Module
2

Measurement Systems

Lesson
9
Signal Conditioning Circuits

Instructional Objective

The reader, after going through the lesson would be able to:

1. Identify the different building blocks of a measuring system and explain the function of each block.
2. Design an unbalanced wheatstone bridge and determine its sensitivity and other parameters.
3. Able to explain the advantage of using push-pull configuration in unbalanced a.c. and d.c. bridges.
4. Define CMRR of an amplifier and explain its importance for amplifying differential signal.
5. Compare the performances of single input amplifiers (inverting and non-inverting) in terms of gain and input impedance.
6. Draw and derive the gain expression of a three-op.amp. instrumentation amplifier.

1. Introduction

It has been mentioned in Lesson-2 that a basic measurement system consists mainly of the three blocks: sensing element, signal conditioning element and signal processing element, as shown in fig.1. The sensing element converts the non-electrical signal (e.g. temperature) into electrical signals (e.g. voltage, current, resistance, capacitance etc.). The job of the signal conditioning element is to convert the variation of electrical signal into a voltage level suitable for further processing. The next stage is the signal processing element. It takes the output of the signal conditioning element and converts into a form more suitable for presentation and other uses (display, recording, feedback control etc.). Analog-to-digital converters, linearization circuits etc. fall under the category of signal processing circuits.

The success of the design of any measurement system depends heavily on the design and performance of the signal conditioning circuits. Even a costly and accurate transducer may fail to deliver good performance if the signal conditioning circuit is not designed properly. The schematic arrangement and the selection of the passive and active elements in the circuit heavily influence the overall performance of the system. Often these are decided by the electrical output characteristics of the sensing element. Nowadays, many commercial sensors often have in-built signal conditioning circuit. This arrangement can overcome the problem of incompatibility between the sensing element and the signal conditioning circuit.

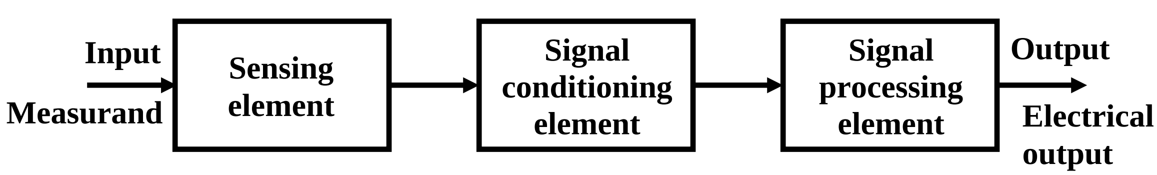

Fig. 1 Elements of a measuring system.

If one looks at the different cross section of sensing elements and their signal conditioning circuits, it can be observed that the majority of them use standard blocks like bridges (A.C. and D.C.), amplifiers, filters and phase sensitive detectors for signal conditioning. In this lesson, we would concentrate mostly on bridges and amplifiers and ponder about issues on the design issues.

2. Unbalanced D.C. Bridge

We are more familiar with balanced wheatstone bridge, compared to the unbalanced one; but the later one finds wider applications in the area of Instrumentation. To illustrate the properties of unbalanced d.c. bridge, let us consider the circuit shown in fig.2 .Here the variable resistance can be considered to be a sensor, whose resistance varies with the process parameter. The output voltage is e_0, which varies with the change of the resistance $x\,(=\Delta R/R)$. The arm ratio of the bridge is p and E is the excitation voltage.

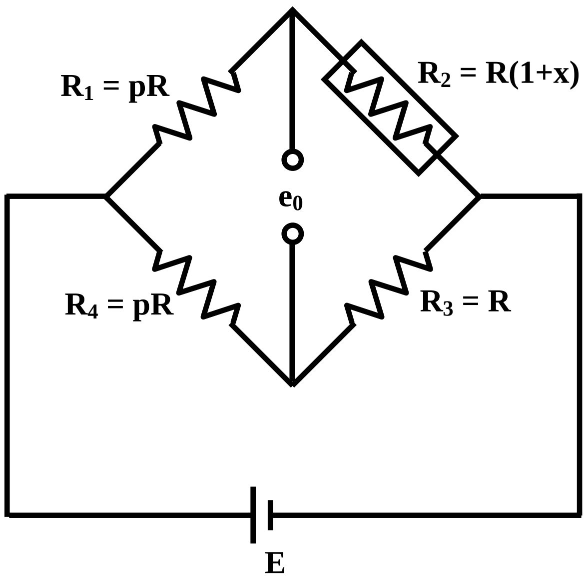

Fig. 2 Unbalanced D.C. bridge.

Then,

$$e_0 = \left[\frac{R(1+x)}{pR+R(1+x)} - \frac{R}{pR+R}\right]E$$

$$= \frac{px}{(p+1+x)(p+1)}E \qquad (1)$$

From the above expression, several conclusions can be drawn. These are:

A. *e_0 vs. x Characteristics is nonlinear* (since x is present in the denominator as well as in the numerator).

B. *Maximum sensitivity of the bridge can be achieved for the arm ratio p=1.*

The above fact can easily be verified by differentiating e_0 with respect to p and equating to zero; i.e.

$$\frac{de_0}{dp} = 0 \text{ gives,}$$

$$x(p+1+x)(p+1) - px(2p+2+x) = 0$$

or, $p^2 = 1 + x$,

i.e. $p = \sqrt{1+x} \approx 1$, for small x. (2)

C. *Nonlinearity of the bridge decreases with increase in the arm ratio p, but the sensitivity is also reduced.*

This fact can be verified by plotting $\frac{e_0}{E}$ *vs.* x for different p, as shown in fig. 3.

D. *For unity arm ratio (p=1), and for small x, we can obtain an approximate linear relationship as,*

$$e_0 = \frac{x}{4}E. \quad (3)$$

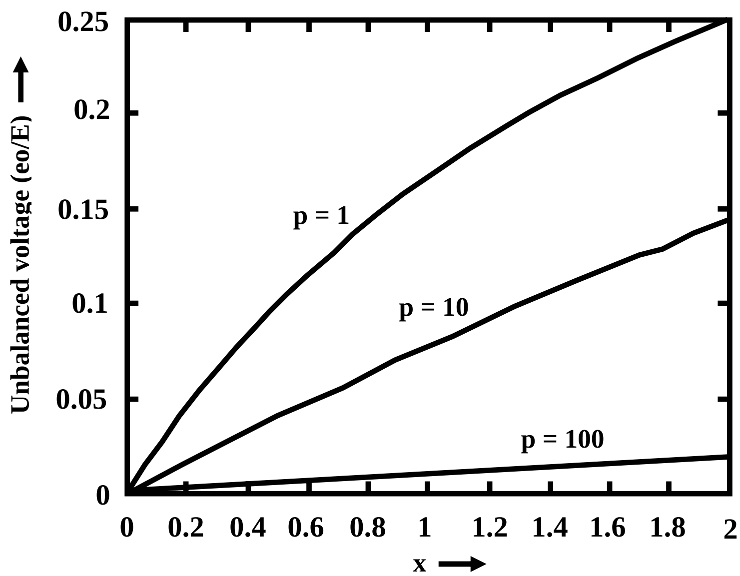

Fig. 3 Bridge characteristics for different arms ratio.

E. We have seen that the maximum sensitivity of the bridge is attained at the arm ratio p=1. Instead of making all the values of R_1, R_2, R_3, R_4 equal under balanced condition, it could also be achieved by selecting different values with $R_1 = R_2$, $R_3 = R_4$ for x = 0. But this is not advisable, since the output impedance of the bridge will be higher in the later case. So, from the requirement of low output impedance of a signal-conditioning element, it is better to construct the basic bridge with all equal resistances.

F. It may appear from the above discussions, that, there is no restriction on selection of the bridge excitation voltage *E*. Moreover, since, more the excitation voltage, more is the output voltage sensitivity, higher excitation voltage is preferred. But the restriction comes from the allowable power dissipation of resistors. If we increase *E*, there will be more power loss in a resistance element and if it exceeds the allowable power dissipation limit, self heating will play an important role. In this case, the temperature of the resistance element will increase, which again will change the resistance and the power loss. Sometimes, this may lead to the permanent damage of the sensor (as in case of a thermistor).

Push-pull Configuration

The characteristics of an unbalanced wheatstone bridge with single resistive element as one of the arms can greatly be improved with a *push-pull* arrangement of the bridge, comprising of two identical resistive elements in two adjacent arms: while the resistance of one sensor decreasing, the resistance of the other sensor is increasing by the same amount, as shown in fig.4. The unbalanced voltage can be obtained as:

$$\begin{aligned} e_0 &= \left[\frac{R(1+x)}{R(1+x)+R(1-x)} - \frac{R}{2R}\right]E \\ &= \left[\frac{1+x}{2} - \frac{1}{2}\right]E \\ &= \frac{x}{2}E \qquad (4) \end{aligned}$$

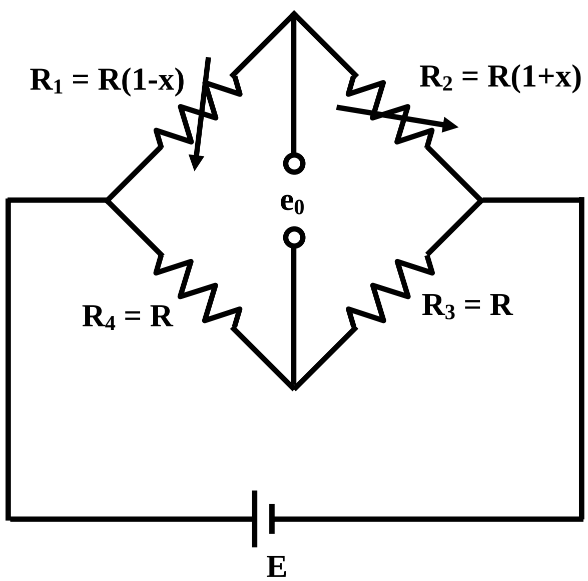

Fig. 4 Unbalanced D.C. bridge with push pull configuration of resistance sensors.

Looking at the above expression, one can immediately appreciate the advantage of using push-pull configuration. First of all, the nonlinearity in the bridge output can be eliminated completely. Secondly, the sensitivity is doubled compared to a single sensor element bridge.
The same concept can also be applied to A.C. bridges with inductive or capacitive sensors. These applications are elaborated below.

3. Unbalanced A.C. Bridge with Push-pull Configuration

Figures 5(a) and (b) shows the schematic arrangements of unbalanced A.C. bridge with inductive and capacitive sensors respectively with push-pull configuration. Here, the D.C. excitation is replaced by an A.C. source and two fixed resistances of same value are kept in the two adjacent arms and the inductive (or the capacitive) sensors are so designed that if the inductance (capacitance) increases by a particular amount, that of the other one would decrease by the same amount.

For fig. 5(a),

$$e_0 = \left[\frac{jwL(1+x)}{jwL(1+x)+jwL(1-x)} - \frac{R}{2R}\right]E,$$

where w is the angular frequency of excitation, L is the nominal value of the inductance and $x = \Delta L / L$. Simplifying, we obtain,

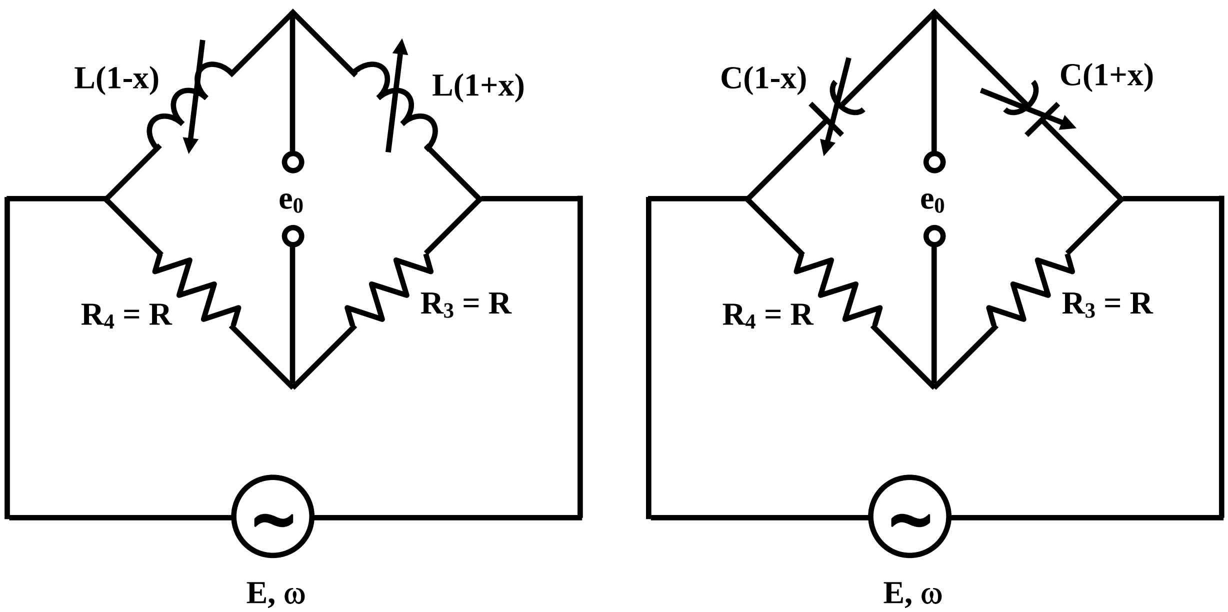

Fig. 5 Unbalanced A.C. bridge with push-pull configuration: (a) for inductive sensor, and (b) for capacitive sensor.

$$e_0 = \frac{x}{2}E, \tag{5}$$

which again shows the linear characteristics of the bridge.

For the capacitance sensor with the arrangement shown in fig. 5(b), we have:

$$e_0 = \left[\frac{\frac{1}{jwC(1+x)}}{\frac{1}{jwC(1+x)} + \frac{1}{jwC(1-x)}} - \frac{R}{2R} \right] E$$

$$= \left[\frac{jwC(1-x)}{jwC(1+x) + jwC(1-x)} - \frac{R}{2R} \right] E$$

$$= -\frac{x}{2} E \qquad (6)$$

where $x = \Delta C / C$. As expected, we would also obtain here a complete linear characteristic, irrespective of whatever is the value of x. But here is a small difference between the performance of an inductive sensor bridge and that of a capacitance sensor bridge (equation (5) and (6)): a negative sign. This negative sign in an A.C. bridge indicates that the output voltage in fig. 4(b) will be 180^0 out of phase with the input voltage E. But this cannot be detected, if we use a simple A.C. voltmeter to measure the output voltage. In fact, if the value of x were negative, there would also be a phase reversal in the output voltage, which cannot be detected, unless a special measuring device for sensing the phase is used. This type of circuit is called a *Phase Sensitive Device* (PSD) and is often used in conjunction with inductive and capacitive sensors. The circuit of a PSD rectifies the small A.C. voltage into a D.C. one; the polarity of the D.C. output voltage is reversed, if there is a phase reversal.

Capacitance Amplifier

Here we would present another type of circuit configuration, suitable for push-pull type capacitance sensor. The circuit can also be termed as a half bridge and a typical configuration has been shown in fig.6. Here two identical voltage sources are connected in series, with their common point grounded. This can be also achieved by using a center-tapped transformer. Two sensing capacitors C_1 and C_2 are connected as shown in the fig. 5 and the unbalanced current flows through an amplifier circuit with a feedback capacitor C_f . Now the current through the capacitors are:

$$I_1 = V.jwC_1 \quad and \; I_2 = -V.jwC_2$$

Hence the unbalanced current:

$$I = I_1 + I_2 = V.jw(C_1 - C_2)$$

And the voltage output of the amplifier:

$$V_0 = -\frac{I}{jwC_f} = -\frac{C_1 - C_2}{C_f} V \qquad (7)$$

As expected, a linear response can also be obtained by connecting a push-pull configuration of capacitance in fig.6. The gain can be adjusted by varying C_f. However, this is an ideal circuit, for a practical circuit, a high resistance has to be placed in parallel with C_f.

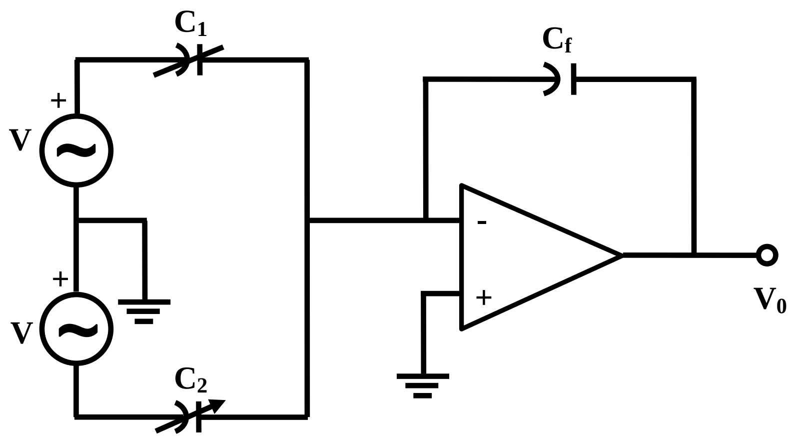

Fig. 6 A capacitance amplifier.

4. Amplifiers

An Amplifier is an integral part of any signal conditioning circuit. However, there are different configurations of amplifiers, and depending of the type of the requirement, one should select the proper configuration.

Inverting and Non-inverting Amplifiers

These two types are single ended amplifiers, with one terminal of the input is grounded. From the schematics of these two popular amplifiers, shown in fig.7, the voltage gain for the inverting amplifier is:

$$\frac{e_0}{e_i} = -\frac{R_2}{R_1}$$

while the voltage gain for the noninverting amplifier is:

$$\frac{e_0}{e_i} = 1 + \frac{R_2}{R_1}$$

Apparently, both the two amplifiers are capable of delivering any desired voltage gain, provided the phase inversion in the first case is not a problem. But looking carefully into the circuits, one can easily understand, that, the input impedance of the inverting amplifier is finite and is approximately R_1, while a noninverting amplifier has an infinite input impedance. Definitely, the second amplifier will perform better, if we want that, the amplifier should not load the sensor (or a bridge circuit).

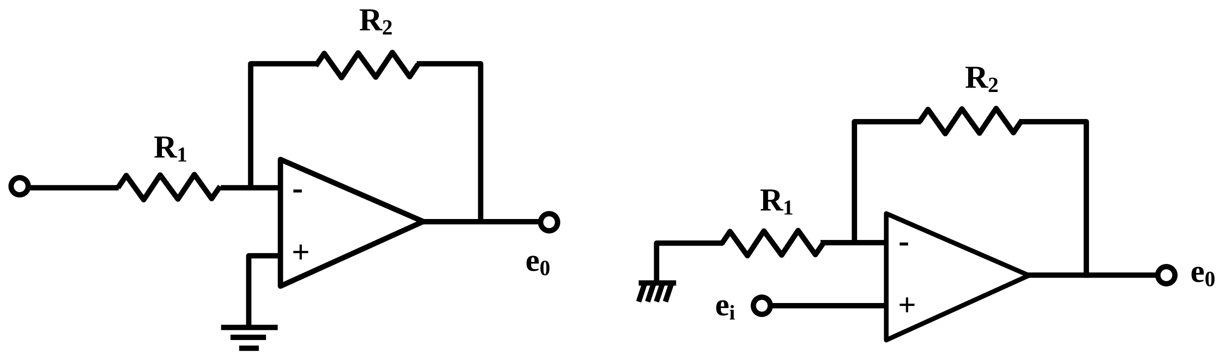

Fig. 7 (a) Inverting amplifier, (b) noninverting amplifier.

Differential Amplifier

Differential amplifiers are useful for the cases, where both the input terminals are floating. These amplifiers find wide applications in instrumentation. A typical differential amplifier with single op.amp. configuration is shown in fig.8. Here, by applying superposition theorem, one can easily obtain the contribution of each input and add them algebraically to obtain the output voltage as:

$$e_0 = \frac{R_4}{R_3 + R_4}(1 + \frac{R_2}{R_1})e_2 - \frac{R_2}{R_1}e_1 \qquad (8)$$

If we select

$$\frac{R_4}{R_3} = \frac{R_2}{R_1}, \qquad (9)$$

then, the output voltage becomes:

$$e_0 = \frac{R_2}{R_1}(e_2 - e_1) \qquad (10)$$

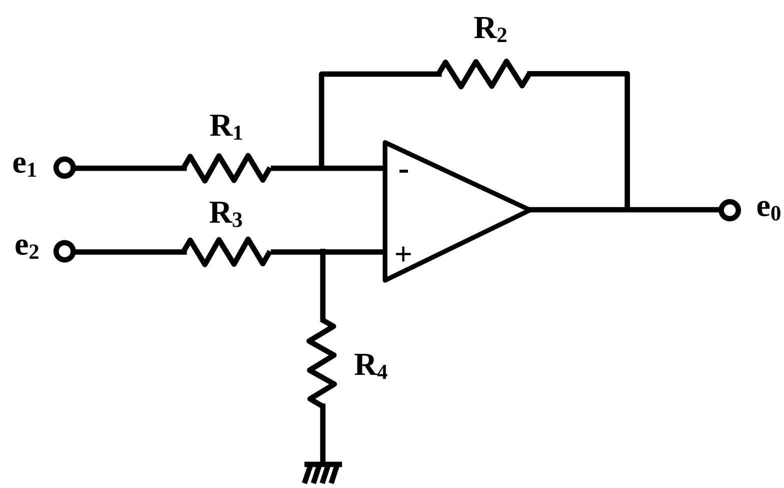

Fig. 8 Differential amplifier.

However, this type of differential amplifier with single op. amp. configuration also suffers from the limitation of finite input impedance. In fact, several criteria are used for judging the

performance of an amplifier. These are mainly: (i) offset and drift, (ii) input impedance, (iii) gain and bandwidth, and (iv) common mode rejection ratio (CMRR).
The performance of an operational amplifier is judged by the gain- bandwidth product, which is fixed by the manufacturer's specification. In the open loop, the gain is very high (around 10^5) but the bandwidth is very low. In the closed loop operation, the gain is low, but the achievable bandwidth is high. Normally, the gain of a single stage operational amplifier circuit is kept limited around 10, thus large bandwidth is achievable. For larger gains, several stages of amplifiers are connected in cascade.
CMRR is a very important parameter for instrumentation circuit applications and it is desirable to use amplifiers of high CMRR when connected to instrumentation circuits.
The CMRR is defined as:

$$CMRR = 20\log_{10}\frac{A_d}{A_c} \qquad (11)$$

where, A_d is the differential mode gain and A_c is the common mode gain of the amplifier. The importance of using a high CMRR amplifier can be explained with the following example:

Example -1

The unbalanced voltage of a resistance bridge is to be amplified 200 times using a differential amplifier. The configuration is shown in fig. 9 with R= 1000Ω and x=2 x 10^{-3}. Two amplifiers are available: one with A_d =200 and CMRR= 80 dB and the other with A_d =200 and CMRR= 60dB. Find the values of V_0 for both the cases and compute errors.

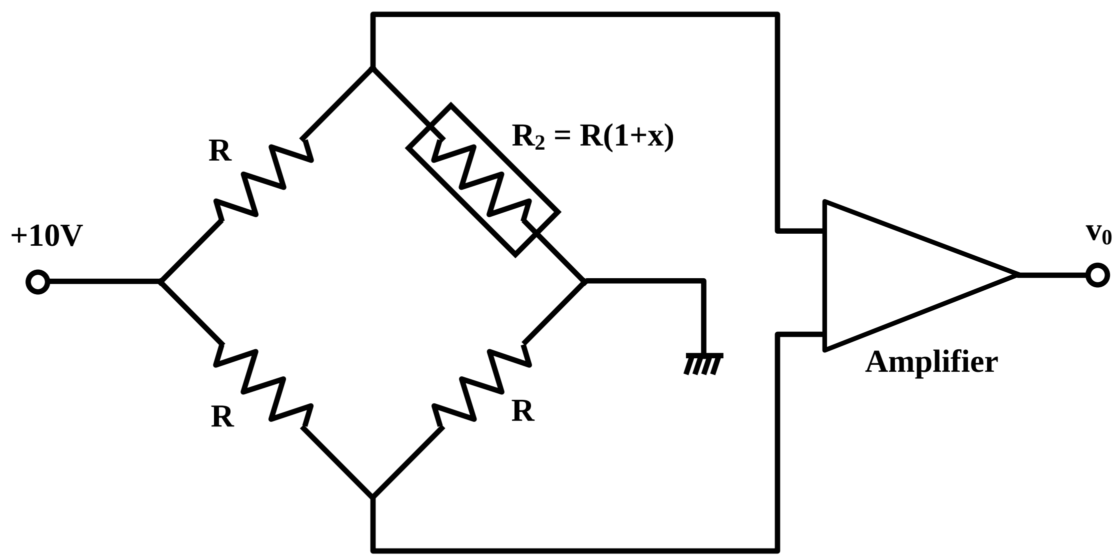

Fig. 9

Solution

Here x=2 x 10^{-3}. Using (3),

$$e_i = \frac{x}{4}x10 = 5\ mv = v_d$$

The common mode voltage to the amplifier is $v_c = 5V$, half the supply voltage.

For amp.-1, $A_d = 200$, $20\log\frac{A_d}{A_c} = 80dB$

Therefore, $\frac{A_d}{A_c} = 10^4$, or, $A_c = \frac{200}{10^4} = 0.02$.

So, $v_0 = A_d v_d + A_c v_c = 200 \times 5 \times 10^{-3} + 0.02 \times 5 = 1.1\,V$

Ideally, the voltage should have been 1.0 *V*, 200 times the bridge unbalanced voltage, but due to the presence of common voltage, 10% error is introduced.

In the second case, CMRR is 60 dB, all other values remaining same. For this case, $A_c = \frac{200}{10^3} = 0.2$. Therefore,

$$v_0 = A_d v_d + A_c v_c = 200 \times 5 \times 10^{-3} + 0.2 \times 5 = 2.0\,V$$

an error of magnitude 100% is introduced due to the common mode voltage!

Referring to fig. 8, if we consider, the op. amp. to be an ideal one, then by selecting the resistances, such that,

$$\frac{R_4}{R_3} = \frac{R_2}{R_1},$$

the effect of the common mode voltage can be eliminated completely, as is evident from eqn. (10). But if the resistance values differ, due to the tolerance of the resistors, the common mode voltage will cause error in the output voltage. The other alternative in the above example is to apply +5 and –5V at the bridge supply terminals, instead of +10V and 0V.

Instrumentation Amplifier

Often we need to amplify a small differential voltage few hundred times in instrumentation applications. A single stage differential amplifier, shown in fig.8 is not capable of performing this job efficiently, because of several reasons. First of all, the input impedance is finite; moreover, the achievable gain in this single stage amplifier is also limited due to gain bandwidth product limitation as well as limitations due to offset current of the op. amp. Naturally, we need to seek for an improved version of this amplifier.

A three op. amp. Instrumentation amplifier, shown in fig.10 is an ideal choice for achieving the objective. The major properties are (i) high differential gain (adjustable up to 1000) (ii) infinite input impedance, (iii) large CMRR (80 dB or more), and (iv) moderate bandwidth.

From fig. 10, it is apparent that, no current will be drawn by the input stage of the op. amps. (since inputs are fed to the non inverting input terminals). Thus the second property mentioned above is achieved. Looking at the input stage, the same current *I* will flow through the resistances R_1 and R_2. Using the properties of ideal op. amp., we can have:

$$I = \frac{e_1 - e_{i1}}{R_1} = \frac{e_{i1} - e_{i2}}{R_2} = \frac{e_{i2} - e_2}{R_1} \qquad (12)$$

from which, we obtain,

$$e_1 = e_{i1} + \frac{R_1}{R_2}(e_{i1} - e_{i2})$$

$$e_2 = e_{i2} - \frac{R_1}{R_2}(e_{i1} - e_{i2})$$

Therefore,

$$e_1 - e_2 = (1 + \frac{2R_1}{R_2})(e_{i1} - e_{i2})$$

The second stage of the instrumentation amplifier is a simple differential amplifier, and hence, using (10), the over all gain:

$$e_0 = \frac{R_4}{R_3}(e_2 - e_1) = \frac{R_4}{R_3}(1 + \frac{2R_1}{R_2})(e_{i2} - e_{i1}) \qquad (13)$$

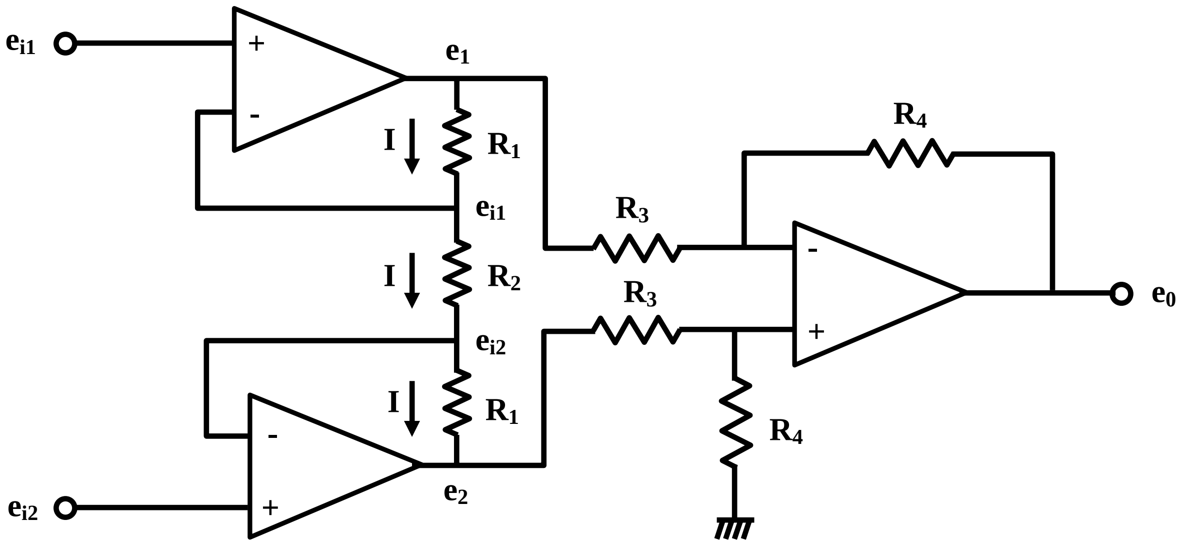

Fig. 10 Three op. amp. Instrumentation Amplifier.

Thus by varying R_2 very large gain can be achieved, but the relationship is inverse. Since three op. amps. are responsible for achieving this gain, the bandwidth does not suffer.

There are many commercially available single chip instrumentation amplifiers in the market. Their gains can be adjusted by connecting an external resistance, or by selecting the gains (50, 100 or 500) through jumper connections.

5. Concluding Remarks

Several issues have to be taken into consideration for the design of a signal conditioning circuit. Linearity, sensitivity, loading effect, bandwidth, common mode rejection are the important issues that affect the performance of the signal conditioning circuits. In this lesson, we have learnt about different configurations of unbalanced D.C. and A.C bridges, those are suitable for resistive, capacitive and inductive type transducers. Besides the characteristics of different types of amplifiers using common operational amplifiers have also been discussed in details. However, the actual design is dependent on the particular sensing element to be used and its characteristics.

Several other types of signal conditioning circuits (e.g. phase sensitive detector, filters and many others) have been left out in the discussion.

Problems

1. A resistance temperature detector using copper as the detecting element has a resistance of 100Ω at 0^oC. The resistance temperature co-efficient of copper is 0.00427/^oC at 0^oC. The sensing element is put in an unbalanced wheatstone bridge as in fig.2, the other arms are fixed resistances of 100Ω each. Plot the unbalanced voltage vs. temperature for temperature variation from 0^oC to 100^oC, if the excitation voltage is E = 2V. Are the characteristics linear or nonlinear? Justify your answer.
2. Explain the advantage of using push-pull arrangement in a bridge circuit.
3. For what arm ratio the sensitivity of an unbalanced wheatstone bridge is maximum?
4. A noninverting amplifier provides higher input impedance to the measuring circuit compared to an inverting amplifier- justify.
5. Define CMRR of an op. amp. Why is it important for designing a measurement system?
6. Design a differential amplifier of gain 10.
7. Discuss the main features of an instrumentation amplifier.
8. A differential amplifier circuit shown in fig. 8 has the resistances: R_1 = 10K, R_2 = 100K, R_3 = 11K and R_4 = 100K. Assuming the op. amp. To be an ideal one, find the CMRR of the amplifier.
9. A simple capacitance amplifier circuit is shown in fig. P1. C_1 represents a capacitive sensor whose nominal value is 50 pF. C_2 is a fixed capacitor of 25 pf. Find the output voltage if the sinusoidal excitation voltage 1V peak-to peak at frequency 1kHz. Assume the op.amp. to be an ideal one.

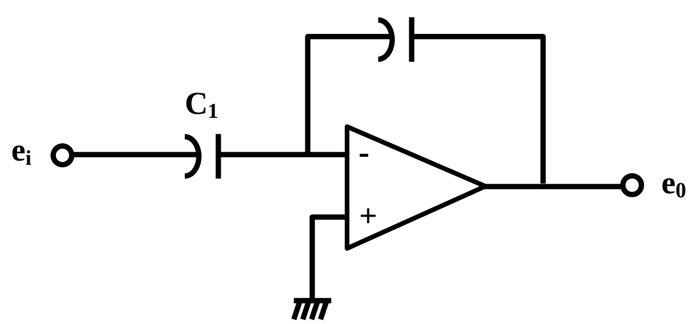

Fig. P1.

Answers

1. For 100^oC change in temperature is change in resistance for the RTD is 42.7Ω. So the condition $\Delta R/R << 1$ is not satisfied. As a result the bridge output is highly nonlinear.
6. Refer fig.8. Any combination of resistances satisfying eqn.(9) and $R_2/R_1 = 10$ will do. Typical values, $R_1 = 10K$ and $R_2 = 100K$.
8. 40.83dB
9. 2

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