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Effect of Design Parameter of Hydraulic Shock Absorber of Heavy Truck Air Suspension System on Road Surface Friendliness

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***Abstract*— This paper presents an effect analysis of design parameter of hydraulic shock absorber of heavy truck air suspension system on road surface friendliness. In order to analyze the effect of design parameters of a hydraulic shock absorber in combination with an air elastic element of an air suspension system, a dynamic model of both hydraulic shock absorber and air spring is established to determine vertical force. And then this vertical force of an air spring is connected to a quarter-vehicle dynamic model of a heavy truck to analyze the effect of the damping coefficients of hydraulic shock absorber on road surface friendliness. A dynamic load coefficient (DLC) is chosen to analyze road surface friendliness. The design parameters of shock absorber respectively are analyzed and evaluated its effect on road surface friendliness. The results indicate that the value of hydraulic shock absorber damping coefficient has a significant effect on the ability to reduce vibrations to the road surface.**

***Index Terms*—Heavy truck, Hydraulic shock absorber, Suspension, Air Spring, Friendliness.**

I. Introduction

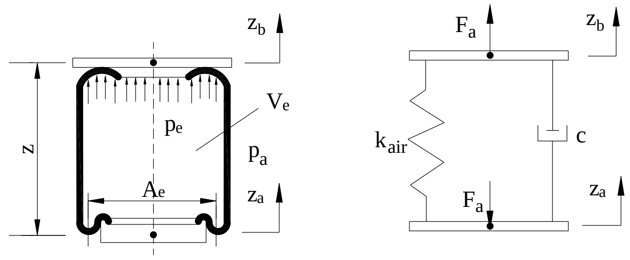
Vehicle dynamic load acting on the road surface is one of the causes of road surface destruction. The suspension system plays an important role in improving the ride comfort of the vehicle as well as reducing the dynamic loads of the wheels acting on the road surface. Viscous damping is an important suspension parameter which must be optimized to make a full contribution to the improvement of vehicle vertical response. The viscous damping characteristics of hydraulic shock absorber were proposed and evaluated its effect on road friendliness [1]. Air suspension systems of a truck was proved to be effective on vehicle ride comfort and road surface friendliness under the operating condition based on a quarter vehicle dynamic model [2]. The optimal parameters of the air suspension system of a semi-trailer truck were found via the genetic algorithm (GA) based on a half-vehicle dynamic model in the direction of the design "road-friendly" vehicles [3,4]. The optimal parameters of the walking-beam suspension system of a heavy truck were found via the genetic algorithm (GA) [5]. The dynamic models of the traditional and new air suspension systems were proposed to compare the performance of the air suspension systems for reducing the negative impacts on the road surface when vehicle moves on the different road conditions [6]. The fuzzy logic controller (FLC) was applied to control variable values of hydraulic shock absorber to improve vehicle ride comfort and road surface friendliness [7], [8]. The damping coefficient of hydraulic shock absorber of an air suspension system was controlled by using the fuzzy logic controller (FLC) in the direction of vehicle ride comfort and road surface friendliness [9]. The vertical dynamic tire loads of a semi-trailer truck acting on road surface equipped with air and leaf- spring suspension systems were analyzed based on a dynamic load coefficient (DLC) and a half- vehicle dynamic model [12]. Two different air spring models (classic air spring; dynamic air spring model) were proposed and analyzed for their characteristic influence on vehicle ride comfort and road surface friendliness.

In this study, a dynamic model combining hydraulic shock absorber and air spring of an air suspension system is set up to determine vertical forces and then these vertical forces are connected to a quarter-vehicle dynamic model of a heavy truck to analyze the effect of the damping coefficients of hydraulic shock absorber on road surface friendliness based on a dynamic load coefficient (DLC).

II. Quarter-Vehicle Dynamic Model

A. *Dynamic model of an air suspension system*

A dynamic model of both a hydraulic shock absorber and an air spring of an air suspension system is established to determine vertical forces, as shown in Fig.2.



(a)Schematic of an air spring (b) Dynamic model

Figure 1: Dynamic model of an air suspension system

Explanation of Fig.1, p_e is the absolute pressure in the air chamber, p_a is the atmospheric pressure, and A_e is the effective area, V_e and A_e are the effective volume and area; z_a and z_b are the displacements of axle and vehicle body, k_a is stiffness coefficient of air and leaf spring suspensions, c is damping coefficient of a hydraulic shock absorber.

The schematic of an air spring is shown in Fig.1(a). The

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absolute pressure of the air spring and the air spring elastic force F_a in the axial direction provided by the compressed air in the bellow are given as below

$$F_a = (p_e - p_a) A_e = k_a (z_b - z_a) = k_a z. \quad (1)$$

According to Hooke's law [10], the stiffness k_a of an air spring can be calculated by Eq.(2)

$$k_a = \frac{dF_a}{dz} = \frac{dp_e}{dz} A_e + (p_e - p_a) \frac{dA_e}{dz}. \quad (2)$$

where, z is the vertical displacement of air spring; $z=z_b-z_a$ is the difference between vehicle body mass and vehicle axle mass.

$$p_e V_e^n = const. \quad (3)$$

where, n is the polytropic exponent and depends on the following working conditions: n = 1 for the isothermal condition, n = 1.4 for the adiabatic condition, and 1 < n < 1.4 for the polytropic condition.

Differentiating Eq.(3) with respect to z yields:

$$\frac{d}{dz}(p_e V_e^n) = V_e^n \frac{dp_e}{dz} + n p_e V_e^{n-1} \frac{dV_e}{dz} = 0. \quad (4)$$

And $\frac{dV_e}{dz} = -A_e$. (5)

From the equations above, the equivalent stiffness can be given as follows:

$$\begin{aligned} k_a &= n(p_g + p_a)\frac{A_e^2}{V_e} + p_g \frac{dA_e}{dz} \\ &= n\left[p_a + (p_0 + p_a)\left(\frac{V_0}{V_e}\right)^n - p_a\right]\frac{A_e^2}{V_e} \\ &+ \frac{dA_e}{dz}\left[(p_0 + p_a)\left(\frac{V_0}{V_e}\right)^n - p_a\right]. \end{aligned} \quad (6)$$

From the equations above, the equivalent stiffness can be given as follows:

$$\begin{aligned} k_a &= n\left[p_a + (p_0 + p_a)\left(\frac{V_0}{V_e}\right)^n - p_a\right]\frac{A_e^2}{V_e} \\ &+ \left[(p_0 + p_a)\left(\frac{V_0}{V_e}\right)^n - p_a\right]\frac{dA_e}{dz}\bigg|_{z=0}. \end{aligned} \quad (7)$$

where, V_0 is the initial effective volume; p_0 is the initial pressure in air bag.

The effective volume and area are defined as

$$\begin{cases} V_e = V_0 - \alpha(z_b - z_a) \\ A_e = A_0 + \beta(z_b - z_a) \end{cases}. \quad (8)$$

where, A_0 is the initial effective volume; α and β are the change of the effective volume and area with respect to z

The dynamic model of air suspension system is shown in Fig 1.(b), the vertical force of the air suspension is defined as

$$F_a = k_a(z_b - z_a) + c(\dot{z}_b - \dot{z}_a). \quad (9)$$

B. *Quarter-vehicle dynamic model of a heavy truck*

A quarter-vehicle dynamic model of a heavy truck with two degrees of freedom is established to analyze the effect of the damping coefficients of hydraulic shock absorber on road surface friendliness based on a dynamic load coefficient (DLC), as shown in Fig.2. Explanation of Fig.2, m_b is the vehicle body mass, m_a is vehicle axle mass, z_b and z_a are the vertical displacements of vehicle body, and vehicle axle masses, k_a, c, and k_t, c_t are the stiffness and damping coefficients of the vehicle and tire, q is road roughness random excitation.

The equations of vehicle motion: A combined method of the multi-body system theory and D'Alembert's principle is chosen [3]. The multi-body system theory is used to separate the system into subsystems which are linked by the force and moment equations. D'Alembert's principle is used to create force and moment equations in order to describe vehicle dynamic subsystems. The equations of motion can be written as

$$\begin{cases} m_b \ddot{z}_b = m_b g - F_a \\ m_a \ddot{z}_a = m_a g + F_a - [k_t(z_a - q) + c_t(\dot{z}_a - \dot{q})] \end{cases}. \quad (10)$$

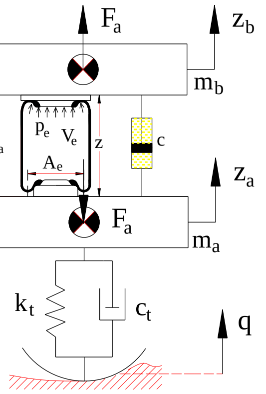


Figure 2: quarter-vehicle dynamic model of a heavy truck with two degrees of freedom

C. *Road surface roughness excitation (q)*

The road surface roughness plays an important role in analyzing dynamic analysis of the vehicle which is assumed to be a zero-mean stationary Gaussian random process. It can be generated through the inverse Fourier transformation [12].

$$q(t) = \sum_{i=0}^{N} \sqrt{2\Delta n G_d(n_i)} \cos(2\pi n_i t + \varphi_i). \quad (11)$$

where, Δn is within a frequency band; φ_i is the random phase uniformly distributed from 0 to 2π; $G_q(i\Delta n_0)$ is the road roughness coefficient which is defined for typical road classes from A to F according to ISO 8068(1995)[13].

III. DYNAMIC LOAD COEFFICIENT

In order to evaluate the dynamic wheel load acting on the road surface, the indicators such as dynamic load-sharing coefficient (DLSC) and dynamic load coefficient (DLC), the dynamic load stress factors, and the maximal and the minimal vertical dynamic load factor [14] were selected for analysis by researchers. In this study, dynamic load coefficient (DLC) is selected for analysis. The dynamic load coefficient DLC is defined as the ratio of a ratio of the root mean square (RMS) of the vertical dynamic tire force over static load.

$$DLC = \frac{F_{t,RMS}}{F_s}. \quad (12)$$

where $F_{t,RMS}$ and F_S are the root mean square of the vertical dynamic and the static tire force. The value of the DLC is in range of 0.05 to 0.3 under normal operating conditions. It may reach zero when the wheels move on a special smooth road or increase up to 0.4 when the tires of the axles spend a significant proportion of their time disconnecting the road surface[15].

IV. Analysis and Discussion

In order to analyze the effect of the damping coefficients of hydraulic shock absorber on road surface friendliness, the dynamic differential equation of vehicle Eq.(10) is simulated and analyzed by Matlab/Simulink software with a set of parameters of vehicle in Tab.1. The vertical dynamic tire loads acting on road surface with ISO class A road surface at v=20 m/s and full load (Case 1) is shown Fig.3. The vertical dynamic tire loads acting on road surface with ISO class B road surface at v=20 m/s and full load (Case 2) is shown Fig.4. The vertical dynamic tire loads acting on road surface with ISO class C road surface at v=20 m/s and full load (Case 2) is shown Fig.5.

Tabl 1: Parameters of the vehicle[2]

Parameters	Values
m_a/kg	1554
m_b/kg	4871
c/ (N.s/m)	2.5539×10^4
k_t/ (N/m)	1.7933×10^6
c_t/(N.s/m)	2.414×10^3
p_a/ Pa	0.1×10^6
V_0/m^3	0.0333
A_0/m^2	0.0906
p_0/Pa	2.865×10^6
n	1.4

From the results in the Fig.3, Fig.4 and Fig.5, we can determine the DLC values through Eq.(12) and DLC values are 0.0776, 0.1644, and 0.2967, respectively. The results indicate that DLC values increase with variable road conditions, which leads to adverse effects on the road surface. The effect of the damping coefficients of hydraulic shock absorber on road surface friendliness will continue to investigate below.

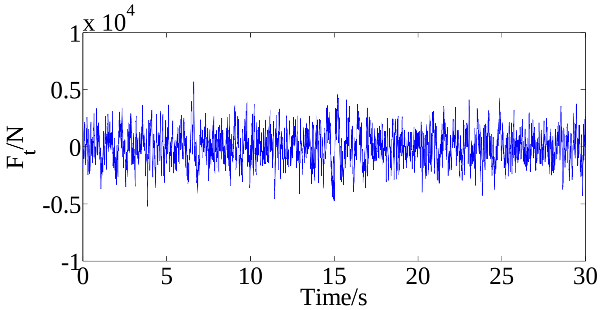


Figure 3: The vertical dynamic tire loads acting on road surface with Case 1

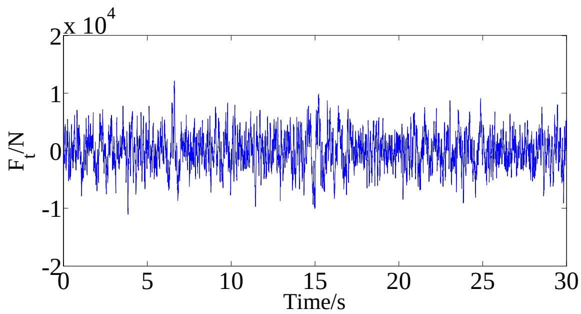


Figure 4: The vertical dynamic tire loads acting on road surface with Case 2

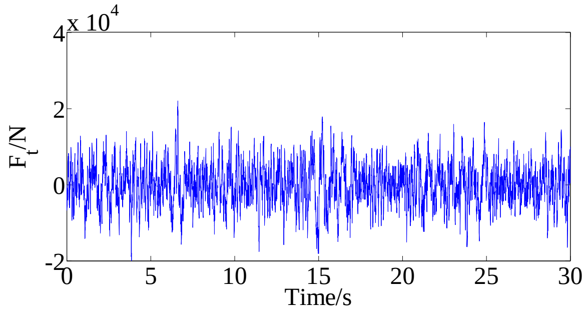
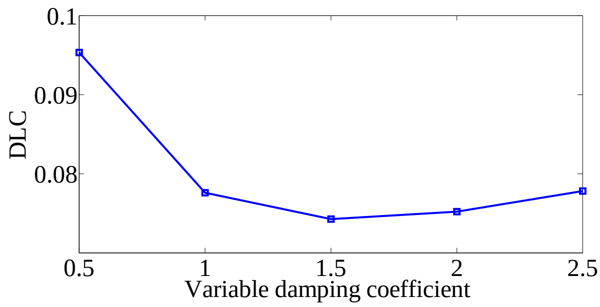
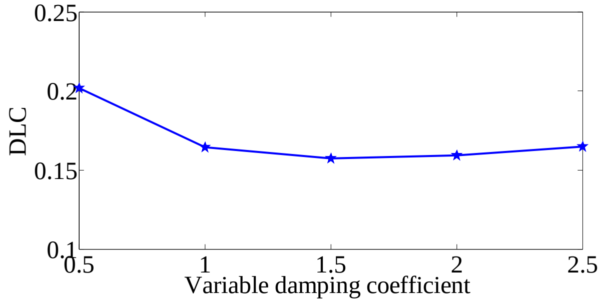


Figure 5: The vertical dynamic tire loads acting on road surface with Case 3

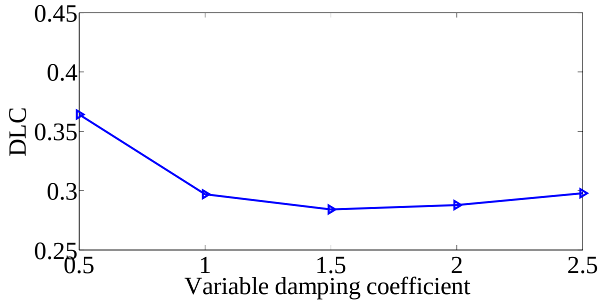
The damping coefficient values of hydraulic shock absorber c_j=[0.5 1 1.5 2 2.5] c in which c, the value of the original damping coefficient of hydraulic shock absorber, is selected to investigate its effects on DLC value when vehicle operates under three conditions such as Case 1, Case 2, Case 3. The DLC values with variable damping coefficient value under three conditions are shown in Fig.6.



(a) Case 1



(b) Case 2



(c) Case 3

Figure 6: DLC values with variable damping coefficient values

The results in Fig. 6 show that c_j value reduces in comparison with original value c, and DLC value increases leading to adverse effects on the road surface. The c_j value increases in comparison with original value c, initial DLC value reduces and then increases with three cases. Especially, DLC value of 1.5xc reaches the minimum value with all three cases, which makes road surface friendliness improve significantly.

V. Conclusion

This paper proposes a dynamic model of both hydraulic shock absorber and air spring of an air suspension system to analyze the vertical force of a heavy truck air suspension system. The model is then connected with a quarter-vehicle dynamic model of a heavy truck to evaluate the effect of damping coefficient of hydraulic shock absorber on road surface friendliness. The obtained results indicate that the DLC value increases with the reduction of damping coefficient, and the initial DLC value reduces and then increases with the reduction of damping with the increase of damping coefficient with three cases. Especially, the DLC value of 1.5c respectively reduce by 8.8% in comparison with 1.0c value and increase by 5.1% with 1.0c value with Case 2.

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