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RESEARCH ARTICLE

DEVELOPMENT OF ACTIVE AIR SUSPENSION SYSTEM FOR SMALL AGRICULTURAL VEHICLES

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ABSTRACT

Air ride suspension carries the load on each axle with a pressurized air bag just as a high pressure balloon. This system provides the smoothest and most shock free ride of any of the known vehicle suspension system. An air suspension includes a multiple air spring assemblies that each includes a piston airbag and a primary airbag mounted over the piston airbag. The primary and piston airbags each have a variable volume that is controlled independently of the other for active suspension control. The system automatically adjusts air pressure in the air bag so that the trailer always rides at the same height, whether lightly loaded or heavily loaded. The higher air bag pressure associated with higher trailer loads automatically provides a stiffer suspension which is required for a smooth ride. The lower air bag pressure for lightly loaded conditions automatically provides for a softer suspension, thus providing the same ride quality for all trailer loading conditions. Since each axle is independently supported by its own air bag, the air ride suspension is known as fully independent suspension system. The automatic control of the air bag pressure is accomplished by a solid state electronic control system specifically designed and packaged for vehicle use. This system continuously checks the ride height of the suspension and accordingly increases air pressure if the ride height is too low, by turning 'ON' an on-board air compressor. The air compressor stops automatically when the proper ride height is reached.

KEYWORDS

Pressurized Air, Vehicle, Air bags, Air Suspension, Pneumatic.

1. Introduction

Suspension system provides comfort from vibrations and bump. Conventional suspension system consists of mechanical linkages, springs and dampers. Modern automotive innovations are concerned with improvements in mechanical parts in combination with complex electronics. Active suspension systems show the significance of using integrated electronics together with complex information processing (Schoner, 2004). This suspension system is controlled via a control panel which is a computer programmable and which is connected to the air bag via a height sensor. Height sensor is attached with the air bags and note the height of an air bag during its operation and air supply is given through the compressor of 2hp which is controlled by the 5/2 solenoid valve. The motion of the working air bag is picked up by the height sensor, which wirelessly transmits signals to the control panel. Special care is taken when the car is operated in a hilly areas there should be dryer before the compressor to remove the humidity otherwise it will badly effect the performance of our system. It also helps to maintain correct vehicle height and wheel alignment. It also control the direction of the vehicle and has to keep the wheel in perpendicular direction for their maximum grip. The suspension also protects the vehicle itself and luggage from damage and wear. The design of front and rear suspension of a car may be different.

2. Material and Methods

It is an active air suspension system of two-degree of freedom, which is used in a modern era of a car to control the jerks and motion of a car during the uneven surface.

2.1 Material Used

2.1.1 Grey Cast Iron (Fe) (Ordinary)

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The composition of cast iron (CI) varies significantly depending upon the grade of pig iron used in its manufacture. CI contains carbon in the range of ~2 to 4 wt. %. The mode and concentration of carbon in the CI is controlled to produce various grades of CI, which differ significantly in their mechanical properties and weldability. Grey CI is named for its grey fractured surface, which occurs because the graphitic flakes deflect a passing crack and initiate countless new cracks as the material breaks. The graphite flakes, which are rosettes in three dimensions, have a low density and hence compensate for the freezing contraction, thus giving good castings that are free from porosity. The flakes of graphite have good damping characteristics and good machinability because the graphite acts as a chip breaker and lubricates the cutting tools (Singh, 2005).

Figure 1: Active Air Suspension Unit

There are two major parts of the apparatus:

- Control system
- Mechanical System

Control system consists of a height sensor and control panel which is controlled by the computer programmable as the CPU which translates the mechanical signals to the computer readable foam of the working limb and the motion of the air bag is controlled and produced motions. The signals are transmitted to the receiver section of control system wirelessly via height sensor.

The mechanical system is designed for the average values of common loads and weight of a car. All the individual parts were designed by keeping a fair factor of safety and then modelled in SolidWorks.

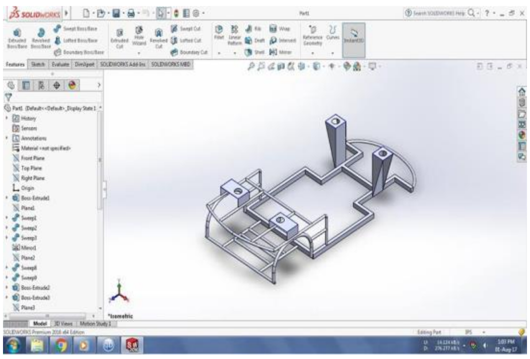

Figure 2: Design of chassis frame on SolidWorks

A free-body diagram consists of car body, suspension, air spring, wheel and tire of a vehicle.

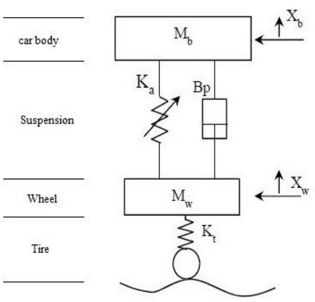

Figure 3: Free Body Diagram of Active Air Suspension

2.2 Mathematical Modeling

The mathematical model used in this model was an air suspension operandi of a quarter-car, which simulates a none-linear model of spring in suspension system. The equation 1, is shown below was considered as the base of mathematical model with linear force spring (Winfred et al., 2002).

$$M_b \ddot{x} = -K(x_b - x_w) - C(\dot{x}_b - \dot{x}_w)$$

$$M_w \ddot{x}_w = -K(x_w - x_b) - K_t(x_w - r) - C(\dot{x}_w - \dot{x}_b) \quad (1)$$

By considering, external force, gravity and parts position (road, wheel, and body); the integrated suspension equation for constant stiffness can improve to equation (2).

$$M_b \ddot{x}_b = -K\big((x_b - h_b) - (x_w - h_w)\big) - C(\dot{x}_b - \dot{x}_w) - M_b g + u_c$$

$$M_w \ddot{x}_w = -K\big((x_w - h_w) - (x_b - h_b)\big) - K_t\big((x_w - h_w) - r\big) - C(\dot{x}_w - \dot{x}_b) - u_c \quad (2)$$

The force-displacement diagram in a normal coil spring is almost linear, however for air-spring, it's related to mechanical behavior of air, inside a cylinder. The method was used is a real time pressure sensing, and calculating stiffness from pressure inside the air spring (Yin et al., 2012).

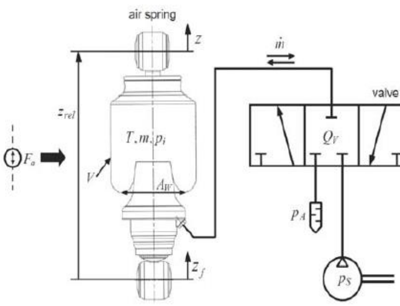

Figure 4: Pneumatic setup and state variables of the force-controlled air-spring

Figure 4 displays the pneumatic setup of the force-controlled air spring. Q_V is the given orifice, P_A and P_S are atmosphere and source pressures, m' is mass flow rate, A_W is the cross sectional area of air-spring (Graf and Maas, 2011).

2.3 Air-Spring

Mechanical behavior of gas inside a cylinder shows, stiffness of air-spring has non-linear relation between force and displacement. The way was used to get acceptable accuracy, was Stiffness calculation from real-time pressure sensing. The gas medium used in the air-spring is pressurized air; which is considered to be an ideal gas. The equation of state describing an ideal gas is known as Boyle-Gay Lussac's law (Brink, 2007).

$$PV = m R T \quad (3)$$

Where, P is the pressure, V is the volume, R is the specific gas constant, T is the absolute temperature and m the mass of air in the volume.

Figure 5: Air-spring used for experimental model

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Mathematical model of the air spring consist of two kinds of variables, the characteristic of valve and air spring chamber are making rate of change of the volume in the air spring, and heat transfer parameters are affecting results (Lee, 2010).

$$P_{cv}=-kP_{cv}\frac{\dot{V}_{cv}}{V_{cv}}+\frac{k-1}{V_{cv}}h_c A_{heat}\left(T_{env}-\frac{V_{cv}}{Rm_{cv}}P_{cv}\right)+\frac{kR}{V_{cv}}\left(T_{in}\dot{m}_{in}-\frac{P_{cv}V_{cv}}{m_{cv}R}\dot{m}_{out}\right) \quad (4)$$

The active air suspension system changes k based on the following formula (Peterson, 2010).

$$K=\frac{nA_e{}^2P_0}{V}+P_g\frac{dA_e}{dZ} \quad (5)$$

Where, K is spring stiffness, n is ratio of specific heat (C_p/C_v), Ae is effective piston area, P_0 is atmospheric pressure, V is volume of air in main spring, P_g is gauge pressure, Z is displacement or height. Finally, the differential equation for the stiffness of the air spring in control volume can be obtained from equations (1), (5).

$$K=\frac{nA_e{}^2P_0}{V_0+A_e(x_w-x_b)}+P_g\frac{dA_e}{(x_w-x_b)} \quad (6)$$

Equation 6 presents the mathematical model for the air spring. In this equation (x_w-x_b) is defined from displacement sensor. P_g in experimental model is a real time measurement of air pressure inside the chamber, and it considered as a constant pressure in stable height for simulations. Ae was dispensable for this this type of air spring. V_0 is the volume of chamber in standard height and it is constant. In addition, n, and P_0 are constant.

2.4 Air-Valve

Due to Lussac's law is mentioned in equation (3), the relation between pressure and the amount of air inside air spring is defined, then the pressures in the chamber and the capacity will be derived. Thus, the pressure gradients in the chamber can be derive similarly.

The 5/2 Solenoid Valve used for the experimental purpose is shown in Figure 6: It controls the flow of Air from compressor and deliver it to the air-spring.

Figure 6: Solenoid Valve used in Suspension

The schematic diagram of 5/2 valve is shown in Figure 7. It shows the 3 inputs (one primary and two secondary inputs) and two exhaust ports.

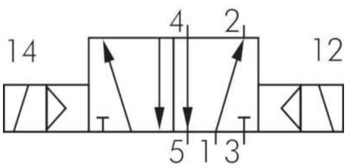


Figure 7: Schematic diagram of 5/2 valve

Table 1: Specifications of 5/2 Valve (Namur Solenoid Valve)	
Specification of Pressure Valve	
Medium	Air
Operating	Internal Piloted
Valve Type	5 Port 2 Position
Orifice Size	35mm2
Port Size	Inlet & Exhaust Port:PF1/4"
Lubrication	Not Required
Pressure Range	0.15~0.8 Mpa
Proof Pressure	12bar
Temp. Range	-5~60°C(23~140°F)
Voltage Range	-15%~10%
Power Consumption	AC=2.0~3.5VA. DC=2.5W
Insulation Class	Class F
Connector	Socket with Plug
Max Frequency	5 cycle/second

2.5 Height Valve

Ride-height–based systems utilize separate sensors that directly measure the actual position of the vehicle's suspension, thereby eliminating several assumptions made on a purely pressure-based system because now precise information on the relationship between the suspension and the chassis is available to help the computer determine the vehicle's ride height. But there's still one problem known as cross-loading. This happens when the ride height is achieved with radically different air pressures on each corner.

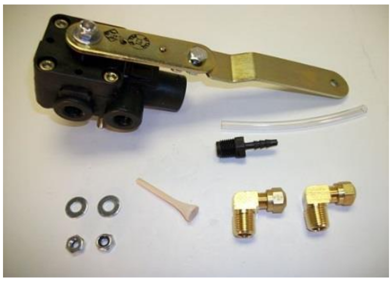


Figure 8: Height Control Valve

Normally, any side-to-side air-pressure variations should be held to 20 percent or less; yet it is possible to fool a pure ride height–based system by overinflating two diagonal corners while leaving the opposing corners significantly underinflated. The computer keeps the car level, but the handling characteristics are not appropriate.

2.6 Combo Systems

The solution is to combine pressure-based and ride-height–based leveling in the same system. Each serves as a check on the other. This is what Air Ride Technologies has done in its new Level Pro system. To save money initially, the setup can first be configured as a pressure-based system only, and the ride-height sensors can be added later, if needed.

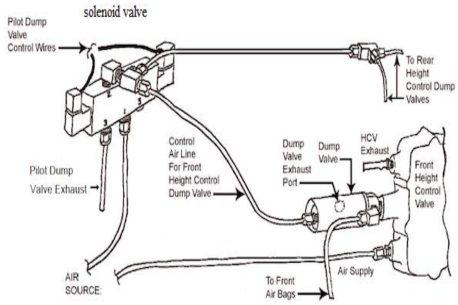


Figure 9: Working of Combo System

Level-Pro systems also include the ability to program three different suspension heights into the computer—low (for profiling),normal (for touring and racing), and high (for clearing obstacles like speed bumps).Simply punch a button, and the car raises or lowers to a preset level yet can still compensate at each preset for changes in fuel load, passengers, or cargo.

Table 2: Properties and features of the physical structure	
Mass of wheel (Kg)	36
Mass of body (Kg)	240
Stiffness of tire (N/m)	160000
Stiffness of air-spring in stable height (N/m)	16000
Damping number (Ns/m)	1400
Friction (N)	6
Gravity (m/s*2)	-9.8
Xb (m)	0.6
Xb, After gravity (m)	0.436
Xw (m)	0.2
Xw, After gravity (m)	0.183

3. RESULT AND DISCUSSION

The mechanical model was subjected to the working loads in ANSYS® R15.0. The results are in accordance with safety factor. These results included the Equivalent Stress, Equivalent Elastic Strain and the total Deformation in the frame of the project. The analysis results are given below:

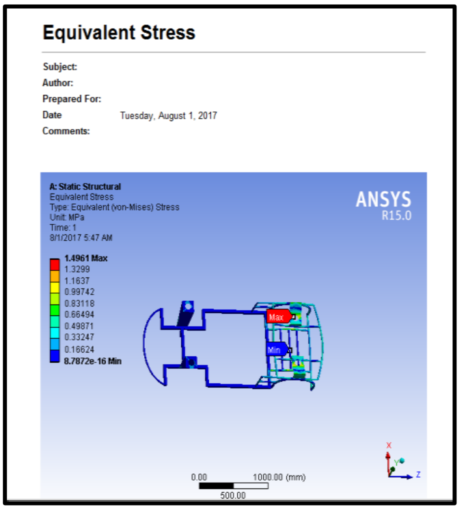


Figure 10: Equivalent Stress of chasis on ANSYS

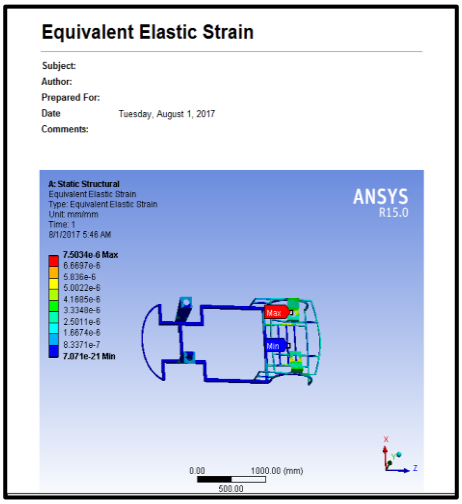


Figure 11: Equivalent Strain of chasis on ANSYS

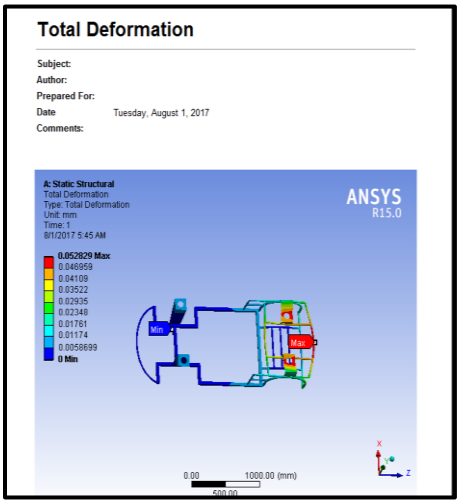
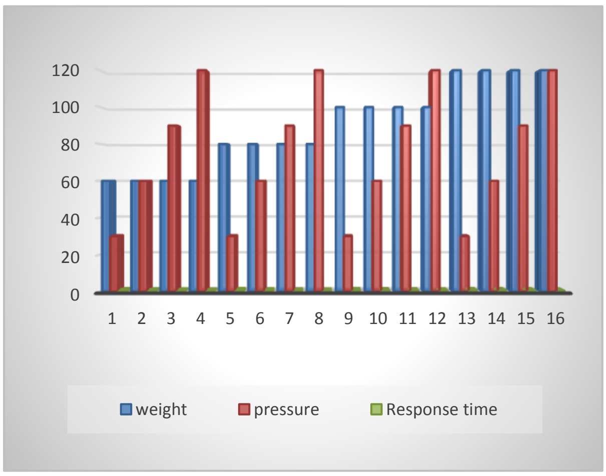


Figure 12: Total Deformation of chasis on ANSYS

We calculated the Response Time of our project by changing the values of pressure of the compressor and the weight on air bags. The outcomes of the experiments are given below in table.

Table 3: Time Response of Airbags at different Pressure and Weight		
Weight	Pressure	Response time
(kg)	(psi)	(sec)
60	30	0.63
60	60	0.51
60	90	0.46
60	120	0.43
80	30	0.68
80	60	0.59
80	90	0.52
80	120	0.47
100	30	0.72
100	60	0.62
100	90	0.58
100	120	0.54
120	30	0.74
120	60	0.69
120	90	0.65
120	120	0.51

The results of the experiment values can also be expressed in the form of graph. The following below graph shows the relation between pressure and weight with response time of Active Suspension.



Graph: between Pressure, Weight and Time Response

4. Analysis and Validation of Active Air-suspension Model

The accuracy of experimental study presents the validation of this model. As it shown in Figure 10, this part explains about evaluation of results similarity between experimental and simulation in order to specify the percentage of model validation.

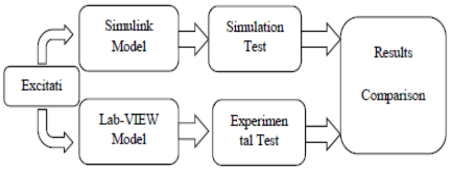


Figure 13: Schematic of validation evaluation design (Sarami, 2009)

Root-Mean-Square (RMS) reductive method utilized for body acceleration and tire force results as the most common method in data reduction for comparison between simulation and experimental studies in active and passive modes. RMS is shown Equation (7).

$$RMS = \frac{\sqrt{{a_1}^2 + {a_2}^2 + \cdots {a_n}^2}}{n} \quad (7)$$

Validation evaluation requires specification of inaccuracy in active and passive segments, based on simulation and experimental comparison. The equation (8) shows the inaccuracy calculation for every part (Shin and Kim, 2009).

$$Inaccuracy = \left[\frac{Simulate - avg\ of\ exp.}{avg\ of\ exp.}\right] \times 100 \quad (8)$$

4.1 Ride Comfort Evaluation

Ride comfort was the essential approach in this study, and it calculated from body acceleration. As the first criterion for performance improvement, the body acceleration was evaluated in active and passive modes. In this section, four acceleration results are presented for simulation in Figure 14, and experimental in Figure 15, in active and passive modes. The improvement result after this comparison will define in this part.

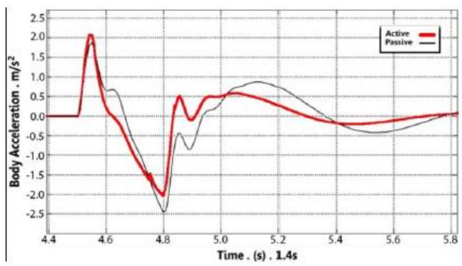


Figure 14: Simulink Diagram for body acceleration in active and passive modes during 1400ms simulation test.

Ride comfort was also evaluated experimentally by using RMS values, and equation (7) used to define percentage of experimental improvement during a specified time.

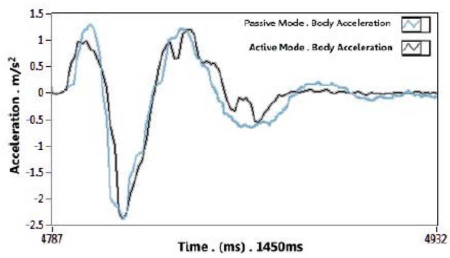


Figure 15: Experimental results for body acceleration in active and passive modes during 1450 ms test.

$$Improvement = \left[\frac{(Active) - (Passive)}{Passive}\right] \times 100 \quad (9)$$

The equation (9) was used to define percentage of comfort improvement and the results for comfort improvement in simulation and experimental studies are shown in Table 4 below.

Table 4: Calculating improvement of Active and Passive Suspension

Mode	Active (m/s^2)	Passive (m/s^2)	Improvement (%)
Simulation	0.639	0.529	20.79
Experimental	0.765	0.672	13.83

4.2 Stability Evaluation

The handling capability of active suspension was evaluated after comfort. A passive suspension is in a compromise between comfort and handling. The new suspension has a performance improvement in comfort, but if there is no decrease in handling performance. The tire deflection and then tire load was investigated in order to define stability in simulation. These tire loads in active and passive mode both are shown Figure 16.

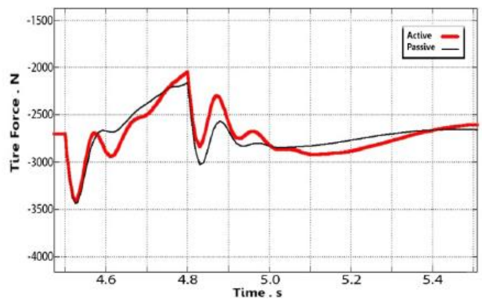


Figure 16: Diagram of tire forces in passive and active simulation test

In experimental part, the tire force was defined from tire deflection in order to investigate the stability. Diagrams of tire deflections for passive and active test are shown in Figure 17.

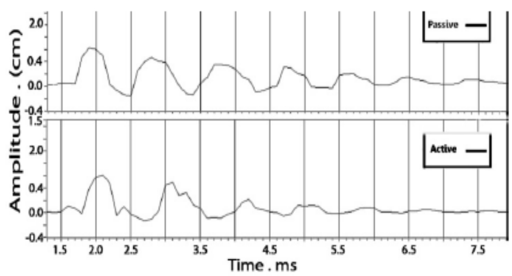


Figure 17. Diagram of tire deflection in passive and active experimental test

Table 5: Simulate and experiment results for tire forces in active and passive mode

Mode	Passive (N)	Active (N)	Improvement (%)
Simulation	674.52	620.85	8.64
Experimental	784.32	735.34	3.83

4.3 Suspension Travel Evaluation

The Maximum Peak-to-Peak (MPTP) value from suspension travel utilized as a reductive function for structural performance. Moreover, it investigated in simulation and experimental study and shown in Figure 18.

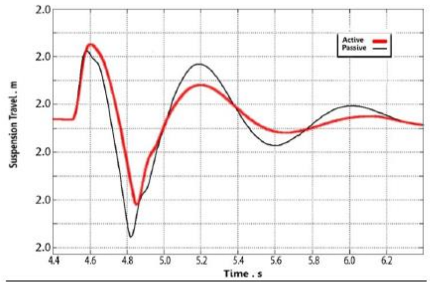


Figure 18: Suspension travel in active and passive simulation test

In order to evaluate structural performance, suspension travel was experimentally defined with its improvement percentage in active and passive modes, which are shown in Figure 19 and Table 6.

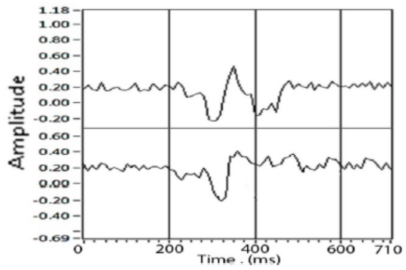


Figure 19: Suspension travel (decimeter) in passive (up) and active (down) in experimental test

Table 6: Simulate and experiment results for suspension travel in active and passive modes

Mode	Passive (m)	Active (m)	Improvement (%)
Simulation	0.0415	0.035	8.64
Experimental	0.068	0.062	3.83

We also run some tests for checking out the performance and leaking failure of our project. The details of the tests are given below:

4.3.1 Testing and Performance

Road Testing Car was tested at various pressures of compressed air keeping the vehicle dynamics into consideration. Maximum permissible load was tested and the result depicted fair values. Brake tests were conducted and the joint efficiencies were observed. They withstood the impacts and could resist the jerks.

4.3.2 Leak Testing Leak

Testing is required by most codes prior to initial operation and each piping system must be tested to ensure leak tightness. The field test is normally a hydrostatic leak test. There are several other types of testing depending on service fluid and there are six different testing methods that can be used at most construction sites.

1. Hydrostatic testing which uses water under pressure.
2. Pneumatic testing which uses gas or air under pressure.
3. In-service testing which involves a walk down for leakage when the system is put into operation.
4. Vacuum testing which uses negative pressure to check for leakage.
5. Static head testing which is normally done for drain piping with water with a known static head pressure left in a standpipe for a set period of time.
6. Tracer leak method for inert gas leak detection.

4.3.3 Pneumatic Leak Testing

The fluid medium used for pneumatic testing is either compressed air or Nitrogen gas. The test pressure by code is usually 1.1 times the design line pressure. Pneumatic testing involves the potential hazard of releasing energy stored in the compressed gas. Care must be taken by gradually increasing pressure in steps up to the test pressure, holding only as long as the code requires, then reducing to the design pressure for inspection of the joints. The inspection of joints is done utilizing a soapy water mix that bubbles when air is escaping.

4.3.4 Soap Solution Test

This is one of the simplest and cheapest methods to spot the leaks in a pneumatic circuit. A soap solution is prepared and is applied at all the joints, fixtures of the hoses, valves, reservoir connections and other sensitive parts. This solution is applied after the tanks are filled to a rated level. All the valves are opened and air starts rushing through the connections. Whenever there is a leak present, with movement of air molecule, soap bubbles start emerging at the leak spot. Thus the leak spot is observed.

5. Conclusion

Active air suspension controls the vertical movement of the wheels with an on-board system and air bags both which provide more flexibility to the system. The normal coil spring is not used in this suspension, thus eliminating its vibration and improving riding comfort. The spring function has been replaced by the air bags but emergency springs are also used. The pressure control range has been widened to maintain a flat vehicle position even while turning. The sensors used are pressure sensors and height sensors.

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