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Experimental Study on Dynamic Characteristics of Gas Spring Resonant System

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Abstract. Gas springs applied to compressors or Stirling generators is an effective way to improve the reliability of engines. It is important to clarify its dynamic characteristics while applying in the power machine. However, there is a lack of methods that can accurately describe the dynamic characteristics of gas springs. In this paper, rotation vector decomposition method and system resonance method to test the equivalent stiffness of a gas spring system are introduced and two methods are experimentally compared. The results show that rotation vector decomposition method is basically consistent with the resonance method, which maximum difference is no more than 10%. In addition, the effects of initial pressure and amplitude on the stiffness and damping characteristics of the gas spring system are analysed, it was found that initial pressure is proportional to the stiffness of the gas spring and damping component of the gas force, while piston amplitude has little effect. The study provides a reference for the structural design of gas springs.

1. Introduction

Deep space exploration is an important field in the study of the origin of the universe, dark matter, planetary evolution and other issues. The free piston Stirling generator (FPSG) has the advantages of long life, high efficiency and high reliability, which is one of the most suitable equipment in deep space power system[1]. The FPSG consists of a Stirling engine, which converts thermal energy into kinetic energy through Stirling cycle, and a linear alternator, which converts kinetic energy into electrical energy. Compared with the traditional Stirling generator with mechanical connecting rod, the power piston and displacer of the FPSG rely on thermal dynamics to achieve strong coupling, which greatly extends the service life.

At present, the displacer in the common generator configuration is supported by planar springs. With the increasing power requirements of deep space missions, it is very important to study high-power FPSG. In order to obtain high power, the sweeping area and moving mass of the piston must be increased. Due to the limitation of the material of the planar spring, the stiffness required to maintain the reciprocating motion of the piston is difficult to provide [2]. Therefore, a new alternative is urgently needed. The gas spring is suitable for the future development trend with the advantages of large axial stiffness, long life, high temperature resistance and small moving mass.

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A 12.5kW prototype (CTPC) was developed by MTI in the 1990s[3]. In 2023, the Technical Institute of Physics and Chemistry developed a 100-kilowatt prototype[4]. Both prototypes use gas springs to provide the stiffness to the movement of the displacer and the power piston. The linear and nonlinear analysis models of CTPC are established by Lewandowski [5] analogy circuit theory. The above study only analyses the thermodynamic and dynamic characteristics of the whole machine from the perspective of the whole machine, and the internal stiffness and damping characteristics of the gas spring chamber hasn't been reported. In this paper, the gas spring resonance system of 250W Stirling generator developed by the Technical Institute of Physics and Chemistry is studied, and the equivalent stiffness of the gas spring system is calculated by means of system resonance principle and rotation vector decomposition method. An experiment system was set up to analyse the effects of the initial pressure and piston amplitude on the stiffness of the gas spring and the proportion of the gas force.

2. Methods of gas spring stiffness

2.1 System resonance method

The work of the electromagnetic force on the piston is

$$W = \int F\,dx = \frac{1}{2} BL * |I| * |dx| * \cos\langle I, dx\rangle \tag{1}$$

If I and dx are in the same phase, which means the work efficiency of the electromagnetic force is the highest, where f is the resonant frequency of the system。The corresponding equivalent stiffness is

$$k = m \cdot (2\pi f)^2 \tag{2}$$

Subtract the corresponding mechanical spring stiffness to

$$k_g = k - k_m \tag{3}$$

As shown in Figure 1, when the excitation frequency increases from 50Hz to 110Hz, the phase difference of piston displacement and current shows an increasing trend under the condition of the same initial pressure and excitation voltage, and the trend is more obvious in the middle

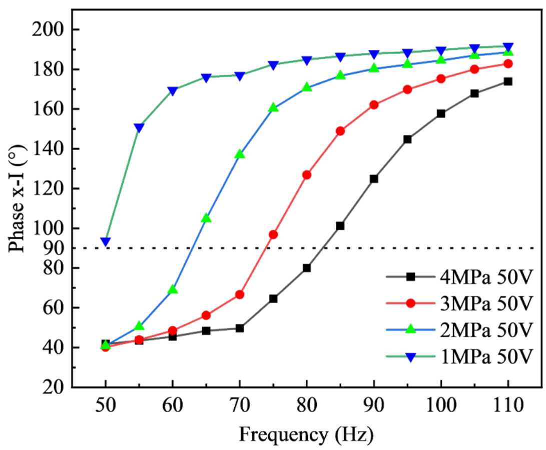

Figure 1. Phase x-I variation with the Frequency and Initial pressure

section. According to the resonance principle of the system, when the phase difference is 90°, the excitation frequency is about 81Hz at the pressure of 4MPa, which can be regarded as the resonance frequency of the system and the gas spring stiffness can be calculated.

2.2 Rotation vector decomposition method

As shown in Figure 2, The gas force can be divided into one component that in phase with displacement and one component in phase with velocity.

$$\Delta pA = F_{gas-x} + F_{gas-v} \tag{4}$$

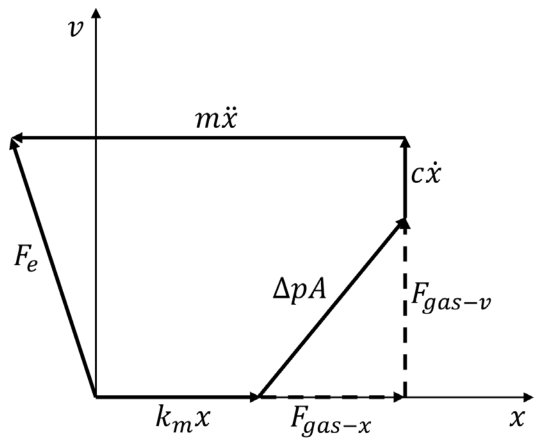

Figure 2. Piston force analysis diagram

Where F_{gas-x} is the component that in phase with displacement, F_{gas-v} is the component that in phase with velocity.

F_{gas-x} differs 90° from the direction of velocity， so

$$dW_{gas-x} = F_{gas-x} v_p cos\langle F_{gas-x}, v_p \rangle = 0 \tag{5}$$

F_{gas-x} has the characteristics of elastic components, which does not consume energy. Therefore F_{gas-x} can be defined as the elastic force with stiffness[6]， the dynamic stiffness expression is

$$k_g = \frac{dF_{gas-x}}{dx_p} = d(\Delta pAcos\langle p, x \rangle)/dx_p \tag{6}$$

2.3 Results of the two methods

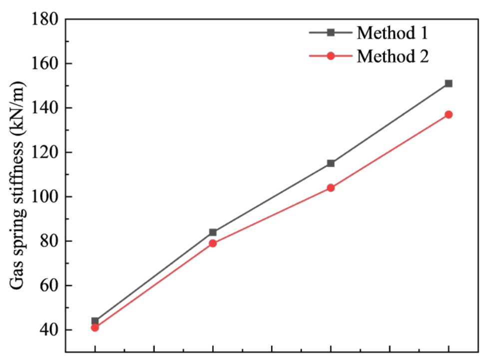

Figure 3. Comparison of gas spring stiffness obtained by two methods

The stiffness of the gas spring increases with the increase of initial pressure in Figure 3, which is in accordance with the physical law. The stiffness of the gas spring measured by the two methods is basically the same with the maximum difference no more than 10%. However, compared with the resonance method, the dynamic stiffness of the gas in the process of moving with the piston and the stiffness of the gas in the non-resonance frequency can be calculated by the rotation vector decomposition method, which makes the test simpler and more accurate.

3. The gas spring resonance system

As shown in Figure 4, The gas spring resonance system is mainly composed of power piston, linear motor and cylinder. The space of gas spring consists of the piston section and the cylinder space. The AC power source supplies power to the linear motor, drives the reciprocating movement of the piston, and changes the volume and pressure of the gas spring space. The pressure of the gas

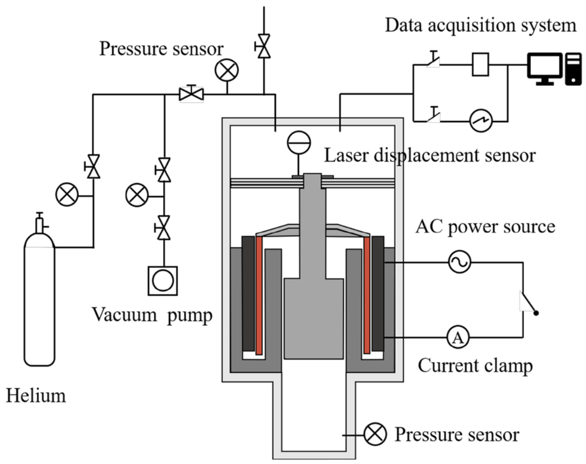

Figure 4. Experimental system of gas spring resonance system

spring space is recorded by the pressure sensor, the laser displacement sensor records the displacement of the piston, and the dynamic change of the current is recorded by the current clamp.

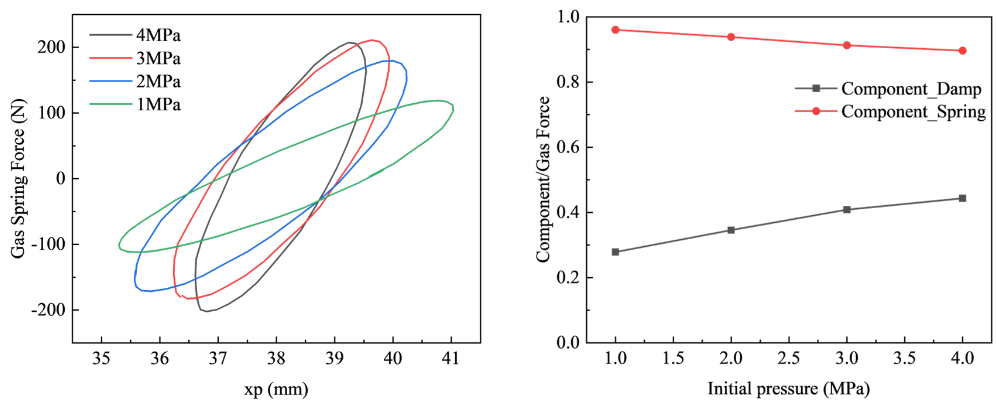

Figure 5. Variation with the initial pressure (a) Gas Spring Force (b) Gas force Proportion

4. The influence of initial pressure and piston stroke

4.1 The influence of initial pressure

As shown in Figure 5(a), the gas spring force changes with piston displacement under the initial pressure of 1MPa, 2MPa, 3MPa and 4MPa at the excitation frequency of 80Hz and the excitation voltage of 50V. At the same initial pressure, gas spring force presents a nonlinear change with the displacement of the piston, that is, there are different gas spring force at the same position, because the gas force generated by the piston movement pushing the gas is not fully converted into the gas spring force. It is partly used as the spring force to provide a restoring force to the piston movement, and partly as the damping force to convert mechanical energy into heat, which makes phase difference between piston velocity and gas pressure. The equivalent slope of gas spring force gradually increases, and the amplitude of piston gradually decreases as the initial pressure increases from 1MPa to 4MPa, because the pressure of the space increases and the stiffness of the gas spring increases.

As shown in Figure 5(b), The variation of spring component and damping component of gas force under different initial pressures are tested at excitation frequency of 80Hz and excitation voltage of 50V. The spring component of gas force is higher than damp component of gas force at the same initial pressure, because the closed space is empty volume, the main function of gas is as the spring force, so that the stiffness of the gas increases, the proportion of work consumption as the damping force is small. When the initial pressure increases from 1MPa to 4MPa, the spring component of gas force proportion decreases from 0.96 to 0.9, and the proportion of spring component increases from 0.28 to 0.44. Because the pressure increases and the gas spring stiffness increases, which can be seen from the viscous damping coefficient

$$c = 2\zeta\sqrt{mk} \tag{7}$$

Where ζ is the damping rate, which is related to the assembly of the piston and can be regarded as the constant; m is the moving mass of the system, which can be regarded as the constant, and k is the spring stiffness of the system. When the stiffness of the planar spring is fixed, the viscous damping coefficient increases due to the increasing of the stiffness of the gas spring, the proportion of spring component also increases. The proportion of damp component increases under the action of two factors.

4.2 The influence of piston amplitude

As shown in Figure 6(a), the gas spring force variation law with piston displacement under different piston amplitudes at excitation frequency of 80Hz and initial pressure of 4MPa are tested. The AC power source provides different excitation voltages that change the amplitude of the

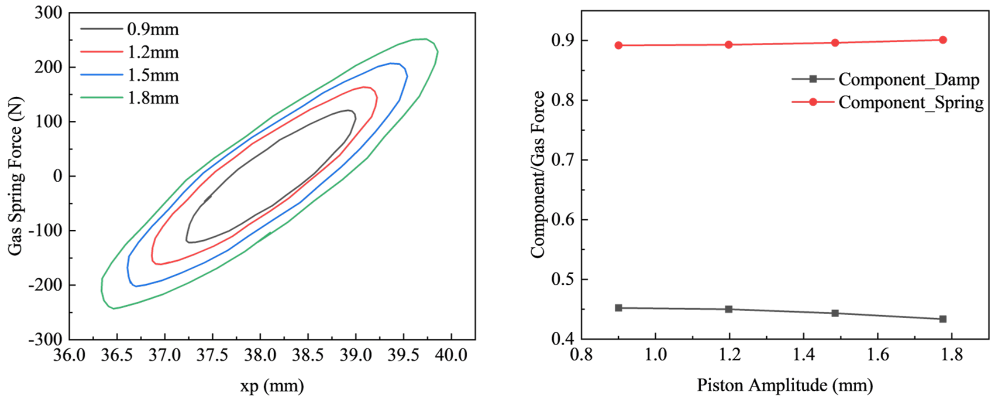

Figure 6. Variation with the piston amplitude (a) Gas Spring Force (b) Gas force Proportion

piston. The amplitude of Gas force spring increases when the stroke of the piston increases, but the shape of curve basically doesn't change. It can be seen that the law between gas spring stiffness and xp does not change with different piston amplitudes.

As shown in Figure 6(b), the variation of the spring component and damping component of the gas force under different piston amplitudes are tested when the excitation frequency is 80Hz and the initial pressure is 4MPa. When the amplitude of the piston increases from 0.9mm to 1.8mm, the proportion of spring component increases from 0.89 to 0.9, and the proportion of damp component decreases from 0.45 to 0.43, and there is no change in the overall view, which indicates that the change of piston amplitude has little influence on the stiffness characteristics of the gas spring and the proportion of the spring component and the damping component, but the maximum amplitude is only 1.7mm, and the amplitude will be increased later to measure the influence of larger amplitude on the stiffness of the gas spring and the proportion of each component.

5. Conclusion

(1) The gas spring stiffness of the system is measured by the system resonance method and the rotation vector decomposition method. The two methods verify each other with the maximum difference no more than 10%, and the latter method is more suitable to measure the gas spring stiffness.
(2) The pressure of the space has a great influence on the stiffness of the gas spring. Under the same excitation frequency and excitation voltage, the initial pressure of the gas spring space is proportional to the stiffness of the gas spring and the damping component of the gas force.
(3) The piston amplitude has little effect on the stiffness of the gas spring and the proportion of each component.

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