Department of Electrical Engineering

Instrumentation Lab EE-702

Experiment No.-9 Characteristic of the Op-amp.

OBJECTIVE

(A) To measure the Common mode rejection ratio (CMRR) of a given Op-Amp.

(B) To design instrumentation amplifier for CMRR of 150 dB and differential gain of 1000.

Equipment / Apparatus required: CRO, Multi meter, 741 IC (Given Op-Amp), Resistances, capacitor, power supply (0-15 V DC), breadboard, connecting wires, low frequency sine wave function generator.

Theory

A common-mode signal is a signal that is common to both input terminals of an amplifier. In an instrumentation system, the wires leading from the transducer to the amplifier can pick up common mode interference. The common-mode signal can be of the order of a few volts, while the difference signal to be amplified is usually smaller, of order of mV. Instrumentation amplifiers must be able to amplify the desirable difference signal (denoted v_d) and reject the undesirable common-mode signal (denoted v_{cm}). The CMRR is a figure of merit of an amplifier that specifies how good it is in rejecting common mode signals. Let A_d be the differential voltage gain of the amplifier and A_{cm} is the common-mode voltage gain. The CMRR is defined as follows: CMRR = $|A_d| / |A_{cm}|$.

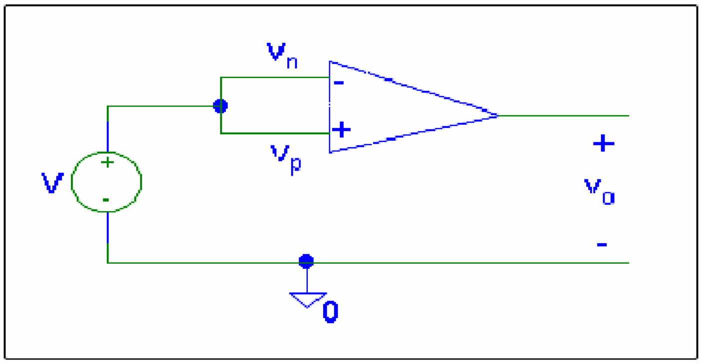

Fig.1 Common-mode and difference mode signals

Consider an op-amp operating open-loop as depicted in Fig.1. The difference signal is $v_d = v_p - v_n$, and the common-mode signal is $v_{cm} = (v_p + v_n)/2$. In the case of Fig.1, the difference signal is $v_d = 0$, and the common mode signal is $v_{cm} = V$. If the op-amp is ideal, the output signal is $v_o = A_d\ v_d$ (only the difference signal appears at the output). The output signal is thus $v_o = 0$ if the op-amp is ideal. However the common mode signal does propagate to the output if the op-amp is non-ideal. For a non-ideal op-amp, the output signal is

$$v_o = A_d v_d + A_{cm} v_{cm} \tag{1}$$

The configuration of a basic difference amplifier is depicted in Fig.2. Using ideal op-amp analysis it is easy to show that the input resistance of the amplifier is $2R_1$ and that the output signal of the amplifier is $v_o = \frac{R_2}{R_1}(v_2 - v_1)$. The amplifier thus has zero common-mode gain and a differential voltage gain of R_2 / R_1. Note that the common-mode gain is not zero if the op- amp is non-ideal, or if the resistors labeled R_1(or R_2) do not have identical values.

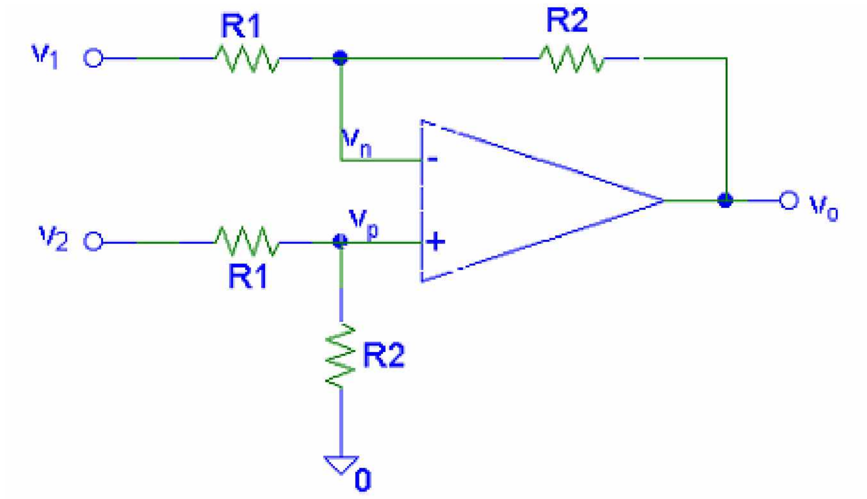

Fig. 2 A difference amplifier

Let v_P and v_n denote the potentials at the + and - terminals of the op-amp of Fig. 2, respectively. Let us now analyze the basic difference amplifier assuming that the op-amp is non- ideal. Specifically, let us assume that the op-amp has finite gain A_d (resulting in v_p-v_n being non zero). We will also assume that the op-amp has infinite input resistance (no current flows into the + or - terminal).

Let v_d and v_{cm} denote the difference and common-mode signals of the difference amplifier, of Fig. 2-2, respectively. We have

$$v_d = v_2 - v_1 \quad \text{and} \quad v_{cm} = \frac{v_1 + v_2}{2} \tag{2}$$

Similarly, let v_{do} and v_{cmo} denote the difference and common-mode signals at the op-amp input. We have

$$v_{do} = v_p - v_n \quad \text{and} \quad v_{cmo} = \frac{v_p + v_n}{2} \tag{3}$$

It is clear from the circuit diagram that

$$v_p = \frac{R_2}{R_1 + R_2} v_2 \tag{4}$$

$$v_n = v_o + \frac{R_2}{R_1 + R_2}(v_1 - v_o) = v_o \frac{R_1}{R_1 + R_2} + v_1 \frac{R_2}{R_1 + R_2} \qquad (5)$$

The output signal v_o expressed in terms of the op-amp differential gain A_d and common-mode gain A_{cm} is

$$v_o = A_d v_{do} + A_{cm} v_{cmo} \qquad (6)$$

Using Eqs. 2-3, 2-4, and 2-5 in Eq. 2-6 yields the following expression for v_0

$$v_o = \frac{A_d}{R_1 + R_2}(R_2 v_d - v_o R_1) + \frac{A_{cm}}{R_1 + R_2}(R_2 v_{cm} + v_o R_1 / 2) \qquad (7)$$

Collecting all the terms containing v_o we obtain the following expression for v_o (in terms of v_d and v_{cm} of Eq. 2-2):

$$v_o = \frac{A_d \frac{R_2}{R_1} v_d + A_{cm} \frac{R_2}{R_1} v_{cm}}{1 + \frac{R_2}{R_1} + A_d - \frac{A_{cm}}{2}} \qquad (8)$$

The denominator of the above equation is approximately equal to A_d since $A_d >> A_{cm}$ and $A_d >> R_2 / R_1$ (the gain of the ideal difference amplifier). We thus have

$$v_o \approx \frac{R_2}{R_1} vd + \frac{1}{CMRR_o} \frac{R_2}{R_1} v_{cm} \qquad (9)$$

where CMRRo = Ad / Acm is the common-mode rejection ratio of the op-amp. It is clear from the above equation that the differential voltage gain $A_{d\text{-}amp}$ and common mode gain $A_{cm\text{-}amp}$ of the amplifier are as described below:

$$A_{d-amp} = \frac{R_2}{R_1} \qquad\qquad A_{cm-amp} = \frac{1}{CMRR_o} \frac{R_2}{R_1} \qquad (10)$$

The common-mode rejection ratio of the difference amplifier is the same as that of the op-amp, as demonstrated below:

$$CMRR_{amp} = A_{d-amp} / A_{cm-amp} = CMRR_o \qquad (11)$$

As mentioned earlier, the common mode signal can be orders of magnitude higher than the difference signal: the common-mode component of Eq. 9 can thus be significant. It is clear from the above discussion that the basic difference amplifier suffers from two disadvantages: low input resistance, and inadequate common-mode rejection.

Procedure

1. Connect the circuit as shown in figure2. use power supply of 15 volts DC and take suitable value of resistances R_1 and R_2
2. Apply the input signal v_1 , v_2 and calculate $v_d = v_2 - v_1$ and $vcm = (v_1 + v_2)/2$
3. Measure the output voltage and calculate CMRR by this equation

$$v_o \approx \frac{R_2}{R_1} vd + \frac{1}{CMRR_o} \frac{R_2}{R_1} v_{cm}$$

$$\therefore \quad CMRR_0 = \frac{R_2 \ v_{cm}}{\left(v_0 R_1 \ -v_d R_2 \right)}$$

The common-mode rejection ratio of the difference amplifier is the same as that of the op-amp.

Verify the $CMRR_0$ value obtained , with the value from data sheet for the particular IC you have tested. This IC and two more of this family will be used next, in the design of instrumentation amplifier

The instrumentation amplifier

An instrumentation amplifier is typically the first stage in an instrumentation system. It is used to amplify the signal produced by a transducer such as a thermocouple or a strain gauge. An instrumentation amplifier is a difference amplifier i.e., it amplifies the voltage difference between its two input terminals, neither of which is required to be a signal ground. An instrumentation amplifier should have the following characteristics: high input resistance, high voltage gain, and high common-mode-rejection-ratio (CMRR).

The instrumentation amplifier consists of an input stage followed by a second stage (which is just a basic difference amplifier). It is easily shown that the differential voltage gain of the first stage is $(1 + 2R_2 / R_1)$. We know that the differential gain of the second stage is R_4 / R_3. The overall differential gain of the instrumentation amplifier is thus

$$A_{d-amp} = \left(1 + 2\frac{R_2}{R_1}\right)\frac{R_4}{R_3} \qquad (12)$$

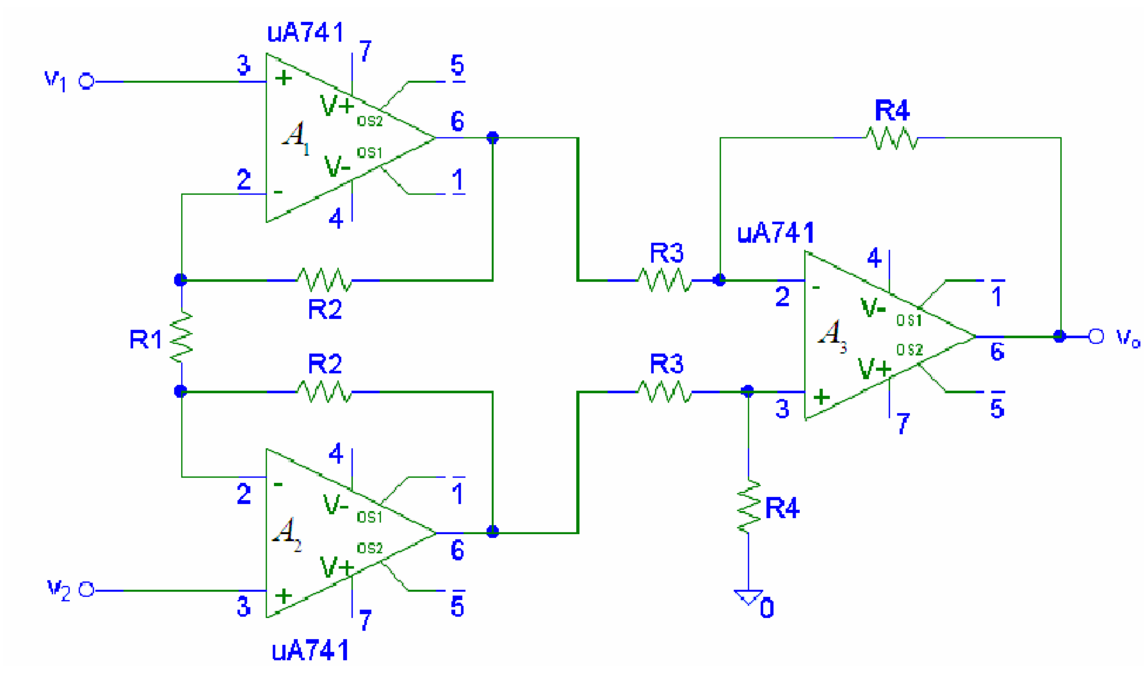

Fig. 3 An instrumentation amplifier

It is easily shown that the common-mode voltage gain of the first stage is unity. We know (see Eq. 10) that the common mode gain of the second stage is $R_4 /(R_3\ CMRR)$. The overall common-mode gain of the instrumentation amplifier is thus

$$A_{cm-amp} = \frac{1}{CMRR_o} \frac{R_4}{R_3} \quad (13)$$

The ratio of Eqs. 12 and 13 gives the CMRR of the instrumentation amplifier. We have

$$CMRR_{amp} = \left(1 + 2\frac{R_2}{R_1}\right) CMRR_o \quad (14)$$

The CMRR of the instrumentation amplifier is thus greater than that of the op-amps by a factor $(1 + 2R_2 / R_1)$ which can be large. In fact, if we set $R_4 = R_3$, we see from Eq. 12 that this multiplying factor is the (large) differential voltage gain of the instrumentation amplifier.

Design Procedure

For design $CMRR_{amp}$ of 150dB and A_{d-amp} (gain) of 1000.

1. Take the values of R1 = 1KΩ, R3 = 1KΩ.
2. Calculate the value of R2 using equation

$$CMRR_{amp} = \left(1 + 2\frac{R_2}{R_1}\right) CMRR_o$$

$CMRR_{amp}$ is common mode rejection ratio of instrumentation amplifier.

$CMRR_o$ is the common mode rejection ratio of Op-amp, which is calculated above.

3. Calculate R_4 using equation

$$A_{d-amp} = \left(1 + 2\frac{R_2}{R_1}\right) \frac{R_4}{R_3}$$

4. Connect the circuit as shown in figure. 3 use power supply of 15 volts DC.
5. Obtain gain frequency plot and test for gain in the mid frequency region.
6. To test the CMRR of instrumentation amplifier connect the circuit as shown in figure 4.

7. Apply input signal V_1 and V_2 Calculate $v_d = v_1 - v_2$ and $v_{cm} = \frac{v_1 + v_2}{2}$.

8. Measure output voltage V_0 and calculate CMRR by

$$v_0 \approx \frac{R_2'}{R_1'} v_d + \frac{1}{CMRR_{amp}} \frac{R_2'}{R_1'} v_{cm}$$

9. Compare the experimental CMRR with given specification and report.

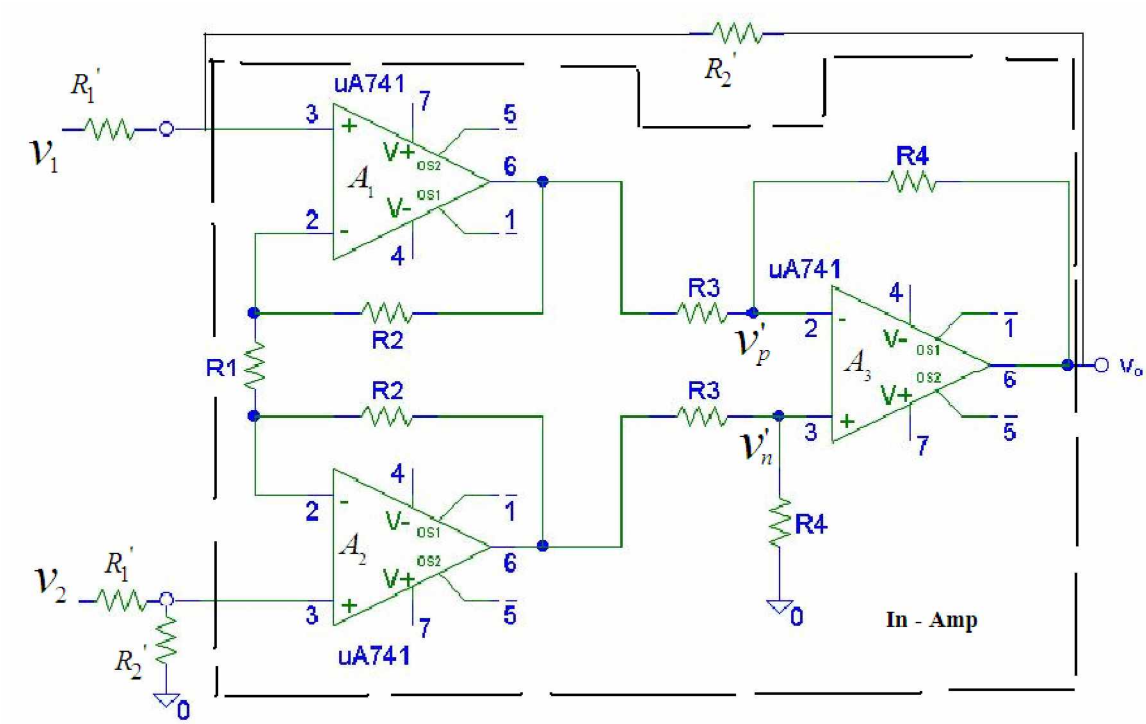

Figure 4. Testing circuit for measuring CMRR of In-Amp

Observation table:

Input voltage V_i = ___________________.

S.No.	Frequency(KHz)	Output voltage(V_0)	Gain($\frac{V_0}{V_i}$)
1	1		
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10	10		

Discussion:

1. Prove that the common-mode voltage gain of the input stage of the instrumentation amplifier is unity.
2. Prove that the differential voltage gain of the input stage of the instrumentation amplifier is (1 + $2R_2/R_1$).

Precautions:

1. Choose A_1, A_2, and A3 to be identical.

References:

1. OP-Amps and linear Integrated circuits – Gayakwad, Ramakant A.
2. Linear integrated circuits – D. Roy Choudhury, Shail B Jain (wiley)