Interconnected State Control Method and Simulations of Four-corner Interconnected Air Suspension

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Abstract. The four-corner interconnected air suspension can effectively improve vehicles ride comfort, but the opening of the interconnection will intensify the roll or pitch of the car body, reducing the vehicle handling stability when the vehicles are in the turning, acceleration and deceleration conditions. To solve the above problems, an interconnected state control method is proposed for four-corner interconnected air suspension, the interconnection state of the pipeline is determined by the relationship between the torque produced by the air spring and the roll angles or pitch angles of the car body. The parameters of air spring pressure, car body roll angle and pitch angle are used in the control method to obtain the optimal interconnection state of four interconnected pipelines through control algorithm calculation. Finally, the opening and closing of four interconnected pipeline solenoid valves are controlled. In order to verify the effectiveness of the control method, the MATLAB/Simulink model of four-corner interconnected air suspension is established and simulated.

Key words: Air suspension, Four-corner interconnection, Simulation and modeling, Control method.

1. Introduction

The air suspension system has the characteristics of variable stiffness, low vibration frequency and convenient body control, which can effectively improve vehicle ride comfort, handling stability and road friendliness [1]. In order to further improve the performance of air suspension, many derivative structures have been proposed, especially interconnected air suspensions. According to different structures, the interconnected air suspension can be divided into lateral interconnected air suspension,
longitudinal interconnected air suspension and four-corner interconnected air suspension etc. Four-corner interconnection can be regarded as the combination of lateral and longitudinal interconnection air suspension namely the adjacent air springs of air suspension are connected, as shown in Fig.1[2]. In terms of performance, four-corner interconnected air suspension has the characteristics of both lateral and longitudinal interconnected air suspension. Compared with the traditional air suspension, the four-corner interconnected air suspension can improve the ride comfort of vehicles on rough roads, reduce torsional load of the vehicle body and improve the vibration isolation performance of vehicles [3]. However, the lateral interconnection will aggravate the roll of the vehicle when the vehicle is in a turning condition [4]. The longitudinal interconnection will aggravate the pitch of the vehicle when the vehicle is in acceleration and deceleration [5].

Recently, some research on interconnected air suspensions have been reported. [6-7] established a nonlinear model of the longitudinal-connected air suspension of tri-axle semi-trailer. The effects of driving conditions and suspension parameters on the dynamic load distribution of the longitudinal-connected air suspension of the tri-axle semi-trailer were studied. [8-9] verified the relationship between increasing the diameter of longitudinal interconnected pipes and improving the dynamic load distribution through t-test. It was concluded that the dynamic load between suspension and chassis of heavy vehicles can be effectively reduced by using larger longitudinal interconnected pipes than the standard size. [10] proposed the imitated skyhook control theory of laterally interconnected air suspension. The theory took the vehicle body roll angle and the “mass roll angle under the spring” as the monitoring parameters and used their product to judge the opening and closing of the air suspension interconnection state.

However, there are few studies concentrated on the interconnection state control of four-corner interconnected air suspension. In this paper, a control method for the interconnected state of four-corner interconnected air suspensions is presented. Firstly, the interconnection state of pipeline can be determined according to the relationship between the air spring torque and the roll angles or pitch angles of vehicle body. Secondly, the method takes the vehicle body roll angle, pitch angle and the air pressure of each air spring as the monitoring parameters. Finally, the optimum interconnection state of the air suspension is obtained through MATLAB/Simulink simulations.

Figure 1. Four-corner interconnected air suspension

2. The establishment of vehicle vibration models
In order to study effectively the roll, pitch and vibration isolation characteristics of four-corner interconnected air suspension on uneven road surface, a seven-degree-of-freedom vehicle dynamic model was established. The suspension dynamic model is shown in Fig.2.
where $m_{fl}$, $m_{fr}$, $m_{rl}$, $m_{rr}$ are front left, front right, rear left, rear right unsprung masses respectively; $z_{fl}$, $z_{fr}$, $z_{rl}$, $z_{rr}$ are front left, front right, rear left, rear right displacements of unsprung masses respectively; $K_t$ is vertical stiffness of tire. $q_{fl}$, $q_{fr}$, $q_{rl}$, $q_{rr}$ are front left, front right, rear left, rear right vertical displacements of the road respectively; $F_{fl}$, $F_{fr}$, $F_{rl}$, $F_{rr}$ are suspension forces of front left, front right, rear left, rear right wheels respectively. The suspension force of a wheel is the resultant force of the air spring force and damping force at the wheel. $M_{bf}$ and $M_{br}$ are body mass carried by the front and rear axle of the vehicle, $k_{bar}$ is the roll stiffness of anti-roll bar; $B_f$ and $B_r$ are respectively front and rear wheel treads; $M_b$ is the body mass, $z_b$ is vertical displacement of spring mass center of mass, $I_r$ is the rotary inertia of the body around the roll axis (X axis), $\theta$ is the body roll angle and the right deviation of the car body is positive, $I_p$ is the rotary inertia of the body around the pitch axis (Y axis), $\phi$ is the body pitch angle, which is assumed positive when the body bends forward, $H_r$ is the vertical distance between the center of sprung mass and the roll axis, $H_p$ is the vertical distance between the center of sprung mass and the pitch axis, $a_y$ is lateral acceleration of vehicle body, $L_f$ and $L_r$ are respectively distance from front and rear axle to the centroid.

The air spring is regarded as a variable mass thermal insulation system according to the first law of system thermodynamics [11]:

$$P(\frac{V}{m})^k = \text{const}$$

where $P$ is the absolute pressure of air in the air spring, $V$ is the air spring chamber volume, $m$ is the air mass in the air spring, $k$ is adiabatic exponent and its value is 1.4 for air.

The pressure response in the front left air spring can be obtained from the Eq. (3):
\[
\begin{align*}
P &= P_0 \left( \frac{mV_0}{m_0V} \right)^k \\
V &= V_0 - \frac{dV}{h} \cdot f_d
\end{align*}
\]  

(3)

where, \(m_0\) is the initial gas mass of the air spring, \(V_0\) is the initial chamber volume of the air spring, \(dV/h\) is the volume change rate of air springs, \(f_d\) is the suspension working space, namely the height change of air spring.

The spring force of the air spring can be calculated by the relationship between the pressure and the effective area of the air spring:

\[
 Fa = (P - P_a)A_e 
\]

(4)

where, \(F_a\) is air spring force, \(P_a\) is atmospheric pressure, \(A_e\) is the effective area of the air spring.

The adjacent air springs are connected through pipelines, when the pressure difference at both ends of the pipeline produces gas flow, the flow characteristics of the pipeline can be equivalent to the characteristics of the throttle orifice. The mass flow rate of gas flowing through the pipeline can be expressed as follows [12]:

\[
\dot{m}(0,t) = \begin{cases} 
AP_{up} \sqrt{\frac{1}{RT_{up}} \frac{2k}{k-1} \left( \frac{P_{down}}{P_{up}} \right)^{\frac{2}{k}} - \left( \frac{P_{down}}{P_{up}} \right)^{\frac{k+2}{k}}} \sgn(P_{down} - P_{up}) \frac{P_{down}}{P_{up}} > v_{cr} \\
AP_{up} \left( \frac{2}{k+1} \right)^{\frac{1}{k}} \sqrt{\frac{1}{RT_{up}} \frac{2k}{k+1}} \sgn(P_{down} - P_{up}) \frac{P_{down}}{P_{up}} \leq v_{cr} 
\end{cases}
\]

(5)

where, \(A\) is the effective area of orifice, \(P_{up}\) is absolute upstream gas pressure, \(P_{down}\) is absolute downstream gas pressure, \(T_{up}\) is upstream gas temperature, \(R\) is the ideal gas constant.

The parameters of simulation model under Matlab/Simulink environment are displayed in Tab.1.

| Parameter                     | Value       | Parameter                     | Value       |
|-------------------------------|-------------|-------------------------------|-------------|
| Body mass \(M_b\) [kg]        | 6700        | Tire stiffness \(K_t\) [kN/m] | 210         |
| Wheel mass \(M_t\) (front/rear) [kg] | 300/500   | Distance between shafts \(L\) [m] | 3.9        |
| X axis rotary inertia \(I_x\) [kg·m²] | 2857      | Front axle wheelbase \(B_f\) [m] | 1.7        |
| Y axis rotary inertia \(I_y\) [kg·m²] | 4983      | Rear axle wheelbase \(B_r\) [m] | 1.5        |
| Sprung mass centroid height \(H\) [m] | 1.1       | Anti-roll bar roll stiffness \(k_{bar}\) | 4433       |
| Distance from centroid to front axle \(L_f\) [m] | 2.7       | Distance from centroid to rear axle \(L_r\) [m] | 1.3        |

3. The principle of interconnection state control method

The four-corner interconnected air suspension can improve vehicle ride comfort under road excitation, but when the vehicle is in the turning, acceleration and deceleration conditions, it will aggravate the roll
or pitch of the body, and reduce the vehicle handling stability. The front axle lateral interconnection is taken as an example, as shown in Fig.3.

**Figure 3. Road surface excitation diagram for front axle laterally interconnected air suspension**

When the front right wheel is subjected to road excitation, the air pressure in the left and right air springs of the front axle is \( P_{fl} \) and \( P_{fr} \) respectively, the effective bearing area is \( S_{fl} \) and \( S_{fr} \) respectively. If the interconnection is closed, the air spring on the right side is compressed, and the air spring pressure \( P_{fr} \) increases. The spring force difference between the left and right suspensions is different. The spring force difference between the left and right suspension can be calculated as follows:

\[
\Delta F = F_{sfr} - F_{sfl} = P_{fr} S_{fr} - P_{fl} S_{fl}
\]

(6)

where, \( F_{sfl} \), \( F_{sfr} \) are spring forces of left and right air springs on front axle. \( M_f \) is body roll torque subjected to the front axle, it can be calculated as follows:

\[
M_f = F_{sfr} T_f / 2 - F_{sfl} T_f / 2 = \Delta F \cdot T_f / 2
\]

(7)

Resulting from the great difference between \( F_{sfl} \) and \( F_{sfr} \) of air spring force, the car body is subjected to bigger roll torque, which results in bigger roll acceleration, bigger body roll angle and smaller vehicle handling stability. If the interconnection is opened, the air of the compressed air spring on the right flows to the air spring on the left side, and the air pressure of the compressed air spring tends to be balanced due to the flow of the air. Both of the air pressures of the two air springs after balancing are \( P_f \), the difference between the left and right spring forces is shown as follows:

\[
\Delta F = F_{sfr} - F_{sfl} = P_f \left( S_{fr} - S_{fl} \right)
\]

(8)

The effective bearing area \( S_{fl} \) and \( S_{fr} \) of the left and right air springs vary little during their working stroke, therefore, when the air spring is interconnected, the spring force difference \( \Delta F \) decreases significantly. Simultaneously, the roll torque \( M_f \) and the body roll angle are reduced correspondingly.
Figure 4. Turning diagram of horizontal road surface for front axle laterally interconnected air suspension

In the turning condition, the front axle lateral interconnection is displayed in Fig. 4. When the vehicle turns to right on the horizontal road surface, axial load transfer is generated by centrifugal force, the load on the left air spring increases, and the load on the right air spring decreases. Therefore, the air pressure on the left air spring rises, and the air pressure on the right side of the air spring decreases. If the front axle lateral interconnection opens at this time, the compressed air on the left side flows to the right under pressure, further aggravating the body roll. If the interconnection is closed, the air pressure on the left air spring increases, and the air pressure on the right side of the air spring decreases.

Therefore, some conclusions can be drawn: when the direction of roll torque produced by air spring is the same as the direction of body roll, the opening of interconnection can reduce the roll torque produced by air spring to promote body roll; When the direction of the roll torque produced by the air spring is opposite to the body roll direction, the interconnection closure can increase the anti-roll torque produced by the air spring and restrain the further roll of the body.

The air pressure of the air spring is closely related to the change of the interconnection state. The body roll angle $\theta$ is an important indicator of body roll, its symbols can characterize the direction of roll, and its absolute value can characterize the degree of roll. The former axis lateral interconnection is taken as an example, when the product of the air pressure difference between the left and right air springs and the roll angle is greater than 0, the roll torque provided by the front axle air spring is the same as the roll direction of the car body, opening lateral interconnection; when the product of the air pressure difference between the left and right air springs and the roll angle is less than 0, that is, the roll torque provided by the front axle air spring is opposite to the roll direction of the car body, closing the lateral interconnection. It can be expressed as follows:

$$\left\{ \begin{array}{ll}
(P_l - P_r) \theta > 0 & Qvalue = 1 \\
(P_l - P_r) \theta \leq 0 & Qvalue = 0
\end{array} \right.$$  \hspace{1cm} (9)

where, $Qvalue$ is the interconnection state of the front axle lateral connection, when the value is 1, the interconnection opens; when the value is 0, the interconnection is closed. $P_l$ and $P_r$ are the air springs pressure on the left and right sides of the front axle.

Similarly, the interconnection state of the rear axle air spring can be judged as follows:
\[
\begin{cases}
(P_r - P_r) \theta > 0 & \text{Hvalue} = 1 \\
(P_r - P_r) \theta \leq 0 & \text{Hvalue} = 0
\end{cases}
\] (10)

where, \(Hvalue\) is the interconnection state of the rear axle lateral connection, when the value is 1, the interconnection opens; when the value is 0, the interconnection is closed. \(P_r\) and \(P_r\) are the air springs pressure on the left and right sides of the rear axle.

In addition to two lateral interconnected pipelines, there are two longitudinal interconnected pipelines in the four-corner interconnected air suspension. According to the above rules, when judging the interconnected state of the longitudinal interconnected pipelines, the air pressure difference between the front and rear air springs on the same side and the pitch angle of the car body should be used. The interconnection state of the longitudinal interconnected pipelines can be judged by follows:

\[
\begin{cases}
(P_f - P_r) \phi > 0 & \text{Zvalue} = 1 \\
(P_f - P_r) \phi \leq 0 & \text{Zvalue} = 0
\end{cases}
\]

(11)

\[
\begin{cases}
(P_f - P_r) \phi > 0 & \text{Yvalue} = 1 \\
(P_f - P_r) \phi \leq 0 & \text{Yvalue} = 0
\end{cases}
\]

(12)

where, \(\phi\) is the pitch angle of the car body; \(Hvalue\) and \(Yvalue\) respectively represent the left and right longitudinal interconnection state. When the value is 1, the interconnection opens; when the value is 0, the interconnection is closed.

4. The comparison of simulation results

In order to verify the vibration isolation characteristics of vehicles, sine sweep excitation with amplitude of 0.015m is applied to four wheels of vehicle, the excitation frequency is 1Hz~20Hz, increasing 0.25Hz per second in the simulation model. The excitation frequencies of each wheel are always the same, but the phases of each wheel are different. In order to apply both the lateral excitation and the pitch excitation, the phase difference between the front and rear, left and right are both 180°. Therefore, the wheel phases of front left, front right, rear left and rear right are 0°, 180°, 180°and 0° respectively. The frequency domain response of mass acceleration on the front left spring of the air suspension under four interconnected states and control methods are shown in Fig. 5.
Figure 5. The response of front left sprung mass with different interconnected modes in frequency domain

When the phase difference of the sinusoidal sweep excitation between the front and back as well as the left and right is both $\pi$, the resonance peak of mass under the spring will appear at 1-2Hz, and the resonance peak of the mass on the front left spring will appear at 9.8-10.2Hz. The root mean square (RMS) of mass acceleration on the front left spring under the interconnection control method is essentially same as that on the front left spring under the four-corner interconnection condition. The RMS resonance peak value of mass acceleration on the front left spring under four-corner interconnection control method is lowest compared with the other three interconnected states, and achieves the desired control effect.

In order to verify the control effect on the random road surface, the driving conditions are set: D level road, speed 30km/h, straight line driving. To express clearly, simulation time 10s. Vehicle body roll angle, pitch angle and root mean square acceleration of front left sprung mass under several interconnection states and interconnection control method are compared in Figures 6, 7 and 8.

Figure 6. The vehicle body roll angle in different interconnected modes on the random road surface
The root mean square values of the body roll angles under the control of non-interconnection, lateral-interconnection, longitudinal interconnection, four-corner-interconnection and interconnection method are at 0.3548°, 0.3378°, 0.3434°, 0.3609° and 0.3221° respectively. Compared with non-interconnection, lateral-interconnection, longitudinal interconnection and four-corner-interconnection, the root mean square values of the body roll angles under control method decreases by 9.2%, 4.6%, 2.1% and 3.88% respectively.

Figure 7. The vehicle body pitch angle in different interconnected modes on the random road surface

The vehicle body pitch angle under interconnected control method has been at a lowest level than other interconnection modes. The root mean square values of the body pitch angles under the control of non-interconnection, lateral-interconnection, longitudinal interconnection, four-corner-interconnection and interconnection method are at 0.4244°, 0.4337°, 0.3814°, 0.3771° and 0.3405° respectively. Compared with non-interconnection, lateral-interconnection, longitudinal interconnection and four-corner-interconnection, the root mean square values of the body pitch angles under control method decreases by 19.8%, 21.5%, 10.7% and 9.7% respectively.

Figure 8. Root mean square of mass acceleration on front left spring in different interconnected modes on the random road surface
The mean square values of mass acceleration on front left spring under interconnected control method have been at a lowest level compared with other interconnection modes. The root mean square values of mass acceleration on front left spring under the control of non-interconnection, lateral-interconnection, longitudinal interconnection, four-corner-interconnection and interconnection method are at 1.3950m/s², 1.3556m/s², 1.4032m/s², 1.3497m/s² and 1.3240m/s² respectively. Compared with non-interconnection, lateral-interconnection, longitudinal interconnection and four-corner-interconnection, the mean square values of mass acceleration on front left spring under interconnected control method decreases by 5.0%、2.3%、5.6% and 1.9% respectively.

5. Conclusions
The influence of air spring torque of interconnected air suspension on vehicle body roll or pitch angles due to the change of interconnection state is analyzed by establishing the vehicle models. Based on it, the principles of interconnection state control method are formulated. Finally, some results from Matlab/Simulink simulation can give the conclusion as follows:
(1) A sinusoidal scanning excitation of 1 Hz to 20 Hz is applied to the vehicle body in the Simulink environment. The RMS resonance peak value of mass acceleration on the front left spring under four-corner interconnection control method is lowest.
(2) In the random road simulation environment, the vehicle body roll angle, pitch angle and the root mean square value of mass acceleration on the front left spring under interconnection method are 0.3221°, 0.3405° and 1.3240m/s² respectively. All are the smallest compared with other interconnection modes.

The results show that this control method can not only reduce the roll angle and pitch angle caused by road excitation, but also improve the anti-roll and anti-pitch ability of the air suspension under turning, acceleration and deceleration conditions, and maintain good vibration isolation characteristics.

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