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The Use of Instrumentation Amplifiers and V-I Converter In a Process Control : Simulation and Implementation

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Abstract—Signal in the form of voltage are often need to be transmitted when we deal with measurement. However, voltage signal transmission creates many problems. The series resistance that appears between the output of the signal conditioner and the load produces some voltage drop. Even a few millivolts of the voltage drops could significantly alter the percentage error of the measurement. Current signal is the same everywhere in a series loop. So, by converting the signal into a current and then sending the current signal will assures that the load will receive all of the signal we sent. In this paper, a simulation and an implementation of using instrumentation amplifiers and V-I converter for sending a voltage signal has been conducted. The process variable being measured is a differential pressure that is sensed by a pressure sensor. The output voltage signal was then amplified by an instrumentation amplifier and fed to a V-I converter for transmission purpose. The results is an increase in output current when the presssure was increased. It can be concluded that the instrumentation amplifier and V-I converter are the devices that are properly used for a voltage signal transmission.

Keywords : Instrumentation amplifiers, signal transmission, V-I converter, voltage signal, current signal, pressure sensors.

1. Introduction

The use of electronics to control industrial manufacturing process is key to the economic success of any company; indeded, to any country. Properly applied electronic controls will improve the precision, accuracy, speed, and economy of a manufacturing procedure. This, in turn, lowers the cost of the product, while providing higher quality.

Industrial electronics covers a various problems that must be solved in industrial practice. Electronic systems control processes from the control of relatively simple devices like electric motors and more complicated devices such as robots, up to the control of entire fabrication processes.

Industrial control system are often classified into two major group, *servomechanism control* and *process control*.

This research is related to a *process control* system. In a *process control*, the variables which are manipulated are those used most often in manufacturing. These include temperature, liquid and solid level, flow rate, pressure, force, composition, pH, humidity, viscosity, and density.

The main purpose of a *process control* system is to *regulate* one or more of the variables above, by keeping the variable at a constant value. Unlike servo control (in which significant, rapid variations in set points were the rule), in process control set-point changes occurs only occasionally and are usually less than 10% of full scale. Therefore, when we analyze and design a process control systems, our main objective is *how well the output responds to a change in load, given a constant set point*. Response rate are slow, often on the order of minutes or hours. This is much longer than typical for servo systems.

Process control systems may be subdivided into two categories, batch and continuous processes. Batch processing involves the timed sequencing of operation performed on the material being processed. Heating to a given temperature for a given time, adding a prescribed amount of second ingredient, and stirring for a given time are examples of operations performed in a batch process. At the end of the sequence time of steps, the material is often passed on to another batch station for further processing and the sequence begun again with new materials. Simply put, following a recipe to make a cake invloves a series of batch processing steps [1].

Another way of describing a *process control* is by saying that a *process control* is a system that combines measuring materials and controlling

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instruments into an arrangement capable of automatic action. A process control system not only measuring and controlling the physical and chemical characteristics of a process material. It also necessary to measure and control the characteristics of secondary materials to properly control a process. In a heat exchanger, for example, the temperature and flow rate of the steam used to heat a process liquid must be controlled so that the process fluid can be directed to a desired temperature [2].

From the above explanation, it is likely that temperature measurement and flow measurement are two examples of measurement of variables which are often involved in a *process control* system.

Various methods could be applied for measuring flow, especially fluid flow. By definition, the movement of liquids in pipes or channels, and gases or vapors in pipes or ducts can be defined as fluid flow [2]. For example the flow rate of the steam used in a heat exchanger mentioned above One of the methods for measuring the fluid flow involves measuring the differential pressure between two determined points along the flow (as will be described in the following sections). In essence, the differential pressure measurement take a differential pressure as the input, and producing a voltage signal as its output. The differential pressure sensor is utilised in connection with the pressure measurement.

There are some problem arises, however, regarding with the voltage signal coming out from the differential pressure measurement. First problem is that those voltage signal is very small for measurement, and the second is the problems related to voltage signal transmission. .

In connection with the above problems, the main purpose of this research is in the designing, simulating and implementing a signal conditioning electronic circuit and a signal transmission electronic circuit for the purpose of conditioning (amplifying) the voltage signal coming out from the differential pressure sensor and converting the voltage signal into a current form for transmisson.

The signal conditioning circuit and the signal transmission circuit present the use of the *Instrumentation Amplifier* integrated circuit for the voltage signal amplification and the *Voltage-to-Current Converter* circuit for the voltage signal conversion. Both of the circuit involves the utilisation of *Operational Amplifiers*.

2. Fluid Flow Rate Measurement

2.1. Differential Pressure Flowmeters

When a fluid passes through a restriction in a pipe, a pressure difference is created. The highest magnitude of differential pressure is between the pressure before the restriction and the pressure downstream after the restriction. The shape and configuration of the restriction affects the magnitude of the differential pressure and how much of the differential is recoverable. A restriction piping for flow measurement is called a primary flow element.

Installation of the *primary flow element* causes a pressure drop which is used to measure the flow.

Some equipment used to obstruct the flow are the *orifice plate* and the *Venturi tube*. The velocity of the fluid through the restriction increases and the pressure decreases when such a restriction is placed in a pipe. The volume flow rate is then proportional to the square root of the pressure difference across the obstruction

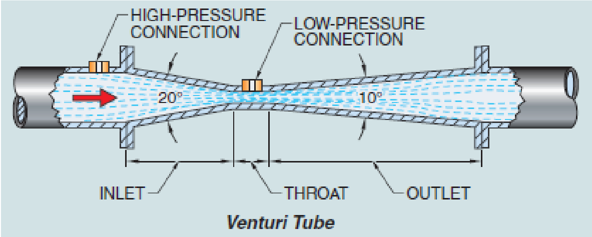

Fig 1. A venturi tube is a primary flow element

2.2. Differential Pressure Flow Equations

The flow equation for fluid flow in pipes connects the flow rate to the area of flow (or orifice diameter) and the square root of the pressure drop (head). The equation is customized to adjust for the different types of measurement units for each type of flow (including steam flow). The equations shows the relationship between flow rate and the various factors that affect that flow rate. The equations are approximations and should not be used for calculation of actual flow. [2]

For steam flow rate, we use an equation

$$W = N \times d^2 \times C \times Y \times \sqrt{\frac{h}{V}} \quad (1)$$

where

W	=	flow rate (in lb/hr)
N	=	constant conversion factor, 1244
d	=	orifice diameter (in in.)
C	=	coefficient of discharge
Y	=	gas expansion factor

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h = differential pressure (in in. water)
V = specific volume (in cu ft per lb, or cu ft/lb)

Picture of a venturi tube is shown in Fig. 1 above.

Another example is when an orifice plate is used, as shown in Fig. 2 and Fig. 3. The figures shows that the flow pattern is interrupted when an orifice plate is inserted into a pipe [3].

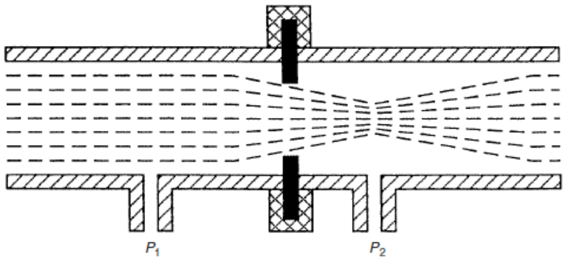

Fig 2. Profile of flow across an orifice plate.

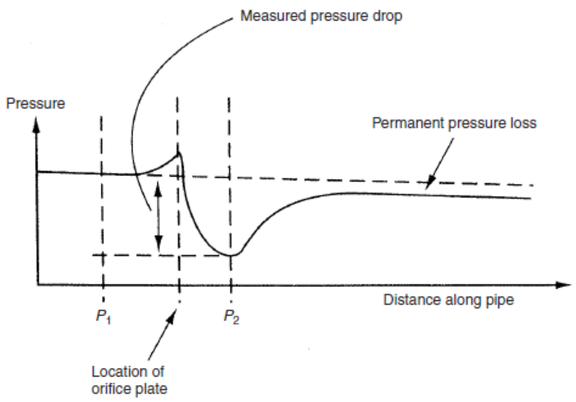

Fig 3. Pattern of pressure variation either side of an orifice plate.

Therefore, for every type of obstruction, we have two pressure measurement connection, namely the high-pressure connection and the low-pressure conection.

3. Pressure Measurement

3.1. About Piezoresistive

We use silicon pressure sensors for measuring the two pressure points (the high-pressure connection and the low-pressure conection).

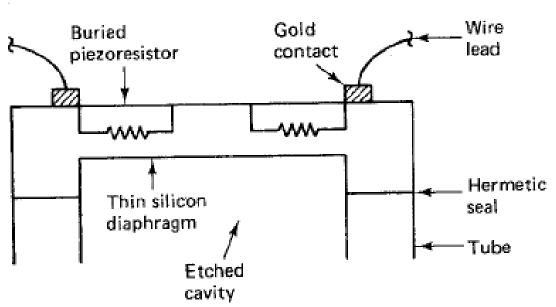

Fig 4. Cross- sectional view of a piezoresistive pressure transducer sensing element.

Fig. 4 is a cross-sectional view of the sensing element. When a pressure is applied, the resistor values will change depending on the amount of strain they undergo, which depends on the amount of pressure applied to the diaphragm.

3.2. About Differential Pressure Measurement

There are three types of pressure measurement available : absolute pressure, differential pressure and gauge pressure [4].

In this research, we apply the differential pressure measurement type. This means that we measure the difference between two pressures which are applied to both ports of Fig. 5. The high-pressure connection and the low-pressure connection of Fig. 1 could be tied to P_1 port and P_2 port of the piezoresistive sensor.

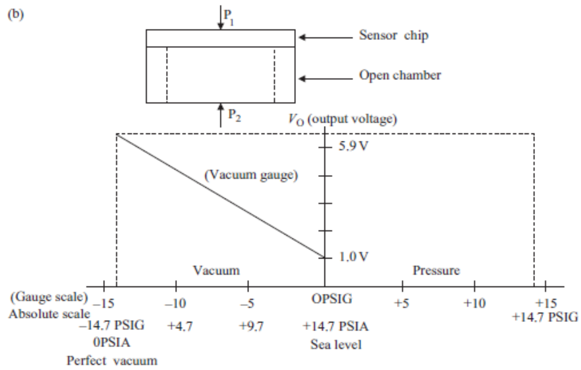

Fig 5. Differential Pressure Measurement.

4. Signal Conditioning and Signal Transmission

4.1. Signal Conditioning

As stated above, the piezoresistive pressure sensor was able to convert the parameter of interest in the manufacturing process, in this case a differential pressure, into an electrical voltage signal.

Unfortunately, this voltage signal may be much too small, go down instead of up, have an undesired dc offset, or be unlinear. So we need a device to amplifiy this small signal. An instrumentation amplifier does this task.

An instrumentation amplifier is a special purpose integrated circuit that utilizes several operational amplifiers (op-amps). It is far superior to a single op amp circuit in applications requiring us to recover a very small difference in potential between two lines when there is a large unwanted voltage common to both lines.

So, the result now we have a clean, high level, linear signal. It is an accurate measure of what is happening in the process under control.

Instrumentation amplifiers have two stages. The first stage is the input stage. It offers very high input impedance to both input signals. Here, we can set the gain with a single resistor. Fig. 6 shows the input stage. It consists of two carefully matched op amps.

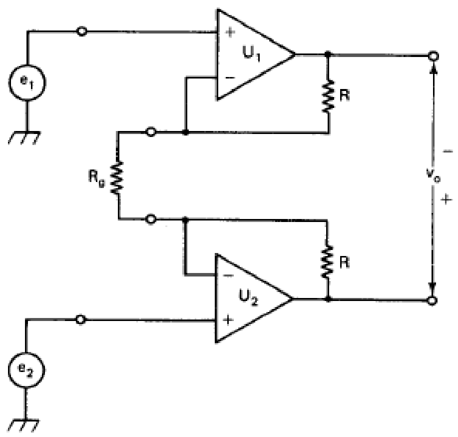

Fig 6. Instrumentation Amplifier input stage.

Each input voltage (e_1 and e_2) is input directly to the non-inverting input of its op amp. This op amp (configured as a voltage follower) causes the IA's to have very high input impedance. The outputs of the operational amplifiers are connected together through a string of resistors. The two R resistors are internal to the integrated circuit, while R_g is the gain-setting resistor. It (R_g) may be internal or connected externally. The output voltage is taken between the outputs of the op amps.

$$\boldsymbol{V_o = (e_2 - e_1)\left(1 + \frac{2R}{R_g}\right)} \qquad \textbf{(2)}$$

The second stage of this IA instrumentation amplifier is a difference amplifier with unity-gain. There are three connections namely the output, negative feedback, and ground reference. The full IA schematic (both stages) is shown in Fig. 7

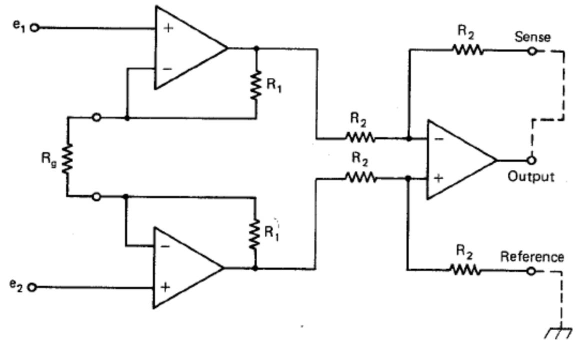

Fig 7. Instrumentation Amplifier full schematic.

It can be seen that three terminals are brought out. The sense terminal gives us access to the negative feedback loop. The reference terminal allows us to establish the dc reference (ground) potential of the output. For normal operation, just connect the sense terminal directly to the output (completing the negative feedback loop), and tie the reference terminal to ground. This configure out as a standard difference amplifier.

Circuit in Fig. 8 explain about this difference amplifier. The output voltage V_o is given by

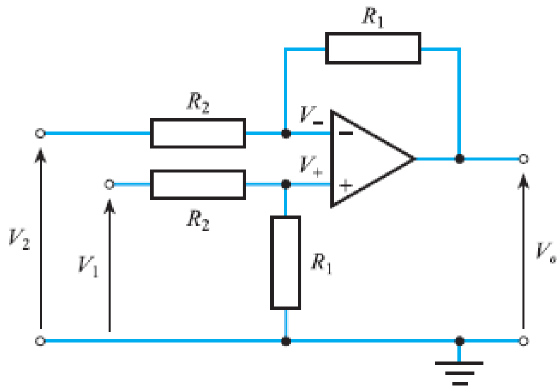

Fig 8. A differential amplifier or subtractor.

$$V_o = (V_1 - V_2)\frac{R_1}{R_2} \qquad (3)$$

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Thus, the output voltage is the product of the differential input voltage $(V_1 - V_2)$ times the ratio of R_1 to R_2. It can be seen that if $R_1 = R_2$, the output V_o is just $(V_1 - V_2)(1) = V_1 - V_2$, hence a unity-gain difference amplifier [5].

Some research works which concerns with these signal conditioning are mentioned as follows. First, there is a research conducted by Chia-Hao Hsu et al. [6] titled *A high performance current-balancing instrumentation amplifier for ECG monitoring systems* discussing about the use of an instrumentation amplifier (IA) with high command-mode rejection ratio (CMRR) and low referred noise input for ECG application. Another research conducted by Federico Butti et al. [7] titled *A chopper modulated low noise instrumentation amplifier for MEMS thermal sensors interfacing* discussed about the use of a CMOS instrumentation amplifier for interfacing with an *integrated thermal sensors*. Next, a research conducted by Buddhi Prakash Sharma et al. [8] titled *Design of CMOS instrumentation amplifier with improved gain & CMRR for low power sensor applications* discussed about a high performance operational amplifier (op-amp) based instrumentation amplifier for low power applications.

4.2. Signal Transmission

Signal voltage transmission creates many problems. The series resistance that appears between the output of the signal conditioning and the load produces voltage drop. Even very small of this voltage loss across the series resistance could significantly change the percentage error of the measurement.

On the other hand, in a series (transmission), loop current is the same. Therefore if we convert this voltage signal into a current first and then sending that current, we can assures that the load will receive all of the signal (current) we sent. There will be no lost because of line resistance or poor connections.

The type of voltage-to-current conversion used depends on the load's resistance and whether the load is floating or tied to ground. Floating load type used here, because the floating load type allows us to apply common-mode rejection techniques at the receiver to reduce the induced noise.

Fig. 9 shows the simplest V-I converter. It is merely a non-inverting amplifier. There are several points that we must consider when using circuit in the Fig. 9. First, the op-amp must not go out of saturation. So we must keep $R_{loop} = R_{wire} + R_{load}$ small enough. Secondly, the op-amp must be able to generate the current required. The standards usually either 20- or 60- mA currents. Because both of these standards are outside the capabilities of most general-purpose op amps, we may add a current boost transistor(s) (see Fig. 10).

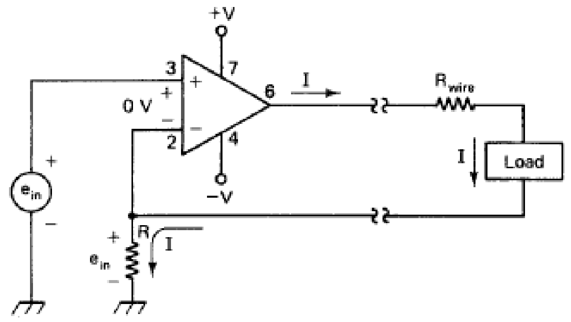

Fig 9. Simple voltage-to-current converter

Third, current from the load must return along a wire to the op-amp (and R). It cannot be driven through the load directly to ground.

Fourth, the worst-case load is an open. Opening the load removes the negative feedback and sends the op amp into saturation. On the other hand, shorting the load simply turns the circuit into a voltage follower. The signal curent is unaffected. And finally,

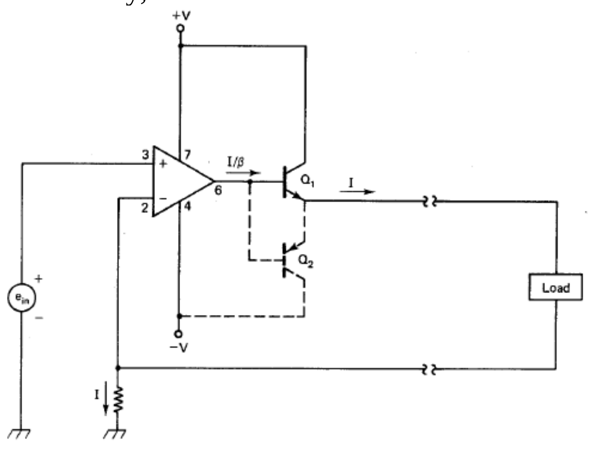

Fig 10. Current-boosted voltage-to-current converter

the circuit in Fig. 10 has one additional problem. When e_{in} = 0, then I_{load} = 0. Zero current appears to the load as a valid signal. However, if the current loop opened, or the transmitting electronics failed, I_{load} = 0 as well. The respond of the load would be as if a e_{in} = 0 were being transmitted. So we must devise a method to allow the load to differentiate between no signal (circuit failure), $I_{load} =$ 0 and the valid input, e_{in} = 0.

We can do this by providing an offset. That is when e_{in} = 0 or e_{in} = minimum, then $I_{load} = I(0) > 0$. A zero minimum input voltage produces a set, nonzero loop current. In this offset circuit, any valid signal would produce some curent greater than or equal to $I(0)$. If $I_{load} = 0$, a circuit failure has occured.

For the reasons above, we therefore choose to build an offset V-I converter. An offset V-I converter is shown in Fig. 11a.

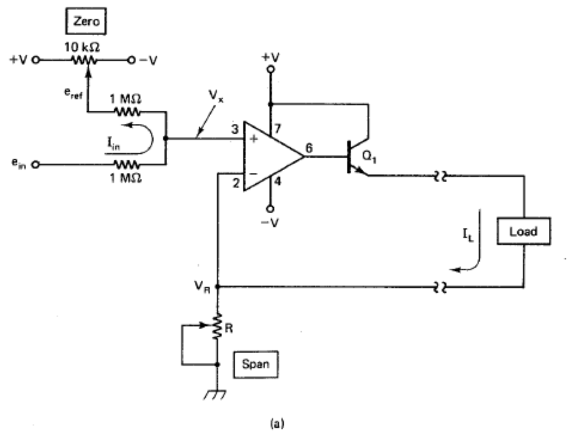

Fig 11a. Offset V-I converter (schematic)

In the Fig. 11a, a non-inverting summer has replaces the non-inverting amplifier in Fig. 10. The output current now is determined by the sum of the input voltage e_{in} and the reference voltage e_{ref}. The two 1-MΩ resistors must be present (and large) to keep one voltage source from loading down the other.

The input voltage-to-output current transfer curve is shown in Fig 11.b. It is linear and can be positioned anywhere in the upper two quadrants by specifying *e(A)*, *I(A)* and *e(B)*, *I(B)* (the two endpoints of the line). Given that an input voltage of *e(A)* will produce a current of *I(A)* and that an input voltage of *e(B)* will produce a current of *I(B)*, we can determine the needed circuit values by

$$R = \frac{e(B) - e(A)}{2[I(B) - I(A)]} \quad (4)$$

and

$$e_{ref} = 2R.I(B) - e(B) \quad (5)$$

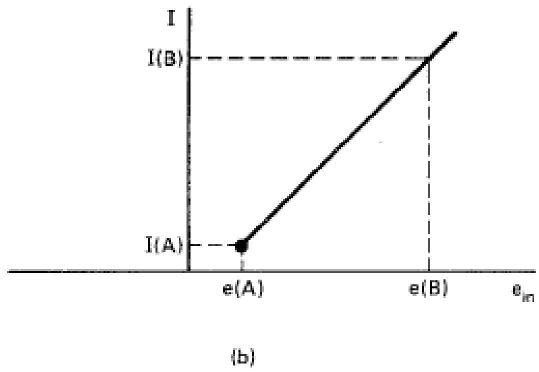

Fig 11b. Offset voltage-to-current converter (transfer curve)

For this signal transmission circuit, there are also some research work examples as follows. A research done by Yui-Hwan Sa et al. [9] titled *A design of new voltage-to-current converter with high linearity and wide tuning* discussed about the design of a new voltage-to-current (V-I) converter with a high linearity and wide tuning. Next, a research conducted by Komsan Chaipurimas et al. [10] titled *4-20 mA current transceiver* discussing about current transceiver capable of simultaneously sending and receiving industrial standard 4-20 mA current signal. The current transceiver was based on the use of a voltage-to-current converter. Also, there is a research conducted by B. L Hart et al. [11] titled *A single rail DC voltage-to-current converter* discussing about the design of a unique voltage-to-current (V-I) DC, which operates with a single positive power supply rail. The V-I converter produces output current which is linear to an input voltage with magnitude up to zero volt.

5. Simulation Results

5.1. Signal Conditioning

The simulation of the signal conditoning circuit and the signal transmission circuit is conducted by using National Instrument Multisim^{TM} 14.0. Multisim is the tools that helps us in the circuit design flow.

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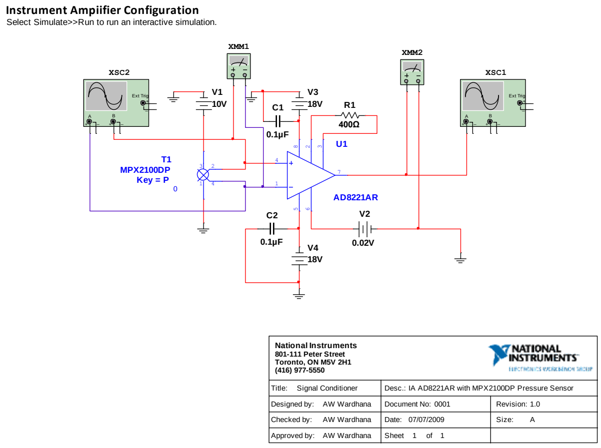

Fig 12. Simulation of Signal Conditioning Circuit with NI MULTISIM ^{TM}

The first circuit simulated is the first stage, the signal conditioning circuit. It is an IA circuit. The schematic of such circuit is shown in Fig. 12 above.

It can be seen that the circuit consists of two components. One component is Silicon Pressure Sensor with MULTISIM model manufacture / ID Motorola / MPX2100DP.

The MPX2100 is a silicon piezoresistive pressure sensors. Its output voltage is highly accurate and linear and directly proportional to the applied pressure [12]. See Fig. 13.

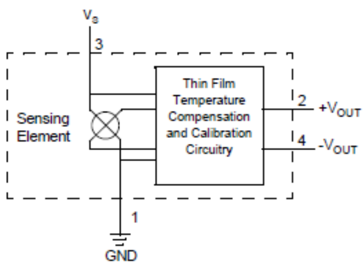

Fig 13. Temperature Compensated Pressure Sensor Schematic

This sensor is a piezoresistive bridges which consists of four nearly equal piezoresistors. See Fig. 14.

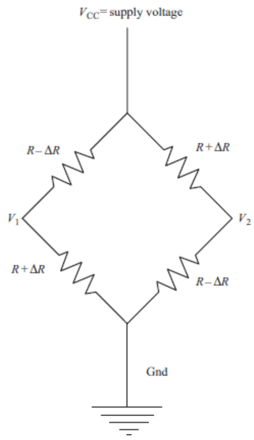

Fig 14. Four resistor bridge used in a piezoresistive sensor.

The actual resistor values at the applied pressure are $R+\Delta R$ and $R-\Delta R$. R is the resistor value when there is no pressure, where the four piezoresistors will have equal value. And then ΔR is the change in resistance when there is an applied pressure or force. The change of value ΔR will be the same for those four resistors. The output signal voltage will be proportional to the amount of supply voltage (V_{cc}) and the amount of pressure or force applied that generates the resistance change, ΔR. The commonly configuration of the Motorola MPX2100 is as shown in Fig. 15.

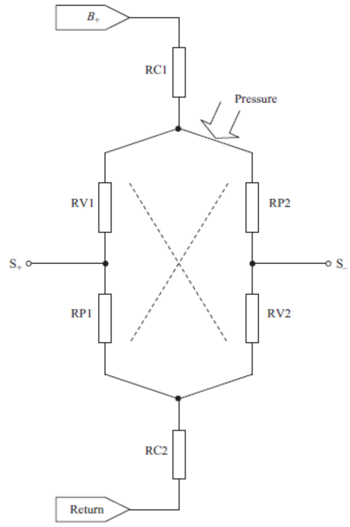

Fig 15. Sensor equivalent circuit.

The devices need a supply voltage up to maximum 16 volt with typical value of 10 volt. Hence, we connect a DC_POWER source of 10 volt to pin 3 of the device and a GROUND to pin

1. They have offset value between -1.0 mV up to 1.0 mV. Offset (V_{off}) is the output voltage when there is no pressure. The remaining pins, pin 2 and pin 4, are connected to positive input and negative input of next component respectively, the instrumentation amplifier. The input pressure range of this device is from 0 to 100 kPa (0 – 14.5 psi) and its Full Scale Span is 40 mV (Typical). Full Scale Span (V_{FSS}) is defined as the difference between its output voltage when full pressure is appllied and its output voltage when minimum pressure is applied.

The other component of this circuit, as mentioned above, is an IA. It is a dual supply IA with MULTISIM Model manufacturer / ID Analog Devices / AD8221 and Package manufacturer / type Analog Device / SOIC-N-8 (R-8) .

The AD8221 is an IA that is programmable and has highest CMRR over frequency [13].

Common-mode inputs are major factor with instrumentation amplifiers. The voltage out of each side of the balanced bridge (voltage V_2 and voltage V_1 in Fig. 14) will be equal, but definitely nonzero. This voltage (very often $\frac{1}{2}$ supply) must be rejected by the instrumentation amplifier, resulting in a zero output.

For example, suppose in Fig. 14 we have a differential voltage signal between V_2 and V_1. We have $4.99285V$ for V_2, and $5V$ for V_1 (assuming a 10 Volt DC supply). These voltages were fed to inputs of the instrumentation amplifier AD8221AR (see Fig. 13). Assuming that we set the gain of the AD8221AR to 100, then

$$V_{out} = Gain\,(V_2 - V_1)$$
$$V_{out} = 100\,(4.99285V - 5V) = -715mV$$

The amplifier must amplify a signal of 7.15mV by 100 while completely ignoring the 5V dc level that is output by both sides of the bridge of Fig. 14 (output by V_2 and V_1). (Note that the 7.15mV signal is the differential voltage from the outputs of the piezoresistive pressure sensor).

How effective the op amp is at amplifying this difference between its inputs while ignoring (rejecting) the same signals at each input is indicated by the Common-Mode Rejection Ratio (CMRR). The ratio of CMRR is normally expressed in decibels.

$$\text{CMRR} = 20\log\frac{Gain}{A_{common\ mode}} \quad (6)$$

where $A_{common\ mode} = \frac{V_{out(common\ mode)}}{e_{common\ mode}}$

Notice that the CMRR goes up with gain. Common-mode signals are not amplified by the input stage, while the differential is.

For example, we want to see the effect of the 5V common- mode on the output. Here, we assume that we use a +10V dc supply for the pressure sensor. Note that when there is no pressure on the sensor, voltage at V_2 is at 5V (i.e. $\frac{1}{2}$ supply) and voltage at V_1 is also at 5V (i.e. $\frac{1}{2}$ supply). Hence a 5V common-mode signal. From the data sheet of the AD8221, it specifies a CMRR of 100dB when the gain G was set to 100.

$$\text{CMRR} = 100\text{dB} \leftrightarrow 100\text{ dB} = 20\log\frac{Gain}{A_c}$$
$$\leftrightarrow 5\text{ dB} = \log\frac{Gain}{A_c}$$
$$\leftrightarrow 10^5 = \frac{Gain}{A_c}$$
$$\leftrightarrow A_c = \frac{100}{10^5} = 0.001$$

Thus, the effect of the 5V common-mode on the output is 0.001 x 5 V = 5mV. That is, when there is no pressure on the sensor (i.e 0 kPa input), a voltage of magnitude 5 mV will appear at the output of the AD8221. For the 715 mV output, the common-mode error is $\frac{5mV}{715mV} \times 100\% = 0.7\%$.

Like most other instrumentation amplifiers, the user can sets the gain from 1 to 1000 with a single resistor. The AD8221 can be operated with single or dual supplies. It appropriates for the applications where the input voltages are ± 10 V.

The transfer function of the AD8221 is

$$\text{Gain} = 1 + \frac{2 \times 24.7\ k\Omega}{R_g} = 1 + \frac{49.4\ k\Omega}{R_g} \quad (7)$$

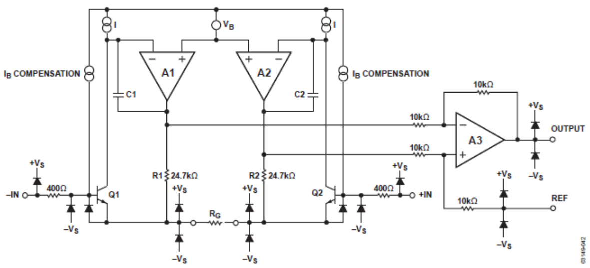

Fig 16. Simplified Schematic of AD8221

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The programmed gain (Eq. 7) will amplify the difference between the voltage on the inverting and noninverting pins. The output signal is the voltage difference between the output pin and the voltage on the REF pin.

Now that we come to the calculation of gain needed. From the Silicon Pressure Sensor, we have a differential voltage output of 40 mV at maximum differential pressure. This voltage will need to be fed to the next circuit, a V-I converter. Assuming that we choose 0V to +5V input range, by using Eq. 7 we obtain the output voltage of the AD8221AR as

$$V_{out} = [V_{in}(+) - V_{in}(-)] \times \left(1 + \frac{49.4\ k\Omega}{R_g}\right) + V_{REF} \qquad (8)$$

We therefore need a gain of $\frac{5V}{40mV}$ = 125. (Note that : $[V_{in}(+) - V_{in}(-)] = 40mV$). Thus, the resistor R_g is used to program the gain of the AD8221.

The gain is set according to

$$\text{Gain} = 1 + \frac{49.4\ k\Omega}{R_g} \text{ or } R_g = \frac{49.4\ k\Omega}{(Gain - 1)} \qquad (9)$$

Therefore, we need a resistor value R_g of $\frac{49.4\ k\Omega}{(Gain-1)} = \frac{49.4\ k\Omega}{(125-1)} = \frac{49.4\ k\Omega}{124}$ = 398.387 Ω. We choose a resistor of 400 Ω for the R_g.

Pin number 6 of this instrumentation amplifier is a reference pin V_{REF}. We drive this pin to level shift the output voltage. See Eq. 8. A voltage source of approximately 0.02 V is used for this V_{REF}.

Hence, we come to the overall circuit of Fig. 12 for the signal conditioning circuit.

When the signal conditioning circuit simulation was run, we obtained the following results for the MPX2100DP component : The offset (V_{off}) is -0.4fV (femto Volt). This offset is within the offset operating characteristic mentioned in its data sheet. So, there was an output voltage of -0.4fV when we applied a minimum rated pressure of 0 kPa (0 psi). Then, when a full rated pressure of 100 kPa (14.5 psi) was applied, a maximum of 40 mV was obtained at its output.

Before we proceed further, we will discussed one term associated with any element in a process control.

When working with any element in a process control, we need a simple, concise, but complete way of describing the element's performance. An equation of the output will not work, since the output of an element depends on its input. So the ratio of output to input is used. Then, given any input, we can predict its output. This proportion of output signal to input signal of an element is called its transfer function.

Simple elements such as amplifiers and potentiomenters have transfer functions which are only a single number, the *gain*. In a process control, the gain is also called *span* [14].

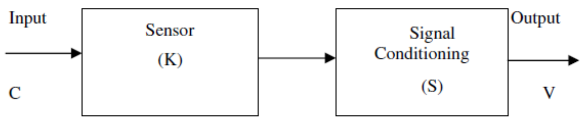

Fig 17. Model of Sensor

If we notice at the left part of the Fig. 17, the sensor can be regarded as an example of an element in a process control. As a consequences, therefore, we can determine its transfer function, that is the proportion of output signal to its input signal. If the sensitivity or gain of the sensor is defined as K, we have

$$K = \frac{Output\ of\ the\ sensor}{Input\ to\ the\ sensor} \qquad (10)$$

In this research the sensor sense a differential pressure applied to its input. So, the differential voltage in mili volt (mV) is the output of the sensor and the input of the sensor is the differential presure in kPa (psi), the sensitivity K will have a unit mV/kPa or mV/psi. From the simulation results, we obtained a full scale span of 40mV when a full rated pressure of 100 kPa (14.5 psi) was applied. Therefore, the sensitivity of the sensor is $\frac{40mV}{100kPa} = 0.40\,\frac{mV}{kPa}$ or $\frac{40mV}{14.5psi} = 2.759\,\frac{mV}{psi}$.

Next, for the signal conditioning component, we obtained the following results. When the differential input $[V_{in}(+) - V_{in}(-)] = 40mV$), we get an output from AD8221 V_{out} of 5V. However, when the is no differential input (i.e. there is no pressure or force applied to the pressure sensor), we get a voltage of -5.867mV at the output of the AD8221. This voltage is the $V_{out(common\ mode)}$ voltage. It is the $e_{common\ mode} \times A_{common\ mode}$ (see Eq. 6).

5.2. Signal Transmission

The next circuit to be simulated is the signal transmission circuit, which is a V-I converter circuit. Fig. 18 shows the schematic of such circuit

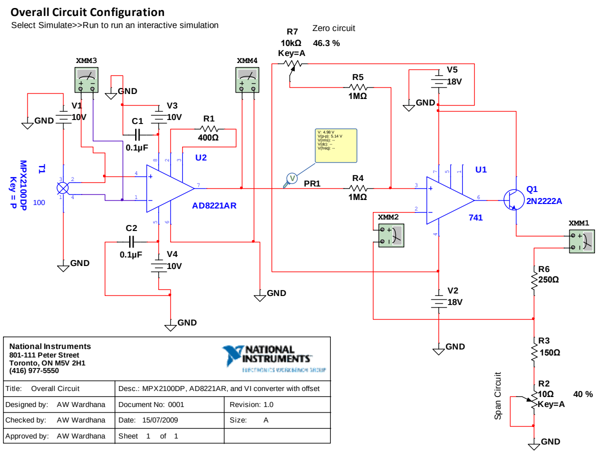

Fig 18. Overall Circuit (MPX2100DP pressure sensor, Instrumentation Amplifier, and an offset V-I converter)

It can be seen in the Fig. 18, if we look at the right part of the figure, that a circuit has been appended to the original signal conditioner circuit of Fig. 12. The circuit appended is a V-I converter circuit. More precisely, it is an offset V-I converter circuit, similar to the one shown in Fig. 11a.

The circuit basically is a non inverting summer circuit. It consists several components as follows.

The first component is an operational amplifier with IIT / 741 as the Model manufacturer / ID. The 741 series are operational amplifiers for general-purpose. They have a range of applications including summing amplifier configuration, the configuration used in this voltage-to-current circuit. The devices need a dual supply of max $\pm 18\,V$.

The circuit also contain a BJT_NPN transistor with Model manufacturer / ID Zetex Q2N2222A. The op amp must be able to generate the curent required. For example in here, the device must be able to generate the currrent in the range 4- to 20-mA. This is above the capabilities of most general-purposes op amps. Therefore, we add a current boost transistor. The transistor Q2N2222A is the boost transistor.

The last part of this signal transmission circuit is the *zero* circuit and the *span* circuit. If we look at Fig. 11a, we can see the *zero* circuit is at the upper-left. The *zero* circuit was equipped with a 10 kΩ potentiometer. The *span* circuit is at the bottom-right. The *span* circuit was equipped with a 10 Ω potentiometer. These *zero* and *span* circuit will form the transfer function of this voltage-to-current converter.

By referring to Fig. 11a, the *zero* and *span* can be explained as follows. Because the op amp has negative feedback,

$$V_x = V_R$$
$$I_L = \frac{V_x}{R} \qquad (11)$$

Summing the loop from e_{in} through e_{ref} (and ignoring the 10-kΩ resistance when compare to 1 MΩ) yields

$$e_{in} - I_{in}(1\ \mathrm{M\Omega}) - I_{in}(1\ \mathrm{M\Omega}) - e_{ref} = 0$$

Solving this for I_{in} gives us

$$I_{in} = \frac{e_{in} - e_{ref}}{2\ \mathrm{M\Omega}} \qquad (12)$$

Summing the loop from e_{in} through V_x, we obtained

$$e_{in} - I_{in}(1\ \mathrm{M\Omega}) - V_x = 0 \qquad (13)$$

$$V_x = e_{in} - \frac{e_{in} - e_{ref}}{2\ \mathrm{M\Omega}}(1\ \mathrm{M\Omega})$$

$$V_x = \frac{e_{in} + e_{ref}}{2} \qquad (14)$$

Notice that equation 14 proves that the circuit is indeed a non - inverting summer circuit. Substituting Eq. 14 into Eq. 11, gives us

$$I_L = \frac{e_{in} + e_{ref}}{2R} \qquad (15)$$

Equation 15 is the transfer equation of the circuit in Fig. 11a. It is the equation for the line of Fig. 11b.

At point A of Fig.11b,

$$I(A) = \frac{e(A) + e_{ref}}{2R}$$

At point B of Fig. 11b,

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$$I(B) = \frac{e(B) + e_{ref}}{2R}$$

Next, we can compare the Eq. 15 $I_L = \frac{e_{in}+e_{ref}}{2R}$

$$I_L = \frac{1}{2R}\,e_{in} + \frac{e_{ref}}{2R}$$

with equation of a straight line,

$y = mx + b$

where the dependent variable is *y* and the independent variable is *x*.

For our plot of output current versus input voltage therefore,

$m = \frac{1}{2R}$ is the $slope$ or $gain$ or $span$ $\quad (16.a.)$

$b = \frac{e_{ref}}{2R}$ is the y intercept or $zero$ $\quad (16.b.)$

Back to our simulation, in this research we need to design an offset V-I converter. This V-I will produce output current of 4 mA with an input of 0 V and output current of 20 mA with an input of 5 V. (Note that we have an output voltage from AD8221 in the range between 0 V up to 5 V).

First, we must select the values of e_{ref} and R by referring to Eq. 4, Eq. 5, and Fig. 11b.

e(A)	=	*0 V*	*I(A)*	=	*4 mA*
e(B)	=	*5 V*	*I(B)*	=	*20 mA*

$$R = \frac{e(B) - e(A)}{2[I(B) - I(A)]} \quad (from\ Eq. 4)$$

$$= \frac{5\,V - 0\,V}{2[20\,mA - 4\,mA]}$$

$$= \frac{5\,V}{32\,mA} = \frac{5\,V}{32 \times 10^{-3}\,A} = \frac{5000}{32}\,\frac{V}{A}$$

$$= 156.\,25\,\Omega$$

Pick a 150-Ω fixed resistor with a 10-Ω series potentiometer. As can be seen in the right-down corner of Fig. 18.

Next, from Eq. 5 we obtain

$$\begin{aligned} e_{ref} &= 2R.I(B) - e(B) \\ &= 2(156.25\,\Omega)(20\,mA) - 5\,V \\ &= 1.25\,V \end{aligned}$$

If we use our plot of output current versus input voltage, we obtained the *slope* or *gain* or *span* of our graph according to Eq. 16.a. is

$$m = \frac{1}{2R} = \frac{1}{2\,x\,156.25\,\Omega} = 0.0032\,\Omega^{-1} = 3.2\,m\Omega^{-1}$$

and we also obtained the *y* intercept or *offset* or *zero* of our graph according to Eq. 16.b. It is

$$b = \frac{e_{ref}}{2R} = \frac{1.25\,V}{2 \times 156.25\,\Omega} = 0.004\,A = 4\,mA$$

This means that our graph intercepts with *y* axis at point 4 mA. This is in accordance with the design requirement that our voltage-to-curent converter ought to produce an output curent of 4 mA when the input is 0 V.

To calibrate this circuit properly, first set *R* and e_{ref} to the values calculated. Next, apply *e(A)* and adjust the *zero* potentiometer (the *R7* 10 kΩ potentiometer) *slightly* to get a load current of *I(A)*. Then apply *e(B)* and adjust the *span* potentiometer (the *R2* 10 Ω potentiometer) slightly to get a load current of *I(B)*. Next re-apply *e(A)* and fine tune the *zero* potentiometer, then *e(B)* to fine tune the span. Several iterations of finer and finer adjustments of *zero* and *span* will allow us to set both endpoints properly.

When the simulation of the overall circuit of Fig. 18 was run, we obtained the following results. If we apply minimum rated pressure (i.e. 0 kPa) to the MPX2100DP, the output of the AD8221AR was 14.132 mV, and the current outputted from the V-I converter is 4.044 mA. Then, if we apply a maximum pressure of 100 kPa to the pressure sensor, the output of the AD8221AR is 5 V, and the ouput of the V-I converter is 19.839 mA.

From the results, it can be seen that this overall circuit works according to the design requirement. That is the circuit has to produce 4mA with an input pressure of 0 kPa and has to produce 20 mA with an input pressure of 100 kPa. Although, we see that the output range of current is not exactly 4-to 20 mA. This can be calibrated by fine tuning *R* and e_{ref} accordingly.

6. Implementation Results

The overall circuit of Fig. 18 was then built on a board. The overall circuit consists of a silicon piezoresistive pressure sensors, the signal conditioning IC, and a voltage to current converter circuit which is a non-inverting operational amplifier configuration. For the pressure sensor, we use the MPX2100 DP silicon piezoresistive pressure sensor, shown in Fig. 19 below. This sensor has an operating pressure of 0 to 100kPa (0 – 14.5 psi) with an output of 0 - 40mV full scale span (i.e. 40 mV for max. pressure).

Fig 19. MPX2100DP silicon piezoresistive pressure sensor,

For the signal conditioning device (signal amplification device), we use the AD620 DIP8 Low power IA Integrated Circuit. It requires only one external gain resistor to set gain from 1 up to 10000 [15]. This instrumentation amplifier can be operated with dual supply from $\pm$2.3V up to $\pm$18V. The physical appearance of such device is shown in the Fig. 20. The two input pins of this device will connect to the output of the sensor, which is an output voltage of the pressure sensor.

Fig 20. AD620AN low power Instrumentation Amplifier (IA)

For the signal transmision device, or for the voltage conversion, we use the LM741 Op-Amp. It is a general - purpose Op-Amp [16]. Its non-inverting input pin will be connected to output of the signal conditioning IC. The appearance of such device is shown in Fig. 21 on the below.

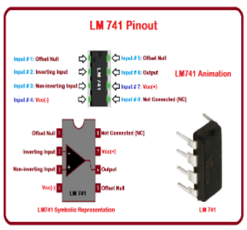

Fig 21. LM741 Operational Amplifier

The LM741 device has many applications, one of them is for summing amplifier. We use this kind of application for our non-inverting summer circuit. The device uses dual power supply voltage range of DC up to maximum ±18V.

Next, as stated above, this signal transmission part was equipped with two potentiometers for zero adjustment and span adjustment. The zero adjustment potentiometer is used for adjusting the lower level of the output current. The span adjustment potentiometer is used for adjusting the upper level of the output current.

The steps for the implementation results can be explained as follows. First, we tested the silicon piezoresistive pressure sensor on its own. Here, we did not use a *primary flow element* for creating the differential pressure. Instead, we produced the differential pressure by simply blowing some air on the positive pressure point P1 of the pressure sensor. We used an electric pump compressor DC 12V 150 psi for creating the pressure.

When we connect a voltmeter to the output of this sensor, we can measure a range of output voltage approximately from 0 mV up to 40 mV.

Next, we connected the pressure sensor to the signal conditioning circuit. As with other instrumentation amplifiers, we can program the gain of the AD620AN by using a single external resistor. The equation for this AD620AN is

$$G = \frac{49.4k\Omega}{R_G} + 1$$

or

$$R_G = \frac{49.4k\Omega}{G - 1}$$

So, for this AD620AN, according to above formula we obtained a 390 Ω resistor for the gain resistor R_g. When the pressure sensor and the AD620 had been connected we obtained, from the output of the AD620, several output voltage with magnitude of approximately as shown in the following *Table 1.*

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Table 1. Results with an external gain resistor $R_G = 398\ \Omega$

No.	Input to AD620 (in mV) This is the output from sensor	Output from AD620AN (in V)
1.	0.0	0.02
2.	5.0	0.53
3.	7.5	0.81
4.	10	1.0
5.	12.5	1.22
6.	15.0	1.48
7.	17.5	1.72
8.	20.0	1.96
9.	22.5	2.10
10.	25.0	2.32
11.	27.5	2.44
12.	30.0	2.67
13.	32.5	2.85
14.	35.0	3.00
15.	37.5	3.20
16.	40.0	3.36

From the table above, it can be shown that we obtained a gain (*G*) in the range between 84 when we applied maximum pressure (40 mV) up to 106 when we applied low pressure.

Last, we tested the signal transmission circuit. This test was conducted by applying an input voltage of magnitude 0 Volt up to 5 Volt to the input of this signal transmission circuit. This range of voltage input represents the no-pressure condition (0 kPa) up to maximum rated pressure condition (100 kPa) at the input of the pressure sensor. When a 0 Volt input was applied (representing no-pressure condition applied to the port #1 positive pressure sensor), the output of the signal transmission is 4 mA. When the magnitude of voltage input was increased (which represents applying some more pressure to the pressure sensor), we obtained an increase in output current of the V-I converter. The more we increase the magnitude of the voltage input, the more we get a linear increase in magnitude of the output current. Note that we used a potentiometer connected to a 5 Volt power supply to vary the magnitude of voltage input. Until we then obtained an output current of 20 mA from the signal transmission circuit when we apply a voltage input of magnitude 5 Volt (representing a full rated pressure to the pressure sensor). This signal transmission circuit testing results are tabulated in *Table 2* below.

Table 2. Results of the signal transmission circuit testing

No.	Voltage Input to V-I converter (in Volt) (representing pressure condition at the pressure sensor) (approx)	Output current from V-I converter (in mA) (approximation)
1.	0	4
2.	0.31	5
3.	0.63	6
4.	0.94	7
5.	1.25	8
6.	1.56	9
7.	1.88	10
8.	2.19	11
9.	2.50	12
10.	2.81	13
11.	3.13	14
12.	3.44	15
13.	3.75	16
14.	4.06	17
15.	4.38	18
16.	4.69	19
17	5.00	20

7. Conclusions and Future Works

7.1. Conclusions

Several conclusions can be obtained from this research, as follows :

1. The silicon piezoresistive pressure sensors can be used in a differential pressure measurement type, to measure pressure between two pressure point.
2. An Instrumentation Amplifier (IA) can be used as a signal conditioning circuit. Common-mode signals are not amplified by the input stage of the IA, while the differential signal is.
3. A V-I converter can be used to convert the voltage from the output of the Instrumentation Amplifier into a current form. Signal transmission in a form of current had been proved to assure that the load will receive all of the signal (current) sent.
4. The overall circuit was simulated by using National Instrument Multisim^{TM} 14.0. It can be shown in the simulation that the overall circuit functions properly according to the requirement.
5. When the circuit was implemented, it converted the input pressure applied to the silison piezoresistive pressure sensor into an output current obtained from the output of V-I converter.

7.2. Future Works

Some future works on this research are as follows :

1. The system can be extended not only using the Instrumentation Amplifier and the V-I converter. Another circuit called the Current-to-Voltage converters can be implemented. It converted the current signal back into a voltage once the final current signal gets to the place where it is to be used.
2. Other types of silicon piezoresistive pressure sensors with different range of input pressure can be used.
3. The circuit can also be implemented for thermocouple use, for measuring temperature. The output of the thermocouple was connected to the two inputs of the signal conditioning.
4. For those who would rather buy a V-I converter than build one, there is the XTR110 precision V-I converter. It is a precision V-I converter which is designed for transmission of analog signal. It is suited for inputs of 0 to 5V or 0 to 10V and can have an output current of 4 to 20mA, 0 to 20mA, 5 to 25mA.

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