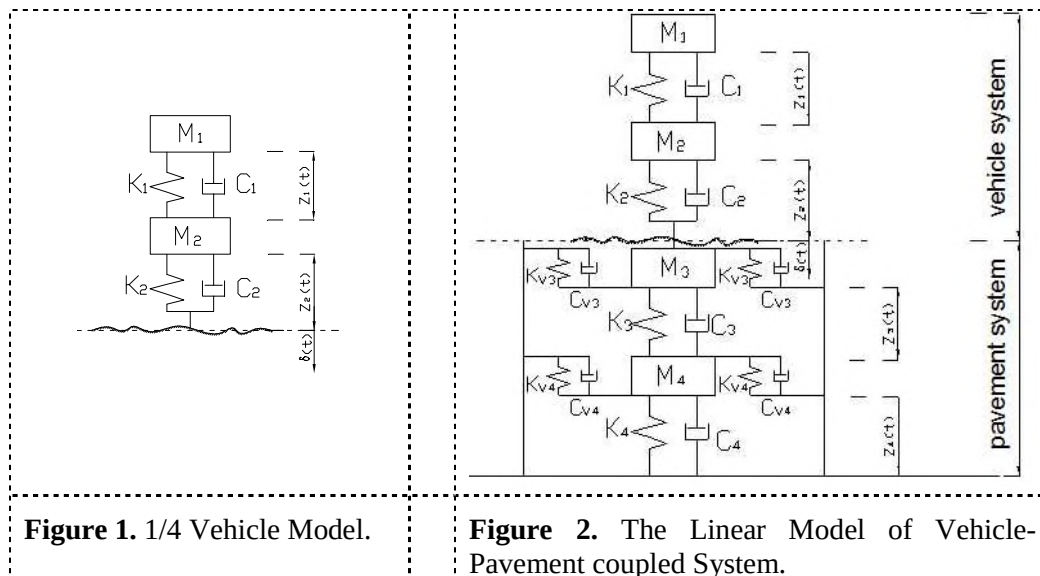


Figure 1. 1/4 Vehicle Model.

Figure 2. The Linear Model of Vehicle-Pavement coupled System.

2.3. Vehicle-pavement coupled model solution

2.3.1. Random vibration of vehicle road coupled model solution. According to D'Alembert theory, the vibration equation of the vehicle-pavement coupled linear model could be expressed in matrix form:

$$[M]\{\ddot{Z}(t)\} + [C]\{\dot{Z}(t)\} + [K]\{Z(t)\} = [K_f]\{\delta(t)\} \quad (1)$$

According to the random vibration theory, the relationship between the excitation and response was the following:

$$Z_i(\omega) = H_{ij}(\omega)\delta_j(\omega) \quad (2)$$

In the formula, $\delta_j(\omega)$ -frequency function for excitation, $Z_i(\omega)$ -frequency function for response, $H_{ij}(\omega)$ -frequency response function, which could be referred to $H_i(\omega)$ for a single incentive input. The formula (1) was transformed with the Fourier transform, using the formula (2), $H_i(\omega)$ ($i=1,2,3,4$) could be obtained.

Based on random vibration theory, the relationship between the excitation spectral density function $S_\delta(\omega)$ and the response spectral density function was obtained as follows:

$$S_i(\omega) = |H_i(\omega)|^2 S_\delta(\omega) \quad (3)$$

$$S_{\dot{i}}(\omega) = \omega^2 S_i(\omega) \quad (4)$$

$$S_{\ddot{i}}(\omega) = \omega^4 S_i(\omega) \quad (5)$$

In the formula: $S_{\dot{i}}(\omega)$ was velocity spectral density function of response function and $S_{\ddot{i}}(\omega)$ was acceleration spectral density function of response function.

2.3.2. Vehicle dynamic load solution. From figure 2, the vehicle-pavement interaction force could be expressed as

$$F(t) = K_2 Z_2(t) + C_2 \dot{Z}_2(t) \quad (6)$$

In the formula: $F(t)$ —dynamic load of vehicle, which was a centralized random process.

The load power density function $S_F(\omega)$:

$$S_F(\omega) = (K_2^2 + C_2^2 \omega^2) S_{Z_2}(\omega) \quad (7)$$

3. Pavement roughness model

At present, the spectral density of typical pavement had various expressions, this paper adopted the following form [8, 9]:

$$G_q(\Omega) = G_q(\Omega_0) \left(\frac{\Omega}{\Omega_0} \right)^{-w} \quad (8)$$

In the formula, Ω_0 -reference space frequency, $\Omega_0 = 0.1 \text{c/m}$; $G_q(\Omega_0)$ -power spectrum density of pavement under the reference space frequency, called the pavement roughness coefficient; W-frequency index, general $W=2$.

v -the vehicle speed, Ω -the spatial frequency of pavement roughness, ω -the circular frequency, f -the natural frequency.

From the formula (8) available showed as follows:

$$S_\delta(\omega) = \frac{1}{2\pi v} G_q\left(\Omega = \frac{\omega}{2\pi v}\right) \quad (9)$$

$$S_\delta(f) = 2\pi S_\delta(\omega = 2\pi f) \quad (10)$$

4. Validation of vehicle-pavement coupled model

In the reference [10], the field study on the interaction between vehicle and pavement obtained the acceleration value at wheel axle of the vehicle. The first peak appeared near 2.3Hz, and the amplitude was 0.317; the second peak appeared near 17.5Hz, and the amplitude was 0.385.

The vehicle-pavement coupled model in this paper was used to simulate the field test. The simulation used the test vehicle data and the pavement structure data valued using the method [11].

The main parameters were as follows: $M_1 = 12.98 \times 10^3 \text{ kg}$, $M_2 = 5.0 \times 10^2 \text{ kg}$, $M_3 = 3.5 \times 10^2 \text{ kg}$, $M_4 = 1.5 \times 10^3 \text{ kg}$, $K_1 = 5.0 \times 10^5 \text{ N/m}$, $K_2 = 1.5 \times 10^6 \text{ N/m}$, $K_3 = 1.0 \times 10^9 \text{ N/m}$, $K_4 = 2.5 \times 10^7 \text{ N/m}$, $K_{v3} = 1.0 \times 10^8 \text{ N/m}$, $K_{v4} = 4.0 \times 10^5 \text{ N/m}$, $C_1 = 1.5 \times 10^4 \text{ N} \cdot \text{s/m}$, $C_2 = 5.0 \times 10^3 \text{ N} \cdot \text{s/m}$, $C_3 = 3.0 \times 10^4 \text{ N} \cdot \text{s/m}$,

$C_4 = 5.0 \times 10^3 \text{ N} \cdot \text{s/m}$, $C_{V3} = 2.0 \times 10^4 \text{ N} \cdot \text{s/m}$, $C_{V4} = 3.0 \times 10^3 \text{ N} \cdot \text{s/m}$, $v = 70 \text{ km/s}$. The field test is on the Qing-Huang Freeway, the simulation used the A grade pavement spectrum.

Using the vehicle-pavement coupled model, the acceleration spectrum at wheel axle of the vehicle was shown in figure 3.

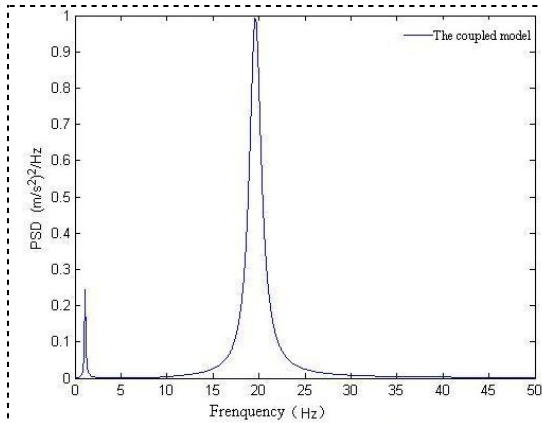


Figure 3. Simulation Result Using the coupled Model.

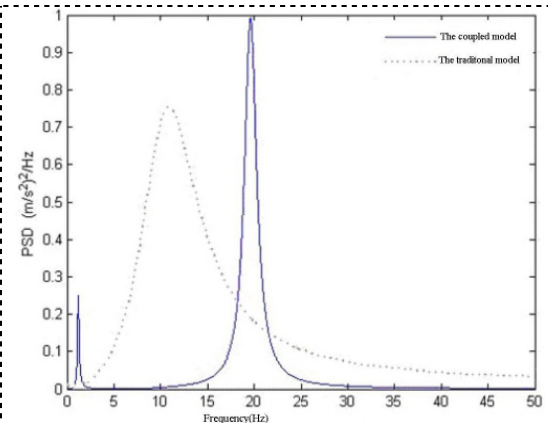


Figure 4. Vertical Acceleration Power Spectral Density Comparison Diagram of Vehicle Non-suspension System.

It could be seen from the simulation results that there were two peaks in the acceleration spectrum, the first peak appeared near 2Hz, and the amplitude was 0.26; the second peak appeared near 20Hz, and the amplitude was 0.98. It could be found that the results of the coupled model could reflect the vibration of the vehicle and match with the field data. The difference in amplitudes was mainly determined by the input data error in measurement process.

Using the same parameters, the traditional model was also used to simulate the field test. And the simulation results were compared with the coupled model, as shown in figure 4. Using the traditional model, there was only one peak in the acceleration spectrum, which appeared near 10Hz. In contrast, the result of the vehicle-pavement coupled model was better match with the field data than that of the traditional model.

5. Analysis on the influence of vehicle-pavement coupled effect on the dynamic load of vehicle

In the research on the pavement structure vibration response, the dynamic load of the vehicle is a key factor. In order to analyse the influence of vehicle-pavement coupled effect on the dynamic load, a comparative study was carried out on the dynamic load of the vehicle, using the vehicle-pavement coupled model and the traditional model.

The same parameters were used in the vehicle-pavement coupled model and the traditional model. The simulation used the C grade pavement spectrum. The parameters were as follows: $M_1 = 4.5 \times 10^3 \text{ kg}$, $M_2 = 5.0 \times 10^2 \text{ kg}$, $M_3 = 3.5 \times 10^2 \text{ kg}$, $M_4 = 1.5 \times 10^3 \text{ kg}$, $K_1 = 5.0 \times 10^5 \text{ N/m}$, $K_2 = 1.5 \times 10^6 \text{ N/m}$, $K_3 = 1.0 \times 10^9 \text{ N/m}$, $K_4 = 2.5 \times 10^7 \text{ N/m}$, $K_{V3} = 1.0 \times 10^8 \text{ N/m}$, $K_{V4} = 4.0 \times 10^5 \text{ N/m}$, $C_1 = 1.5 \times 10^4 \text{ N} \cdot \text{s/m}$, $C_2 = 5.0 \times 10^3 \text{ N} \cdot \text{s/m}$, $C_3 = 3.0 \times 10^4 \text{ N} \cdot \text{s/m}$, $C_4 = 5.0 \times 10^3 \text{ N} \cdot \text{s/m}$, $C_{V3} = 2.0 \times 10^4 \text{ N} \cdot \text{s/m}$, $C_{V4} = 3.0 \times 10^3 \text{ N} \cdot \text{s/m}$, v (speed) = 30 m/s.

The results of the power spectral density of the dynamic load (the forces between vehicle and pavement) were as shown in figure 5. In figure 5, it could be found that the peaks all appeared near 1.5Hz, but the peak amplitudes of the two models differed greatly. The peak amplitude of the coupled model was 8 times more than that of the traditional model. To evaluate the maximum force between vehicle and pavement as (was mean square deviation), the maximum force of the coupled model was 2.4 times than that of the traditional model (The maximum force was central, not including the static

load of the vehicle). So it was obvious that the vehicle-pavement coupled effect had a great influence on the interaction between the vehicle and the pavement.

The research results under different speed, different grade pavement spectrum and different vehicle load all showed that the maximum force between vehicle and pavement of the coupled model was several times higher than that of the traditional model. So the vehicle-pavement coupled effect was an important factor that could not be ignored in the research on the force between vehicle and pavement.

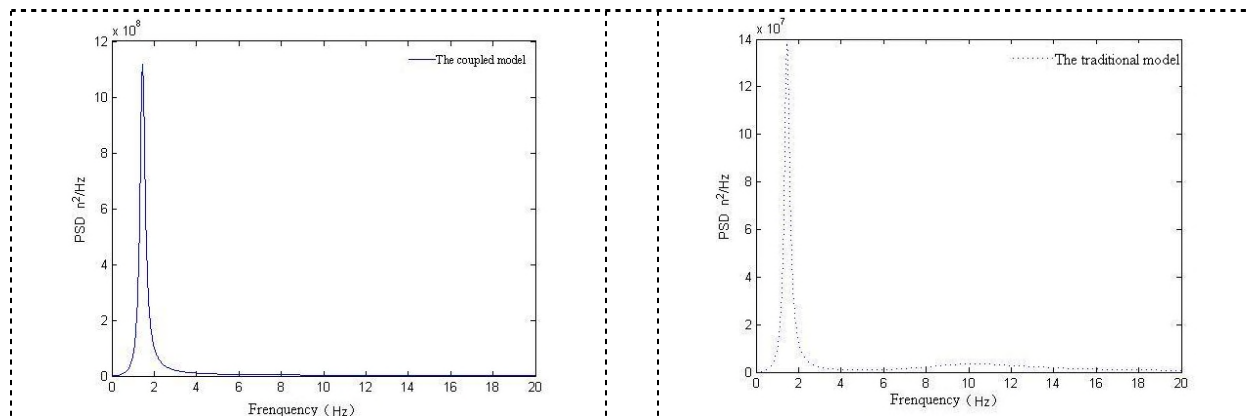


Figure 5. Power Spectral Density Comparison Diagram of the Forces between Vehicle and Pavement.

6. Analysis on the influence of vehicle-pavement coupled effect on the dynamic load of vehicle

In order to analyse the reason for the influence of vehicle-pavement coupled effect, the acceleration spectral density of the vehicle suspension system and the vehicle non-suspension system were obtained using the coupled model and the traditional model separately.

The curve of the coupled model almost completely coincided with that of the traditional model. The peaks all appeared near 1.5Hz. It could be seen that the vehicle-pavement coupled effect on the vibration of the vehicle suspension is not very seriously. So the research on the vehicle vibration was feasible to use the traditional model. In figure 7, it also could be seen that the peak frequency of the vehicle suspension appeared near 1.5Hz as the same as the peak frequency of the force between vehicle and pavement. It means that the force between vehicle and pavement mainly controlled by the suspension system of the vehicle, this phenomenon was in accordance with the actual observation.

The vibration of vehicle non-suspension of the coupled model varied significantly with that of the traditional model. Using the coupled model, there were two peaks which appeared near 1.5Hz and 20Hz; using the traditional model, there was only one peak which appeared near 10Hz. So the vehicle-pavement coupled effect had very important influence on the frequency distribution of the vehicle non-suspension. Using the coupled model, one of vibration peaks frequency of the vehicle non-suspension was 1.5Hz, which was close to the vibration peak frequency of the vehicle suspension. So the vehicle suspension system and the non-suspension system had occurred resonance at the frequency 1.5Hz, thus the maximum amplitude of the force between vehicle and pavement increased many times than that using the traditional model.

7. Conclusion

A new linear elastic model of the vehicle-pavement coupled system was established. The new model was verified with the data measured in field and the new model could reflect the real vibration between vehicle and pavement. Using the new model, the study on the vehicle dynamic load considering the vehicle-pavement coupled effect showed that the vehicle dynamic load (centralization) was influenced largely by vehicle-pavement coupled effect. Numerical calculation indicated that the maximum of random forces using coupled model was 2.4 times than that using uncoupled model. Inquiring the reason, it was found that the vibration peak frequency of the vehicle non-suspension system was similar with the vibration frequency of the vehicle suspension system using the coupled model and resonance vibration lead to vehicle dynamic load increase significantly.

References

- [1] Cebon D 1985 *The Dynamic Interaction between Wheeled Vehicles and Road Surface*. Cambridge University Engineering Department, Ph. D Dissertation.
- [2] Magdy Y M 1996 *Three Dimensional Mechanistic Analysis of Vehicle-Pavement Interaction*. Arizona State University, Ph. D Dissertation.
- [3] Sun L, Deng X J 1997 *China Civil Eng. J.* **30** 34-40.
- [4] Zhang Y M 2001 *Study on dynamic characteristics of Expressway Subgrade*. Lanzhou: Lanzhou Railway Institute, Ph. D Dissertation.
- [5] Chen H 2004 *Dynamic finite element analysis of highway subgrade under traffic load*. Lanzhou University of Technology, Ph. D Dissertation.
- [6] Deng X J, Sun L. 1998 *Vehicle-ground structure system dynamics*. Beijing: People's Communications Press.
- [7] Wang Z M, Zhang T Q, Wu X G 2007 *J. Zhejiang Univ.* **41(6)** 1007-11.
- [8] Zhao J H, Wang Z R, Guan Ch L 2000 *Measurement analysis and application of pavement roughness*. Beijing: Beijing Institute of Technology press.
- [9] State Standard of the People's Republic of China. *Vehicle vibration input method for road surface roughness* (GB7031-86), 1986.
- [10] Chen J 2002 *A Basic Study on Interaction between Vehicle and Roadway*, Jilin University, Ph.D. Dissertation.
- [11] Chen G 2000 *The analysis on random vibration of vehicle/track coupling system*. SouthWest JiaoTong University, Ph.D. Dissertation.
- [12] Wu S Q, Law S S 2011 *Probabil. Eng. Mech.* **26(2)** 281-93.
- [13] Zhang Y W, Lin J H, Zhao Y 2010, *J. Sound Vibr.* **329(21)** 4440-54.