

# Some Applications of Operational Amplifier

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**Abstract-** OPAMP is very useful in measuring dc and ac low voltages by using ordinary table voltmeters and thus some of the undergraduate experiments where low voltages are to be measured can be modernized using new and novel techniques. Here, for example, variation of breakdown voltage of a Zener diode with temperature and variation of thermo emf of a thermo couple with temperature are considered. Also, logarithmic and antilogarithmic amplifiers are discussed. An operational amplifier is a high gain electronic voltage amplifier which is dc coupled and contains a differential input and usually a single ended output. An op amp produced an output voltage which is often several times larger than the voltage difference between its input terminals. The differential inputs of an operational amplifier consist of V- input & a V+ input. Op-amps amplify the voltage difference in between the two, i.e. the differential input voltage.

## I. INTRODUCTION

OPAMP is an eight-pin integrated circuit (IC 741 readily available in markets) consists of an inverting input terminal (pin 2), a non-inverting input terminal (pin 3) and an output terminal (pin 6). However the circuit inside OPAMP IC is very much complicated. It consists of a monolithic silicon IC containing 17 transistors (6 pnp and 11 npn), 10 resistors, 4 diodes and 1 capacitor. To activate this OPAMP  $\pm 9$  V to  $\pm 12$  V dc power-supplies are connected (pins 4 and 7). The specifications of this OPAMP are<sup>1</sup>: (i) Infinite input resistance. (ii) Small output resistance. (iii) Infinite open loop gain. (iv)  $0^\circ$  to  $180^\circ$  phase shift. (v) Here we apply OPAMP in different types of measurements of physical properties of substances and corresponding electronic circuits are: (i) Inverting amplifier for the measurement of variation of thermo emf with temperature. (ii) Differential amplifier for the measurement of variation of breakdown voltage of Zener diode with temperature. (iii) Logarithmic and antilogarithmic amplifier. Although the theoretical background of these experiments are not new yet we shall try to make a distinction mark of our experiments Thermo emf occurs due to variation of electron density with temperature. If the sample is made up of dissimilar materials thermo emf due to Peltier effect is prominent whereas Thomson emf comes into play for a sample of single material.<sup>2</sup> Peltier ( $\pi$ ) and Thomson ( $\sigma$ ) coefficients are defined in terms of thermo emf V

and absolute temperature T as

$$\pi = T \frac{dV}{dT} \quad \text{and} \quad \sigma = \pm T \frac{d^2V}{dT^2} \quad (1)$$

$\sigma$  is zero for lead, positive for copper like metals and negative for iron like metals. Thermo emf varies with temperature parabolically and its rate of change with absolute temperature, called thermo-electric power  $P = dV/dT = dV/dt$  varies linearly with temperature difference (t) in degree Celcius as  $P = a + bt$ . For copper-constantan thermo couple the values of these coefficients are<sup>2</sup>

$$\begin{aligned} a_{\text{Cu-Pb}} &= 2.76 \mu\text{V}/^\circ\text{C} \\ b_{\text{Cu-Pb}} &= 0.012 \mu\text{V}/^\circ\text{C}^2 \\ a_{\text{Constantan-Pb}} &= -38.1 \mu\text{V}/^\circ\text{C} \\ b_{\text{Constantan-Pb}} &= -0.089 \mu\text{V}/^\circ\text{C}^2 \\ a_{\text{Cu-Constantan}} &= 40.86 \mu\text{V}/^\circ\text{C} \\ b_{\text{Cu-Constantan}} &= 0.101 \mu\text{V}/^\circ\text{C}^2 \end{aligned} \quad (2)$$

Using potentiometer and a moving coil galvanometer with lamp and scale arrangement to measure thermo emf is a standard old technique and indirect method used in undergraduate laboratories. Here an alternative new and simplified method is described where no such accessories are needed, only a voltmeter and an OPAMP are used to measure directly the thermo emf of the thermo couple. Also, this circuit is better in terms of cost and space requirements. When an OPAMP is used as inverting amplifier the output voltage  $V_0$  measured by a voltmeter is related to the input voltage V by the closed loop gain ( $R_F/R$ ) where R is the resistance arranged in series in the inverting input circuit and  $R_F$  is the feedback resistance between input and output circuit.<sup>1</sup> If the voltage at the virtual ground position is  $V_i$  then from Kirchoff's current law we can write  $(V - V_i)/R = (V_i - V_0)/R_F$

For  $V_i \rightarrow 0$  and when the input voltage is created by a copper- constantan thermo couple as shown in Figure 1 then we have

$$V = -V_0 R/R_F \quad (3)$$

### (i) Experimental

In the circuit diagram shown in Figure 1 output is connected to an ordinary table voltmeter with desired range (0–10V, 0.1V). To increase accuracy high impedance meters with different ranges may also be used. The non-inverting input terminal of OPAMP

(IC 741) described earlier is directly grounded and the inverting input is connected to the hot junction of the copper-constantan thermo couple (called two junction thermo couple) after the input carbon resistor  $R$ .<sup>3</sup> The end of the cold junction is grounded. A feedback carbon resistor  $R_F$  is connected between input and output. At first both the junctions are kept in ice bath and temperature is noted.  $R_F/R$  is kept fixed to 1000 throughout the experiment and the output voltage reading is noted which is the offset voltage. To minimize it to zero as far as practicable pin 1 and pin 5 of OPAMP are connected to a 1 K $\Omega$  potentiometer pot whose sliding pointer is connected to pin 4 or -12 V supply. By adjusting the pot the output reading of offset voltage is minimized as far as practicable and that minimum voltage value is considered as zero reading. Now one junction is kept at ice bath and the other junction is made hot by placing it in the oil filled test tube placed inside a water bath and is heated by a heater or a spirit lamp. Water is stirred to make uniformity in temperature and the temperature is noted at an interval of about 5°C. At each temperature output voltage is noted. When the hot junction is made cold and the cold junction hot the negative sign in the output voltage changes to positive sign. This shows the reversible nature of thermo emf. Thermo emf  $V$  is determined at each temperature using equation (3) and is plotted as shown in Figure 2 (circled points). The thermo electric power  $P$  determined from this straight-line plot comes out as 40  $\mu\text{V}/^\circ\text{C}$  and the result is consistent with standard experimental value. The straight line is observed due to the small range of temperature. To verify the results in another way<sup>4</sup> the cold junction shown in Figure 1 is cut off and after the hot junction of the thermo couple (called one junction thermo couple) it is grounded. This junction is placed in the oil filled test tube and is heated. At each temperature output voltage is noted and the thermo emf  $V$  is determined. Graph is a straight-line (rectangular points) similar to two junction thermo couple. The average value of thermoelectric power is again comes out to the standard value of 40  $\mu\text{V}/^\circ\text{C}$  while the theoretical value according to equation (2) is 40.961  $\mu\text{V}/^\circ\text{C}$ .  $R_F/R$  is kept fixed to 1000 because the output voltage should not be greater than the stabilized dc supply to the OPAMP due to its saturation property. We generally consider thermo emf variation within 0°C to 100°C where its variation is about 2 mV. For smaller range we can fix  $R_F/R$  to higher value within the saturation level of OPAMP to achieve more accuracy (upto three decimal places) of the measured values. The circuit for one junction thermo couple with a digital meter calibrated to a Celcius scale could be used as ordinary thermometer.

3. Differential Amplifier Used to Measure the

Variation of Breakdown Voltage of Zener Diode with Temperature

**B. Basic Principles and Theory**

Zener<sup>5,6</sup> is a special type of heavily doped silicon diode operated in the breakdown region where theoretical current voltage relation

$$I = I_s[\exp(eV/kT) - 1] \quad (4)$$

fails and the reverse saturation current  $I_s$  increases abruptly with slightest variation of breakdown voltage  $V$ . For  $V < 5$  V Zener breakdown occurs where high electric field (20 KV/mm) for very narrow depletion region ruptures covalent bonds and electrons are pulled out. Since energy of valence electrons increase with temperature less electric field is necessary to tear off an electron from its covalent bond. So Zener breakdown voltage decreases with increase in temperature. For  $V > 6$  V avalanche breakdown occurs. Here minority carriers after gaining sufficient energy while moving through the junction collide with crystal ions and impart sufficient energy to disrupt covalent bonds. Thus in a cumulative process avalanche of carriers within a short

time is generated. As vibration of atoms increases with temperature so probability of collision increases. Thereby hole electron pairs get less opportunity between collisions to gain sufficient energy. Thus more reverse voltage is required as temperature increases, i.e. avalanche breakdown voltage increases with temperature. From equation (4) we can define static (dc)  $r_s$  and dynamic (ac)  $r_d$  resistances in both forward and reverse bias at a specified current  $I_t$  as

$$r_s = [V / I]_{I_t} \quad (5)$$

$$r_d = [\partial V / \partial I]_{I_t} = [(kT / eI_s) \exp(-eV / kT)]_{I_t} \quad (6)$$

(i) Differential amplifier<sup>1</sup> is generally used to amplify the difference between two signal voltages. A basic differential amplifier uses an OPAMP with two input signal voltage  $V_1$  and  $V_2$  at inverting input terminal and non-inverting input terminal respectively and one output signal voltage  $V_0$ , each measured with respect to ground. Since gain is infinite so potential at inverting and non-inverting input terminals will be same. Applying Kirchoff's current law we get

$$(V_1 - V_i)/R = (V_i - V_0) / R_F \quad (7)$$

and  $(V_2 - V_i)/R = V_i/R_F \quad (8)$

Subtracting equations (7) and (8) we get

$$(V_1 - V_2)/R = -V_0/R_F$$

$$\text{or, } V_0 = -R_F(V_1 - V_2)/R = -R_F / R \quad (9)$$

Here the closed loop gain of the amplifier is  $(R_F / R)$ . So the difference between  $V_1$  and  $V_2$  is amplified. A plot of  $V_0$  against  $V = V_1 - V_2$  will be a straight line passing through the origin with slope  $(R_F/R)$ . Thus in case of two Zener diodes in the differential amplifier circuit as shown in Figure 3 the output voltage will be

$$V_0 = -[ R_F / R ](V_{Z_s} - V_{Z_d} ) \quad (10)$$

Here  $V_{Z_s}$  is the Zener voltage of the sample Zener diode and  $V_{Z_d}$  is that for dummy one. By increasing the closed loop gain  $(R_F/R)$ ,  $V_0$  can be magnified. If  $V_{Z_s} = V_{Z_d}$  output is zero and if  $V_{Z_s}$  changes with temperature,  $V_0$  is non-zero. So the variation of static and dynamic resistances with temperature can be determined from the increment ( $r$ ) in their values from the value  $r$  at specified test current  $I_t$  at room temperature. Finally this increment is obtained from equation (10) as

$$r = (V_{Z_s} - V_{Z_d}) / I_t = -R V_0 / R_F I_t \quad (11)$$

The circuit diagram for differential amplifier mode of OPAMP (IC 741) is set up and the voltage gain characteristics is verified for  $R_F/R = 10$ .<sup>10</sup> Two Zener diodes (0.25W, 4.7V) readily available in the market are taken and the ends of them are soldered with connecting lead wires. Zener diodes with some parts of connecting leads are coated with nail polish to make them insulating. One of these Zeners is taken as sample ( $Z_s$ ) and the other as dummy ( $Z_d$ ). Forward and reverse characteristics curves are drawn for sample and dummy Zener diodes at room temperature 20°C.<sup>10</sup> From these curves static and dynamic resistances ( $r_s, r_d$ )  $Z_s$  is placed in oil filled test tube kept in water bath whose temperature is observed by a thermometer.  $Z_d$  is kept at room temperature. OPAMP is placed on the breadboard and the circuit diagram for differential amplifier mode is done as shown in Figure 3. Pin 4 of the OPAMP is connected to -12V supply and pin 7 to +12V supply to activate the OPAMP. Pin 2 is connected through a series carbon resistor R to reverse bias terminal of  $Z_s$  and pin 3 through R to reverse bias terminal of  $Z_d$ . Pin 6 is the output connected to a voltmeter and a feedback carbon resistor  $R_F$ . Pin 1 and pin 5 of OPAMP are connected to a 1 KΩ potentiometer pot whose sliding pointer is connected to pin 4 or -12 V supply for null adjustment. Offset null is adjusted to zero by potentiometer pot when the forward bias terminals of  $Z_s$  and  $Z_d$  are placed to ground and  $R_F/R=10$ . It is kept intact throughout the experiment.<sup>10</sup> The temperature of the heat bath is increased by steps of 5°C and the output voltage is measured by the voltmeter after keeping the current through each  $Z_s$

and  $Z_d$  to a fixed value  $I_t = 10$  mA. This ensures us that each Zener is in the same breakdown condition. The output voltage is measured both at temperature increasing and decreasing conditions and from the mean value we determine  $r$  from equation (11) for different temperatures. Temperature versus  $r$  graph is plotted as shown in Figure 4 and from the slope of the curve temperature coefficient of resistance is determined to be as 0.182 Ω/°C. From equation (6) in the reverse bias condition  $r_d \rightarrow (kT/eI_t)$  and the temperature coefficient of  $r_d$  is  $(k/eI_t) \approx 0.0086$  Ω/°C which is much lower than the experimentally observed value. This is due to the fact that equation (6) is not valid in the breakdown region. Also the exponential factor of equation (6) should be multiplied by a factor  $\beta > 1$ .<sup>11</sup> Dynamic resistance  $r_d$  is measured generally from the slope of the tangent to the characteristics curve at the test current as shown in equation (6) while  $r_s$  is the ratio of voltage and current at the test current according to equation (5). So  $r$  may be thought of as the nature of variation for both  $r_s$  and  $r_d$ . Equation (11) says that for Zener breakdown  $V_{Z_s}$  decreases with increase in temperature while for avalanche breakdown  $V_{Z_s}$  increases with temperature. Thus in the first case  $V_0$  is positive while in the second case it is negative. Increase in resistance  $r$  in Figure 4 shows Zener breakdown for 4.7 V Zener diode. We have given the comprehensive information on the complete circuits with component values and explained why these circuits are better in terms of cost.

### 3) Logarithmic and Antilogarithmic Amplifier

#### (i) Logarithmic amplifier

When the output voltage  $V_0$  changes as the logarithm of the input voltage  $V_{in}$  we have logarithmic amplifier.<sup>1,5</sup> The circuit of logarithmic amplifier is shown in Figure 5. When a forward bias diode D is connected in the feedback circuit and a resistance R is connected in the inverting input terminal then for the potential at the virtual ground position being  $V_i$  we have from Kirchoff's current law  $I_1 = I_2$

$$\begin{aligned} \text{or, } (V_{in} - V_i)/R &= I_2 \\ &= I_s[\exp(-eV_0/kT) - 1] \\ &= I_s \exp(-eV_0/kT) \quad (12) \end{aligned}$$

This is because  $V_i \rightarrow 0$  and we use equation (4). Here we neglect unity because it is very small in comparison to the exponential term of the output voltage  $V_0$  and a negative sign appears because  $V_0$  is applied in the feedback. So we get

$$V_0 = -(kT/e) \ln(V_{in}/R I_s) \quad (13)$$

So it will act as logarithmic amplifier.<sup>12</sup> Circuit connection of logarithmic amplifier is made according to Figure 5a. Since the carbon resistor is connected in the inverting input terminal and the

diode is in the feedback circuit of the OPAMP as shown so different input voltages are applied to input like  $\pm 0.05V$ ,  $\pm 0.1V$ ,  $\pm 0.2V$  and  $\pm 0.3V$  and at each case output voltage  $V_0$  is measured. A graph of  $V$  against  $V_0$  is plotted<sup>13</sup> as shown in Figure 6. The process is repeated for another  $R$ . The slope of the graph is measured in the straight portion as  $V_0/V = 1.136$ .

#### (ii) Antilogarithmic amplifier

When a forward bias diode  $D$  is connected in the inverting input terminal and a resistance  $R$  is connected in the feedback circuit then for the potential at the virtual ground position being  $V_i$  we get from Kirchoff's current law (Figures 5b) as  $I_1 = I_2$ . So  $I_1 = (V_i - V_0)/R$ . Since  $V_i \rightarrow 0$  and from equation (4) we get  

$$V_0 = -RI_1 = -RI_2 [\exp(eV_{in}/kT) - 1]$$

Here also as in the previous case we neglect unity. So it will act as antilogarithmic amplifier.<sup>1,5,12</sup> Circuit connection is made as shown in Figure 5b. Since diode is connected in the inverting input terminal and  $R$  is in feedback circuit of the OPAMP so different input voltages are applied to input like  $\pm 0.05V$ ,  $\pm 0.1V$ ,  $\pm 0.2V$  and  $\pm 0.3V$  and at each case output voltage  $V_0$  is measured.<sup>13</sup> A graph of  $V$  against  $V_0$  is plotted as shown in Figure 7. The process is repeated for another  $R$ . The slope of the graph is measured in the straight portion as  

$$V_0/V = 1.11.$$

Thus characterization of logarithmic and antilogarithmic amplifiers is made. We can use these circuits for temperature variations also.

### CONCLUSION

These experiments may be thought of as modern and new based on the undergraduate theoretical knowledge and available instruments in the laboratory and components in the markets. Some of the techniques used so far in such colleges are old enough. We use the novel idea of using OPAMP to replace one such standard experiment and the results are consistent. Also, we present some distinction mark of our experiments from any laboratory experiments done in many colleges in terms of comprehensive information on the complete circuits with component values, accuracy of the measured values, in terms of cost, modern laboratory space utilization, etc.

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