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RESEARCH ON STIFFNESS OF AIR-SPRING WITH AUXILIARY CHAMBER AND ITS EQUIVALENT MODEL

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Abstract. *On the basis of briefly analyzing the traditional methods of determining air-spring's stiffness, a non-linear model of air-spring is set up. Nonlinear characteristic of geometry, pressure load's variation, volume of auxiliary chamber and other problems are settled basically in the article. Discuss the relationships between initial pressure and the inherent frequency, between auxiliary chamber and air spring stiffness, between different initial pressure and air spring stiffness. As an example, the vertical stiffness characteristic of circle round type air-spring is analyzed. The result suggests that air-spring's stiffness can be analyzed by finite element method. Finally, according to the analytical results, equivalent model of air springs is set up. Compare the stiffness of original model and equivalent model of air spring.*

1 INTRODUCTION

Air spring suspension provides significant advantages compared with conventional coil spring suspension, which has been validated by many researchers. [1-7] Recently air suspension has been used widely in suspension systems. Air spring becomes one of key components of the secondary suspension of EMU, which has been widely applied in railway vehicle in our country. With the changing of the vertical deformation, volume of compressed air、pressure and temperature of air spring will change, which results in the exchange of gas of air spring with auxiliary chamber through the orifice. Characteristics of air spring suspension system plays a very important role in the vehicle's comfort, vertical dynamic characteristics of air spring is more complex, so the study on dynamic property of air spring has very important significance.

The early research on air springs mainly focused on the material and manufacturing processes and resulted in increased spring durability and improved mechanical properties [8-14]. There have also been numerous researchers who have focused on numerical methods to investigate the dynamic characteristics of an air spring suspension with control [15–25].

2 AIR SPRING VERTICAL MODEL

Air spring suspension system consists of air spring main body (including airbag, upper cover plate and rubber pad), orifice, differential pressure valve and the height control valve.

2.1 Mechanical properties of rubber material

The strain energy density function model of rubber material adopts Mooney-Rivlin model. For natural rubber, Mooney-Rivlin constitutive model can describe the small and medium deformation of rubber enough accurately, and it can simulate all mechanical behavior of rubber materials, generally applicable to the strain of about 100% tensile and 30% compression. And due to its simplicity and practicality, the constitutive model of rubber, it is also used most widely. In this paper, the deformation is in the model range, so Mooney-Rivlin constitutive model is used to describe the rubber with sufficient accuracy. Rubber material adopts the MOONEY-RIVLIN material type in ABAQUS.

According to the MOONEY-RIVLIN type rubber material, energy density function:

$$W = C_1(I_1 - 3) + C_2(I_2 - 3) + \frac{1}{D_1}(J - 1)^2$$

Where C_1、C_2 are rubber material coefficients； D_1 is dynamic coefficient.

2.2 Mechanical model of air spring with auxiliary chamber

Air spring is a body of revolution composed of the upper cover plate, the main air chamber, the auxiliary air chamber, rubber pad, which can be simulated by the axisymmetric model. The upper cover plate and the Auxiliary air chamber can be simulated by the rigid element. The main air chamber is made of vulcanized rubber layers and cord-reinforced fabric layers, simulated by shell element with rebar element. Rubber pad is made of vulcanized rubber and steel plate, simulated by axis element[15-25].

The compressed air in the main air chamber and auxiliary chamber is simulated by from the fluid element. The fluid link element is created between the main air chamber and auxiliary chamber to transfer the air pressure.

Figure 1 is 180 ° axisymmetric model of the main body of air spring, figure 2 for 180 ° axisymmetric model of the rubber pad. Figure 3 for 180 ° axisymmetric model of auxiliary chamber. Figure 4 for 180 ° axisymmetric model of air spring with auxiliary chamber.

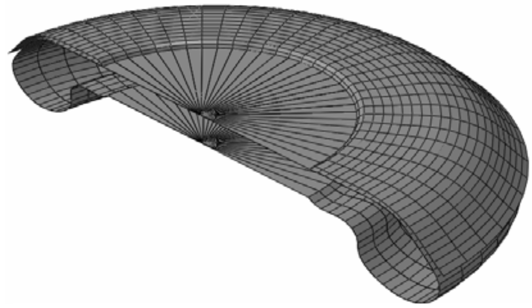

Figure 1. 180 ° axisymmetric model of the main body of air spring

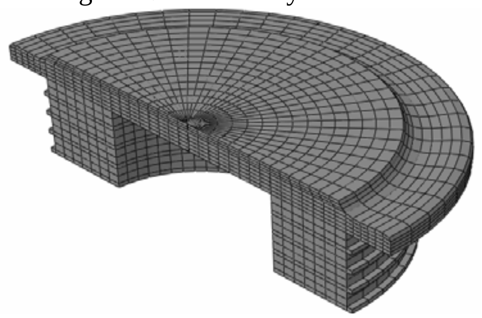

figure 2. 180 ° axisymmetric model of the rubber pad

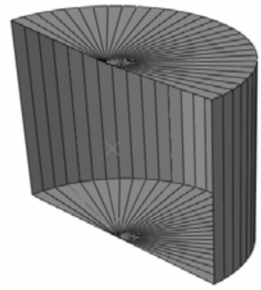

Figure 3. 180 ° axisymmetric model of auxiliary chamber

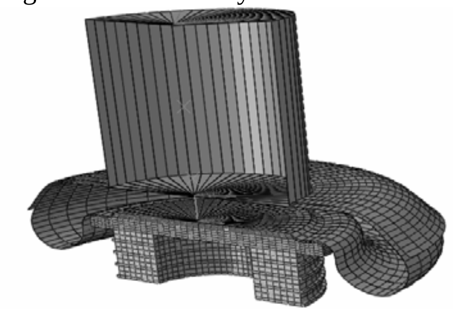

Figure 4. 180 ° axisymmetric model of air spring with auxiliary chamber

3 PARAMETER INFLUENCE

3.1 Nonlinear characteristic of geometry

Air spring includes all kinds of nonlinear characteristics; therefore, also the static stiffness of air spring shows nonlinear characteristics. Figure 5 is the geometric nonlinear characteristic curve that is the static stiffness characteristic curve under different displacement.

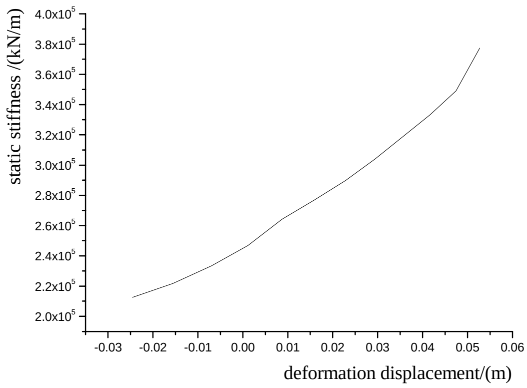

Figure 5． nonlinear characteristic curve of geometry

It can be seen from figure 5 that the stiffness at the design location is about 240kN/m. The displacement is positive when stretching, while the compression displacement is negative. The stiffness decreases with increase of the compression displacement， and increases with the increase of the stretching displacement. The static stiffness curve shows strong nonlinear characteristics.

3.2 Pressure load

Figure 6 is the relationship curve between the initial pressure and static stiffness. It can be seen from figure 6, stiffness the design position increases with the increase of the initial work pressure in direct proportion.

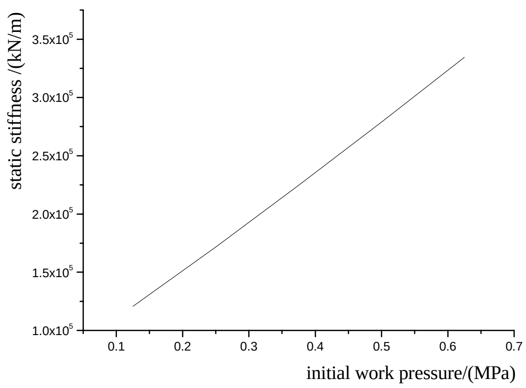

Figure 6． relationship curve between the initial pressure and static stiffness

3.3 Volume of auxiliary chamber

Figure 7 is the relationship curve between volume of auxiliary chamber and the static stiffness curve. It can be seen from figure 7, the stiffness decreases with the increase of volume of auxiliary chamber. The stiffness decreased sharply, in the process of building of auxiliary chamber, and then decline gradually decreases with the increase of volume of auxiliary chamber. When the volume of auxiliary chamber reaches to a certain extent, the stiffness of air spring decreases slowly, due to space limitations, volume of auxiliary chamber can't increase unlimitedly, generally for 70 L.

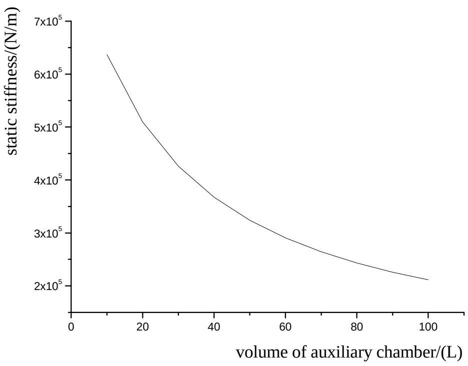

Figure 7. relationship curve between volume of auxiliary chamber and the static stiffness curve

3.4 Relationship curve between initial pressure and the inherent frequency

Figure 8 is the relationship curve between initial pressure and the inherent frequency. The inherent frequency of air spring decreases with the increase of initial work pressure. According to the principle of vibration isolation, the lower the natural frequency, the better vibration isolation effect is.

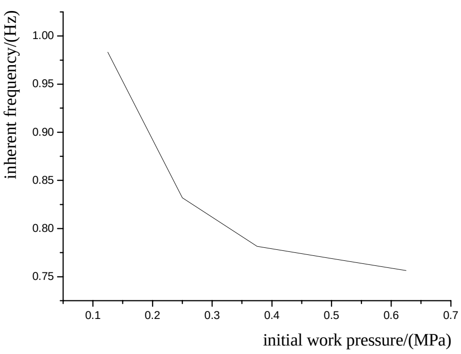

Figure 8. relationship curve between initial pressure and the inherent frequency

4 EQUIVALENT MODEL OF AIR SPRING

Air springs are often used in the secondary suspension of passenger railway vehicles, and their modelling has important implications for the accuracy of quasi-static and dynamic multi-body simulations. The overall behaviour of this suspension element can be described in terms of vertical and horizontal behaviour, generally with a weak interaction between the two, although the vertical preload has an important influence on the lateral behaviour of the suspension.

In the vertical direction, air spring suspensions show behaviour highly dependent on the preload and on the amplitude and frequency of dynamic displacements. When deflated, air springs sit down on a rubber emergency spring.

Models of the vertical air spring behaviour can be classified into ‘equivalent mechanical models’ and ‘thermodynamic models’. Equivalent mechanical models are based on the use of lumped parameter springs, dashpots and masses. These allow a relatively simple mathematical description of the suspension, but they generally do not account for the levelling system behaviour and do not provide an estimate of air consumption. Furthermore, these models may not be well suited to consider non-conventional suspension configurations (e.g. cross piping of the bellows) or active/semi-active suspension control.

Thermodynamic models instead aim at representing the actual mechanical and thermodynamic processes occurring in the air spring suspension, and hence, all parameters in such models have a clear physical meaning. Despite this, tuning may be needed to define the values of model parameters describing the concentrated and distributed losses in the pneumatic circuit.

4.1 Equivalent model of air spring

The simplest model of the air spring suspension in the vertical direction consists of a spring with a viscous dashpot in parallel. However, this model only reproduces the quasi-static stiffness of the suspension, and it is difficult to define a correct value for the damper parameter, because the actual dissipative effects in the suspension are far from linear.[15]

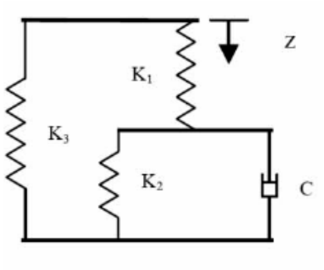

Figure 9. Equivalent model of air spring

4.2 Comparison curve between the stiffness of original model and equivalent model

Figure 10 is the comparison curve between the stiffness of original model and equivalent model of air spring. It can be seen from figure 10 that this model can simulate the quasi-static stiffness of the suspension to some extent, but to appropriate in a wider frequency range, we need a kind of more complicate equivalent model.

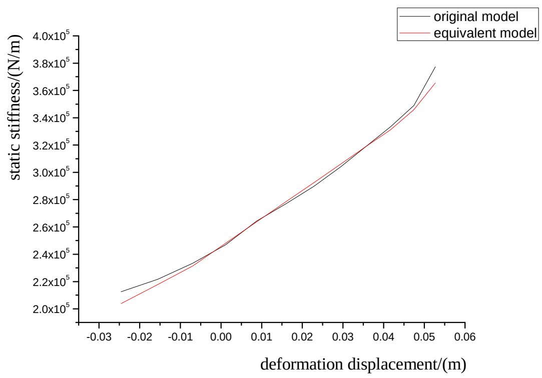

Figure 10. comparison curve between the stiffness of original model and equivalent model

5 CONCLUSIONS

- Axisymmetric model of air spring with auxiliary chamber is set up.
- The static stiffness curve shows strong nonlinear characteristics.
- Stiffness the design position increases with the increase of the initial work pressure in direct proportion.

- Stiffness decreases with the increase of volume of auxiliary chamber. When the volume of auxiliary chamber reaches to a certain extent, the stiffness of air spring decreases slowly.
- The inherent frequency of air spring decreases with the increase of initial work pressure.
- This equivalent model can simulate the quasi-static stiffness of the suspension to some extent, but to appropriate in a wider frequency range, we need a kind of more complicate equivalent model.

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REFERENCES

[1]. Caiying Mi, et al. Stability Analysis of the Secondary Suspension System of Tilting Diesel Locomotive-Stiffness Method, Journal Of Southwest Jiaotong University, Vol.35 No.6 , 2000

[2]. Caiying Mi, et al. Horizontal directional rigidity and stability analysis of system of paralleled helical spring in series with rubber spring at their one end, Diesel Locomotives, No.10(total332), 2001

[3]. Caiying Mi. A new method to determine the lateral rigidity of a system formed by the high and round spring in series with rubber springs at its two ends, Diesel Locomotives, No.4(total314), 2000

[4]. Caiying Mi. A Method for Analyzing the Lateral Stiffness of Flexcoil Springs, Journal Of Southwest Jiaotong University, Vol.33, No.3, 1998

[5]. Hongwen Yan. Application of FEM to Design of Rubber Elements in Rolling Stock, Electric Drive For Locomotives, No.6, Nov.10,2007

[6]. Li Liu, Weihua Zhang. Frequency variety analysis and equivalent algorithm of metal spring stiffness, Journal Of Traffic And Transportation Engineering, vol.7,No.5, pp:24-27, 2007

[7]. Li Liu, Weihua Zhang, Study on dynamic characteristics of metal helical spring, Sciencepaper Online , vol.2,No.9,pp:678-684,2007

[8]. Zheng Meng. "Research On Rubber Spring Dynamic Stiffness And Its Influence On Subway Vehicle Dynamics"[D], Southwest Jiaotong University Master Thesis, 2011

[9]. Qingqun Lan and Pingbo Wu. Static and dynamic analysis of rubber spring for rolling stock, Machinery Design＆Manufacture, 2008,11

[10]. Weixiao WANG, et al. Structure Analysis of Cone Rubber Spring, Railway Rolling Stock, vol.47,No.2,2009

[11]. Jiwei Zhang. Finite Element Analysis of Dynamic Characteristics for Main Rubber Spring of Hydraulic Engine Mount，Jilin University Master Thesis，2007

[12]. Jie Wu. et al. Computational Method for Dynamic Properties of Rubber Isolators Using Hyperelastic-viscoelastic-plastoelastic Constitutive Model, Journal Of Mechanical Engineering, vol.46,No.14, 2010

[13]. Liang Zuo. Finite element analysis of Common Rubber Components Used in Locomo-

tive and Vehicle, Southwest Jiaotong University Master Thesis,2006
[14]. Luhong Ma, et al. Analysis Of Combined Elastic Damping Devices on Multiple Dof Parallel Mechanism, Journal Of Mechanical Engineering, Vol.40,No.1, 2004
[15]. Stefano Bruni, et al. Modelling of suspension components in a rail vehicle dynamics context, Vehicle SystemDynamics, Vol.49,No.7, pp:1021-1072,2011
[16]. Alan Facchinetti, et al. Mathematical modelling of the secondary airspring suspension in railway vehicles and its effect on safety and ride comfort, Vehicle System Dynamics: International Journal of Vehicle Mechanics and Mobility, Vol.48,S1, pp:429-449, 2010
[17]. J S Tang. Passive and semi-active airspring suspensions for rail passenger vehicles-theory and practice. Proceedings of IMechE Conference, Vol. 210, pp:103-117,1996
[18]. Stefano ALFI, et al. Active Control Of Airspring Secondary Suspension For Improving Ride Comfort In Presence Of Random Track Irregularity. Journal Of Mechanical Systems For Transportation And Logistics,Vol.3,No.1, pp:143-153,2010
[19]. S. Bruni , et al. Control and monitoring for railway vehicle dynamics, Vehicle System Dynamics, Vol. 45, Nos. 7-8, pp:743-779.,2007
[20]. E. Foo, et al. Active suspension control of flexible-bodied railway vehicles using electro-hydraulic and electro-magnetic actuators, Control Engineering Practice, Vol. 8, No. 5 , pp:507-518,2000
[21]. Y. Sugahara, et al. Suppressing Vertical Vibration in Railway Vehicles through Primary Suspension Damping Force Control, Journal of System Design and Dynamics, Vol. 1, No. 2, pp: 224-235, 2007
[22]. K. Toyofuku , et al. Study on dynamic characteristic analysis of air spring with auxiliary chamber, JSAE Review, Vol. 20, No. 3, pp:349-355,1999
[23]. N. Docquier, , et al. Multiphysic modelling of railway vehicles equipped with pneumatic suspensions, Vehicle System Dynamics , Vol. 45, No. 6, pp:505-524,2007
[24]. G. Quaglia, et al. Air suspension dimensionless analysis and design procedure, Vehicle System Dynamics, Vol. 35, No. 6, pp:443-475,2001
[25]. Y. Sugahara, et al. Suppressing Vertical Vibration in Railway Vehicles through Air Spring Damping Control, Journal of System Design and Dynamics, Vol. 1, No. 2, pp: 212-223, 2007