Proceedings of IDETC/CIE 2005
ASME 2005 International Design Engineering Technical Conferences
& Computers and Information in Engineering Conference
September 24-28, 2005, Long Beach, California USA

DETC2005-84370

STUDY ON THE SENSITIVITY OF CONTROLLABLE PARAMETERS IN AN ACTIVE VIBRATION ISOLATION SYSTEM OF AIR SPRING WITH RUBBER BELLOW

Shuai Chang-geng
Inst. of Vibration & Noise,
Naval Uni. of Engineering,
Wu Han, PRC 430033
chgshuai@163.com

He Lin
Inst. of Vibration & Noise,
Naval Uni. of Engineering,
Wu Han, PRC 430033

Lv Zhi-qiang
Inst. of Vibration & Noise,
Naval Uni. of Engineering,
Wu Han, PRC 430033

ABSTRACT

The characteristics of control parameters of air spring with rubber bellow are analyzed through finite element method and thermodynamic equation respectively. The analysis results indicate that the vertical stiffness of air spring is sensitive to the varying of vertical displacement and volume, and nonlinearly varies with vertical displacement. When the air spring is pressed down or pulled up under the exterior excitation, the height of air spring can be controlled to keep stable through adjusting the volume of air spring by the use of hydraulic transformer.

INTRODUCTION

The air spring with characteristics of adjustable nonlinear static or dynamic stiffness and damping can isolate the vibration and shock through the nonlinear resilience and damping force produced by compressing air. Its natural frequency does not change significantly with changes in load. This unique feature of air spring, combined with accurate height control, will allow the use of the same air spring at each mounting point of an unevenly loaded machine[1]. Furthermore, the air spring cannot only reduce structurally transmitted noise and protect structural members from vibrating machinery, but also are quiet in themselves since there is no spring chatter as found in conventional coil springs. Besides, air spring, which is easy to actively control, can be widely used in the field of vibration isolation designing[2].

The control system for air spring commonly includes the air supply system, height control system, and safety device[1,3]. Before designing the control system, it is essential to determine its control parameter, for example, the stiffness or damping of air spring[4-7]. Through changing the parameter, the vibration isolation performance of air spring can be optimized[1,3]. In this paper, a formula of the vertical stiffness of air spring is derived from the state equation of actual gas. The sensitivity of the vertical stiffness of air spring with rubber bellow for the varying of pressure, volume and displacement is analyzed and discussed through finite element and thermodynamic method respectively.

NOMENCLATURE

K vertical stiffness of air spring, N/m
F loads applied on the air spring in the vertical direction, N
x vertical displacement, m
A effective load area, m^2
p pressure in the air spring, atm
p_a normal atmosphere, atm
V inner volume of the air spring, L
n mole number of air in air spring, mol
T temperature, K
R gas constant, 0.082atm • dm^3 • mol^{-1} • K^{-1}

a constant, 1.4 atm • dm^6/mol^2

b constant, 0.037 dm^3/mol

C constant

A_0 effective load area at equilibrium position, m^2

PRINCIPLE OF ACTIVE VIBRATION ISOLATION SYSTEM OF AIR SPRING

The principle of the active vibration isolation system of air spring is shown in figure 1. A machine is put on the table that is supported by the air spring. This air spring is set on the foundation. Owing to the natural vibration isolation characteristics of air spring, the vibration of table produced by the machine will be isolated even without active control system. The control system comprises cylinder-piston mechanism which works to diminish the movement of the table and attenuate the transmission of vibration from the table to the foundation. Its operation is as follows.

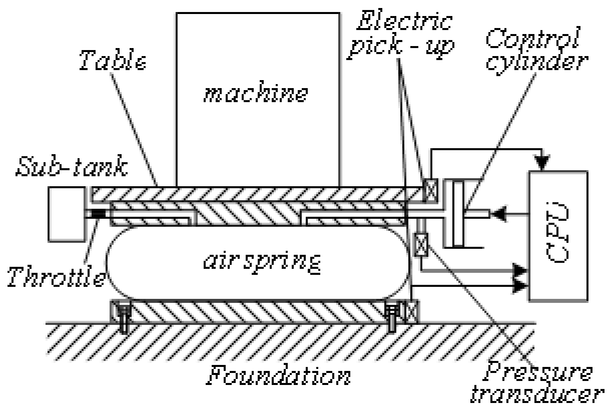

Figure 1: the rig of active vibration isolation system of air spring

At the instant of upward movement of the table induced by the machine, the air in the air spring is forced to flow out by the rightward movement of the piston in the control cylinder. In the same manner, at the instant of downward movement of the table, the air is forced to flow in by the leftward movement of the piston.

The pressure in air spring and the movements of the table and foundation can be detected by electric pick-ups and be transferred to the CPU. After analyzed, processed and optimized, the control signal is sent out and operates the piston.

The sub-tank connected to the air spring, shown in figure 1, enlarges the equivalent volume of the air spring and functions favorably for the isolation effect. In the pipe which connects the sub-tank and the air spring, a throttle is set, which restricts the airflow between air spring and sub-tank. The flow resistance at the throttle has the effect of energy dissipation and consequently damps the action of the air spring. Thus the air spring vibration isolation system can be damped appropriately by adjusting the opening of the throttle.

NUMERICAL ANALYSIS FOR CHARACTERISTICS OF CONTROL PARAMETERS OF AIR SPRING

Finite element analysis

The air spring shown in figure 1 consists of a rubber bellow, which is axial symmetric in vertical direction. The finite element analysis model can be an axisymmetric plane of the air spring, as shown in figure 2, through which the vertical stiffness characteristic of the air spring can be given. The rubber bellow is made from composite materials reinforced by fibers cords which are anisotropy. The Marc, a kind of nonlinear finite element analysis software, provides an element of Rebar which can be applied to model the material characteristics of the bellow.

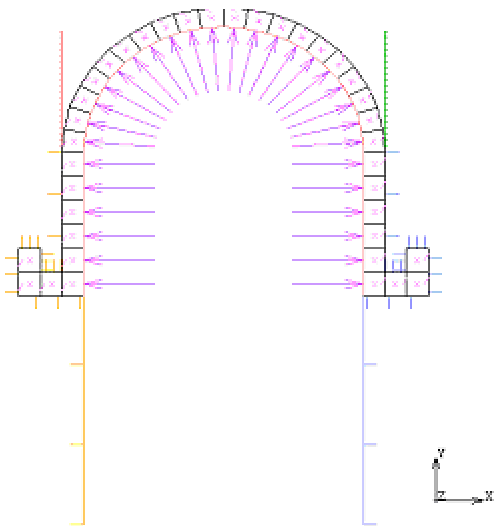

Figure 2: the finite element analysis model of the air spring

In the finite element model of the air spring, the nonlinear contact between the plate and the rubber bellow should be considered when the air spring is pressed or pulled. The plate and the rubber bellow are defined as rigid body and flexible body respectively.

When the table moves in the vertical direction, the volume and the pressure in the air spring will vary, which should be appropriately modeled and simulated through finite element analysis. An element of Cavity in Marc software can be used to simulate the variety. Figure 3 shows the air charging process and the variety of the pressure and volume of the air spring during its movement in the vertical direction. On the equilibrium height of specified rated load, the pressure in air spring is 1.6 Mpa. When the table moves down, the volume in the air spring is compressed and the pressure increases. Similarly, the movement of table upward will increase its effective volume and reduce the inner pressure.

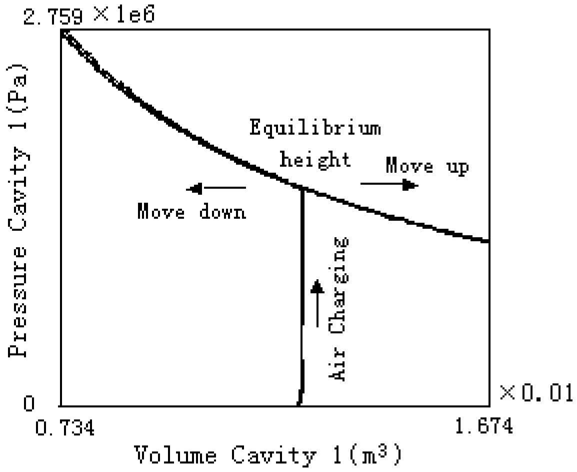

Figure 3: the varying of the pressure and volume of the air spring during movement in the vertical direction

The vertical static characteristic of the air spring shown in figure 1 is analyzed through the Marc software on the conditions of different working pressure. Its results indicate that the relation between the load and the displacement is nonlinear, as shown in figure 4. The horizontal coordinate in figure 4 denotes the vertical displacement of air spring. The longitudinal coordinates denote the loads. The curves 1, 2, 3, 4, 5, 6 show the vertical characteristic of air spring respectively in working pressure of 1Mpa, 1.2Mpa, 1.4Mpa, 1.6Mpa, 1.8Mpa, 2.0Mpa.

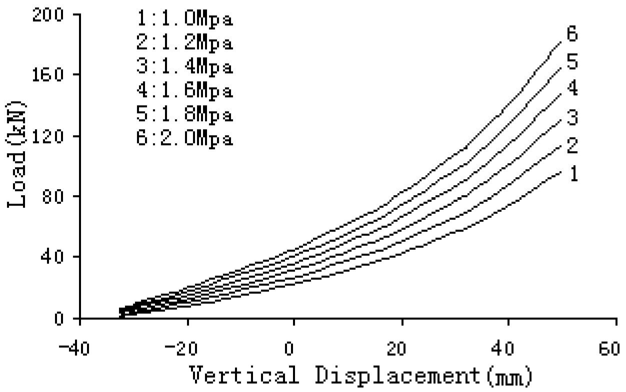

Figure 4: the curves of the vertical static characteristic of air spring with different working pressure

Thermodynamic analysis

At the equilibrium, the vertical stiffness of air spring can be expressed as:

$$K = \frac{dF}{dx} = A \cdot \frac{dp}{dx} + (p - p_a) \cdot \frac{dA}{dx} \qquad (1)$$

The effective size of the air spring shown in figure 1 is small, and its payload is large. Therefore, the working pressure in the air spring is high. The variety of pressure in the air spring should be described by the actual gas state equation. The equation can be shown as follows:

$$\left(p - p_a + n^2 a / V^2\right)(V - nb) = nRT \qquad (2)$$

According to equation (1) and (2), the vertical stiffness K of air spring can be given by

$$K = A^2\left(\frac{p - p_a}{V - nb} + \frac{n^2 a(2nb - V)}{V^3(V - nb)}\right) + (p - p_a)\frac{dA}{dx} \qquad (3)$$

in which, the effective load area A satisfies

$$A = -\frac{dV}{dx} \qquad (4)$$

It is assumed that the relation between the effective load area A and the vertical displacement x is linear, shown as follows

$$A = Cx + A_0 \qquad (5)$$

According to equation (2) and (5), the equation (3) can be expressed as

$$K = (Cx + A_0)^2\left(\frac{nRT}{(V - nb)^2} - \frac{n^2 a}{V^2(V - nb)} + \frac{n^2 a(2nb - V)}{V^3(V - nb)}\right) + (p - p_a)C \qquad (6)$$

Figure 5 shows three curves, which denote the varying of stiffness, pressure and volume respectively with vertical displacement. The value of y-axis in the stiffness curve multiplied by 10^6 is the stiffness of air spring on different vertical displacement, the unit of which is N/m. The unit of the value of y-axis in the pressure curve is Mpa. The value of y-axis in volume curves multiplied by 10 is the inner volume

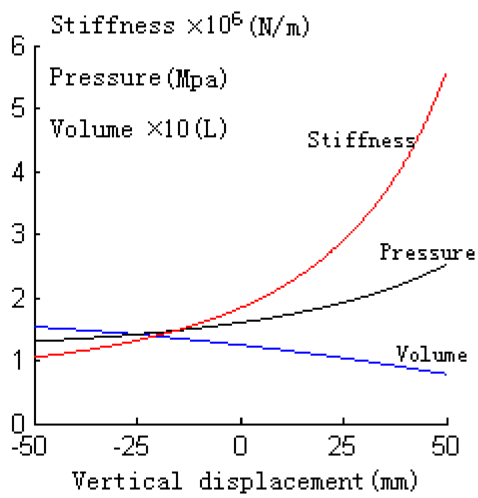

Figure 5: the curves of stiffness, pressure and volume of air spring with the vertical displacement.

of air spring on different displacement, the unit of which is L.

It can be seen from figure 5 that when the table moves down, its vertical stiffness and pressure increase and the inner volume is compressed, which is coincident with the results of finite element analysis.

DISCUSS

The volume of sub-tank in figure 1 has great effects on the vibration isolation system of air spring. The effectiveness improves as the volume rises and approaches saturation when the volume of sub-tank is about twice that of the air spring itself. The properly opening of the throttle can give the system the damping to a certain extent. When the opening is large, the flow resistance of air is small and consequently the damping of the system is also small. On the other hand, when the opening is small, the airflow through the throttle is small and the energy dissipation at the throttle also becomes small. Therefore, there is an optimum opening to give maximum damping.

There are two kinds of main control methods for the active vibration isolation system of air spring, one of which is that the mass of air in air spring can be changed through plenum chamber and pressure regulation system while the inner volume is constant. The other is that the inner volume can be adjusted and the mass of air in air spring is constant, which can be implemented through controlling hydraulic transformer, as shown in figure 1. According to equation (5), if the height of air spring is controlled to keep stable, the effective load area A is constant. The load F and the area A satisfy

$$F = (p - p_a)A \qquad (7)$$

Thanks to the action of exterior excitation, the load F changes. It is assumed that the rated load of air spring is 1.2×10^5 N, the inner pressure is 1.6 Mpa, and the volume is 12.5 L. When an exciting force of 10 kN is applied on air spring downward at an instant, the inner pressure will rise to 1.725 Mpa according to equation (6), and the volume is compressed to 11.5 L, as shown in figure 6. In this case, the height of air spring can be kept invariant.

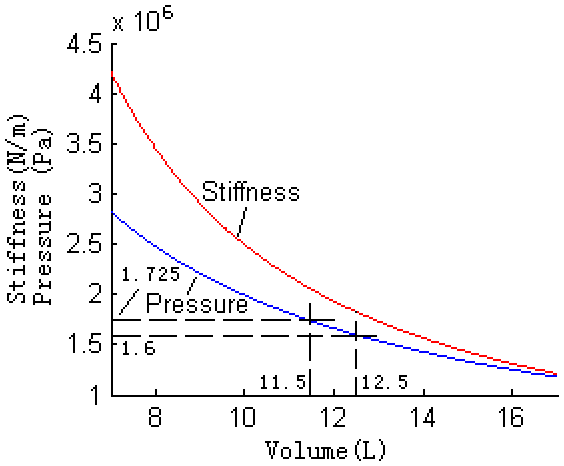

Figure 6: plots of stiffness and pressure with volume at the equilibrium position

CONCLUSIONS

The results of finite element analysis and thermodynamic analysis indicate that the vertical stiffness of the air spring is sensitive to the varying of vertical displacement and volume. When the air spring is pressed down, its volume is compressed and the inner pressure increases. Similarly, the movement of air spring upward will increase its effective volume and reduce the inner pressure. The vertical stiffness of air spring nonlinearly varies with its volume on the conditions of the same height. During the movement of the table up and down under the exterior excitation, the height between the table and foundation can be controlled to keep stable through adjusting the volume of air spring by the use of hydraulic transformer.

REFERENCE

1 Zhu De-ku, 1989, Air Spring and its Control System. Shan Dong Science and Technology Press.

2 J. L. Shearer, 1954, Continuous control of motion with compressed air, Ph.D thesis, MIT, Department of Mechanical Engineering.

3 T. Takagami, Y. Jimbo, Study of an active vibration isolation system, Precision Engineering, 1988, 10(1), 3-7.

4 Xu Qing-shan. The Developments and Trends of Vibration Isolation Technology. Journal of Mechanical Strength. 1996, 16(1), 37-42.

5 Zhuang Biao-zhong, Wang Jian-Hua, Xin Hong. The Descriptive Methods of Dynamic Characteristics in Nonlinear Vibration Isolation System. Journal of Vibration and Shock. 1986, (4), 33-36.

6 D. R. Otis, A. Pourmovahed. An algorithm for computing nonflow gas processes in gas springs and hydropneumatic accumulators. Journal of dynamic systems, measurement, and control, 1985, 107, 93-96.

7 G. J. Stein. Results of investigation of an electropneumatic active vibration control system for driver's seat. Journal of Automobile Engineering, Proc Instn Meah Engrs, 1995, 209, 227-234.