Simulation Methods in Air Spring System with Auxiliary Chamber

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Abstract

AAAAir springs are playing an increasingly important role in locomotive damping system. Finite element simulation performance has become an indispensable part of their design. Former studies of air spring with auxiliary chamber have mostly focused on theoretical and experimental analysis. Few systematic literatures discuss its FEM simulation system. This article aims to dissertate the procedures of air spring simulation, make a comparison of advantages and disadvantages by different methods in each procedure, point out the meaning and effect of different parameters, and form an optimized simulation system, which including rubber constitutive model selection based on experimental data, rubber-cord composite material description, non-linear nature of rubber in contact with the rim of air spring, fluid exchange property between the capsule cavity and the auxiliary chamber, the element choice, meshing tools, load steps and so on.

In this paper, two typical air springs are simulated, screw-fastening type and self-sealing type. The capsule performance of the screw-fastening type and the whole air spring performance of self-sealing type (containing capsule and the auxiliary spring) are calculated. The performance includes load-pressure relationship at different viscosities of fluid exchange property between capsule cavity and auxil-iary chamber, the vertical stiffness and lateral stiffness.

Thus the air spring simulation system is proposed. Firstly, by comparing a limited of experimental data of vertical stiffness results, the viscosity characteristics in accordance with the air spring system under realistic conditions can be optimized. Secondly, the performance on the remaining working conditions of the air spring in this optimized viscosity can be calculated in detail, including lateral stiffness, deformation, and stress and so on.

The conclusions are as follows. (1) Comparison with experimental results, the load - pressure relation error is less than 5%。The vertical stiffness error is less than 10%. The lateral stiffness error is around 20%. (2) Air spring stiffness is not only directly related to the fluid exchange property between capsule cavity and auxiliary chamber, but also positively correlated with the size and air pressure inside the capsule. (3) The load-pressure relationship is almost independent of viscosity. (4) The vertical stiffness has a positive linear correlation with viscosity and the lateral stiffness is basically not affected by viscosity.

Keywords: air spring; rubber constitutive law; rebar layer; air cavity; auxiliary air reservoir; fluid exchange

The stiffness of air spring is flexible, and can be adjusted by changing the air pressure in its capsule, which makes it suitable for a wide range of operating conditions. Most of the air springs has two cavities. The capsule cavity mainly endures the vertical load. The auxiliary chamber is designed to ease the dramatic pressure changes of capsule cavity under large deformation. Consequently the stiffness and mechanical properties of air spring system can be maintained in a stable level.

1. Difficulties in air spring studies

Like tires, air spring has long been troubled by "three non-linear" problems, which consist of "material nonlinearity", "geometric nonlinearity" and "contact nonlinearity". Material nonlinearity refers to hyper-elastic and some other non-elastic properties of rubber. Besides, the rubber-cord composite material also have discontinuities.

Geometric nonlinearity means that the shape of capsules and auxiliary springs are not regular. It's difficult to solve out the solution by theory of Elasticity. Moreover, the large deformation of rubber can hardly satisfy small deformation assumptions.

Contact nonlinearity occurs when the capsule has contacts with top plate and bottom plate. The contact area is changing according to the deformation and the position of the capsule.

Due to these difficulties, not only the theoretical studies of air spring is based on some ideal assumptions which deviate from the reality, but also the FEM simulation of air spring is hard to get a convincing result.

To predict the mechanical properties of air spring under different conditions (pressure, load, displacement, vibration frequency), the following aspects need to be carefully tackled on:

(1) Description of the constitutive law of rubber material and rubber-cord composite material;

(2) Description of the fluid exchange properties between the capsule cavity and the auxiliary chamber;

(3) Definition of contacts, boundary conditions and constraints;

(4) Partition and distribution of the mesh. Because of large deformation of the rubber material, serious distortion of elements would occur, which makes the iteration difficult to converge. So the quality of the mesh must be assured,

especially the mesh of capsule near top bead and bottom bead.

Existing literatures are mainly focus on these areas described above.

In theoretical studies, Facchinetti and others established a simplified model by using spring-damping system, which includes equivalent model, linear model and non-linear model. They used Matlab to solve differential equations, and concluded that the linear model had higher computing speed and precision[1, 2]. Besides, based on thermodynamics, Yuan derived the relation between the damping value of fluid exchange and the diameter of the orifice, solved the equation by using Runge-Kutta method, and the model had been verified by the experimental result[3-7]. Asami and following researchers, studied the problem further, and found that the performance of air spring (including frequency characteristics) depending on the capsule form, volume of auxiliary chamber, and the orifice diameter[4, 8-10]。On these basis, Wang using the Laplace transform, established a linearization model of dynamic stiffness[11, 12]。

However, these theoretical models are simplified in some indispensable aspects, namely the linearization process of differential equations, and ignoring the air cavity volume change of capsule (which causes the pressure change in capsule cavity). Moreover, the aforementioned theoretical model are incapable of describe the contact properties, which is related to the deformation of capsule. All these contribute to the deviation of the result.

In FEM section, the methods of simulation of air spring without auxiliary chamber are relatively mature, but the whole air spring FEM model with auxiliary chamber is still in development. This article has a quite meaningful exploration.

2. Air spring simulation steps

2.1. Selection of constitutive model of rubber and cord

2.1.1. Selection of rubber hyper-elastic model

Due to the large deformation, it’s usually difficult to describe mechanical behavior of rubber, hence there is need to introduce concepts of strain energy density, three strain invariants and statistical laws of thermodynamics to form the constitutive relations.

The rubber behavior is also highly depend on experiment types, including uniaxial tensile, planar tensile and biaxial tensile. The experimental machine of the last two types is fairly hard to get. In this case of lack of experimental data, wrong choice of constitutive models would cause great error. Consequently the selecting principle is proposed:

On condition of limited testing data:

(1) Small strain conditions: Neo-Hooke Model;

(2) Detailed data on a single type of test: reduced polynomial model (for example, Yeoh Model);

(3) With initial shear modulus And stretch limit data such as: Arruda-Boyce Models and Van der Waals Model (with);

(4) Avoid using Ogden Model and the complete polynomial models in a limited test data.

On condition of full set of test data (uniaxial tensile loading, planar tensile, biaxial tensile) :

(1) Van der Waals Model (with);

(2) Ogden Model;

(3) Complete polynomial models can be used, but not as much as Ogden Model.

2.1.2. Rubber-cord composite material description

Cord layer is made of nylon 66 or polyester. The first description is to use reinforcement model, and dealing the two materials separately. As a second description, theory of fiber-reinforced composite material also can be used to derive the constant of combined material, in which rubber and cord are treated as a whole anisotropic part.

In most FEM studies, cord material is defined as rebar element, and considered to be linear elastic. Young’s modulus and Poisson ratio are only two parameters to describe the material’s behavior, which are available through a uniaxial test. If the nonlinear properties need to be taken into account, more complex experiments are needed like creeping test to get viscoelastic characteristics and others.

However, by composite material theory, the rubber-cord structure can be seen as a linear elastic, transversely isotropic composite plate or shell. Four mutually independent constants can determine the material behavior, include elastic modulus in longitudinal (main) direction (E_1), elastic modulus in transverse direction (E_2), in-plane shear modulus (G_{12}) and Poisson’s ratio (μ_{12}). These parameters can be directly obtained by material test or by formulas in composite material theory (such as Hermans formula, Halpin-Tsai formula).

2.2. Processing of CAD Drawings

Handling of DWG format drawings is greatly affect the efficiency of modelling. If not imported property in a compatible format, you will need to spend much time on the geometry cleanup and repair. Through practice, the following processes are figured out to be most stable and least exhausting:

(1) In AutoCAD, convert DWG format into DXF;

(2) In Solidworks, convert DXF format into STP. Note that in configure options, select the output as a two-dimensional sketches instead of solid part;

(3) In Abaqus, after import the STP sketches, the format is automatically transformed into default SAT format.

2.3. Critical Analysis steps in FEM

To get reliable FEM results, simulation must be carefully refined at each step, especially at several critical steps.

2.3.1. Creating materials and rebar section

The simulation model involves three types of material: hyper-elastic rubber, linear elastic steel cord and nylon cord.

Use Shore A hardness of Rubber to get its parameters of wide-used Mooney-Rivilin model. The rebar constants, including cord bar area, bar spacing, and bar angle can be got from cord type.

When directly setting up surface section of cord in Abaqus, it's necessary to assure the element normal directions are uniform to make the angles of the cord have a proper and unite reference direction.

2.3.2. Creating constraints

Rigid body constraint. The stress and strain state of auxiliary chamber wall is of no importance. As a result, they are treated as a rigid part.

Embedded constraints. All steel and nylon cord is embedded in the rubber host region and restrain the capsule shape.

Tie constraint. In some contact area, the contact of capsule and top plate and bottom plate maintains to be totally overlapped. So tie the two overlapped surface to avoid contact calculation is better for the convergence of solution.

2.3.3. Create interactions

The interaction of FEM model consists of three types.

General contact defines the normal and tangential behavior of two contact surface. The pressure-over closure of normal behavior is "hard" contact and can separate after contact. In tangential behavior, the type of friction formulation is penalty and the friction coefficient is 0.3~0.5.

Fluid cavity. Two closed air cavity of capsule and auxiliary chamber need to define the ambient air pressure, cavity pressure, and molecular weight of the air. In simulation of this paper, the fluid properties are both set to be air in the fluid cavity, whose molecular weight is 28.9 g/mol.

Fluid exchange between the capsule cavity and auxiliary chamber cavity is chosen to be bulk viscosity. Through the comparison between the experimental results and simulation results, viscosity can be specified its value on actual working condition.

Contact properties affect the convergence. If the defined friction between the capsule and plate is too large, the shear deformation of rubber element would be excessive, which lead to difficulty in convergence because of element distortion. However if the friction is too small, due to insufficient constraints, tangential sliding and elongating of capsule edge would occur. Additionally, the quantity of mesh should be moderate. Too few elements can't get accurate results, while too many induce contact problems like opening, slipping, sticking and over closure, which makes it hard to convergent too.

Fluid exchange properties determine the performance of air spring, which will be detailed discussed in section 3 and section 4.

2.3.4. Create load steps

Mounting step is to move the top plate from its initial location to working location.

Inflating step is to increase the pressure in capsule cavity and auxiliary chamber to working pressure, which differs from 0.2 MPa to 0.7 MPa.

When we calculating vertical stiffness of air spring, the top plate is fixed, the displacement of bottom plate must loop from positive value to negative value. Because the position of capsule influences its shape and contact with plate, consequently change the stiffness, several steps of complete displacement cycle can remove system error.

2.3.5. Create output

When selecting output variables, rebar output and cavity output need to be paid close attention to.

Rebar output involves three particular variables, including RBANG (Angle in degrees between rebar and isoperimetric direction), RBROT (change of rebar angle), and RBFOR (force in rebar).

To get changing features of cavity, the PCAV (pressure in cavity) and CVOL (volume of cavity) need to be selected in history variables.

Besides, to calculate stiffness, it's also necessary to output the reaction force of the nodes along the fixed boundary edge in top plate, and the displacement of the nodes along the moving boundary in bottom plate. Then using a python program to do the post-processing work, because the stiffness calculations are under a variety of working situations, which can be very tedious to analyze the result one by one.

2.3.6. Create mesh

To ensure high quality of rubber mesh, the capsule must be divided into different part, especially the area near the top bead and bottom bead.

In particular, after selecting a closed air cavity surface, the fluid cavity element (FAX2) is generated automatically. The cavity surface of capsule includes capsule inner surface, inner surface of top plate and bottom plate. The cavity of auxiliary chamber includes the inner surface of its wall, which is assigned as discrete rigid body property (analytic surface can't be chosen as part of cavity surface because it has no element to transform into fluid cavity elements, which have shared the nodes with its adjacent solid elements of rubber and plate).

3. Simulation results of screw-fastening air spring capsule

3.1. Simulation model

Apply the procedures of air spring simulation in section

2 to the screw-fastening air spring (containing an auxiliary chamber of 40 L) in current section.

The FEM assembly model of this air spring is as follows.

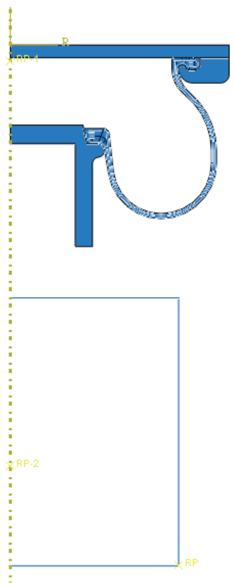

Figure 1 Assembly of screw-fastening air spring capsule system

Attention should be paid to the distribution of the mesh near the contact area. The final mesh is as presented below.

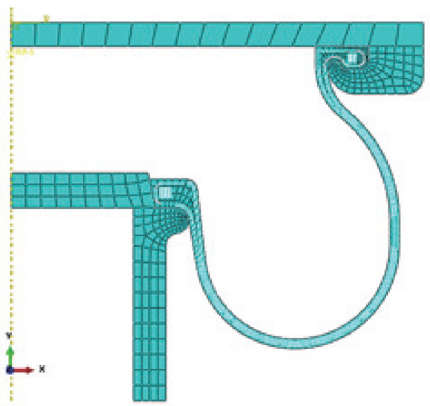

Figure 2 Mesh of screw-fastening air spring capsule system

3.2. Simulation results and comparison with experimental data

3.2.1. Load-pressure relation

When there is no auxiliary chamber in air spring, the load-pressure relation has been calculated by two different solvers in Abaqus, standard implicit and dynamic explicit. The result can be seen in figure3.

Figure 3 shows that the vertical load and pressure have a linear relation, regardless of the solver type. And the results have good consistence with experimental data.

The table1 below contains linear fit parameters of vertical load and capsule cavity pressure.

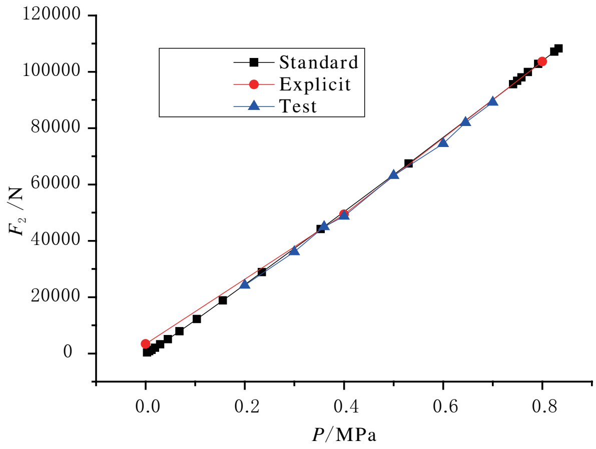

Figure 3 Load-pressure relation of different solver

Table 1 Linear fit of vertical load and capsule cavity pressure of different solver (No auxiliary chamber)

No auxiliary chamber	Intercept/N	Slope /(N/MPa)
Standard	-832.28504	130363.1503
Explicit	3381.3	129580
Test	-2411.9157	130147.1864

When the auxiliary chamber is taken into account and viscosity is set as a variable, the vertical load-pressure relation under different viscosity can be calculated as figure 4 demonstrates.

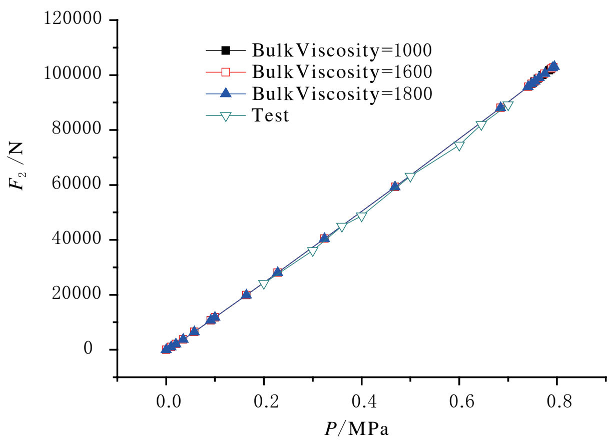

Figure 4 Load-pressure relation of different viscosity

The results are assemble to figure 3, and the linear fit parameters are shown below.

Table 2 Linear fit of vertical load and capsule cavity pressure of different viscosity (with auxiliary chamber)

Bulk Viscosity	Intercept/N	Slope/(N/MPa)
1000	-1013.53289	130589.4629
1600	-1016.57257	130608.4035
1800	-1017.43336	130613.6967
Test	-2411.9157	130147.1864

Conclusions can be drawn from former discussion that the vertical load-pressure relation is determined by the shape of the capsule and the plate. The slope of the line is the effective area of the capsule.

3.2.2. Simulation results of vertical stiffness

The following part is calculated by Abaqus standard.

When there is no auxiliary cavity, vertical load is 96kN and the vertical displacement amplitude is 20 mm, the experimental stiffness is 337 N/mm, while the stiffness obtained by simulation is 637 N/mm. The error is almost 100%. The volume of this screw-fastening air spring capsule cavity is around 25 L and the volume of auxiliary chamber is 40 L. The existence of auxiliary chamber can greatly reduce the vertical stiffness, which is the reason why the stiffness result of capsule without auxiliary chamber is larger than the actual value.

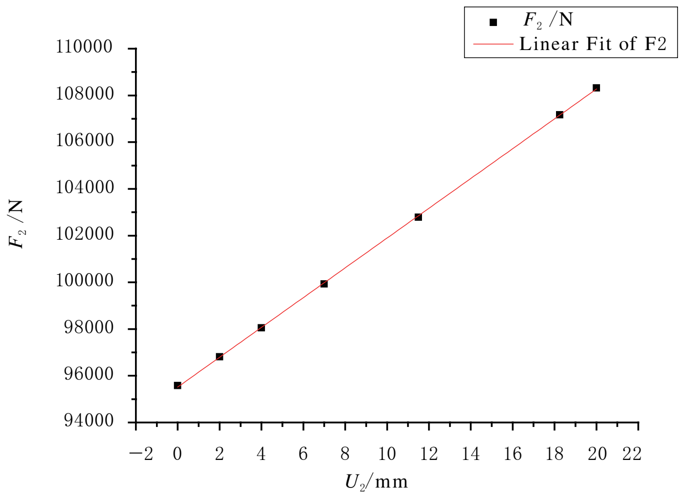

Figure 5 Vertical load-displacement relation of capsule without auxiliary chamber (96 kN)

Fluid exchange property influences the stiffness of capsule to a large degree. The following figure shows the vertical load-displacement relation of different viscosity.

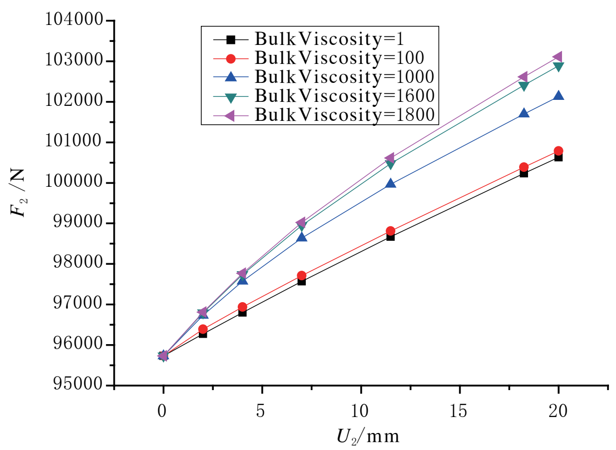

Figure 6 Vertical load-displacement relation of capsule with auxiliary chamber of different bulk viscosity (96 kN)

As is described before, do a linear fit of the data in figure 5 and get the parameters in table 3 below.

Table 3 Linear fit of vertical load and displacement of different viscosity (with auxiliary chamber, 96kN)

Bulk Vis-cosity	Intercept/N	Slope/(N/MPa)	Experimental data
1	95802.7507	243.75211	337
100	95882.1179	248.39162	
1000	96154.1603	309.14227	
1600	96166.2656	347.82375	
1800	96161.6807	359.28502	

The result of table 3 shows that the larger the viscosity is, the higher the vertical stiffness is. The intercept in tables stands for the vertical load when vertical displacement is zero. The slope, which is the vertical stiffness, changes from 243 N/mm to 359 N/mm. The linear fit of vertical stiffness and viscosity is as figure7 shows.

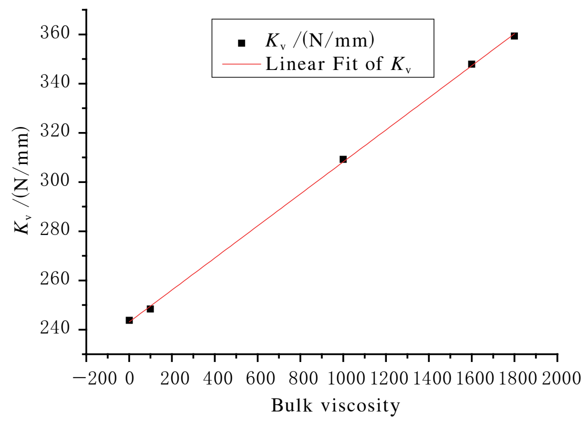

Figure 7 Linear fit of vertical stiffness and viscosity (96 kN)

When the displacement load is cycling, the damping dissipation energy can easily been seen, as figure 8 presents.

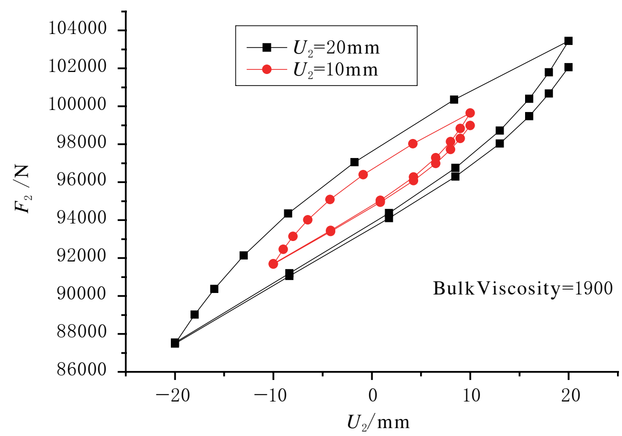

Figure 8 Vertical load-displacement relation of capsule with auxiliary chamber of different displacement amplitude (96 kN)

Similarly, as table 3 and figure 7 shows, when the vertical load is 82 kN and 45 kN, the linear relation between vertical stiffness and viscosity can also be calculated. However, to get a stiffness on average, the displacement must be loaded in cycling as figure 8 shows, instead of getting stiffness from figure 6.

The viscosity caused by fluid exchange is influenced by the pressure in the cavity. This correlation can be imported in Abaqus to describe the property of the fluid exchange. Based on relation between vertical load and capsule cavity pressure, the capsule cavity pressure of 96 kN, 82 kN and 45 kN can be obtained. As a result, the corresponding values are 0.741 MPa, 0.638 MPa and 0.352 MPa. Using the linear relation between vertical stiffness and viscosity (figure 7), the viscosity at experimental condition can be calculated to be 2500, 2100 and 1900, as the experimental stiffness (96 kN, 82 kN, and 45 kN) had been tested as 337 kN/mm (table 3), 308N/mm and 200 N/mm. In this method, the viscosity property can be described by importing the three set of viscosity and cavity pressure.

The following figure is the vertical stiffness calculated by viscosity, which has been optimized by the method mentioned above.

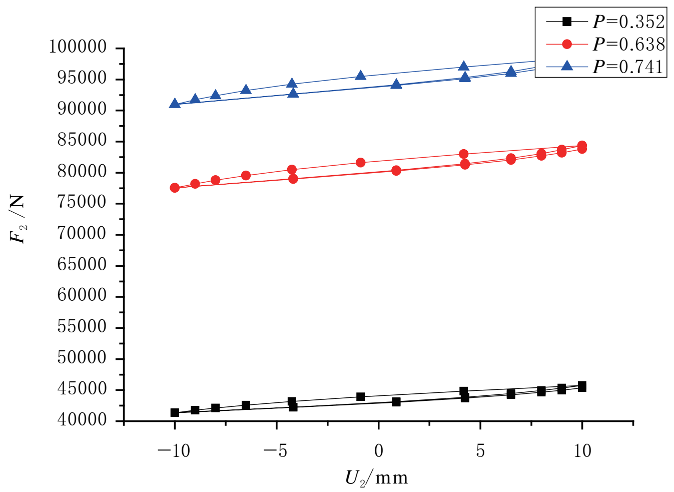

Figure 9 Vertical load-displacement relation of capsule with auxiliary chamber of optimized viscosity

The vertical stiffness of figure9 is very close to the experimental value, as table4 shows, which indicates that the optimized viscosity can properly describe the fluid exchange property.

Table 4 Vertical stiffness of capsule calculated by optimized viscosity

F_2/kN	Slope/(N/MPa)	Test/(N/MPa)	Error
45	191	206	8%
82	295	312	5%
96k	327	346	5%

3.2.3. Simulation result of lateral stiffness

With 20 mm lateral displacement, the lateral load-displacement relation is shown in figure 10.

After linear fitting, the lateral stiffness is obtained in table 5.

Table 5 Lateral stiffness of capsule calculated by optimized viscosity (U_1=20 mm)

$F_2(U_1=\pm 20)$/kN	Slope/(N/MPa)	Test/(N/MPa)	Error
45	90	128	30%
82	106	154	31%
96	110	171	35%

It can be concluded that when lateral displacement amplitude is small, the calculation error is relatively as high as 30%. The reason might lays on the modeling of rebar and some other factors.

When lateral displacement is 80 mm, to get a convergent result becomes ever more difficult. On this condition, figure 11 illustrates the lateral load-displacement relation.

Figure 11 Lateral load-displacement relation of capsule (U_1=80 mm)

Figure 11 only has results of F_2=45 kN and 82 kN. The solution of F_2=96 kN however didn't manage to get a convergent result. Lateral stiffness got by linear fit is as follows.

Table 6 Lateral stiffness of capsule calculated by optimized viscosity (U_1=80 mm)

$F_2(U_1=\pm 80)$/kN	Slope/(N/MPa)	Test/(N/MPa)	Error
45	107	103	4%
82	131	135	3%
96	/	145	/

On the contrary to the error in table 5, the error of lateral stiffness of large lateral in table 6 displacement is very small. But there is almost no viscous dissipation in lateral deformation, which means that the viscosity has little influence on lateral stiffness.The lateral stiffness is affected by many reasons which requires further study.

4. Simulation results of self-sealing air spring (with auxiliary spring)

4.1. Simulation model

The air spring simulated in this section is self-sealing type, which contains capsule, auxiliary chamber and auxiliary spring. It's also more complicated than the air spring in section 3.

The following figure is the assembly model and mesh.

The model construction is similar to the detailed procedures described in section2. The point which needs especially precision is the mesh distribution of the auxiliary spring.

4.2. Simulation results and comparison with experimental data

4.2.1. The volume, pressure and viscous dissipation of two cavity

In mounting step, which lasts 1 second, the top plate moves 143 mm downwards to make the air spring stay at working location.

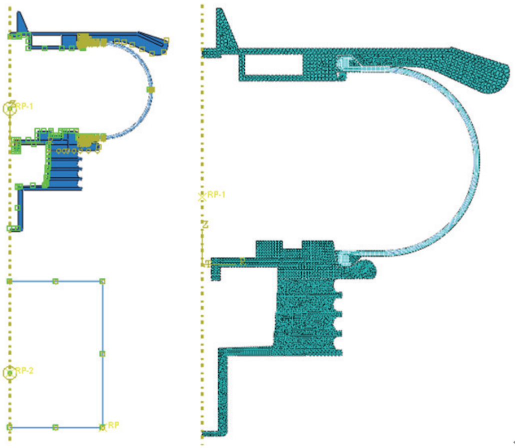

Figure 12 Assembly model and mesh of self-sealing air spring system

In inflation step, which also lasts 1 second, the top plate and bottom plate is fixed, and the pressure in capsule cavity and auxiliary chamber increases at a same pace.

The cycling vertical displacement load begins after two seconds, which last 8 seconds and change directions every 2 second. The figures show the results of 10mm and 30mm vertical displacement amplitude. Both displacement have 5 pressure levels (0.1, 0.2, 0.3, 0.4 and 0.5 MPa).

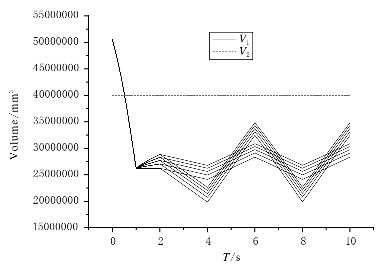

Figure 13 Volume changes of capsule cavity and auxiliary chamber

Figure 13 shows that the volume of auxiliary chamber never changes during the steps, while the volume of capsule cavity changes according to the position and shape of capsule.

In mounting step, due to the downward movement of top plate, the capsule volume decreases. In inflation step, the pressure increasing in capsule cavity results in the inflation of capsule, so the volume of capsule becomes larger than before. In step of vertical cycling displacement, the capsule' s volume changes correspondingly.

Based on thermodynamics, in a closed air cavity at a constant temperature, the cavity pressure and volume have an inversely proportional relationship. Figure 14 describes the pressure-time relation of capsule cavity and auxiliary chamber.

Pressure changes reflect the setting of boundary condition and displacement load of each step. In mounting step, the 8th freedom (which in Abaqus stands for cavity pressure) increases from 0 to 0.1 MPa (atmosphere pressure). At the inflating step, pressures of two cavities increase from 0.1 to the same value. In following steps, under different inflation pressure, the pressure changing amplitudes are different too, but they all vary around the inflation pressure. Besides, it can be seen that the changing amplitudes of auxiliary chamber' s pressure are all smaller than the capsule' s. That' s because the volume of auxiliary chamber is always 40 L, much larger than capsule cavity' s volume, which is around 27 L. Thus the auxiliary chamber is more capable of resisting the pressure change.

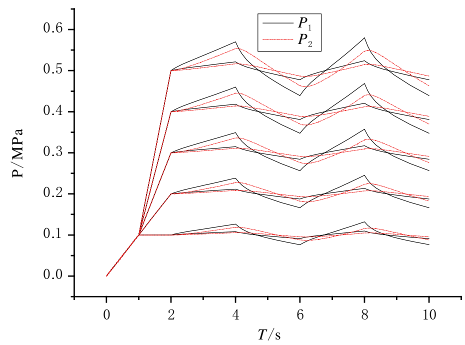

Figure 14 Pressure changes of capsule cavity and auxiliary chamber

The follow figure is the ratio of viscous dissipation energy and strain energy of whole model.

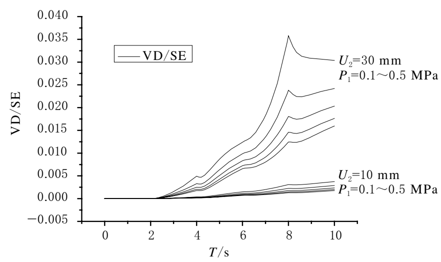

Figure 15 The ratio of viscous dissipation energy and strain energy

Several conclusions can be drawn from figure15. The larger the capsule pressure and displacement are, the higher the ratio is. In mounting step and inflation step, because the increasing pace of pressure in two cavities is same as each other, there is no fluid exchange during these process. And when displacement is around 10 mm, the ratio remains a very low level. By contrast, the ratio increases greatly when displacement becomes 30mm. This can be explained by the fact that when the vertical displacement is large, the capsule cavity volume changes also significantly, which causes the pressure difference between two cavities and viscosity of fluid exchange becomes more severe.

4.2.2. Simulation results of vertical stiffness and experimental data comparison

Similar to the method described in section 3.2.3, firstly calculate the vertical stiffness-viscosity relation under different inflation pressure and a vertical displacement of 30mm, as figure16 shows.

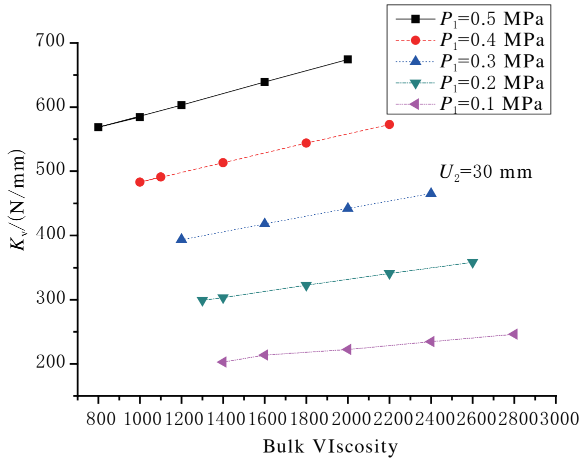

Figure 16 Vertical stiffness-viscosity relation of self-sealing air spring under different inflation pressure

Result in table 6 can gain by making linear fits of figure16. And the experimental results also are shown in table6:

Table 6 Linear fit of vertical stiffness-viscosity relation of self-sealing air spring

P_1/MPa	U_2=30 mm		Test
	Intercept/(N/mm)	Slope	
0.5	496.91409	0.08865	580
0.4	408.60623	0.07487	478
0.3	321.89083	0.05994	378
0.2	239.42942	0.04585	286
0.1	163.35134	0.0297	/

According to test data and the linear relation between vertical stiffness, the viscosity data on test condition can be easily figured out by (Test-Intercept)/Slope.

Through this method, the viscosity property is determined and the rest of the air spring’ s performances can be calculated, as section3 has done before, so this repeating part is omitted in this paper.

5. Conclusions

Simulation results above shows that dynamic characteristics of air spring are closely related to the viscosity of fluid exchange property between capsule cavity and auxiliary chamber cavity. Therefore viscous data is particularly important in simulation.

However, viscous data directly by experiment is difficult to quantify. And theory prediction by calculation the viscous dissipation of orifice are not compatible with the actual working situation, that is, the viscous dissipation caused by air flowing through the pipe walls is omitted.

Based on the factors mentioned above, the paper sets up an air spring simulation system. Firstly based on several experimental data of vertical stiffness, the viscous characteristics of fluid exchange in air spring system can be obtained. Then at such level of viscous dissipation, the detailed performance of air spring, including lateral stiffness, torsional stiffness, strain, stress and so on can be calculated.

5.1. Error of simulation result

Load-pressure relation is in good accordance with experimental data.

Vertical stiffness under the certain viscosity has error around 5% or less.

Lateral stiffness has error from 5%~30%.

5.2. Influence of viscosity

Performance of air spring and fluid exchange property between two cavities are directly related.

Vertical load-pressure relation is basically independent of viscosity. Because in inflating process, the internal pressure of capsule cavity and auxiliary chamber cavity is increasing at a same pace, there is no fluid exchange, so that viscosity has little effect. But if pressure of auxiliary chamber is kept a certain value, while the pressure of capsule cavity is rising, a pressure difference between two cavities would occur, as a result the fluid exchange takes into effect.

Vertical stiffness and viscosity vary linearly. The air volume of capsule cavity changes a lot in the vertical deformation process, causing the pressure in capsule cavity higher than auxiliary chamber cavity. Consequently, the fluid exchange occurs.

Lateral stiffness also basically has no relation with viscosity. That’ s because the lateral deformation of capsule doesn’ t change its volume in general, so that the pressure difference between two cavities is very small and fluid exchange is insignificant.

5.3. Other relative factors

Stiffness and capsule cavity pressure have a nearly linear relation, and the slope of curve is the effective area of capsule.

Stiffness is affected by displacement amplitude. Because the displacement changes the position and shape of the capsule, eventually affects the effective area.

Loading velocity and frequency changes the stiffness in a large scale. When the loading velocity is not fast, the deformation process can be seen as a static state. When the frequency is increasing, the fluid exchange can’ t compensate the pressure change in capsule synchronously. The fluid exchange even can be omitted when the loading frequency reach a certain value, at this time the auxiliary chamber can’ t have influence on the capsule. Generally, the higher the loading frequency is, the larger the change of capsule pressure is. As a result, vertical load becomes large and the vertical stiffness increases.

References

[1] ZHAO CHANG-LONG C M-R. Research on models of air spring in reelway vehiecle [J]. Railway vehicle, 2012, 50(9): 2.

[2] FACCHINETTI A, MAZZOLA L, ALFI S, et al. Mathematical modelling of the secondary airspring suspension in railway vehicles and its effect on safety and ride comfort [J]. Vehicle Syst Dyn, 2010, 48(429-49.

[3] YUAN LIANG-MING G X-T. Research on vertical dynamic properties of air spring in railway vehiecle [J]. China railway science, 2004, 25(4): 37.

[4] LI FU F M-H. Parameter study of air spring dynamics [J]. Journal of Southwest Jiaotong University, 2003, 38(3).

[5] LEE J-H, KIM K-J. Modeling of nonlinear complex stiffness of dual-chamber pneumatic spring for precision vibration isolations [J]. Journal of Sound and Vibration, 2007, 301(3–5): 909-26.

[6] DOCQUIER N, FISETTE P, JEANMART H. Multiphysic modelling of railway vehicles equipped with pneumatic suspensions [J]. Vehicle Syst Dyn, 2007, 45(6): 505-24.

[7] LI FU F M-H. Kinetic parameter study of vehicle air spring [J]. China railway science 2003, 24(5): 91.

[8] ASAMI T, YOKOTA Y, OKURA M, et al. Validation of the Accuracy of Approximation in a Design Formula for an Air Spring by Using Numerical Analysis; proceedings of the ASME 2013 Pressure Vessels and Piping Conference, F, 2013 [C]. American Society of Mechanical Engineers.

[9] SAYYAADI H, SHOKOUHI N. Effects of air reseroir volume and connectiong pipes' length and diameter on the air spring behavior in rail-vehicles [J]. Iranian Journal of Science and Technology Transaction B-Engineering, 2010, 34(B5): 499-508.

[10] ALONSO A, GIM NEZ J G, NIETO J, et al. Air suspension characterisation and effectiveness of a variable area orifice [J]. Vehicle Syst Dyn, 2010, 48(sup1): 271-86.

[11] WANG JIA-SHENG Z S-H. Research on linearization model of dynamis stiffness of air spring with auxiliary chamber [J]. Journal of vibration and shock, 2009, 28(2): 72.

[12] PU H, LUO X, CHEN X. Modeling and analysis of dual-chamber pneumatic spring with adjustable damping for precision vibration isolation [J]. Journal of Sound and Vibration, 2011, 330(15): 3578-90.