A Comparison of Ride Performance of Hydro-Pneumatic Suspension System with Those of Rubber and Leaf Suspension Systems

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Abstract. The objectives of this study is to compare the performance of the hydro-pneumatic suspension system of heavy truck on cab ride comfort with rubber and leaf springs of suspension systems. To compare the three types of suspension systems, a three-dimensional dynamic model of heavy truck with 15 degrees of freedom (DOF) is established based on Zhou Changfeng model under random excitation of road surface for simulation and analysis. The root mean square (r. m. s) acceleration of the vertical cabin, pitch angle, and roll angle of cabin is chosen as objective functions. Matlab/Simulink software is used to simulate and calculate the values of objective functions. The ride performance of the hydro-pneumatic suspension system on vehicle is analyze and compared to two other suspension systems when vehicle operates under different operating conditions. The results show that the values of objective functions with the hydro-pneumatic suspension system are significantly reduced in comparison with the rubber and leaf suspension system. The ride performance of Hydro-pneumatic suspension system is much better than that of the rubber and leaf suspension systems.

1. Introduction

Hydro-pneumatic suspension system is becoming more and more widespread in the engineering vehicles because of its good nonlinear stiffness and vibration reduction characteristic. Optimizing the parameters of interconnected hydro-pneumatic suspension system of a three-axle vehicle for ride comfort and handling was developed by [1]. Analytical modelling, simulation and experimental study of a hydro-pneumatic suspension system to increase ride comfort and to obtain excellent performance in rough terrains was studied by [2]. The parameters of the hydro-pneumatic suspension system were optimized for ride comfort and the mathematical model of the hydro-pneumatic suspension system was derived and then incorporated into a quarter car vehicle model [3]. The new hydropneumatic suspension with the interconnection type about right and left was improved and the structure parameters and mathematical model of the new system was established by [4]. A multibody cosimulation approach was used to investigate the effects of hydropneumatic parameters on the ride safety and aid with design optimization and tuning of the suspension system was developed by [5]. A hydro-pneumatic suspension model built with the advantage of fractional order in viscoelastic material modeling considering the
mechanics property of multiphase medium of hydropneumatic suspension system was researched by [6]. The performance of the hydro-pneumatic suspension system of heavy truck on the ride quality of road surfaces was analyzed by [7]. The dynamic models of the traditional and new air suspension systems to compare the performance of the air suspension systems for reducing the negative impacts on the road surface using a 3D dynamic model with 14 DOF was proposed by [9]. The dynamics models of a heavy truck using Zhou Changfeng model was developed for analyzing and evaluating the effects of suspension systems on road surface friendliness [12]. A three-dimensional nonlinear dynamical model of a typical heavy truck with 16-DOF (degree of freedom) was established to analyze and evaluate the performance of the air suspension system of heavy trucks with semi-active fuzzy control [15]. A 3-D dynamic model with 13 DOF was established to control the cab’s isolation system of heavy truck using Fuzzy logic controller [16]. The acceleration responses and dynamic load coefficient (DLC) were chosen as an objective function for analyzing the effects of suspension design parameters of a semi-trailer truck on vehicle ride comfort as well as road surface friendliness [17].

In this paper, the three-dimensional nonlinear dynamic model of heavy truck with 15 DOF is established based on Zhou Changfeng model [8] and the dynamic models of three types of suspension systems such as the hydro-pneumatic, leaf and rubber springs of suspension systems are proposed to compare their effect on vehicle ride comfort. The performance of the hydro-pneumatic suspension system on vehicle ride comfort through three objective functions according to the international standard ISO 2631-1:1997[13] is analyzed and compared to the rubber and leaf springs of suspension systems when vehicle is operated under the different operating conditions.

2. Vehicle dynamic model

2.1. Full vehicle dynamic model.
The dynamic model of AD250 articulated dump truck in Fig.1 consists of 15 degrees of freedom.

![3-D dynamic model of the heavy truck](image)

From the full vehicle dynamic model as shown in Fig.1, the motion equations of unspung mass, sprung mass and cab mass are written using Newton’s second law. The general dynamic differential equation for the 3-axle heavy truck is given by the following matrix form:

\[
[M]\ddot{z}+[C]\dot{z}+[K]z=[C_r]\dot{q}+[K_r]q.
\]

(1)
where $[M]$, $[C]$, and $[K]$ are vehicle mass, damping, and stiffness matrix of the suspension system; $[C_t]$ and $[K_t]$ are damping and stiffness matrix of the wheel system; $\{z\}$ is the vector of displacements; $\{q\}$ is the vector of excitation of road surfaces.

2.2. **Mathematic model of the suspension systems.**
To analyze the performance of the hydro-pneumatic suspension system of heavy truck on the ride quality, the lumped model of three different types of suspension systems is established to determine the vertical forces of the suspension systems, as shown in Fig.2.

2.3. **The rubber suspension system.**
From Fig.2 (a), the vertical nonlinear dynamic force of the rubber spring suspension system [8] is determined by

$$ F_r = k_1s + k_2s^3 + \left[ k_{11}(z_b - z_a + s) + k_{21}(z_b - z_a + s)^3 \right] + c(\dot{z}_b - \dot{z}_a) \left( 1 + \text{sgn}(\dot{z}_b - \dot{z}_a) \right) \left( \frac{1}{2} \right) $$

where $k_{11}$, $k_{21}$ are stiffness of rubber spring, $c$ is damping coefficient, $s$ is the displacement of rubber spring when vehicle is static, $z_b$ and $z_a$ are vertical displacement of sprung and unsprung mass, $\gamma$ is the ratio of compression to tensile damping.

![Fig.2. Lumped model of three different types of suspension systems](image)

2.4. **The hydro-pneumatic suspension system.**
From Fig.2 (b), the vertical dynamic force of hydro-pneumatic suspension system[7] can be computed by

$$ F_h = -\rho \left( A_1 - A_p \right)^3 \left( z_b - z_a \right)^2 \text{sign}(z_b - z_a) + \rho_0 \left( \frac{V_0}{V_0 + A_p(z_b - z_a)} \right)^n - m_b (\dot{z}_b - \dot{z}_a). $$

where $C_d$ is the coefficient of discharge; $A_1$, $A_e$, and $A_p$ are the area of the orifice, cylinder and floating piston; $\rho_0$ and $V_0$ are the initial pressure and volume in air chamber; $m_b$, $n$ are the mass and the polytrophic rate ($1 \leq n < 1.4$).

2.5. **The leaf suspension system.**
From Fig.2 (c), the vertical dynamic force of the leaf suspension system is calculated by
\[ F_i = k_l (z_i - z_a) + c (\dot{z}_i - \dot{z}_a). \] (4)

where \( k_l \) and \( c \) are the stiffness of the leaf spring and damping coefficient of the suspension system.

2.6. Road surface roughness.
To analyze the effects on vehicle ride, the road surface roughness plays an important role. The road surface roughness is assumed to be a zero-mean stationary Gaussian random process. It can be generated through the inverse Fourier transformation [10], [18].

\[ q(t) = \sum_{i=0}^{N} \sqrt{2\Delta n G_d(i\Delta n)} \cos(2\pi \Delta nt + \varphi_i). \] (5)

where, \( \Delta n \) is within a frequency band; \( \varphi_i \) is the random phase uniformly distributed from 0 to \( 2\pi \); \( G_d(i\Delta n) \) is the road roughness coefficient which is defined for typical road classes from A to F according to ISO 8068(1995) [11].

3. Simulation and analysis results
Matlab/Simulink software is used to simulate with a set of parameters of vehicle and suspension parameters by the references [14] and compare the ride performance of hydro-pneumatic suspension system with leaf and rubber spring of suspension systems. The simulation results of the time domain responses of the cab vertical, pitch angular, roll angular accelerations \( a_z, a_{\phi} \) and \( a_{\theta} \) when vehicle moves on the ISO class C road surface at \( v=40 \) km/h and full load are shown in Fig.3. From the results of Fig.3 we see that the peak acceleration amplitudes with hydro-pneumatic suspension systems respectively reduce in comparison with leaf and rubber springs of suspension systems. The performance of the hydro-pneumatic suspension will be continued to analyze and compare in the section below.

![Fig.3 The vehicle cab vertical, pitch angular, roll angular accelerations](image-url)
To analyze the different road surface conditions on the ride performance of vehicle suspension systems, five road surface conditions from ISO class A (very good) to ISO class E (very poor) in ISO 8068[12] are used to compare when vehicle moves at the speed of 40km/h and full load. The values of the weighted RMS accelerations of the vertical, pitch and roll vehicle cab ($a_{wz}$, $a_{wphi}$ and $a_{wteta}$) according to the international standard ISO 2631-1 are shown in Fig.4.

![Graphs showing road surface conditions and vehicle cab accelerations](image)

**Fig.4.** The $a_{wz}$, $a_{wphi}$ and $a_{wteta}$ values with five different road surface conditions

Fig.4 shows that the $a_{wz}$, $a_{wphi}$ and $a_{wteta}$ values of three types of suspension systems quickly increase when vehicle moves on the different road surfaces, especially, when vehicle moves on bad road surface conditions such as ISO class C and ISO class E. The $a_{wz}$ values with the hydro-pneumatic suspension system reduce by 63.5%, 63.8%, 61.4%, 50.1%, and 50.8% in comparison with the rubber spring of the suspension system, and reduced by 60.1%, 60.3%, 57.8%, 45.5%, and 46.7% in comparison with the leaf spring of the suspension system with the identical operating conditions and that is similar to the $a_{wphi}$ and $a_{wteta}$ values. Vehicle ride comfort has been a significant improvement the hydro-pneumatic suspension system.

To compare the ride performance of three types of the suspension systems, the vehicle speeds of 20 km/h, 30 km/h, 40 km/h, 50 km/h, 60 km/h, 70 km/h were considered when vehicle moves on the ISO class C and full load. When the vehicle moves at different speeds, the $a_{wz}$, $a_{wphi}$ and $a_{wteta}$ values with the hydro-pneumatic suspension system comparing with the rubber and leaf springs of the suspension systems are shown in Fig.5. Fig. 5 shows that the $a_{wz}$, $a_{wphi}$ and $a_{wteta}$ values with the hydro-pneumatic suspension system are much lower than those of the rubber and leaf springs of the suspension system when vehicle moves at the different speeds. The $a_{wz}$ values with the hydro-pneumatic suspension system reduce by 52.1%, 62.1%, 61.4%, 55.3%, 50.5%, and 44.9% in comparison with the rubber spring of the suspension system and reduce by 53%, 59.8%, 57.8%, 39.6%, 34.8%, and 34% in comparison with the leaf spring of the suspension system and that is similar to the $a_{wphi}$ and $a_{wteta}$ values.
Fig. 5. The $a_{\text{wz}}$, $a_{\text{wp}}$ and $a_{\text{w}}$ values at the different vehicle speeds

4. Conclusions
In this study, the three-dimensional nonlinear dynamic model of heavy truck with 15 DOF is established based on Zhou Changfeng model and the dynamic models of three types of suspension systems such as the hydro-pneumatic, leaf and rubber springs of suspension systems are proposed to compare their effect on vehicle ride comfort. From the analysis results, the conclusions may be drawn as follow: (i) The peak acceleration amplitudes with hydro-pneumatic suspension systems respectively reduce in comparison with leaf and rubber springs of suspension systems and (ii) The $a_{\text{wz}}$, $a_{\text{wp}}$ and $a_{\text{w}}$ values with the hydro-pneumatic suspension system significantly reduce in comparison with the rubber and leaf spring of the suspension systems in all operating conditions of vehicle. Cab ride comfort has been a significant improvement the hydro-pneumatic suspension system.

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