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АНАЛИЗ ВЛИЯНИЯ ЖЕСТКОСТИ ШИН НА КОЛЕБАНИЯ КУЗОВА ЛЕГКОВОГО АВТОМОБИЛЯ

ANALYZING OF THE TIRE STIFFNESS IMPACT ON THE PASSENGER CAR BODY OSCILLATION

Нгуен Бинь Хьем[1], **Ле Ван Нгиа**[1], **Чан Чонг Дат**[1], **Та Тьен Лой**[1],
Харитончик С. В.[2], д-р техн. наук, проф.,
Руктешель О. С.[2], д-р техн. наук, проф.,
Кусяк В. А.[2], канд. техн. наук, доц.,
[1]Группа «Автомобили», Факультет Транспорта и Преобразования Энергии, Институт Механики, Университет Ханоя Техники и Науки, г. Ханой, Вьетнам
[2]Белорусский Национальный Технический Университет, г. Минск, Республика Беларусь

Nguyen Binh Khiem[1], Le Van Nghia[1], Tran Trong Dat[1], Ta Tien Loi[1],
S. Kharytonchyk[2], Doctor of techn. Scienc., Prof.,
O. Rukteshel[2], Doctor of techn. Scienc., Prof.,
V. Kusyak[2], Ph. D. in Eng., Ass. Prof.,
[1]Automotive Engineering Group, Department of Vehicle and Energy Conversion Engineering, School of Mechanical Engineering, Hanoi University of Science and Technology, Hanoi, Vietnam,
[2]Belarusian National Technical University, Minsk, Belarus

Шины воспринимают неровности дорожного покрытия при движении транспортного средства. Жесткость шин является важнейшим параметром их эксплуатационных характеристик и одним из ключевых факторов, влияющих на работу подвески. В работе используется комбинация экспериментальных методов и моделирования для исследования воздействия давления и нагрузки на жесткость шин и анализа влияния этих параметров на колебания кузова транспортного средства, его виброускорения и время отклика. Определение жесткости шин при вариации давления и нагрузки проводилось экспериментально на испытательном стенде с последующей передачей этих данных в 1/4 модель подвески для анализа вибрации кузова автомобиля. Как показали результаты *теоретических и экспериментальных исследований в условиях отсутствия нагрузки (в снаряженном состоянии автомобиля) изменение давления в шинах практически не оказывает влияния на работу подвески. Вариация давления в шинах приводит к изменению амплитуд колебаний кузова транспортного средства не более чем на 6,6 %, а продольного ускорения кузова не более чем на 11,9 %. При этом время затухания колебаний остается постоянным во всем диапазоне давлений в шинах и составляет 1,35 секунды.*

Tires perceive road surface unevenness when vehicles are moving. Tire stiffness is the most important parameter of their performance characteristics and one of the key factors affecting on the suspension system operation. The paper illustrates a combination of experimental and simulation methods to investigate the effects of pressure and load on tire stiffness and analyze the influence of these parameters on vehicle body vibrations, longitudinal body acceleration and response time. Tire stiffness was determined experimentally with pressure and load changes on a test bench, which were then converted into a 1/4 susp vehicle body oscillation ension simulation model for analyzing vehicle body vibration. The theoretical and experimental results demonstrate that under unloaded vehicle conditions the performance of the suspension system remains consistent. Changes in tire pressure lead to deviations in vehicle body oscillation amplitudes by no more than 6,6 % and longitudinal body acceleration by no more than 11,9 %. At the same time, the damping time of oscillations is consistent across all tire pressure conditions, measured at 1.35 seconds.

Ключевые слова*: подвеска, жесткость шин, давление в шинах, испытательный стенд, 1/4 модель подвески автомобиля, моделирование, вибрация кузова автомобиля.*

Keywords*: suspension, tire stiffness, tire pressure, test bench, quarter-car suspension model, simulation, vehicle body oscillation.*

INTRODUCTION

The suspension system plays a crucial role in ensuring the safety and comfort of a vehicle. It is a primary concern for both users and manufacturers, leading to numerous studies focused on improving the smoothness of the suspension system. Within the suspension system, tires significantly impact overall performance.

Many studies have demonstrated the influence of tires on the suspension system. Parczewski [1] and Andrzej Zuska et al. [2] have shown that changes in tire pressure cause variations in the radial transformation and lateral stiffness of the wheel, reducing the radial stiffness of the tire and resulting in changes in the equivalent vertical stiffness of the suspension system. Additionally, it increases the braking distance for both straight-line and curved-line driving and develops the vehicle's understeer tendency. Ha D. V. [3] investigated semi-trailers and found that tire stiffness affects the dynamic load of the vehicle, reducing the tire's road-friendliness. Similarly, Van L.V. [4] indicated that increasing tire stiffness raises the dynamic load and vice versa.

This paper evaluates the impact of tire characteristics, specifically the variation in pressure applied to the wheels, on the performance of the suspension system in a 2014 Toyota Vios. The study employs a combination of experimental methods and simulation to analyze vehicle body oscillation, acceleration, and response time, thereby assessing the influence of these parameters on the suspension system. The experiments determined that tire stiffness depends solely on pressure and specific load. These parameters were then used as inputs for the suspension system simulation model. The resulting graphs of vehicle body oscillation and acceleration provide insights into how tire pressure characteristics affect the suspension system's performance.

METHOD

Quarter-car suspension model.

A quarter-car model was constructed to investigate vehicle vibrations. Fig 1 illustrates the system's dynamics where m_a and m represent the sprung and unsprung masses respectively. Additionally, the system includes an elastic component characterized by stiffness C and spring force F_c, and a damping component represented by damping coefficient K and damping force F_k.

The coordinates of the sprung and unsprung masses are z and z_1, respectively, with the height of the pump on the road surface denoted as h. Therefore, the following forces acting on the system are expressed by equations (1) and (2):

$$F_C = F_{dh} = C_\lambda = C \cdot \left(z_1 - z\right); \tag{1}$$

$$F_K = F_{gc} = K_v = K\left(\dot{z}_1 - \dot{z}\right). \quad (2)$$

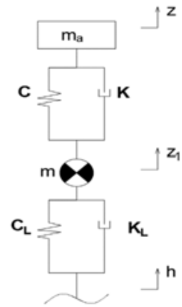

Figure 1 – Quarter-car suspension model

The tire has C_L as the tire stiffness F_{CL} as the elastic force of the tire, K_L as the damping coefficient of the tire, and F_{KL} as the damping force of the tire. Therefore, the deformation force is presented by (3):

$$F_{CL} = C_L \cdot \lambda_1 = C_L\left(h - z_1\right) \text{ and } F_{CK} = K_L . v_1 = K_L\left(\dot{h} - \dot{z}_1\right).$$

Separating the sprung and unsprung masses, applying the forces and balancing the forces according to D'Alembert's principle, the system of oscillation equations is obtained by (4) and (5):

$$m_a \cdot \ddot{z} = C \cdot \left(z_1 - z\right) + K \cdot \left(\dot{z}_1 - \dot{z}\right); \quad (4)$$

$$. m \cdot \ddot{z}_1 = CL \cdot \left(h - z_1\right) + KL \cdot \left(\dot{h} - \dot{z}_1\right) - C \cdot \left(z_1 - z\right) - K \cdot \left(\dot{z}_1 - \dot{z}\right). \quad (5)$$

The input parameter for the model is the height of the road surface irregularities. When the wheel drops from a height of 0.175 m to the road surface, solving the system of equations yields the real-time oscillation graph of the sprung mass. The suspension system parameters, damping, and tire stiffness are taken according to the design specifications of the vehicle model used in the study. Tire stiffness is an input parameter for the quarter-car model and this parameter can change depending on actual conditions. Therefore, this article conducts experiments to evaluate the effect of load on tire stiffness.

Real experiments.

To gather parameters for the simulation process, the study conducted experiments to determine tire stiffness under various load and pressure conditions. The experimental setup included a suspension system test bench, height gauge, 2014 Toyota Vios, load measurement devices, and tire pressure measurement devices.

The experimental procedure began with placing the vehicle on the test bench and using a tire pressure gauge to determine the tire pressure. Subsequently, different loads were applied to the vehicle, measured at four distinct load levels (as indicated by the load measurement devices). For each load, a height gauge was used to measure tire deformation, and the data was recorded. This process was repeated with different tire pressure settings.

Tire stiffness depends on various factors, including tire material, tread pattern, tire pressure, and load. Changes in tire stiffness (C_L) alter the force F_{CL}, thereby affecting the performance of the suspension system. As tire pressure and load increase, tire stiffness also increases, leading to reduced shock absorption efficiency. Table 1 illustrates the variation in stiffness with pressure for different load levels.

Table 1 – Tire stiffness variation with pressure and load

1,8 bar	*G* (N)	2 bar	*G* (N)	2,2 bar	*G* (N)	2,4 bar	*G* (N)
C (N/cm)	1960	*C* (N/cm)	2150	*C* (N/cm)	2163	*C* (N/cm)	2474
	2010		2135		2157		2529
	2060		2125		2135		2514
	2121		2178		2185		2468
	2116		2166		2170		2466
C_{tb} (N/cm)	2053	C_{tb} (N/cm)	2151	C_{tb} (N/cm)	2162	C_{tb} (N/cm)	2490

This research computes the average tire stiffness with the same pressure at different loads to evaluate an overview of tire stiffness according to pressure but disregarding the vehicle's load. Figure 2 illustrates stiffness as a function of pressure. To facilitate the calculation of tire stiffness at any pressure, the following second order polynoml model (6) can be employed:

$$y = 4029{,}9 - 2466{,}8 \cdot x + 755{,}63 \cdot x^2, \tag{6}$$

in which y represents the tire stiffness (N/cm), and x denotes the tire pressure.

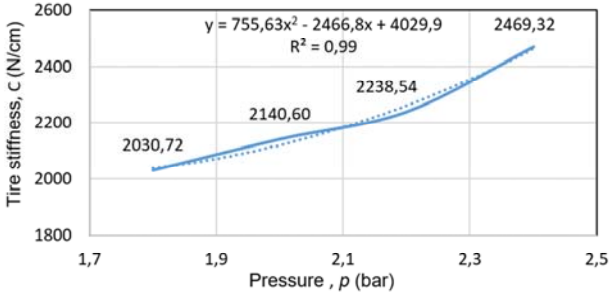

Figure 2 – Tire stiffness corresponding to tire pressure

RESULTS

Experiments were conducted by fixing the vehicle's mass and varying the tire pressure, leading to changes in tire stiffness for investigating the vehicle body oscillation concerning changes in tire stiffness. The research examines the vehicle's mass when unloaded, equivalent to 240 kg (quarter-car model), and the tire pressure ranging from 1.8 bar to 2.4 bar in the quarter-car model. The value of tire stiffness was calculated corresponding to each pressure value, as shown in tab. 1.

Substituting the vehicle parameters and each stiffness value into the previously constructed quarter-car model in the software (fig. 2), the article obtains the vehicle body oscillation amplitude graph (fig. 3) and the acceleration graph of the vehicle body (fig. 4) corresponding to each different pressure.

Figure 3 shows that changes in pressure have minimal effects on the vehicle body oscillation with the same mass. At a pressure of p = 1.8 bar, maximum amplitude Z_{max} = 8.47 cm and minimum amplitude Z_{min} = 4.39 cm by absolute from the new road level. Meanwhile, at a pressure of p = 2.4 bar, maximum amplitude Z_{max} = 8.97 cm and minimum amplitude Z_{min} = 5.78 cm. Therefore, the difference in oscillation amplitudes between the two cases can be evaluated. The difference in oscillation amplitudes corresponding to Z_{max} is 6 % and Z_{min} is 6.6 %. The damping time of oscillation in both cases is the same, averaging 1.35 seconds. These results indicate that the influence of pressure on the vehicle body displacement is negligible, only about 6 %, which is quite small.

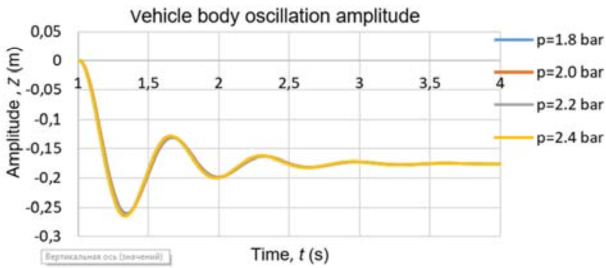

Figure 3 – Vehicle body displacement graph

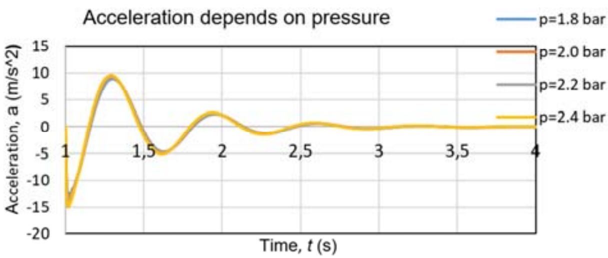

Figure 4 – Vehicle body acceleration graph

Figure 4 shows that changes in pressure have minimal effects on the vehicle body acceleration with the same mass. At a pressure of p = 1.8 bar, the maximum acceleration a_{max} = 13.4 m/s² and the minimum acceleration a_{min} = 9.22 m/s² by absolute values. Meanwhile, at a pressure of p = 2.4 bar, the maximum acceleration a_{max} = 15 m/s² and the minimum acceleration a_{min} = 9.66 m/s². The difference in acceleration between the two cases, corresponding to the maximum acceleration value, is 11.9 %, and for the minimum acceleration value, it is 4.8 %. It can be seen that the change in acceleration in both cases is quite small, and the damping time of oscillation is the same. This indicates that when driving on the road, the driver may have difficulty perceiving the difference in vehicle body oscillations when driving with different tire pressures. Similarly, as observed in the investigation of vehicle body displacement, the acceleration along the vehicle body with respect to pressure also remains relatively small, below 12 %.

CONCLUSION

The article evaluated the effectiveness of the suspension system by examining tire stiffness, which varies with tire pressure. The relationship between tire stiffness and pressure is described by a quadratic equation based on experimental data. The simulation results demonstrated that, under unloaded conditions, changes in tire pressure resulted in vehicle body oscillation amplitudes varying by no more than 7 %, and longitudinal body acceleration differing by no more than 12 %. The damping time of oscillations was consistent across all tire pressure conditions, measured at 1.35 seconds. This indicates that, with a constant load, drivers are unlikely to perceive significant differences in vehicle body oscillation when driving with varying tire pressures.

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