Modern Sensors and Applications

ENGR 472

FINAL REPORT

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Introduction

Brakes are an important component in a vehicle. Stopping or slowing down a vehicle is as vital as running it. In light vehicles, hydraulic brake systems are used to stop or decelerate the vehicle, but is the hydraulic brake system effective when it comes to heavy vehicles? A pneumatic brake or compressed air brake system is the type of brake system in which the compressed liquid fluid from the hydraulic system is replaced with the compressed air for applying pressure to the master cylinder's piston which in turn presses the brake pads in order to stop or decelerate the vehicle.

As mentioned previously, the brake system is crucial for a vehicle but as when it comes to the application every vehicle is not the same, as some vehicle are used for light utility purposes like cars and bikes and others are used for heavy purposes like buses and trucks, so there is a need of different braking system due to the following reasons:

- As the load over light vehicles and heavy vehicles varies the brake force required to stop the heavy vehicle is far more than that of a light vehicle, so the heavy vehicles should be equipped with a braking system that can provide enough brake force that can stop or decelerate the vehicle.
- When considering light weight vehicles, hydraulic brakes provide enough brake force to stop or decelerate the vehicle due to its short dimension. However, in heavy vehicles the effectiveness of hydraulic brake systems is a major issue.
- When a leak is present in the hydraulic braking system, safety is a great concern. The efficiency of the braking is readily reduced or even lost completely. However, in a pneumatic air brake system, if a leakage is present, even if not detected prior failure, wheel brakes are activated so that the vehicle reaches a safe stop as air is always available. This makes air brakes safer when compared to hydraulic brakes, but a leakage sensor warning about air leakage would reduce the risk even more. **[2,3,4]**

Pneumatic air brakes

They are used to keep moving, rotating machine parts in constant tension or to stop them in a shorter time.

Working principle

The system is driven by air, the diaphragm in the air tank pushes the pusher forward and the shoes hold the rotating disc. When the air is evacuated, the pusher comes back by means of the spring and the braking process is terminated.

Purpose of pneumatic brake:

Keeping the movement in constant tension by means of proportional valve, Emergency stop function of the moving mass, Providing stop at certain times, Braking function at certain moment values. **[11]**

Applications of The Pneumatic Air Brake System

Most of the applications for the pneumatic air brake system are for heavy duty vehicles, for example busses and trucks, due to its major advantage of preventing brake failure, furthermore reasons why it is not used for light duty vehicles or cars, because of the fact that even though the air brake system is way safer and better than the hydraulic braking it needs a lot of space for it to be installed unlike the hydraulic braking, and another major factor is the price, If the air brake system is installed then the total cost for manufacturing the car would increase. Furthermore, for light duty vehicles hydraulic brakes does the job effectively. **[1,3,4]**

Different Applications

General usage areas;

- In the operation of air, water and chemical system valves
- When operating heavy or hot doors
- For filling and unloading silo in construction, steel, mining and chemical industry
- Forging and compression processes in concrete and asphalt pavements
- Lifting and moving in continuous casting machines
- In spray painting
- Holding jigs and fixtures in assembly machines and machine tools
- In soldering and welding processes
- For forming processes such as bending, drawing and rolling

- In spot welding machines
- Riveting
- In bottling and filling machines
- In test equipment
- Component and material handling
- In pneumatic robots **[12]**

Airplanes

A pneumatic system is any system that uses compressed air to move something. In aircraft, many different parts of the aircraft can be moved with pneumatic components or hydraulic components, which are the same except that they use pressurized water instead of air. Some parts that use pneumatic or hydraulics are ailerons, elevators, rudders and the flaps. **[15]**

Pneumatic System in Airplanes

1. High Stage Valve

It is mounted on the output of the high pressure stage of the engine. It is air controlled and works with air. It is normally closed. When the low pressure stage of the motor cannot meet the needs of the pneumatic system, this valve is opened and the need of the pneumatic system is met. This valve is open at low revs of the engine and closed at high revs of the engine. There is a position indicator (indicator) on the valve that indicates whether it is open or closed.

2. Medium Pressure Pneumatic Check Valve (Intermediate Pressure Check Valve)

It prevents the reverse flow of air when the engine is at the intermediate pressure outlet and the high pressure stage is activated. The valve consists of two semicircular valves.

3. Pressure Regulator and Shut-Off Valve

It goes from a port at the inlet of the valve to the reference pressure regulator to the high pressure switch inside the air regulator. If the air pressure exceeds 180 PSI, the pressure switch is activated and makes the "Bleed Trip Off" lamp on the overhead panel come on. The valve regulates the pressure of the air from the engine bleeds to 45 PSI.

4. Pre-Cooling System (Precoller System)

Pre-cooler is put into the system to cool the air with air. When the precooler outlet temperature increases, the precooler control valve activates and the cold air coming from the engine fan and the bleed air are cooled within certain limits. The aim is to direct the bleed air temperature to the system within the limits. The precooler control valve (Fan Air Valve) is normally open. It is completely pneumatically controlled and works pneumatically. It works according to the temperature value received from the sensor at the front 6 cooler outlet.

Safety and Protection Warning Schemes

1. Safety Relief Valve

Both valves are behind the rear cargo compartment and adjacent to the rear outflow valve. The valve works with air pressure. There are two valves of the same type. It works independently from each other. If the pressure difference exceeds 8.65 PSI, the valve opens, allowing the excess pressure in the cabin to go to the atmosphere. The valve closes at 8.65 PSID.

2. Negative Relief Valve

It opens when the cabin pressure is lower than the outdoor pressure. The valve has a cover hinged at the top and operated with a spring load. If the pressure outside the airplane exceeds the pressure inside the airplane by 1 PSID, the valve cover opens inward, allowing outside air to enter. The lid closes automatically when the pressure returns to normal. **[17]**

Aircraft pneumatic systems use compressed air. There are many benefits of using air instead of fluid for aircraft pneumatic systems:

1. Not Flammable

Air itself is not flammable, so there is less likelihood of fire or fire hazard with the aircraft pneumatic system than liquid hydraulic systems. Therefore, pneumatic systems are much safer.

2. Lightweight

Air is light and does not require a return line like hydraulic fluid systems.

3. Simpler

Aircraft pneumatic systems are simpler in design than other systems, so they are easier to design, manufacture, install and maintain at all stages, which ultimately helps to reduce costs.

4. Quantity

The liquid should be replenished regularly, that is, it should be purchased periodically. Air is everywhere, so the pneumatic system can be refilled anytime, anywhere.

5. Cost

Aircraft pneumatic systems use free air. This makes the pneumatic system a better option, reducing refilling and purchasing costs. **[16]**

Components

As mentioned previously, the pneumatic air-brake system is of extensive use, especially in trucks.

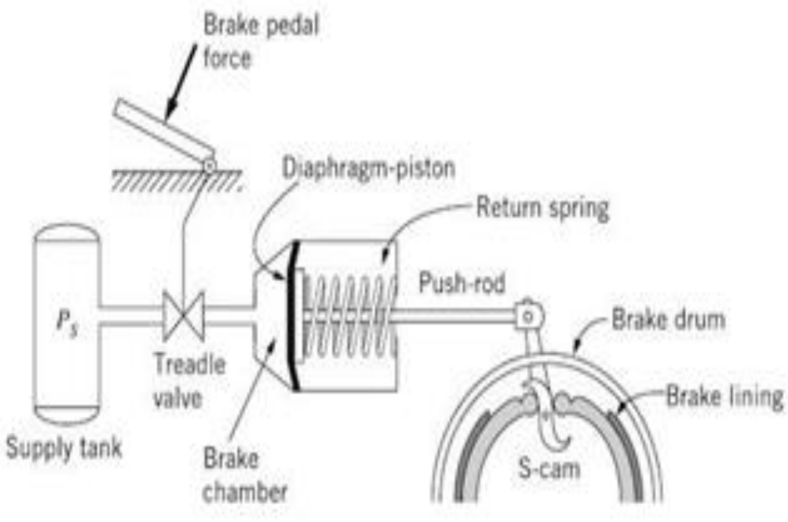


Figure 1 Schematic of System

The components of the complete system (Figure 1) without the inclusion of the sensing system should include two subsystems, mechanical and pneumatic subsystems.

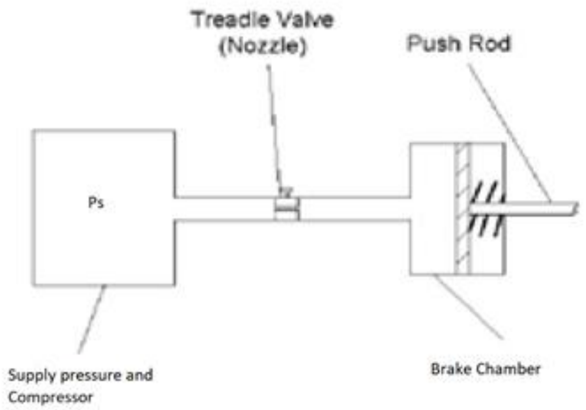


Figure 2 Pneumatic Subsystem

In Figure 2, the simplified pneumatic subsystem can be seen. It is composed of the supply pressure that is charged by a compressor and connected to the brake chamber. Through this connection, a treadle valve is present. This valve is responsible to control the flow of air into the chamber. The treadle valve is controlled by the brake pedal in the car. When force is applied, the valve opens and air flows into the brake chamber where the compressed air provides force on the diaphragm-piston, and the system is mechanical.

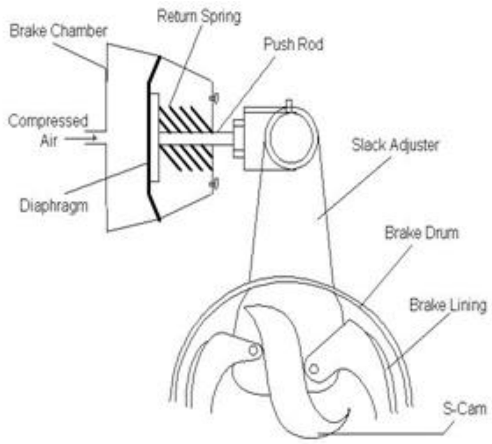


Figure 3 Mechanical Subsystem

Figure 3 shows the mechanical subsystem separately. This is where the compressed air flow force is utilized for brake application. When the air at high pressure pushes the piston, it moves the push-rod to the right, rotating the S-Cam. This presses the brake lining against the inside of the brake drum increasing friction force and thus providing wheel brake. A return spring is present to revert the push-rod position when the treadle valve is closed. **[5]**

Disc brakes offer lower sensitivity of the brake torque to the brake pad friction coefficient, better fade resistance and improved brake efficiency when compared to drum brakes. The main absence of self-energization which refers to the augmentation of the moment due to the actuation force acting on the brake pad by the moment due to the friction force acting on the brake pad available in drum brakes results in the need for higher actuation air pressures when compared to drum brakes. Figure 4 illustrates the schematic of a drum brake.**[10]**

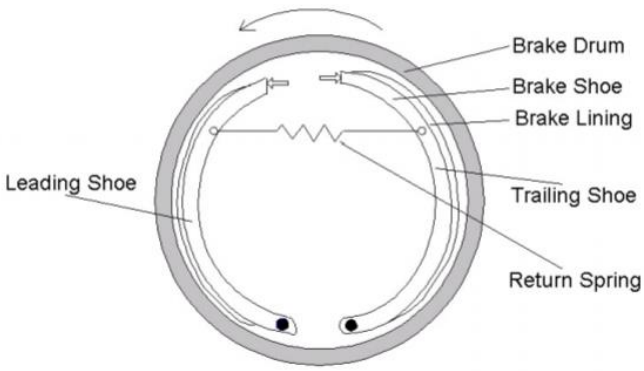


Figure 4 Schematic of a Drum Brake

Patent for Pneumatic Air Brake System:

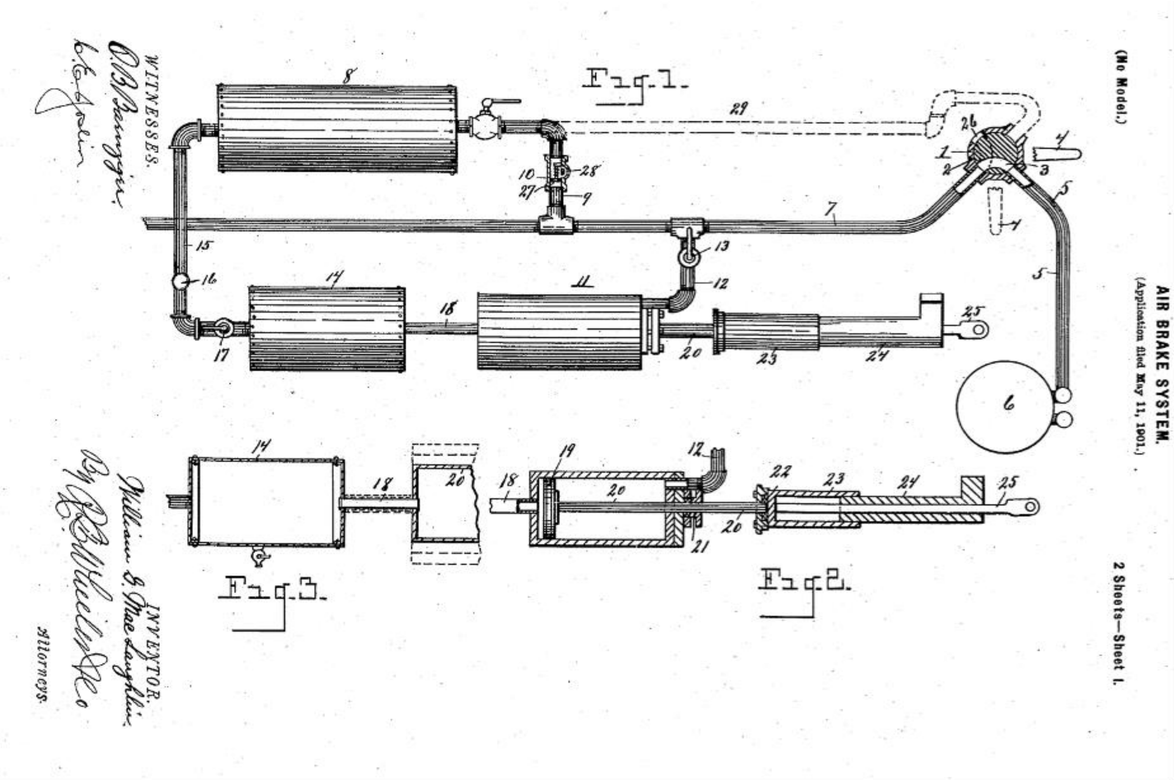


Figure 5 Air Brake System

further details for the patents in [25,26,27]

System Parameters

Table 1 System Parameters and Values

System Parameter	Value
Diaphragm/push-rod mass, m	10 kg
Return spring, k	1250 N/m
Viscous friction coefficient, b	12 N-s/m
Preload spring force, F_{PL}	450 N
S-cam load force constant, k_1	2650 N/m
S-cam load force constant, k_2	23,700 N/m^2
Maximum push-rod stroke, x_{max}	0.04 m
Diaphragm area, A_b	0.0129 m^2
Minimum chamber volume (seated), V_0	$1.64(10^{-4})$ m^3
Atmospheric pressure, P_{atm}	$1.0133(10^5)$ N/m^2
Gas constant, R	287 N-m/kg-K
Air temperature, T	298 K
Discharge coefficient, C_d	0.8
Valve orifice height, h	0.002 m

Mathematical Modeling

To understand the pneumatic brake system thorough study of the dynamics and mathematical modeling was done. Which resulted in understanding of the working principle of the brake system and also gave a clear idea of its dynamic equations. The mathematical model will further consist of the feedback loop which will be used in controlling the system. The parameters obtained such as displacement and force would therefore determine the pressure required to control the pneumatic brake system.

The mathematical model will link the pneumatic with the mechanical system in which the masses, force and displacement governed by Newton's 2nd law would be analyzed.

$$\sum F = PA_b + F_c - P_{atm}A_b - Kx - F_{PL} - b\dot{x} - F_{load} = m\ddot{x}$$

Where P is the air pressure in the brake chamber, $A_b$is the area of the diaphragm-piston, $P_{atm}$is the atmospheric pressure, $F_c$is the contact force, K is the spring constant, b is the viscous friction coefficient, $F_{PL}$is the preload spring force and F_{load} is the load force from actuating the S-cam in the brake drum. Rearranging the above equation so that all the terms involving displacement are on the left-hand side.

$$m\ddot{x} + b\dot{x} + Kx = (P - P_{atm})A_b + F_c - F_{PL} - F_{load}$$

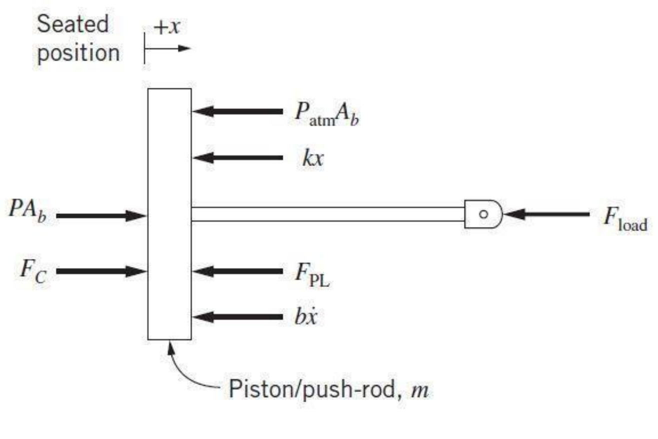


Figure 6 Free-body diagram of the mechanical subsystem

The contact force only exists when the preload spring force exceeds the differential pressure force and of course the piston is seated with $x = 0$

$$F_c = \{F_{PL} - (P - P_{atm})A_b\ , \qquad if \quad (P - P_{atm})\, A_b < F_{PL}\ and\ x = 0$$
$$0 \qquad if \quad (P - P_{atm})\, A_b \geq F_{PL}\ or\ x > 0$$

Load force required to actuate S-cam can be modelled as a nonlinear function.

$$F_{load} = k_1 x - k_2\, x^2$$

Where k_1 and k_2 are linear and quadratic stiffness terms. We will choose $k_2 > 0$ so that the force required to engage S-cam decreases with large displacement. Simulink model of the mechanical part was constructed to observe the proposed mechanism.

For the Pneumatic subsystem, consisting of single chamber meaning the is a single modeling equation of first order, with a single state variable P, input mass flow rate w

$$P = \frac{nRT}{V} \cdot \left(w - \frac{P}{RT}\dot{V}\right)$$

Where R is the gas constant, T air temperature, n is the exponent of the polytropic expansion process, v is the volume. We assume that it's an isothermal process so

$$n = 1$$
$$V = V_0 - A_b\, x$$
$$\dot{V} = A_b \dot{x}$$

Where V_0 is the volume when diaphragm is seated i.e., x=0, $\dot{V}$ is the volumetric flow rate. The input mass-flow rate w has two conditions, either chocked or "unchecked". If the ratio of the "low" downstream pressure to the "high" upstream pressure is more than the Critical pressure ratio then the flow is unchocked. Otherwise, it is chocked. The formulas for the mass flow rates are as follows: is modeled by the orifice-flow equations

$$w = C_d A_v P_s \sqrt{\frac{2\gamma}{(\gamma-1)RT}\left[\left(\frac{P}{P_s}\right)^{\frac{2}{\gamma}} - \left(\frac{P}{P_s}\right)^{\frac{\gamma+1}{\gamma}}\right]}\ \text{if}\ \frac{P}{P_s} > C_r \quad \text{"Unchocked"}$$

$$w = C_d A_v P_s \sqrt{\frac{\gamma}{RT} C_r^{\frac{\gamma+1}{\gamma}}}\ \text{if}\ \frac{P}{P_s} \leq C_r \quad \text{"chocked flow having Mach 1"}$$

where γ is the ratio of the specific heat = 1.4 for air, C_d is the discharge coefficient for losses, Av is the orifice area and is equal to the product of orifice height h and valve displacement y and PS is the supply pressure. The Critical pressure ratio Cr and is equal to 0.528 for air.

The upstream pressure is the highest pressure in the chamber, driving the flow. It can have the value of either the supply pressure if the valve displacement is more than zero, or the atmospheric pressure if valve displacement is zero. The downstream pressure is the minimum pressure. It has the value of P (the chamber pressure), it might also have the value of the atmospheric pressure, depending on which is the minimum. Clearly, from the mass flow rate equations, if the upstream and downstream pressures are nearly equal ($P2 / P1 \approx 1$), then no gas flows through the orifice. Gas begins to flow through the orifice at an increasing speed as the pressure ratio $P2/P1$ decreases from unity i.e., as P1 increase. Below is the schematic for the pneumatic subsystem. **[18]**

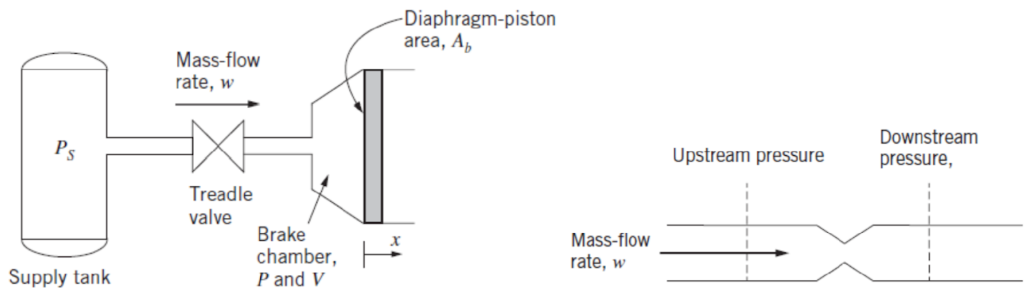


Figure 7 Air-brake pneumatic subsystem

Block Diagram

The Figure 8 below shows the block diagram of the air brake system in which it is clearly seen how the mechanical and pneumatic system will work along the sensors . Block diagram is used to understand the system thoroughly and from it derive the corresponding transfer functions of both mechanical and pneumatic systems.

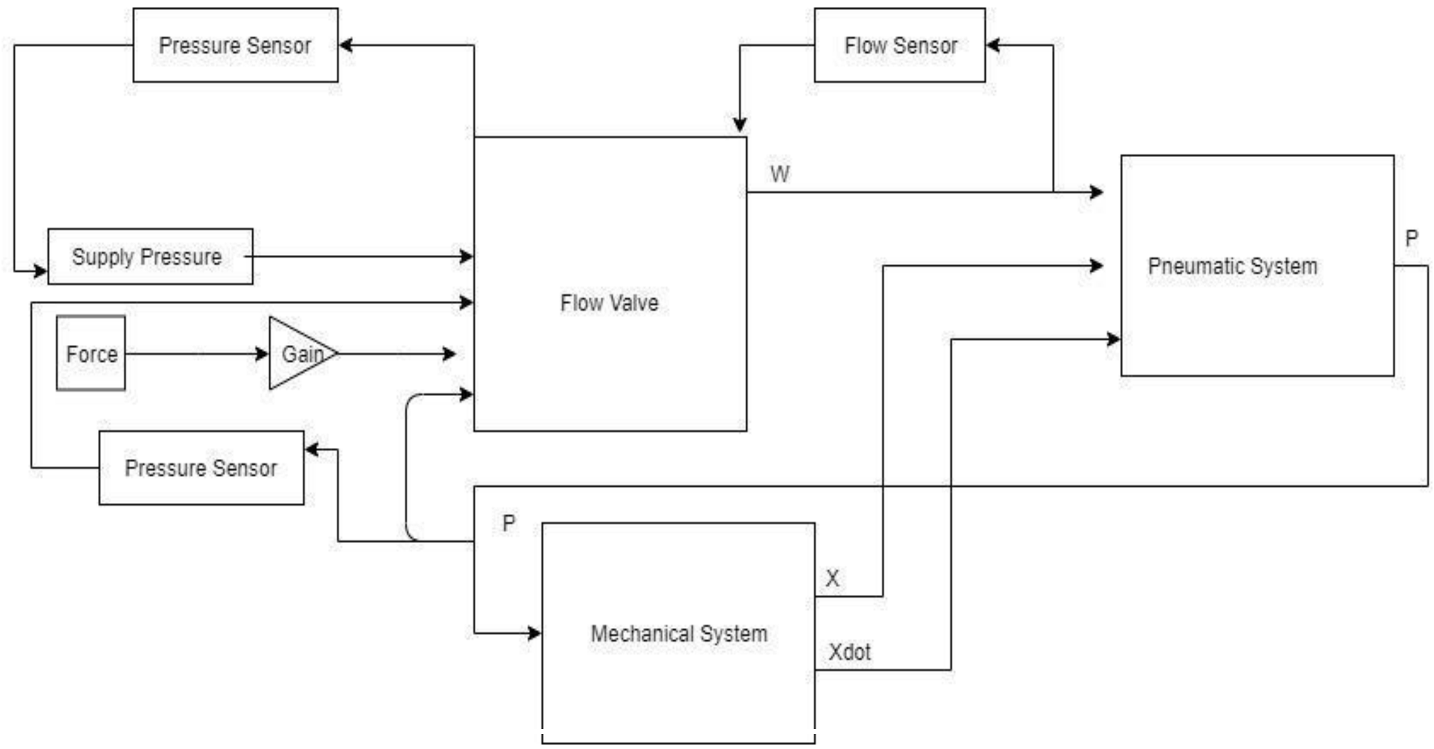


Figure 8 Block Diagram

Simulink model

The Figure 9 shows the integrated system Simulink model. The system has two inputs, one constant supply pressure, and the other is a step input for a unit force after 0.5 seconds multiplied by 0.002 m displacement per Newton giving the step input for y. Along with the chamber pressure P, these three parameters are the inputs to the Flow through the treadle valve subsystem.

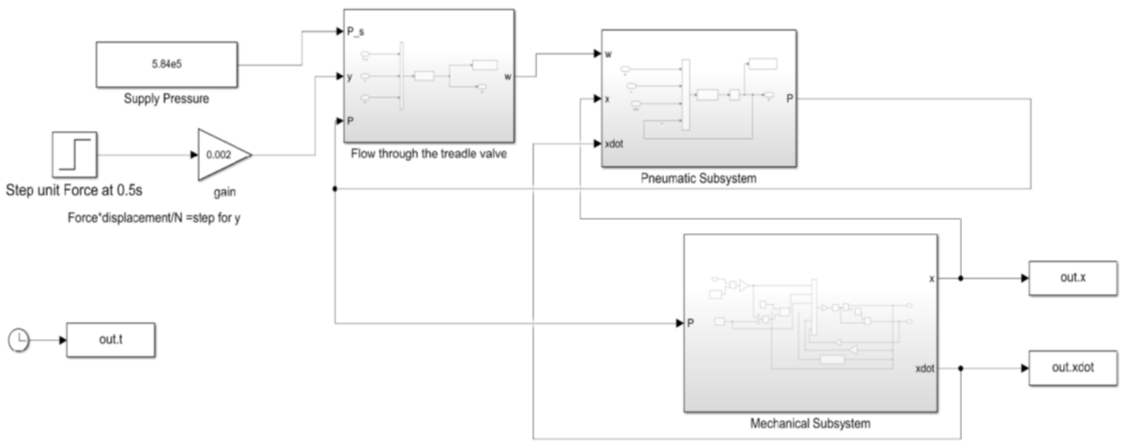


Figure 9 Integrated System Simulink model

The mass flow rate (w) through the orifice can be found from the chocked and unchocked equations given previously. These equations are complicated; therefore, they are fed to Simulink through a MATLAB script. To simplify our integrated system diagram, the flow through the orifice has been put as a subsystem. The interpreted MATLAB Fcn Block has been used to input the formulas for the mass flow rate to Simulink. The function is a MATLAB script given below the orifice subsystem. To solve the mass flow rate function three inputs must be provided, the supply pressure, the valve displacement, and the chamber pressure. To combine these inputs, use the mux block from the signal routing library.

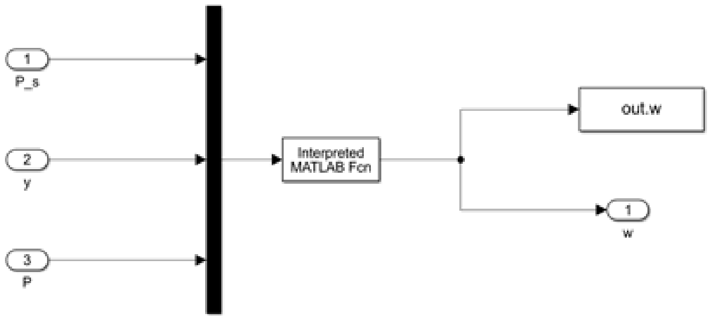


Figure 10 Flow through treadle valve Subsystem

```
%this script programs the function for the mass flow rate computation

%We start programming the script by constructing our function
function w = OrficeFloweq(u)
% system parameter
h = 0.002; % height of valve opening, m
% give air constants
gamma = 1.4;
Cd = 0.8;           % discharge coefficient accounting for losses
R = 287;            % gas constant (air)
T = 298;            % temperature in Kelvin
P_atm = 1.0133e5;   % atmospheric pressure in Pascal
% System inputs (inputs to the mass flow rate equation)
P_s = u(1);         % supply pressure in Pascal
y = u(2);           % valve displacement in m
P = u(3);           % pressure in brake chamber in Pa (system variable)
% To find the valve orifice area A_v
Av = abs(y)*h;      % valve orifice area in m^2
% Remember there are two pressures that can drive the flow
% if the valve displacement is positive then the supply pressure
% is driving the flow, otherwise it is the atm pressure
if y > 0
Pdriving = P_s;           % Supply Pressure is driving the flow
else
Pdriving = P_atm;         % Atmospheric Pressure is driving the flow
end

% critical pressure ratio
Cr  =(2/(gamma+1))^(gamma/(gamma-1));  % = 0.528 for air
PR = P/Pdriving;          % pressure ratio downstream/upstream
% After determining the critical pressure ratio and the down/up stream
ratios
% we must compute whether the flow is chocked or not
% mass flow rate equations for compressible flow in kg/s
if PR > Cr
% flow is "unchocked"
w = sign(Pdriving-P)*Cd*Av*Pdriving*sqrt(((2*gamma/(gamma-
1))/(R*T))*(PR^(2/gamma)...
- PR^((gamma+1)/gamma)));
else
% flow is choked
```

```
w = sign(Pdriving-
P)*Cd*Av*Pdriving*sqrt((gamma/(R*T))*Cr^((gamma+1)/gamma));
end
 end
```

The next Subsystem is the pneumatic system, it has four inputs: the mass flow rate, the piston displacement, the piston velocity, and chamber pressure. Combine these inputs using the mux block and use the interpreted MATLAB Fcn for the $\dot{P}$ as it is also given in a complicated equation. Then use the Limited integration Block to apply limits from 0 to infinity for pressure (so that the pressure is never negative). The initial condition for pressure is the atmospheric pressure. The diagram is given below.

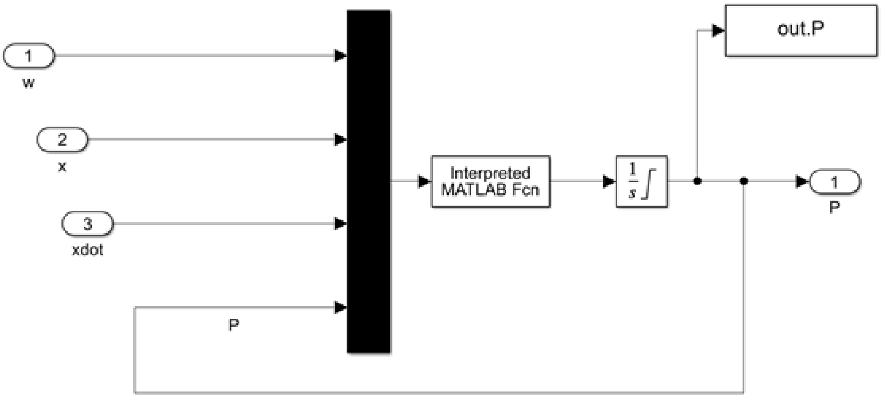


Figure 11 Pneumatic Subsystem

```
% this script solves the equation for (P-dot) the pressure change rate
% Inputs:
% w = mass-flow rate (kg/s)
% x = diaphragm displacement in m
% xdot = diaphragm velocity in m/s
% P = brake chamber pressure in Pascal
% Output: Pdot Pa/s
%
function Pdot = chamberPdot(u)
% Parameters
Ab = 0.0129;                 % diaphragm area m^2
V0 = 1.64e-4;                % initial volume of the chamber m^3
R = 287;                     % air gas constant N-m/kg-K
n = 1;                       % polytropic expansion index
T = 298;                     % air temperature in K
```

```
% system inputs
w = u(1);                     % mass flow rate kg/s
x = u(2);                      % piston displacement in m
xdot = u(3);                  % piston velocity in m/s
P = u(4);                     % brake chamber pressure in Pascal
V = V0 + Ab*x;                % brake chamber volume formula in m^3
Vdot = Ab*xdot;               % Volume change rate in m^3/s
% pdot formula in Pa/s
Pdot = ((w*R*T)/V)-((P*Vdot)/V);
end
```

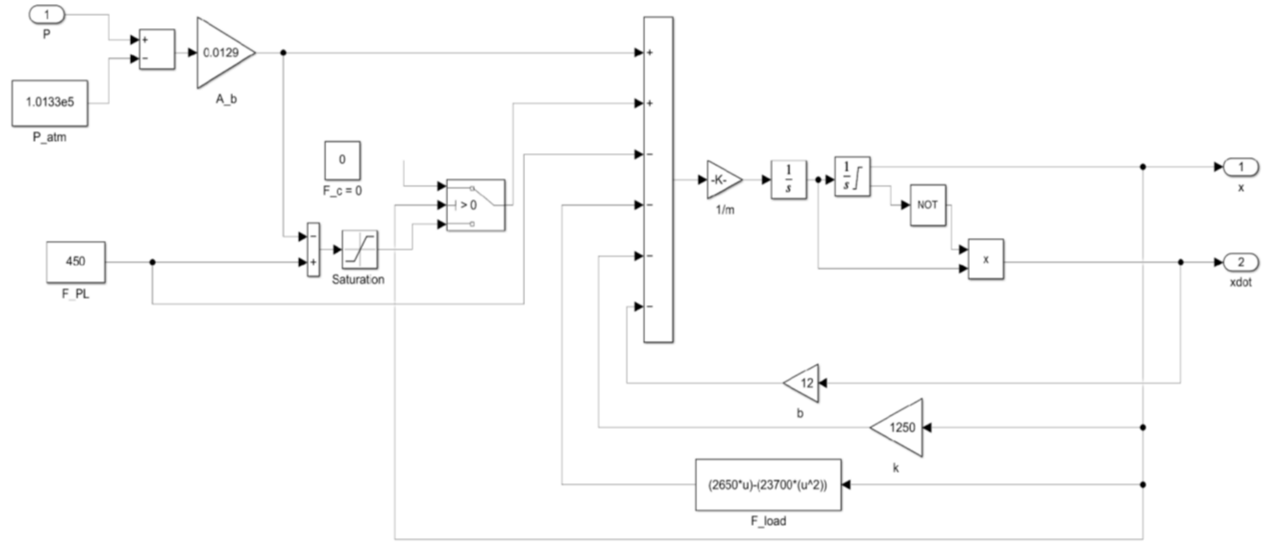


Figure 12 Mechanical subsystem for the pneumatic air brake

Figure 12 shows the mechanical subsystem. The inputs can be deduced from the model; $(P-P_{atm})A_b$, Preload force, contact force and load force. Therefore, we construct our model accordingly. We add the constant blocks for the atmospheric pressure, the preload force and contact force (the zero value). The contact force has two conditions, recall that x can either be positive or zero, so saturation is added with the limit between 0 to infinity. A switch is added to be able to compute the correct value of contact force F_c. When x=0 then the contact force is the difference between the force due to the Pressure and the preload force. When x > 0 contact force is zero. The connections between the block are as shown in the figure. Using the Subtract block from the Math operations library, we can sum the inputs. Then multiply (using the gain block) by 1/m which will give the $\ddot{x}$. To get x, integrate twice, however in the second integration, use a limited integration because as mentioned previously x cannot be negative so the lower limit is 0 and the upper limit is 0.04 m which is the maximum rod stroke. By applying this upper limit to x, the velocity $\dot{x}$ should be zero at the maximum value of x, to apply this, the saturation port of the limited integral is allowed so that it is connected to the logical operator from the Logic and Bit operations library. The NOT Boolean operation is selected which outputs 0 (false) or 1 (true). The reason we add this block is that we need a signal to indicate whether the displacement x has reached its limit or not. When x is at the maximum value (0.04) the NOT operator will produce zero. When x is not maximum, it will have a value of 1. If we multiply this Binary result with $\dot{x}$, the velocity will be zero when the displacement is 0.04. This operation of making the velocity zero at the maximum displacement value is called the hard stop. **[18]**

Simulation Results

After constructing the Simulink models, displacement, chamber pressure and mass flow rate simulations are done in MATLAB. The figures are shown below. The response for the displacement is expected to have oscillations and converge to 0.04m as t goes to infinity. The first graph shows the simulation of displacement x in time. The graph has three oscillations and as expected has the maximum value of 0.04 m at t=0.71s. It took 0.21s after the step input (at 0.5 s) to reach the peak.

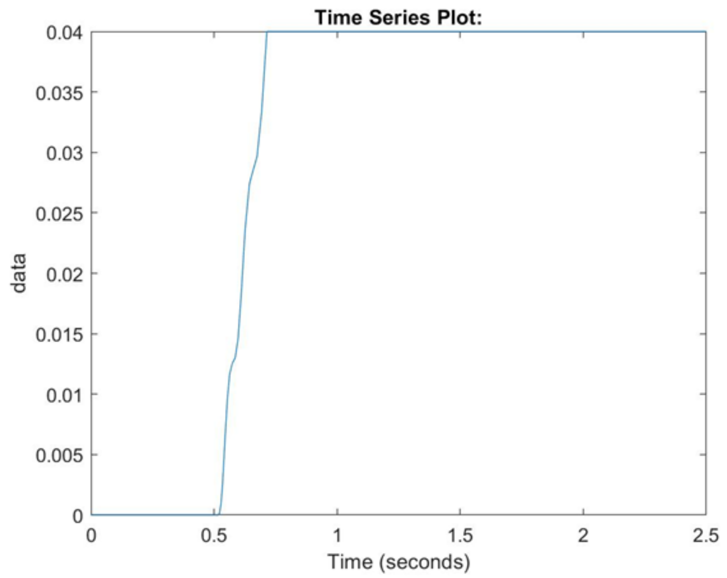


Figure 13 Piston displacement x

The next graph is for the simulation of chamber pressure. It also exhibits oscillations as the displacement does. It reaches a steady state pressure of around $5.84(10^5)$ Pa. Oscillations stop when the displacement reaches a steady value (hard stop). The constant pressure signals that there is no flow so at this instant we expect the mass flow rate to be zero.

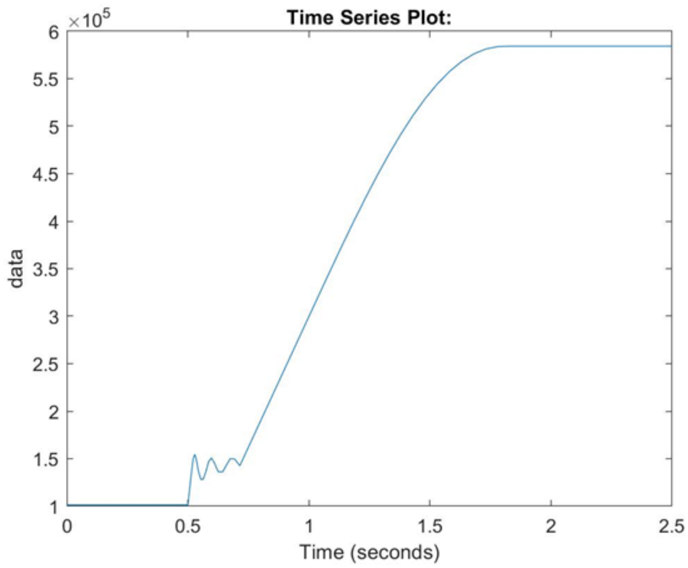


Figure 14 Chamber Pressure P

The final graph can be seen below simulating the mass flow rate. The flow is chocked at the beginning (until the final displacement is reached). Recall that the pressure at which the flow becomes chocked is equal to $0.528P_S$ and is equal to $3.084(10^5)$ this happens at around 1.02s therefore at this time the flow is expected to become unchocked. The mass flow rate begins at a maximum value of 0.00438 kg/s. At time 1.02 s the flow becomes unchocked and the mass flow rate starts decreasing. At the time mass flow rate is constant the pressure is also increasing at a constant rate (P' is constant). At time 1.82s the mass flow rate becomes zero, which is the exact time the pressure reaches its steady state value. At this time the pressure is no longer driving the flow, so w becomes zero.

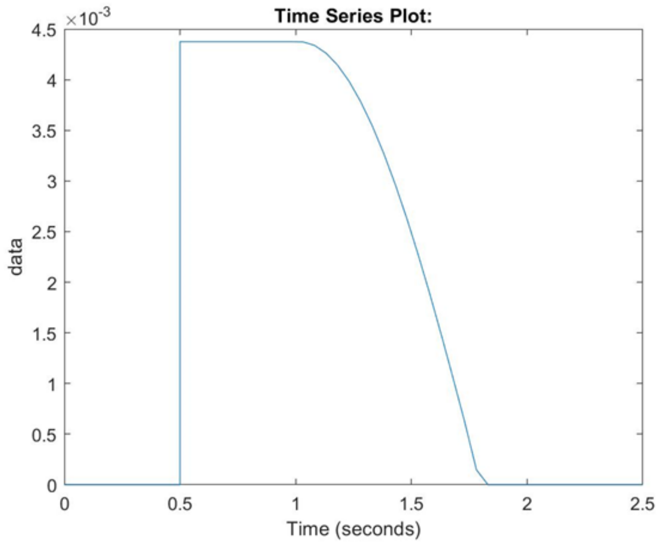


Figure 15 Mass Flow Rate w

Simscape modeling

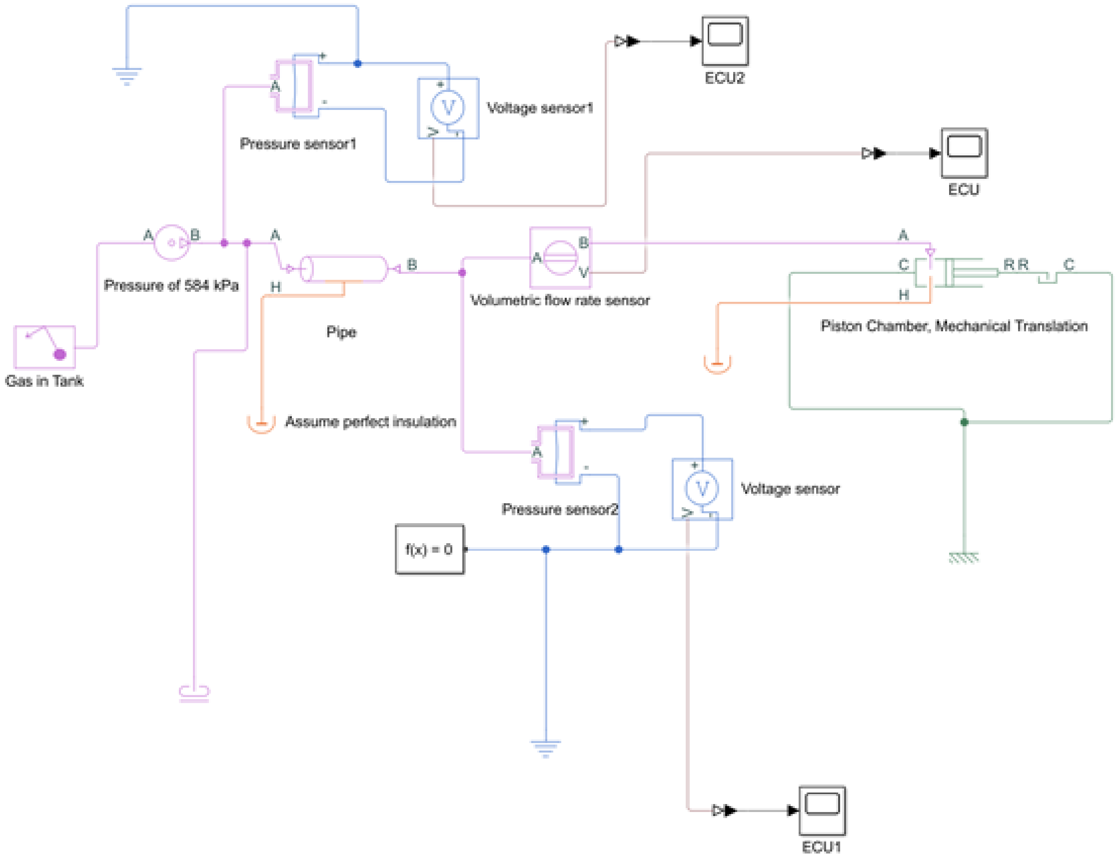


Figure 16 Simscape Model

The purpose of simscape modeling is that it provides a better understanding of the system and outlines the sensors locations. The scope represents the ECU of a car. The pressure sensor -1- is mounted in the air tank. It reports the leakage from the tank to the ECU. Leakage in the air tank is usually the most dangerous, therefore, the ECU will report an error on the dashboard and activate the safety brakes to stop the car completely. The pressure sensing is modelled as follows; pressure sensor reading the pressure alterations and converting them into electrical voltage. This voltage difference is sensed using a voltage sensor. The voltage is converted into signals that reach the ECU. When the pressure is lower than 584 kPa, then leakage is present. The next pressure sensor is just before the air enters the chamber, which detects leakage from pipes. The sensor will send signals to the ECU so that pressure from supply is increased. A warning should be present on the dashboard. To check whether there is flow, a flow sensor is added.

Flow Rate Volumes of Gases

Measures to save energy and ensure quality in the production process are particularly important in industrial processes. The ability to precisely measure the volumetric flow rates and the volumetric flow of gases plays an important role in this. The flow rate sensor used for this must be able to give precise measurement results for different gases at high extreme pressures and wide temperature ranges. It must also be able to do this in the most difficult environmental conditions such as explosive areas and open air. Another criterion involved in the selection of a suitable sensor is the prevention of maintenance and the associated high secondary costs. Ease of installation and ensuring reliable measurement values are important.**[6]**

Sensors

Sensors Working Principle

Sensors are devices that transform or transduce physical quantities such as pressure or acceleration into output signals which are usually electric that serve as inputs for control systems. Generally, a sensor is a device that receives a stimulus and response with an electrical signal.

Figure 17 Signal Transform

Furthermore, a sensor acquires a physical quantity and converts it into a signal that is suitable for processing and regarding the sensor, the transducer is an active element of the sensor.

The transducer is a device that converts one form of energy to another and may be used as actuators in various systems. The actuator is the reverse of the sensor which converts electrical signal into generally nonelectrical energy.

There are two types of sensors which are direct and complex, the direct sensor converts a stimulus into an electrical signal, or it modifies an electrical signal by using an appropriate physical effect. The figure below shows the diagram of a direct sensor.

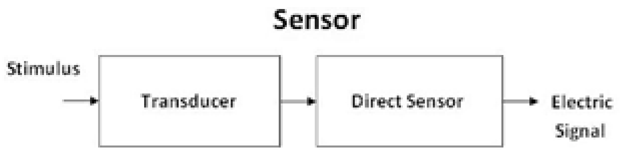


Figure 18 Diagram of a Direct Sensor

The complex sensor needs one or more transducers of energy before a direct sensor can be applied to generate the electrical output. The figure below illustrates the transducers of various types of energy in a sensor system of a complex sensor.

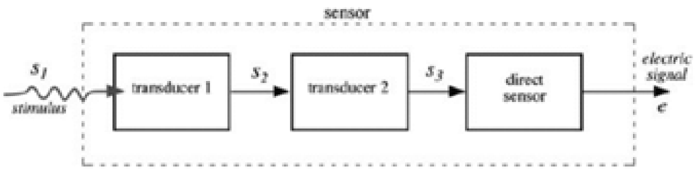


Figure 19 Complex Sensor Diagram

Further in inspecting the working principle of the sensor, it can be classified as a passive or active sensor.

The passive sensor does not need any additional energy source and directly generates electric signals in response to an external stimulus and it targets data through the detection of vibrations, light, radiation, heat or other phenomena and the thermocouple, photodiode and piezoelectric sensors are an example of the passive sensors.

Unlike passive sensors, the active sensors require external power for their operation that is called excitation signal. The excitation signal is modified by the sensor to produce the output signal and the thermistor, resistive strain gauge and X-ray machine are an example of the active sensors.

Moreover, the sensors also can be classified as an absolute or relative sensor. The absolute sensor detects a stimulus in reference to an absolute physical scale that is independent of the measurement conditions. The relative sensor produces a signal that relates to some special case.

Due to many stimuli that cannot be converted into electricity because of the sensor's types and classifications, it requires multiple conversion steps in order to send the signals.

Sensors react to changing physical conditions by altering their electrical properties. Thus, most artificial sensors rely on electronic systems to capture, analyze and relay information about the environment. These electronic systems rely on the same principles as electrical circuits to work, so the ability to control the flow of electrical energy is very important.

Put simply, a sensor converts stimuli such as heat, light, sound and motion into electrical signals. These signals are passed through an interface that converts them into a binary code and passes this on to a computer to be processed.

Many sensors act as a switch, controlling the flow of electric charges through the circuit. Switches are an important part of electronics as they change the state of the circuit. Components of sensors such as integrated circuits (chips), transistors and diodes all contain semiconducting material and are included in the sensor circuits so that they act as switches. For example, a transistor works by using a small electrical current in one part of the circuit to switch on a large electrical current in another part of the circuit.[28]

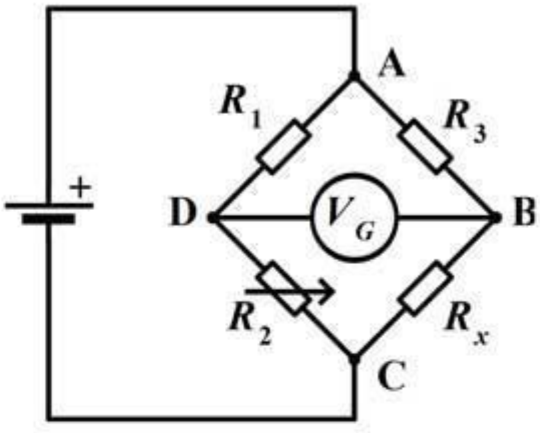
Working principle of Pressure Sensors

Over the past decades the demand for the pressure measuring instruments has increased significantly. During the manufacturing of the pressure sensing technologies they were mechanical and originally used in Bourdon tube gauges to move a needle and give a visual indication of pressure. Nowadays the measurement of the pressure is applied electronically using pressure transducers and pressure switches. Common uses of the in the automotive industries, Biomedical Instrumentation, aviation and the marine industry.

Pressure transducers have a sensing element of constant area and respond to force applied to this area by fluid pressure. The force applied will deflect the diaphragm inside the pressure transducer. The deflection of the internal diaphragm is measured and converted into an electrical output. This allows the pressure to be monitored by microprocessors, programmable controllers and computers along with similar electronic instruments.[29]

Due to the huge variety of the pressure sensors there are different working principles on such different pressure sensors.

- Strain gauge-based pressure sensors also use a pressure sensitive element where metal strain gauges are glued on or thin film gauges are applied on by sputtering. This measuring element can either be a diaphragm or for metal foil gauges measuring bodies in can-type can also be used. The big advantages of this monolithic can-type design are an improved rigidity and the capability to measure the highest pressures of up to 15,000 bar. The electrical connection is normally done via a Wheatstone bridge which allows for a good amplification of the signal and precise and constant measuring results. See our offer of strain gauge-based pressure sensors.It is one of the most used signal conditioning circuit which is used to convert a resistance change to a voltage change as derived in the Figure 20



$$At\ balance\ R_b = R_d$$

$$Also, R_b = \frac{R_2}{R_1 + R_2} \quad and \quad R_d = \frac{R_x}{R_3 + R_x}$$

$$Therefore\ at\ balance, \frac{R_2}{R_1+R_2} = \frac{R_x}{R_3+R_x}$$

$$Rearranging, \quad R_x = \frac{R_2 R_3}{R_1}$$

Figure 20 Wheatstone bridge

- Capacitive pressure sensors use a pressure cavity and diaphragm to produce a variable capacitor. The diaphragm is deformed when pressure is applied, and capacitance decreases accordingly. This change in capacity can be measured electrically and is then set in relation to the applied pressure. These sensors are limited to low pressures of roughly 40 bar.
- Piezo-resistive pressure sensors consist of a diaphragm – mostly made of silicon – with integrated strain gauges to detect strain as a result of applied pressure. These strain gauges are typically configured in a Wheatstone bridge circuit to reduce sensitivity and increase the output. Due to the material being used the pressure limitation is at around 1,000 bars.

- Resonant pressure sensors use the changes in resonance frequency in a sensing mechanism to measure stress caused by applied pressure. Depending on the design of these sensors, the resonating element can be exposed to the media, where the resonance frequency then depends on the density of the media. Sometimes these sensors are also sensitive to shocks and vibration.[30]

Working principle of Flow Sensors

Prime considerations when selecting a flow sensor include: the type of fluid being measured, its temperature and pressure, viscosity, conductivity, corrosiveness, and cleanliness.

Flow sensors can be divided into two groups: contact and non-contact flow sensors. Contact flow sensors are used in applications where the liquid or gas measured is not expected to become clogged in the pipe when it meets the sensor's moving parts. In contrast, non-contact flow sensors have no moving parts, and they are generally used when the liquid or gas (generally a food product) being monitored would be otherwise contaminated or physically altered by encountering moving parts.

The two most common types of contact flow sensors are vortex and mechanical flow sensors. Vortex flow sensors consist of a small latch (known as the "buff body") that flexes back and forward when encountering a flowing liquid or gas. The differences in pressure (i.e. the vortices) generated by the latch are measured to determine the flow rate. Mechanical flow sensors use propellers that spin at a rate that is directly proportional to the flow rate as illustrated in the figure below. Mechanical flow sensors can also be controlled to cause the flow rate to increase or decrease.

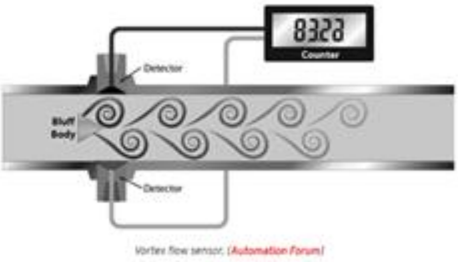


Figure 21 Mechanical Flow Sensor

Ultrasonic flow sensors are the most popular type of non-contact flow sensor. Ultrasonic flow sensors send pulses of high frequency sound across the flowing liquid or gas medium. These sensors measure the time between the emission of the sound and its contact with the sensor's receiver to determine the flow rate of the gas or liquid.[31]

Sensors from the Industry

1. SS 20.600 Air Flow Sensor

Figure 22 SS 20.600 Air Flow Sensor

The "true professional" for industrial processes and pneumatic technologies.
The Thermal SCHMIDT ® Flow Sensor SS 20.600 offers the perfect solution for demanding industrial applications. It can be used for gas monitoring in process burners, compressed air monitoring, consumption recording of gases and much more.
Installation of this sensor; Screw the sensor to the pipe with the compression fitting provided with the sensor, align the sensor by centering it in the gas flow and connect the electrical wiring. This sensor does not contain any moving parts, therefore the sensor requires little maintenance. From time to time, depending on contamination in the environment, the sensor tip may need to be flushed with air or rinsing with water. **[6]**

Air leak measurement
- Measurement possibility up to 0.2 m / s
- Does not experience slippage depending on the age of the product. **[6]**

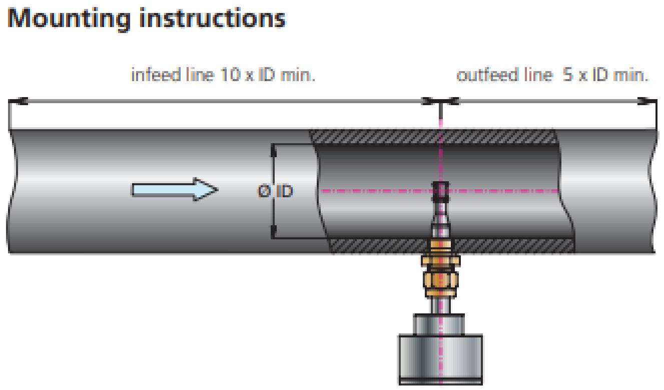


Figure 23 Mounting Instructions

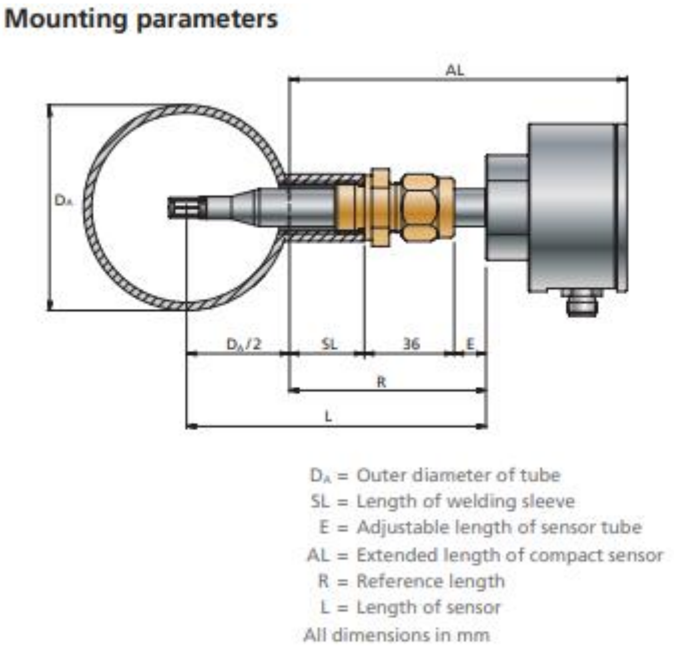


Figure 24 Mounting Parameters

Electrical Connection

Number of connection pins:	8 (plus shield connection at the metallic housing)
Type:	Male
Fixation of connecting cable:	M12 thread (spigot nut at the cable)
Type of protection:	IP67 (with screwed cable)
Model:	Binder, series 763
Pin numbering:	

View of plug-in connector of the sensor

Figure 4-1

The pin assignment of the plug-in connector can be seen from the following Table

Pin	Designation	Function	Wire color
1	Pulse 1	Output signal Flow (digital: Impulse)	White
2	U_B	Operating voltage: 24 V_{DC} ± 20%	Brown
3	Analog T_M	Output signal Temperature of medium (analog: U / I)	Green
4	Analog w_N	Output signal Flow (analog: U / I)	Yellow
5	AGND	Reference potential for analog outputs	Gray
6	Pulse 2	Galvanically decoupled pulse output (relay)	Pink
7	GND	Operating voltage: Ground	Blue
8	Pulse 2	Galvanically decoupled pulse output (relay)	Red
	Shield	Electromechanical shielding	Meshwork

Table

The analog signals have an own AGND reference potential.

Figure 25 Electrical Connection

The sensor must be operated only with the original connecting cable by SCHMIDT Technology.

“ In order for the sensor to operate in accordance with its specified use, the permissible ± requires a DC voltage of 24 VDC nominal value with a tolerance of 20%. Different values can lead to measurement errors and even defects, and therefore should be avoided.

Operate the sensor only within the defined voltage range (24 VDC ± 20%) Low voltage can cause failure; overvoltage can cause irreversible damage. “ [32]

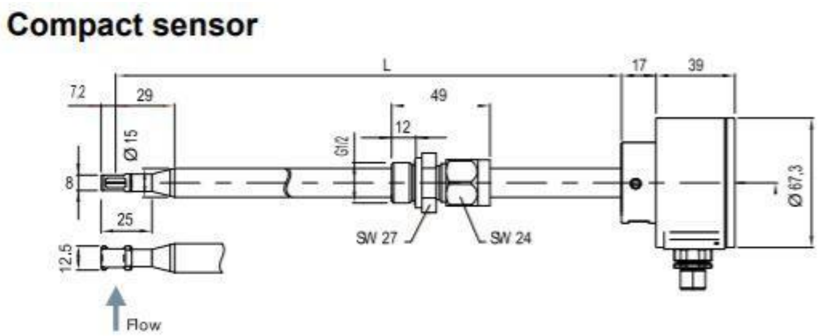


Figure 26 Technical Drawing of flow sensor

Technical Datasheet of SS 20.600 Air Flow Sensor

Table 2 Technical Datasheet of flow sensor

Properties	Values
Medium to be measured	Standard: Air or nitrogen Optional: natural gas, biogas, CO2 and special gases or gas mixtures
Lower detection limit wN	0.2 m/s
High precision wN	± 1 % of measured value + (0.4 % of final value; min. 0.08 m/s) 21 (only for air, nitrogen, oxygen)
Electronics operating temp	- 20 … + 70 °C
Sensor tube material	Stainless steel 1.4571
Humidity range	0 … 95 % rel. humidity, non-condensing
Operating pressure (max.)	Standard version: 16 bar Oxygen version: 20 bar Optional version: 40 bar
Supply voltage	24 VDC ± 20 %
Mounting tolerance	± 3° relative to flow direction
Weight	Approx. 500 g max. (without connecting cable)
Pulse outputs **- Signaling:** **- Pulse output 1:** **- Pulse output 2:**	High-side driver connected to supply voltage (without galvanic separation) High level: > supply voltage - 3 V Short circuit current limitation: 100 mA Leakage current: IOff < 10 µA

	Semiconductor relay (output galvanically separated) max. 30 VDC / 21 VAC,eff / 50 mA
Measuring accuracy TM	± 1 K (10 ... 30 °C); ± 2 K remaining measuring range @ wN > 5 m/s
Response time (t90) wN	1 s (jump from 0 to 5 m/s in air)

2. P2VA1 / P2VA2 Pressure Transducers

Figure 27 P2VA1/P2VA2 Transducers

These conform to TEDS transducer definition; Featuring integral, high quality and low noise amplifier; It is a pressure transducer used for high pressures. Like the P3MBP BlueLine series, these transducers have a monolithic (one-piece) steel measuring body in their core.
It has maximum reliability and durability under heavy dynamic loads as there are no welds or clamping points in its housings. This feature comes to the fore especially when used at high pressures; When used for long periods, sensor technology often needs to be upgraded.
In addition, P2VA1 / P2VA2 transducers contain high quality and low noise amplifiers. This amplifier also meets the TEDS transducer definition. Thus, the most important data are stored electronically in the transducer. P2VA1 / P2VA2 are suitable for use in many areas from hydraulics to gases. They can be used for precise analysis of production processes as well as for fast control loops where even short pressure peaks can be addressed completely. It is designed for higher measuring ranges and high pressure applications, such as water supply and internal high pressure forming. The high accuracy of the P2VA1 / P2VA2 improves the processing qualities, feed rates and seal wear of water supply equipment.**[8]**

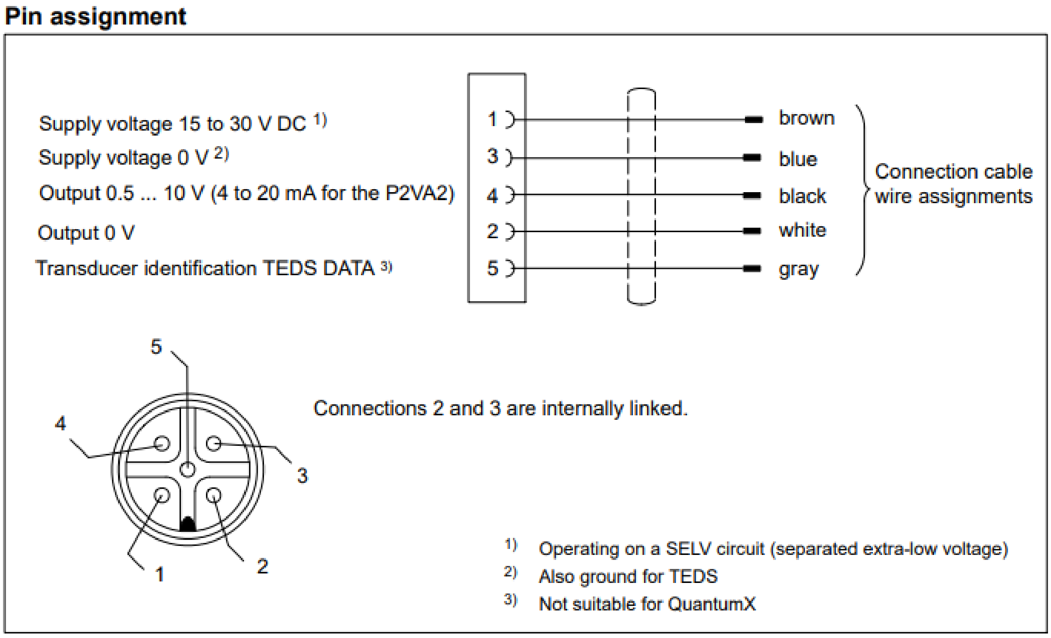


Figure 28 Pin Assignment of P2VA1/P2VA2

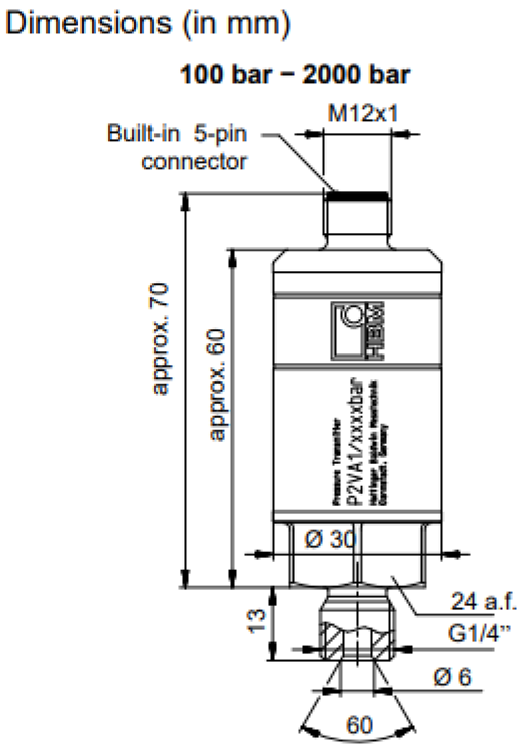


Figure 29 Dimensions of P2VA1/P2VA2

Technical Dimensions of P2VA1/P2VA2 Pressure Transmitter is shown in Figure 29.

3. HAF Zephyr Digital and Analog Airflow Sensors

Figure 30 HAF Airflow Sensors

Honeywell HAF Zephyr ™ Digital Air Flow Sensors provide accuracy and high precision for precise measurements of airflow (or no airflow) and other non-corrosive gases in industrial and medical applications. Honeywell HAF Sensors have high stability to reduce errors due to thermal effects and zero drift to avoid false readings over time. High stability, often eliminating the need for system calibration after PCB assembly and periodically over time. **[14]**

Table 3 Operating Characteristics

Characteristic	Parameter	Note
Supply voltage	3.3 Vdc ±10%; 5.0 Vdc ±10%	–
Current draw	16 mA max. (no load)	–
Power: 3.3 Vdc 5.0 Vdc	 40 mW typ. (no load) 55 mW typ. (no load)	–
Operating temperature range	-20 °C to 70 °C [-4 °F to 158 °F]	–
Compensated temperature range	0 °C to 50 °C [32 °F to 122 °F]	1
Accuracy: forward flow reverse flow	 ±0.25% FSS or ±2.5% Reading, whichever is greater ±0.25% FSS or ±15% Reading, whichever is greater	2, 4
Total error band: forward flow: reverse flow:	 ±0.25% FSS or ±4.5% Reading, whichever is greater ±0.25% FSS or ±15% Reading, whichever is greater	3, 4
Null accuracy	±0.08 %FSS	4, 8
Response time	1 ms typ.	5
Resolution	11 bit	–
Warm up time	15 ms	6
Calibration media	gaseous nitrogen	7
Null stability	±0.06 FSS max. deviation from null output after 1000 hrs at 25 °C	–
Reverse polarity protection	no	–

4. AWM Air Flow Sensors

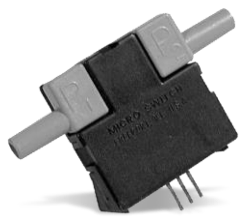


Figure 31 AWM Air Flow Sensors

Honeywell Detection and Control AWM Airflow Sensors include a variety of compact sensors that offer fast response time to detect full flow events. All sensors have analog outputs. Honeywell Detection and Control AWM Airflow Sensors have low power consumption, making them suitable for use in portable devices as well as in battery-powered systems.**[13]**

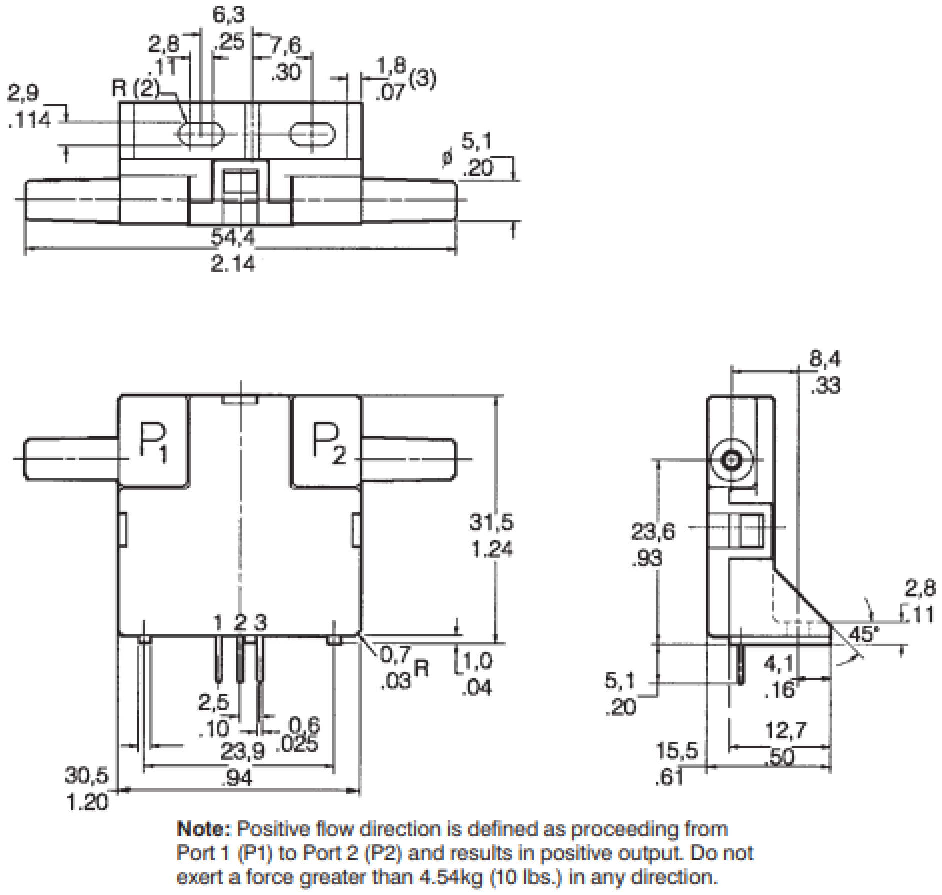


Figure 32 Mounting Dimensions

Specification

Table 4 Specification of AWM3000 Air Flow Sensors

Shock	• 100 g peak (5 drops, 6 axes)
Operating Temperature	• -25°C to 85°C [-13°F to 185°F]
Flow/Pressure Range	• ±5.0 mbar [2.0 in H20] • +200 SLPM • 0 mbar to 1.25 mbar [0 H20 to 0.5 H20] • +30.0 sccm • 0 mbar to 5.0 mbar [0 H20 to 2.0 H20] • ±1000 sccm (1 SLPM)
Output Voltage at Trim Point	• 5.0 Vdc at 200 sccm • 20.0 mA dc ±1 mA dc • 20.0 mA dc ±1.0 mA dc • 5.0 Vdc at 2.0 in water • 5.0 Vdc at 1000 sccm (1.0 SLPM) • 3.4 Vdc at 25 sccm • 5.0 Vdc ±0.15 Vdc
Compensated Temperature	• -25°C to 85°C [-13°F to 185°F]
Response Time	• 1 ms typ., 3 ms max. • 3 ms max. • 60 ms max.

Port Style	• Straight
Common Mode Pressure	• 25 psi
Null Offset	• 1 Vdc ±0.10 Vdc • 4 mA dc ±0.3 mA dc • 1 Vdc ±0.05 Vdc • 4 mA dc ±0.4 mA dc • 1 Vdc ±0.08 Vdc • 3 Vdc ±0.050 Vdc
Weight	• 10.8 g
UNSPSC Commodity	• 41111931 Flow Sensors
Repeatability	• ±0.50 % Reading • ±1 % Reading
Media Compatibility	• Dry gas only
Signal Conditioning	• Amplified
Supply Voltage	• 8.0 Vdc to 15.0 Vdc • 8.0 Vdc min., 10.0 Vdc typ., 15.0

	Vdc max. • 10.0 Vdc ±0.01 Vdc
Series Name	• AWM3000
Power Consumption	• 50 mW typ. • 50 mW typ., 60 mW max. • 100 mW typ.
Null Shift over Temperature	• ±2.0 mA dc max. • ±100 mV dc • ±25.0 mV dc • ±0.050 Vdc max.
Output Shift over Temperature	• ±24 % Reading • ±4 % Full Scale • - 31% Reading to 24% Reading • ±5 % Reading • ±32 % Reading
Storage Temperature	• -40°C to 90°C [-40°F to 194°F]

5. CS-V2-2016 Pressure Sensor

Figure 33 CS-V2-2016 Pressure Sensor

Applications

- Constructing machines
- Machine tools
- Control and measurement
- Pneumatic and Hydraulic Systems
- Compressors and pumps **[20]**

Technical Data Sheet of CS-V2-2016 Pressure Sensor

Table 5 Properties of CS-V2-2016 Pressure Sensor

Housing	316L
Non-linearity	0.5 BFSL
Parameter	Bar
Type of Pressure	Relative, absolute and vacuum
Range	0…16 bar, 32 bar overpressure limit
Process connections	G 1/4A according to DIN 3852-E

Sealing	NBR
Permissible temperature	0…+80 °C
Output signal	4…20 mA, 2-Leiter
Power supply	8…30 VDC
Accuracy	< ±1 % of span (optionally < ±0,5 % of span)
Electrical Connection	Angular connector DIN EN 175301-803 A, ingress protection IP 65, wire cross-section up to max. 1.5 mm², cable diameter: 6…8 mm
Weight	80 g

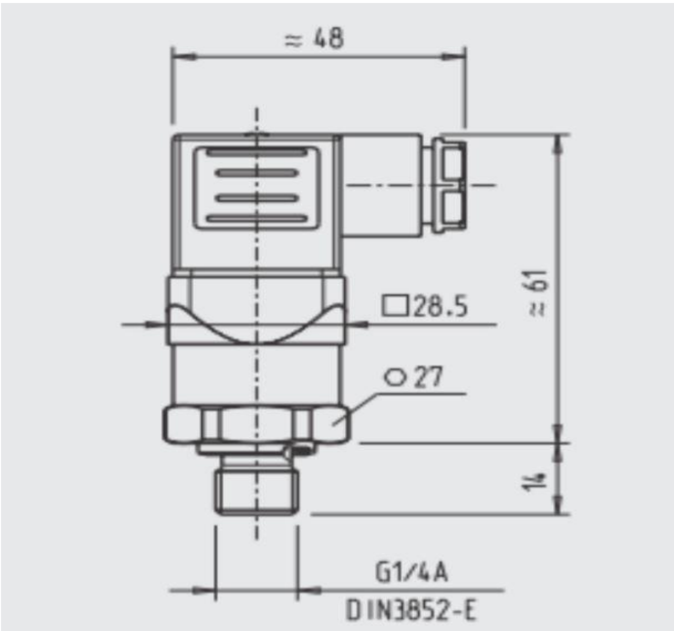


Figure 34 Technical Drawing

Electrical Connection

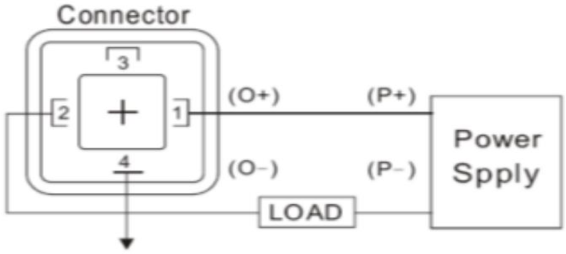


Figure 35 Electrical Connection of CS Pressure Sensor

The electrical connection of CS-V2-2016 Pressure Sensor is shown in Figure 35.

6. P1A Pressure Sensor:

Figure 36 P1A Pressure Sensor

P1A features a highly modular compact geometry, and it features outstanding shock and vibration performance, impressive lon

P1A features a highly modular compevity and lifetime performance and high quality over the long run. It’s made from 304 stainless steel, and the pressure ranges from to 0.25 up to 0 to 16 bar (gage), and 0 to 1.6 up to 0 to 16 bar (absolute), and -1 to 0 up to -1 to 0 bar (gage)

Technical Data Sheet of P1A Pressure Sensor

Table 6 Technical Data Sheet of P1A sensor

Properties	Values
Pressure Ranges	0 to 0.25 up to 0 to 16 bar (gage) 0 to 1.6 up to 0 to 16 bar (absolute) -1 to 0 up to -1 to 0 bar (gage) *
Electrical Connection	Packard Electric Metri-Pack 150 Series *

Pressure Connection	G1/4A DIN 3852-E, 1/4 - 1/8 NPTF *
Housing Material	304 Stainless Steel (1.4301)
Connector Material	PBT (30% Glass Fibre)
Output Signal	4 - 20 mA, 0.5 - 4.5 VDC, 0 - 5 VDC, 0 - 10 VDC
Operating Life Cycle	min. 10 million full pressure cycles over the full range
Vibration Resistance	IEC 60068-2-64 (RANDOM) 20 PSD
Shock Resistance	100 g minimum according to DIN EN 60068-2-27
Weight	≤ 50 grams
Environmental Temperature	-30°C to + 100°C (depending on internal and external seal ring capability
Accuracy	≤ 1 % of span
Non-linearity	0.2 % of span
Power Consumption	≤ 600 mW
Insulation Voltage	500 VDC
Response Time	≤ 5 ms max. to 63% of full scale pressure with step change on input

Other Attributes:

- Small Compact Size
- Highly Modular Product Configurations
- Kavlico Ceramic Capacitive Technology Outstanding Long Term Stability and Performance
- Vacuum to 16 Bar Gage and Absolute
- Media Resistant CCAP Technology **[19]**

Figure 37 Technical Data Sheet of P1A sensor

Pressure Sensor with Electrical Connection

M12 Pin Call Outs				
Output	Pin 1	Pin 2	Pin 3	Pin 4
4-20 mA	Vsup	...	Iout	...
0.5-4.5 VDC ratiometric	Vsup	...	Vout	GND
0-5 VDC 0-10 VDC	Vsup	...	Vout	GND

18 mm Pin Call Outs				
Output	Pin 1	Pin 2	Pin 3	Pin 4
4-20 mA	Vsup	Iout	...	...
0.5-4.5 VDC ratiometric	Vsup	Vout	GND	...
0-5 VDC 0-10 VDC	Vsup	Vout	GND	...

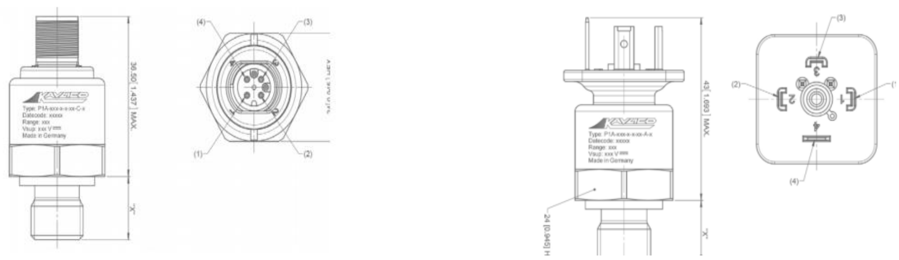


Figure 38 Electrical Connection of P1A Pressure Sensor

High-level systems such as ABS, EBS, TEBS are now used in heavy vehicles. Most important of all, thanks to the sensors that note the pressure changes, all the above-mentioned apparatus transmit the error reports to the driver display. In addition, with the help of brake diagnostic tools, all the disruptions in the brake system can be detected with a single tool**. [9]**

Sensor calibration:

It is simply a set of adjustments performed on a sensor to make sure that it is working properly and as accurately as possible and for it to be error free, errors in sensors are the algebraic difference between the actual value and the one indicated, errors can be caused by many factors. For example, Error due to Improper Zero Reference, Error due to Shift in Sensor's Range, Error due to Mechanical Wear or Damage.[21]

Pressure sensor calibration:

The pressure sensor is a mechanism that changes pressure into an electrical signal. That electrical signal will only benefit us if it accurately represents the pressure supplied to the sensor. Calibration is the process by which the sensor electrical signal is adjusted so that it has a known relationship to the applied pressure. After the calibration process the electrical signal can be measured and that can be used to find the pressure at the sensor.[22]

Flow sensor calibration:

The Flow sensor calibration is the process of comparing the pre-set scale of a flow sensor to a standard scale of measurement and adjusting its metering to conform to the standard. Calibration is an essential aspect of instrumentation in a broad range of industries that require high-accuracy measurements with a negligible percentage of error. [23,24]

Pressure Sensor Transfer Function

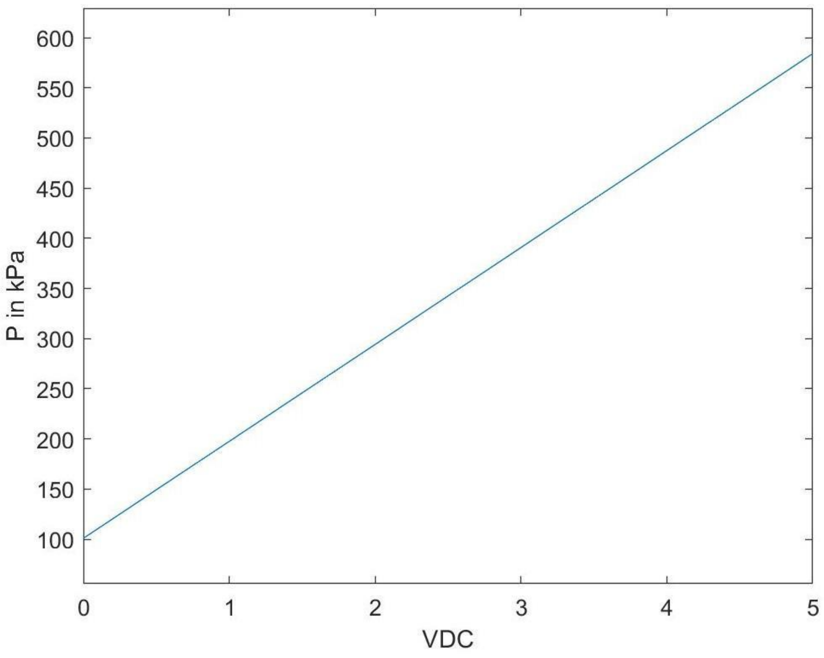


Figure 39 Pressure Sensor Transfer Function

The Figure above illustrates the transfer function of the pressure sensors used. It can be seen that the relation is linear. The minimum pressure is the atmospheric pressure. The maximum VDC is 5 signalling that the maximum pressure is reached (584 kPa).

Flow Sensor Transfer Function

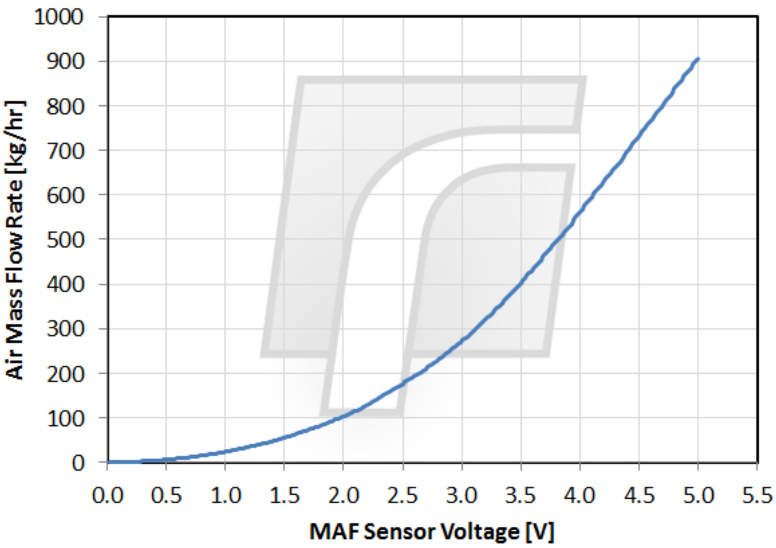


Figure 40 Flow Sensor Transfer Function

The relation in the flow sensor transfer function is nonlinear and the transfer function we used to obtain the gain resulted in a value of **0.1** based on the equation below

$$G(s) = \frac{Y(s)}{E(s)} = \frac{output}{input}$$

Simulink model with sensor

Pressure sensors exhibit a linear behavior between voltage and pressure. It is assumed that these sensors can be modelled as a linear gain to the feedback loop in the pneumatic subsystem. The system response is expected to be much faster with less noise after the inclusion of the sensor.

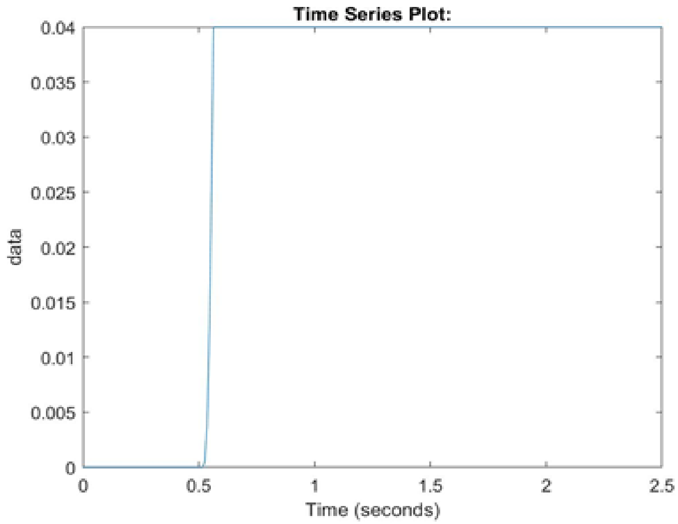


Figure 41 Piston Displacement x with Sensor

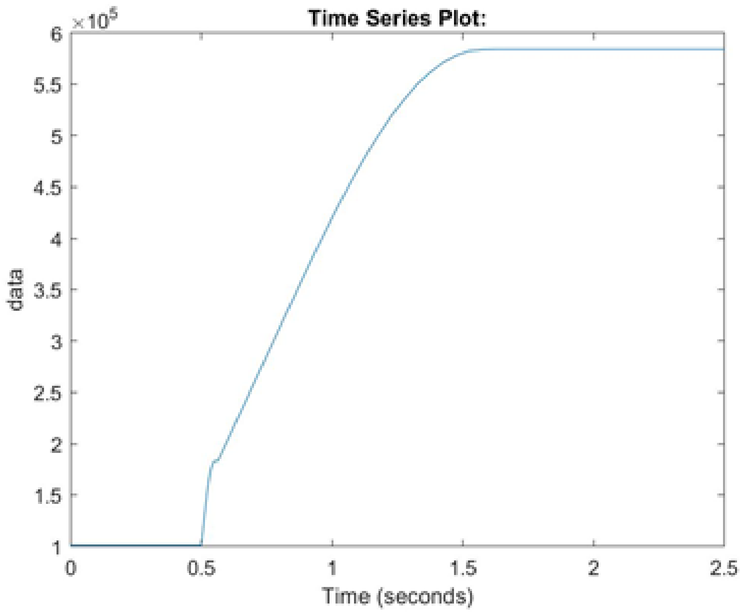


Figure 42 Chamber Pressure P with Sensor

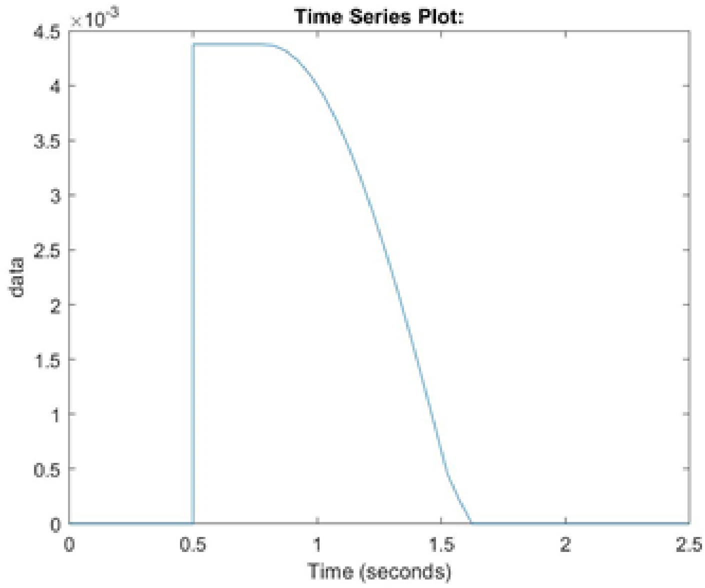


Figure 43 Mass Flow Rate

The plots above prove our concept. It can be deduced that the response has become much faster compared with the original system. Starting with the displacement plot, it can be seen that the piston is smoothly moving without any noise and reaches steady state quickly. From the pressure plot, the oscillations have been reduced significantly and the steady state value is reached in around 0.3 seconds. This has a direct effect on the mass flow rate, as can be deduced from the flow rate plot. Therefore, we can conclude our study accordingly, proving how much sensors improve the air-brake system in leakage matters and system response.

Electrical Connection

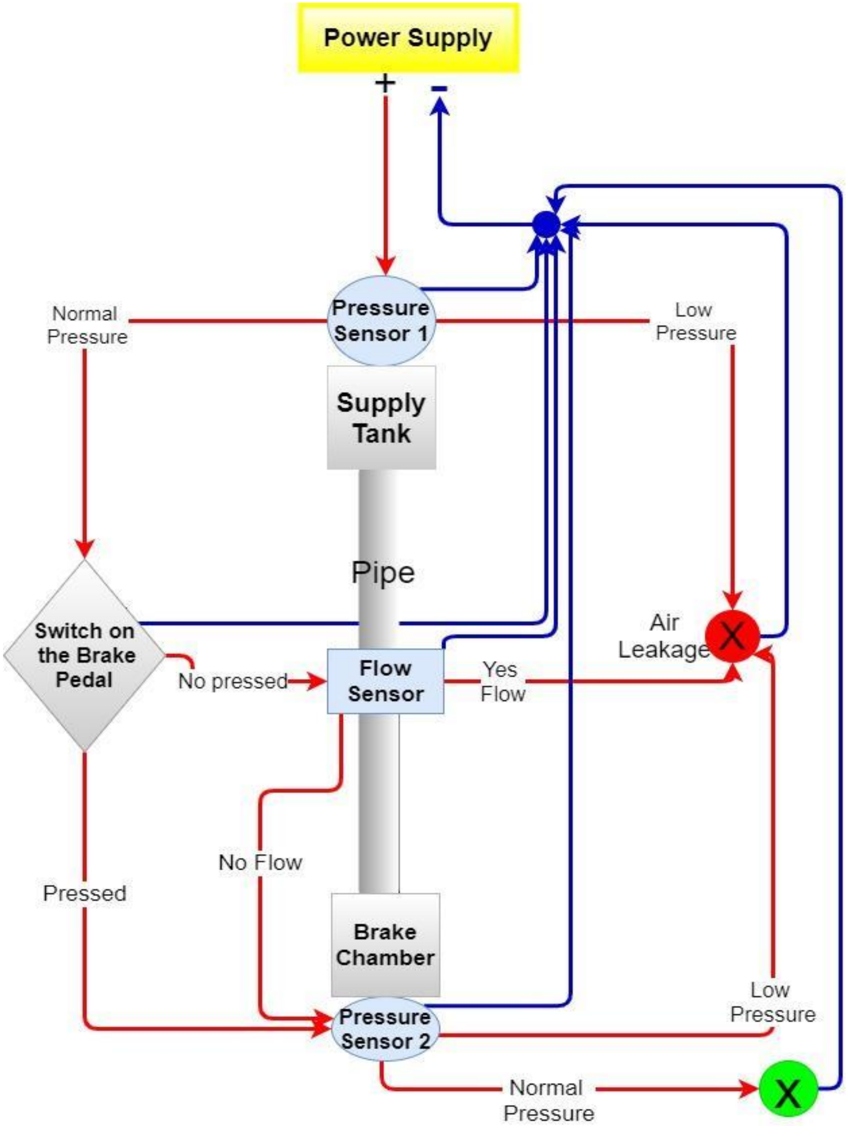


Figure 44 Electrical Circuit Diagram

As shown in Figure 44, firstly the voltage goes out from The Power Supply to The Pressure Sensor mounted on The Supply Tank. If the value on this Pressure Sensor is lower than normal, voltage goes to The Red Error Lamp. This means there is an air leak in the Supply Tank.

In case the pressure in this sensor is normal, the button mounted on the brake pedal is checked. If the button on the brake pedal is not pressed, voltage goes to The Flow Sensor and this sensor works, if there is air flow on the pipe even though the brake pedal is not pressed, The Error Lamp turns on. Because when the brake pedal is not pressed, there should be no air flow in this pipe.

In case the button on the pedal is pressed, voltage goes to the second Pressure Sensor in The Brake Chamber. In addition to this, if The Flow Sensor does not detect flow in the pipe, voltage goes to The Pressure Sensor mounted on The Brake Chamber and this sensor is checked. If the pressure in this sensor is normal, the green light will turn on. Provided that there is low pressure, the error lamp will turn on again.

The negative ends of the sensors, button(switch) and lamps are connected to the negative part of The Power Supply.

Conclusion

This study aimed to improve the pneumatic air brake system of a heavy duty truck by detecting air leakage using pressure and flow sensors. The system is composed of mechanical and pneumatic subsystems. The model was constructed using MATLAB Simulink to obtain the dynamic response. The system had some oscillations. Next, the sensors to be used were found and chosen according to their working range. After that, the chosen sensors were included into the pneumatic system model as a gain block to get the improved system response. The results showed that the oscillations were decreased significantly and the steady-state is reached faster. Finally, electrical connection to the sensors was constructed as can be seen from Figure 44 concluding this study.

Future Work

For Future work it can be concluded that with better precision and efficiency in sensors, the system will be able to operate more smoothly hence further reduction in the oscillation and a reasonable improvement in the steady state. A system can be set up and added to the project to detect where the air leak originates from.

Team Members Roles

The team includes 3 Mechanical Engineers, 1 Electrical Engineer, 1 Electrical and Electronics Engineer, and 1 Computer and Mechanical Engineer. The roles are divided up based on the engineering field requirement.

Literature search was done by all group members.

For the Mechanical Engineering part in the project, Abdullah Al Nabhani, Adnan Dalol, Muhammed Ali Servan, and Zaid Zaidan cooperate to achieve the required tasks as the project includes Mechanical Systems and Pneumatic Systems as well.

Regarding the Electrical part, Özge Hülya Durgut and Hafiz Huzaifa Azeem achieve any related tasks including the Electrical Systems.

In details, Mechanical Engineers Adnan Dalol, Muhammed Ali Servan, Zaid Zidan and Abdullah Al Nabhani were responsible of obtaining the mathematical models of the system.

Simulink modelling was done by Engineers Adnan Dalol and Hafiz Huzaifa Azeem.

Matlab codes were done by Engineer Abdullah Al Nabhani.

Block Diagrams and Electrical Circuit Design for the system and individual sensors was done by Engineer Özge Hülya Durgut.

System description and component research was done by Engineers Muhammed Ali Servan, Zaid Zidan, and Abdullah Al Nabhani.

REFERENCES

[1] Pneumatic Air Brake, Published March 11, 2018
https://www.totalgyan.com/automotive/pneumatic-air-brake-working/

[2] Pneumatic braking system, Published May 8, 2015

https://www.slideshare.net/samykw/pneumatic-braking-system

[3] The Engineer, InnovationDiscoveries.space Airbrake System: Components, Working Principle, and Applications September 30, 2019 https://innovationdiscoveries.space/air-brake-system-components-working-principle-and-applications/

[4] Mechanical Booster, Air Brake System https://www.mechanicalbooster.com/2017/12/air-brake-system.htm

[5] BOWLIN, C. L., A Pressure Control Scheme for Air Brakes in Commercial Vehicles (2005) (https://www.researchgate.net/publication/3465161_Pressure_control_scheme_for_air_brakes_in_commercial_vehicles)

[6] Marmatek SS60 Hava Akış Sensörü (https://marmatek.com/urun/hava-akis-sensoru/)

[7] Sensortek HBM P15 http://www.sensortek-hbm.com/urun/p15/

[8] Sensortek HBM P2VA1/P2VA2 (http://www.sensortek-hbm.com/urun/p2va1-p2va2/)

[9] Havalı Fren Sistemi (https://tr.wikipedia.org/wiki/Haval%C4%B1_fren_sistemi)

[10] SUBRAMANIAN, S. C., MODELING THE PNEUMATIC SUBSYSTEM OF A S-CAM AIR BRAKE SYSTEM (2003) https://core.ac.uk/download/pdf/4268216.pdf

[11] Pnömatik Havalı Fren UPF - 250
https://www.unityotomasyon.com.tr/Urun/36/pnomatik-havali-fren-upf-250.html

[12] BİLGİNER, S., Temel Pnömatik Sistemler, Endüstriyel Otomasyon, Published January 29, 2016
https://www.elektrikport.com/teknik-kutuphane/temel-pnomatik-sistemler-endustriyel-otomasyon/16968#ad-image-0

[13] Mouser Electronics, AWM730P1 Flow Sensor
https://www.mouser.com.tr/ProductDetail/Honeywell/AWM730P1?qs=HRrB3wlRWuqi6GeSjRY8og%3D%3D

[14] Mouser Electronics, HAFUHH0100L4AXT Flow Sensor
https://www.mouser.com.tr/ProductDetail/Honeywell/HAFUHH0100L4AXT?qs=xch9k0p861f7ZxFTWsSpqw%3D%3D

[15]What is the pneumatic system of an aircraft? Published May 27, 2014
https://howthingsfly.si.edu/ask-an-explainer/what-pneumatic-system-aircraft

[16] Benefits of Aircraft Pneumatic Systems
https://asc-aero.com/aircraft-pneumatic-systems/

[17] Milli Eğitim Bakanlığı, Uçak Bakım Sistemleri (2012)
http://megep.meb.gov.tr/mte_program_modul/moduller_pdf/Temel%20U%C3%A7ak%20Sistemleri.pdf

[18] Kluever, Craig, 2014, Dynamic Systems: Modeling, Simulation and Control

[19] Kavlico, P1A Pressure Sensor Data Sheet
https://www.cdiweb.com/datasheets/kavlico/p1a_data_sheet_letter.pdf

[20] CS Instruments, Pressure Sensors CS Data Sheet https://www.cs-instruments.com/fileadmin/cs-data/Datenblaetter/Data%20sheets%20-%20EN/Data_sheet_pressure_sensors_EN.pdf

[21] Sensor Calibration, Real Pars https://realpars.com/sensor-calibration/

[22] Basics of Pressure Sensor Calibration, Validyne Engineering
https://www.validyne.com/blog/basics-validyne-pressure-sensor-calibration/

[23] https://ifsolutions.com/how-do-you-calibrate-a-flow-meter/

[24] How To Calibrate a Flow Meter, Young Calibration
https://www.youngcalibration.co.uk/news/how-to-calibrate-a-flow-meter

[25] https://patentimages.storage.googleapis.com/11/73/42/64f2289c0a1e5e/US476880.pdf

[26] https://patentimages.storage.googleapis.com/8b/18/06/059bd435cede41/US705592.pdf

[27] https://patentimages.storage.googleapis.com/f8/7d/dc/92561de47048ba/US1552584.pdf

[28] Electricity and Sensors , Science Learn https://www.sciencelearn.org.nz/resources/1602-electricity-and-sensors#:~:text=How%20do%20sensors%20work%3F&text=Put%20simply%2C%20a%20sensor%20converts,a%20computer%20to%20be%20processed.

[29] Working Principle of a Pressure Sensor https://www.variohm.com/news-media/technical-blog-archive/working-principle-of-a-pressure-sensor#:~:text=Pressure%20transducers%20have%20a%20sensing,converted%20into%20an%20electrical%20output.

[30]What is a Pressure Sensor?, HBM https://www.hbm.com/en/7646/what-is-a-pressure-sensor/

[31] What is a Flow Sensor? , Fierce Electronics https://www.fierceelectronics.com/sensors/what-a-flow-sensor

[32] SCHMIDT® Flow Sensor SS 20.600 Instructions for Use https://www.schmidttechnology.com/de/sensorik/download/ss_gebrauch/Instr_SS20.600_en.pdf

[33] AMPLIFIED AIRFLOW SENSORS, AWM3000 Series https://sps.honeywell.com/us/en/products/sensing-and-iot/sensors/airflow-sensors/amplified-airflow-sensors/awm3000-series