BASIC PRINCIPLES OF AIR SPRINGS

GENERAL DISCUSSION

The pneumatic (air) spring is basically a column of confined gas in a container designed to utilize the pressure of the gas as a force medium of the spring. The compressibility of the gas provides the desired elasticity for suspension use.

The air spring’s ability to support a mass depends upon its effective area, which is a nominal area found by dividing the load supported by the spring, by the gas pressure at any given position. The effective area is a function of the outside diameter of the flexible member and, for rolling lobe varieties, the outside diameter of the piston. Whether the effective area remains constant, increases, or decreases during deflection is governed by the design of the spring and its components. The spring rate is the result of change in effective area and the change in gas pressure as the spring is deflected. The gas pressure varies with the speed and magnitude of deflection; for a unit of deflection, the pressure and therefore, the spring rate will be different for isothermal, adiabatic, or polytropic processes.

Air springs provide an adjustable spring rate, adjustable load carrying ability, simplicity of height control, and low friction. They are adaptable for light or heavy suspension applications.

2. COMPRESSION PROCESSES

For a specific spring design, the minimum air spring rate occurs under isothermal compression conditions and the maximum spring rate occurs with adiabatic compression. The polytropic rate varies between the isothermal and the adiabatic. The isothermal rate results when all the heat of gas compression escapes so that the gas remains at a constant temperature. The isothermal rate is approached when the spring is deflected very slowly to allow time for the heat to escape. The gas temperature remains constant, and the gas pressure rise is minimal.

Adiabatic rate occurs when all the heat of compression is retained within the gas. This condition is approached during rapid spring deflection when there is insufficient time for the heat to dissipate. The higher temperature of the gas results in a higher gas pressure and, therefore, a higher spring rate.

When the heat of compression is partially retained within the gas, a polytropic rate results. This occurs during most normal spring deflections and produces neither isothermal nor adiabatic rates, although in typical use it is much closer to the adiabatic situation.

3. LOCKED-IN SYSTEM

Air springs which are not connected to a gas source with height control or other valve arrangements are often called Locked-In systems. In a locked-in system, air springs use a fixed mass of gas as the elastic medium. A given amount of gas is sealed in the system, and remains constant for all conditions of load or deflection.

As the load on a “locked-in” air spring increases, the gas volume is reduced and the spring rate increases. Conversely, when the load on the spring is reduced, the gas expands and the increased gas volume results in a reduced spring rate. Thus, the natural vibration frequency of a suspension system using an air spring with the air locked-in generally increases as the load on the system increases.

4. ACTIVE-AIR SYSTEM

Air springs which are connected to a constant source of air through a height control or other valve arrangement are often referred to as being part of an “Active-Air” system.

The air springs maintain a relatively constant volume at a given operating height regardless of static load or gas pressure. This is the more common system in use at this time. At a given height, the load-carrying ability and the spring rate are varied by changing the pressure of the confined gas. With this type of system, an external source of compressed gas is needed to maintain the spring height as the load on the spring is changed. The natural vibration frequency of the constant volume air spring remains more uniform with changes in load than does the natural frequency of air springs in a locked-in system.
5. SPRING CHARACTERISTIC FEATURES SPECIFIC TO AN ACTIVE-AIR SYSTEM

Effective static deflection is determined by the dynamic rate at the static design position. It can be shown graphically by drawing a line tangent to the dynamic load-deflection curve at the static design position and extending it through the zero load line, then measuring the distance back to the static design position. (See Fig. 2.1.) Natural frequency is directly related to the effective static deflection.

Spring rates vary in direct proportion to the force. The natural frequency of the system stays reasonably constant throughout the normal force range.

System natural frequencies may vary by spring design, spring volume, and spring position within the system.

Figure 2.2 shows the effect of piston shape on the effective area ($A_e$) and on the dynamic force ($F_d$) curves versus spring position. The three figures (2.2a, 2.2b, and 2.2c) show the same rolling lobe flexible member with different piston types. The graphs demonstrate what effect the piston shape has on spring characteristics.

Figure 2.2a shows a straight wall piston which has a neutral effect on the effective area and spring force. The effective area curve ($A_e$) is essentially flat, and increases only slightly as the spring compresses. The spring force ($F_d$) increases as the spring is compressed due to the increase in pressure.

Figure 2.2b shows a back tapered piston which allows for the lowest spring rate. The effective area varies due to the shape of the piston. It decreases as the spring compresses, until the bottom flare of the piston takes effect, at which time, the effective area begins to increase. The force to compress also decreases over the back tapered portion of the piston, and increases again as the piston flares out which prevents rapid compression and bottoming out.

Figure 2.2c shows a positive tapered piston. This style of piston provides the highest spring rate. Both the effective area and spring force increase rapidly as the spring compresses.
6. BASIC CYLINDER AND PISTON SPRINGS

Cylinders with pistons can be used as pneumatic springs but they have several major drawbacks:

(1) Sliding friction transmits significant forces through the spring. Short impulses are especially detrimental.

(2) It is difficult to maintain zero gas leakage past the piston and rod seals for the desired life of the unit. (4) The effective area cannot be manipulated.

(5) The piston and rod guide present wear problems.

An advantage is that high operating pressures may be used, and the unit can combine load-carrying and damping functions.

7. BASIC DESIGN CONSIDERATIONS

The flexible member structure carries only a portion of the developed spring force, with the remainder being transmitted directly through the gas column to the rigid supporting members. Stress is imposed upon the flexible member by both the internal air pressure and, in the case of the rolling lobe type air spring, by the piston contour. High initial stresses and severe fluctuations in stress result in reduced durability.

Air spring designs which have the lowest maximum stress and low stress variation with cycling will achieve the best durability. Durability is also directly coupled with imposed stress which are the result of the suspension design. Goodyear Engineered Products by Veyance Technologies, Inc. recommends that the nominal internal design pressure not exceed 100 PSIG. However, more conservative operating pressures will generally result in increased life.

To maintain their correct shape, air springs should have at least slight positive internal pressure under all deflection conditions. When flexed with no positive internal pressure, rolling lobe air springs may fold between the piston and the top mounting metals, resulting in pinching and/or rupture of the flexible member. Generally, 10 PSIG minimum pressure will prevent operation troubles. In some cases, half this pressure will suffice, but in a few special cases up to 20 PSIG may be required.

8. BASIC CALCULATION CONSIDERATIONS

The basic gas laws apply for design calculations of general characteristics in the pressure, temperature, and natural frequency ranges normally used by air springs. In addition to these factors, an effective area varying with deflection must frequently be considered. This can be accomplished by changing the size or shape of the piston.

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It may also be necessary to take into account the fact that a nonproportional change in volume may occur during deflection.

9. GAS LAW PROCESSES

A. Definitions–Units

The mass of a vehicle and of its cargo is measured in pounds-mass (lbm) and is usually called “weight”; this mass, less the unsprung mass, acts upon the suspension springs as a load, or more accurately as a vertical downward force F (now designated ‘force of gravity’), equaling mass times acceleration of gravity and measured in pounds-force (lbf). It is generally accepted that the terms pounds-mass (lbm) and pounds-force (lbf) are interchangeable. Both are usually referred to as pounds (lb).

With an air suspension spring, the load is supported by a force which is developed as the product of gas pressure and the effective area within the air spring. In this manual the force is measured in pounds, the gas pressure is measured in pounds per square inch (that is, the pressure above atmospheric pressure), and the effective area is measured in square inches.

\[ F(lbf) = P(PSIG) \times A_e \text{ (in}^2\text{)} \]

The pressure of the atmosphere at sea level is in balance with a 29.9 inch column of mercury at 32˚F; it equals 14.7 PSIG. The sum of the atmospheric pressure. The fundamental gas laws deal with this absolute pressure

B. Vertical Supporting Force

As shown above, the supporting force (F) is created as the product of gas gauge pressure and effective area:

\[ F = P \times A \]

Effective area (Ae) can be found directly when the force and pressure are known. Then it is the result of dividing force by pressure.

C. Constant Pressure, No Gas Flow, Constant Effective Area

With Constant Pressure:

\[ \frac{V_1}{T_1} = \frac{V_2}{T_2} \text{ or } \frac{V_1}{T_1} = \frac{T_1}{T_2} \]

where: \( T = \text{absolute temperature} \)

\( V = \text{total pneumatic spring and auxiliary volume} \)

These relationships affect the air spring system when the system is at rest and only temperature changes occur. Dynamically, the only way to maintain constant pressure is in combination with infinite volume and thus is not generally useful.

D. Constant Volume, Non-Flow Process

This process (see Fig. 2.3) can be shown as:

\[ \frac{P_1}{T_1} = \frac{P_2}{T_2} \]

where: \( P = \text{absolute pressure} \)

\( T = \text{absolute temperature} \)

From a practical standpoint, with true gasses this is a desirable but unattainable process because of the nature of the flexible member. Extremely large volumes may allow an approximation of the process and there are ways to obtain small ratios of volume change to total volume with feasible total volumes. (An example, interconnecting springs with only one spring undergoing a volume change at a time.)
E. Constant Temperature, Non-Flow Process (Isothermal Process)

\[ P_1 \times V_1 = P_2 \times V_2 \]

where:
- \( P \) = absolute pressure
- \( V \) = total volume
- \( PV \) = constant

This process (see Fig 2.4) must be taken into account when examining the static stability of systems. It determines the practical limit of low rate operation. Under isothermal conditions, the spring rate must be appreciably in the positive range.

F. Adiabatic, Non-Flow Process: This is defined as a process with no heat transferred to or from the working fluid (see Fig. 2.5).

\[ \frac{T_2}{T_1} = \left( \frac{P_2}{P_1} \right)^{\frac{n-1}{V}} = \frac{P_2 V_1}{P_1 V_2} \]

where:
- \( T \) = absolute temperature
- \( P \) = absolute pressure
- \( V \) = volume
- \( n \) = polytropic exponent

This is a theoretical process; in practice it is not attainable with air springs. However, for rapid deflections it is closely approached.

G. Polytropic, Non-Flow Process (Normal Pneumatic Spring Operation)

\[ \frac{T_2}{T_1} = \left( \frac{P_2}{P_1} \right)^{\frac{n-1}{V}} \]

where:
- \( T \) = absolute temperature
- \( P \) = absolute pressure
- \( V \) = total volume
- \( n \) = polytropic exponent

This is the general case where the terms pressure, volume and temperature all vary (see Fig. 2.6). Air springs operate in the full range from nearly isothermal to almost adiabatic. A generally acceptable value for \( n \) is 1.38 when the natural frequency of the system is being determined.