Study on stochastic vibration of air spring in high-speed EMU considering gas exchange

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Abstract

Air spring is widely used in the modern industry because of its excellent non-linear characteristics and good stability. In this paper, the finite element model of air spring is established by using non-linear dynamic simulation of Abaqus which is finite element software. Rubber bags are set for homogeneous of the hyperelastic rubber material with Mooney-Rivlin model for analysis. In addition, the cord is arranged inside the rubber capsule, including angle, density, material, number of layers, etc. In the rubber capsule, the role of fluid-solid coupling are established between the gas and the rubber capsule, and the relationship between pressure and body flux can be extracted through AMESim, the additional air chamber is established to effect gas exchange between the rubber capsule and the additional air chamber. Then convert the road spectrum signal into a stochastic signal through MATLAB. And the road spectrum signal is loaded into the model for simulation. The detection conditions are set to detect the acceleration of the three directions of the vehicle body. The vibration analysis of the air spring is analyzed comprehensively by comparing the excitation signal with the response signal. It is concluded that the air spring has a very good vibration-damping characteristic under the stochastic excitation of road spectrum.

Keywords: Air spring; Gas exchange; Stochastically motivated; High-speed EMU (Electric Multiple Unit)

1. Introduction

The air spring is a non-metallic elastic element which is filled with compressed gas in a flexible, air-tight cavity, utilizes the compressibility of the air to achieve a resilient spring and to achieve a damping change through the control of the orifice. Its stiffness has a high quality nonlinear characteristics, the stiffness of the entire accessories characteristics can be changed by controlling the internal pressure and other parameters, so the use of air springs in daily life is more and more widely, not only in the car, especially in equipment, such as vibration transport. The field is becoming more and more mature, in the high-speed EMU, the use of air springs are also very popular. The use of air spring as a two-line suspension system of high-speed EMU vehicles and the direction characteristics of the air spring has great impact on the smooth operation of the vehicle [1]. In addition, due to the structural limitations of the air spring, the air spring can’t be designed too large, through the establishment of auxiliary chamber achieving the expansion of the total air volume to reduce the air spring natural frequency and increase the stability of the air spring [2].

2. Structure of the air spring

The air spring of EMU is generally used in the form of inflated and then compressed. The rubber heap is made of rubber gasket and steel splint, the rubber capsule is a composite structure which is made of internal rubber, external rubber, rebar layer and forming a ring made of a layered. The air spring is designed with an air intake, then the compressed air enters the rubber capsule through the height adjustment valve, and the auxiliary chamber is provided with an orifice between the rubber capsule and the auxiliary chamber [3]. When the air passes through the orifice, the throttling effect is generated, suspended vertical damping. Allowing the relative horizontal displacement between the upper and lower cover to play the role of emergency buffer when emergency conditions lead to damage to the air spring fracture. The air spring takes the method of self-sealing to seal the rubber capsule in order to ensure that the rubber bag does not leak, that is, the air pressure inside the capsule can seal the capsule and the card slot of the upper and lower covers [4]. Its position and structure are shown in Fig. 1.

3. Features of air spring

The natural frequency of the air spring keeps constant in transportation, but, the stiffness of the conventional steel spring is almost constant, and the natural vibration frequency of the conventional spring varies greatly depending on the load. But the load on the air spring vibration frequency has little effect, the locomotive using air springs, empty and heavy truck when the frequency remains basically unchanged.

It makes the vehicle more stability. EMG vibration acceleration is an important index to evaluate the stability of EMU
operation. When using the air spring, the locomotive in the empty, heavy truck vibration acceleration is basically constant, it means that it has a higher stability.

The natural frequency can be changed depend on the volume of the auxiliary chamber. In order to minimize the natural frequency to avoid resonance, the air spring is usually equipped with an auxiliary chamber to increase the natural frequency. Auxiliary chamber, inside the bogie beam, can effectively reduce the natural frequency to improve the stability of EMU.

High-frequency vibration can be absorbed by air spring in a good sound insulation performance. Due to the limitations of the structure and materials of the conventional steel round springs, the friction between the rubber capsule and the inner and outer cylinders is very serious, and it is easy to transmit high-frequency vibration, which is prone to noise. The main components of the air spring are rubber and the air inside the capsule. It is difficult to pass the noise. When the train is running on the track, in the moment of the vibration environment, rubber bags in a short time can only shrink or deformation and it will not transmit the vibration, so it is difficult to pass high-frequency vibration.

The stiffness characteristics can be adjusted appropriately applied to the choice of air spring parameters reasonably. The vertical stiffness characteristics and lateral stiffness characteristics of the air spring are related to the initial pressure of the rubber capsule. The stiffness of the air spring is controlled by adjusting the initial pressure in the rubber capsule to meet the requirements of the motor group. Therefore, the heavy-duty shaking table mechanism can be removed.

The hydraulic shock absorber is replaced by air spring. There is an orifice between the rubber capsule and the auxiliary chamber. When the air spring is applied, the compressed air, through the orifice, has a damping effect to achieve the function of vibration to replace the traditional hydraulic shock absorber.

There is no fatigue damage and a lower weight. Air spring is lighter than steel wheel spring, thus reducing the weight of the body, so as to achieve the requirements of high-speed car lightweight. The main failure of the leaf spring comes from fatigue damage, but there is no such a problem in air spring due to material. So its life is relatively longer. In addition, when replacing is more convenient as the lower weight of the air spring [5].

4. Establishment of finite element model

Abaqus contains a wealth of units and models that can simulate the problem of fluid-solid coupling, mainly considering the interaction between solid and fluid. Air spring analysis which contains a lot of finite element mechanics in the nonlinear problem are special, well can abaqus meet the requirement [6].

The air spring model which is established in Abaqus consists mainly of four parts, including the upper cover, the support rubber, the body rubber capsules and the auxiliary chamber, and a half-symmetry model can be established because of the symmetrical characteristic of the air spring, shown in Fig. 2.

The upper cover and the auxiliary chamber are set as rigid body, and the upper plate is set with the mass. The whole model applies the gravitational condition. In the global coordinate system, the y direction is vertical, the x direction is horizontal, and the z direction is longitudinal.

The rubber capsule is a hyperelastic material and is calculated by an isotropic Rivlin model.

$$U = \sum_{i,j=0}^{\infty} C_{ij} (I_1 - I_3)^i (I_2 - I_3)^j$$

(1)

The calculation model is simplified accordingly. Only to retain the first two, then, it becomes Mooney-Rivlin model which is widely used in the project [7-8].

$$W = C_{10}(I_1 - 3) + C_{01}(I_2 - 3)$$

(2)

where W is the strain energy function; I_1 is the first strain constant of the rubber material and I_2 is the second strain constant of the rubber material; C_{10} and C_{01} are material constant which can be obtained by uniaxial tensile test [9].

Rubber tube with rebar whose material is nylon, the material density \( \rho = 1.14 \times 10^3 \text{ton/mm}^3 \), Young’s modulus of 2GPa, the rebar diameter is calculated by 0.7mm and a single cord cross-sectional area is 0.3848451mm². The spacing between the cords are 1mm, the cord angle is set to 0°. The angle of the rebar is related to the local coordinate system, the angle is related to the local coordinate system 1 axis which is shown in Fig. 3a, rubber cord orientation is shown in Fig. 3b.

I axis for the radial direction, the angle of the cord is the angle between the cord and the 1 axis. The actual thickness of the model is 5mm. Shell thickness is defined of 5nm. The geometric characteristic parameters are defined as: rebar cross-sectional area is defined of 3.85x10^{-3} mm²; the distance of the same layer rebar between is defined of 1mm; the material for nylon which is defined of 1140 kg/m³.

An auxiliary chamber initially is set to volume of 70L. Rubber capsule internal is set to pressure of 200,000Pa. And then three different directions of stochastic load are applied to the auxiliary chamber. Finally, make an analysis of the air spring on the plate in the vertical, horizontal, longitudinal direction of the three stochastic reactions.

In order to simplify the air spring model, the upper cover plate is set as the discrete rigid body to take the place of the vehicle body, and the 1/4 car model quality is applied to the air spring. The upper cover plate is simulated by using the four-node three-dimensional bilinear rigid quadrilateral (R3D4) form, and it is processed of the gravity in the simulation. Air spring airbag is simulated by using the 4-point shell unit. The upper and lower cover of the airbag is set to rigid body, and the material is set to steel. The rubber pile is set to alternately stack way with steel plate and rubber plate. Eight-node linear hexahedral element (C3D8R) is used in the model. The rubber sheet material is hyperelastic. The steel plate is
made of steel and it is set as a rigid body. Then and then it is made rigid. The auxiliary chamber and the rubber chamber of the air spring are respectively provided with reference points, and the fluid chamber properties are respectively given to complete the attribute definition of the gas chamber.

The contact conditions of air spring model on the cover plate and airbag cover are set for the tie. The upper cover and the outer surface of the airbag are set for general contact. Contact properties are defined as tangential frictionless, normal for the hard contact. The bottom plate and rubber sheet are set to tie contact. Tie contact conditions is set between rubber sheet and steel plate. And the reference point of the upper cover is set to be coupled to the upper cover. The steel plate is coupled with its reference point. And then define the fluid exchange properties of the fluid cavity. It is finally complete the interaction attribute definition.

4.1. Design of air spring condition for EMU

Simulation experiments are mainly set to two steps. In step-1, the degree of freedom of the cover and rubber pile bottom is fixed while the air spring inside and auxiliary chamber are inflatable. The inflation time is defined to 0.1 s and the inflation pressure is 200,000 Pa. In step-2, release the corresponding direction of the freedom of the upper cover, and set the stochastic vibration in the corresponding direction. Analysis time is defined to 1.6 s. The final simulation results finally come out.

4.2. Gas exchange between the auxiliary chamber and airbag

4.2.1. Definition of gas exchange attributes

Firstly, establish the auxiliary chamber and airbag to two fluid chambers by defining the fluid cavity properties, so that the fluid cavity of the property is gas. Then define the fluid exchange. In the step-1 inflated process, the inflatable internal pressure is 200,000 Pa. The diameter of the orifice is ϕ=14mm. Then use the volume leak rate module to define the fluid exchange. The gas exchange between the two fluid cavities is simulated by using the AMESim. The internal pressure of cavity 1 is set as 200,000 Pa, the volume of the cavity 2 is set as 70L. Through the simulation, we can get the parameters of the model of the three directions. The time domain signal is load the data into the model of the three directions respectively as the basis of simulation incentives.

4.2.2 Gas exchange in AMESim

In this study, in order to simulate the gas exchange between the internal air of the air spring and the auxiliary chamber, the Abaqus and AMESim software are used to simulate the model of the air in the AMESim.

Firstly, sketch the Pneumatic module to create global gas properties. The parameters can be extracted using the following equations [11]

\[
gamma = \frac{C_p}{C_v} \\
r = \frac{C_p - C_v}{C_v}
\]

where \(C_p\) is constant-pressure specific heat, \(C_v\) is the constant-volume specific heat, \(\gamma\) is the specific heat ratio, \(r\) is the perfect gas constant.

Secondly, two fluid chambers are established. The fluid chamber 1, whose internal pressure is 200,000Pa, is set as the source to simulate air spring internal inflational pressure. The fluid chamber 2 is set to fluid cavity whose volume is 70L, connect them with pipe. The flow rate at port 1 is calculated by the basic formula [12].

\[
v = \sqrt{\frac{2 \cdot D \cdot |\Delta P|}{L \cdot \rho \cdot f_f}}
\]

where \(v\) is the gas velocity, \(D\) the pipe diameter, \(\Delta P\) the pressure drop, \(L\) the pipe length, \(\rho\) the density, and \(f_f\) is the friction factor. From this, the mass flow rate, enthalpy flow rate and Reynolds number can be readily calculated.

Set the orifice diameter to 14mm, The mass flow rate is determined with

\[
m = A \cdot C_q \cdot C_m \cdot \frac{P_{up}}{\sqrt{T_{up}}}
\]

where \(A\) is the orifice area, \(C_q\) is the flow coefficient, \(C_m\) is the flow parameter, \(P_{up}\) is the upstream pressure, \(T_{up}\) is the upstream temperature [13].

Extract the relationship between the pressure and body flux shown in Fig. 4, then Import the data into the gas exchange properties of Abaqus to simulate.

4.3. Stochastic excitation signal application

The stochastic excitation of the road spectrum is the power spectral density function, as shown in Fig. 5. It is the three directions of the stochastic excitation conditions. It is converted the frequency domain signal into a time domain signal by the MATLAB Fast Fourier Transform (IFFT) [14]. The interception time is 1.63s. The time domain signal is loaded into the model of the three directions respectively as the basis of simulation incentives.

4.3.1. Air spring response for vertical stochastic vibration excitation

In vertical stochastic excitation, the base for vertical stochastic vibration excitation is set. The model horizontal x direction and longitudinal z direction of the displacement are...
constrained. The vertical y direction of freedom is set. The vertical damping characteristics of the air spring are obtained by applying a vertical stochastic stimulus. We can observe the vibration of the body. The acceleration graph is shown in Fig. 6a and 6b.

It can be seen from Fig. 6 that the acceleration of the vehicle body fluctuates up and down at 0 and the average amplitude is -3.10E-3 in excitation but -6.66E-4 in response as shown in Table 1. The variance of excitation is 0.00142 but 0.000224 in response. It can be seen that the vertical characteristics of the air spring have a better damping characteristics.

![Figure 1](image1.png)  
**Figure 1.** Air spring suspension in a high-speed railway vehicle

![Figure 2](image2.png)  
**Figure 2.** Abaqus model of air spring

![Figure 3a](image3a.png)  
**Figure 3a.** Definition of cord angle

![Figure 3b](image3b.png)  
**Figure 3b.** Model of half air spring

![Figure 4](image4.png)  
**Figure 4.** Volumetric flow rate VS pressure difference
4.3.2. Air spring response with horizontal stochastic vibration excitation

In horizontal stochastic excitation, the base for horizontal stochastic vibration excitation is set. The model vertical y direction and longitudinal z direction of the displacement are constrained. The horizontal x direction of freedom is set. The horizontal damping characteristics of the air spring are obtained by applying a horizontal stochastic stimulus. We can observe the horizontal of the body. The acceleration graph is shown in Fig. 7a, Fig. 7b.

It can be seen from Fig. 7 that the acceleration of the vehicle body fluctuates up and down at 0 and the average amplitude is -9.74E-3 in excitation but 4.55E-4 in response as shown in Table 2. The variance of excitation is 4.46E-3 but 7.92E-7 in response. It can be seen that the horizontal characteristics of the air spring have a better damping characteristics.

<table>
<thead>
<tr>
<th>Table 1. Vertical stability comparison</th>
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<tbody>
<tr>
<td>Average</td>
</tr>
<tr>
<td>Excitation</td>
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<tr>
<td>Response</td>
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</table>

4.3.3. Air spring response with longitudinal stochastic vibration excitation

In longitudinal stochastic excitation, the base for longitudinal stochastic vibration excitation is set. The model horizontal x direction and vertical y direction of the displacement are constrained. The longitudinal z direction of freedom is set. The longitudinal damping characteristics of the air spring are obtained by applying a longitudinal stochastic stimulus. We can observe the longitudinal of the body. The acceleration graph is shown in Fig. 8a, Fig. 8b.

It can be seen from Fig. 8 that the acceleration of the vehicle body fluctuates up and down at 0 and the average amplitude is -1.4E-2 in excitation but -3.25E-3 in response as shown in Table 3. The variance of excitation is 0.061752 but 1.09E-5 in response. It can be seen that the longitudinal characteristics of the air spring have a better damping characteristics.
tics.

Figure 7a. Horizontal excitation of system

Figure 7b. Horizontal response of body

Table 2. Horizontal stability comparison

<table>
<thead>
<tr>
<th></th>
<th>Average</th>
<th>Variance</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Excitation</td>
<td>-9.74E-03</td>
<td>4.46E-03</td>
<td>m/s²</td>
</tr>
<tr>
<td>Response</td>
<td>4.55E-04</td>
<td>7.92E-07</td>
<td>m/s²</td>
</tr>
</tbody>
</table>

Figure 8a. Longitudinal excitation of system

Figure 8b. Longitudinal response of body

Table 3. Longitudinal stability comparison

<table>
<thead>
<tr>
<th></th>
<th>Average</th>
<th>Variance</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Excitation</td>
<td>-1.40E-02</td>
<td>0.061752</td>
<td>m/s²</td>
</tr>
<tr>
<td>Response</td>
<td>-3.25E-03</td>
<td>1.09E-05</td>
<td>m/s²</td>
</tr>
</tbody>
</table>

5. Conclusions

This study summarizes the advantages of air spring in modern industry, focuses on the use of Abaqus to establish simulation model, take advantage of Matlab to derive the time threshold signal in three directions and analyzes the gas exchange properties with AMESim, and analyzes the effects of air spring under the stochastic excitation with the role of the auxiliary chamber in three directions after the vibration characteristics. The method, simulate the actual conditions, owns an excellent practical value. It shows that the air spring has a very good vibration damping characteristics.

References


[14] Li Qin Sun, Zhong Xing Li, Xu Feng Shen, Hua Wei Zhao. Model and Simulaion of Air Spring Stiffness Characteristics Based on van der Waal Equation [J]. Advanced Materials Research, 2013, 2592 (779)