Lecture 2 - A

Analog Signal Conditioning

EE 521: Instrumentation and Measurements

Lecture Notes Update on September 10, 2009

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1 Op-Amps - Handbook

Handbook of Operational Amplifier http://focus.ti.com/lit/an/sboa092a/sboa092a.pdf

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2 Differential Amplifiers (DA)

Overview

- Used for a wide variety of applications.
- Responds to the use difference in the input signals.
- Discriminates against changes in the dc power supply voltage.

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DA Basics

Given two inputs $v_{i,1}$ and $v_{i,2}$ define *difference mode* and *common-mode* input and output signals as

$$v_{id} = (v_{i,1} - v_{i,2})/2, \qquad v_{ic} = (v_{i,1} + v_{i,2})/2 \tag{1}$$

$$v_{od} = (v_{o,1} - v_{o,2})/2, \qquad v_{oc} = (v_{o,1} + v_{o,2})/2 \tag{2}$$

See Figure 1.

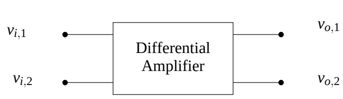

Figure 1: Differential amplifier block

Middlebrook Equations

$$v_{od} = A_{dd}v_{id} + A_{dc}v_{ic}, \qquad v_{oc} = A_{cd}v_{id} + A_{cc}v_{ic} \tag{3}$$

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Output Equations

For single output $v_o = v_{o,1}$

$$\begin{aligned} v_o &= \frac{A_{dd}+A_{cd}+A_{dc}+A_{cc}}{2}v_{i,1} + \frac{A_{cc}+A_{dc}-A_{dd}-A_{cd}}{2}v_{i,2} \\ &= A_D v_{id} + A_C v_{ic} \end{aligned} \tag{4}$$

Note. These gains are frequency dependent.

Ideal DA

$$A_{cc} = A_{cd} = A_{dc} = 0 \tag{5}$$

$$A_C = 0, \qquad A_D = A_{dd} \tag{6}$$

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Common-Mode Rejection Ratio (CMRR)

How close is the real differential amplifier close to an ideal one?

$$CMRR \equiv \frac{(|v_{ic}| \textit{ to give a certain } v_o)}{(|v_{id}| \textit{ to give the same } v_o)} \tag{7}$$

$$CMRR = \left|\frac{A_{dd}}{A_{cc}}\right| = \left|\frac{A_D}{A_C}\right| \tag{8}$$

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2.1 CMRR - Measurement

Measurement of A_D and A_C

- First case, connect both inputs to v_{s1} generating a common mode input signal which results in an output v_o.
- Second Case, connect the + input to v_{s2} and negative input to ground.

$$v_{id} = v_{s2}/2, \quad v_{ic} = v_{s2}/2$$

- Adjust v_{s2} such that the output is equal to v_o generated in the common mode input.

$$A_C = v_o/v_{ic} = v_o/v_{s1}$$

also

$$v_o = A_D v_{s2}/2 + A_C v_{s2}/2$$

consequently,

$$A_D = v_o(2/v_{s2} - 1/v_{s1}) \tag{9}$$

and

$$CMRR = A_D/A_C = (2v_{s1}/v_{s2} - 1) \tag{10}$$

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2.2 Source Resistance Asymmetry

DC Equivalent Input Circuit

Most frequently, common-mode input resistance, R_{ic}, measured between one input to ground using common mode input, and a difference-mode input resistance, R_{id}, measured using difference mode input from either inputs to ground, are provided by the manufacturer. 2 - A.9

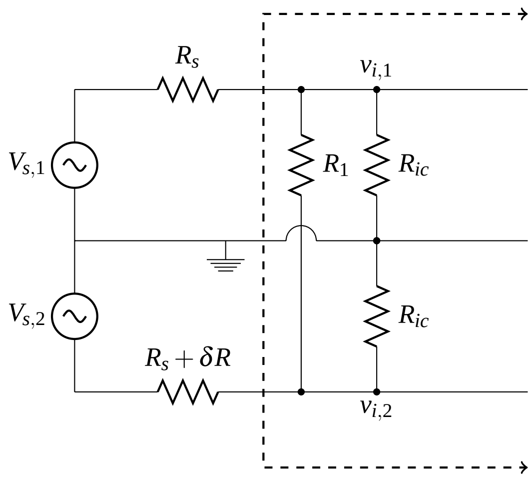

Figure 2: Differential amplifier input circuit at dc showing source resistance unbalance.

DA Input Circuit

See Figure 2 2 - A.10

CMRR-Computation

Under difference mode excitation, the current into the non-inverting input is given by:

$$i_d = 2v_{id}/R_1 + v_{id}/R_{ic} \tag{11}$$

and

$$i_d/v_{id} = 1/R_{id} = 2/R_1 + 1/R_{ic} \tag{12}$$

$$R_1 = 2R_{id}R_{ic}/(R_{ic} - R_{id}) \tag{13}$$

If $R_{ic} = R_{id}$, then $R_1 = \infty$. Using this assumption as well as the fact that δR is numerically negligible, then under common mode excitation v_{sc},

$$\frac{v_{id}}{v_{sc}} = \frac{R_{ic}\delta R}{2(R_{ic}+R_s)^2} \tag{14}$$

$$\frac{v_{ic}}{v_{sc}} = \frac{R_{ic}}{R_{ic}+R_s} \tag{15}$$

For purely difference mode excitation v_{sd}

$$\frac{v_{id}}{v_{sd}} = \frac{R_{ic}}{R_{ic}+R_s} \tag{16}$$

$$\frac{v_{ic}}{v_{sd}} = \frac{R_{ic}\delta R}{2(R_{ic}+R_s)^2} \tag{17}$$

Using $v_o = A_D v_{id} + A_C v_{ic}$,

$$v_o = A_D v_{sc} R_{ic} \delta R/[2(R_{ic}+R_s)^2] + A_C v_{sc} R_{ic}/(R_{ic}+R_s) \tag{18}$$

and

$$v_o = A_D v_{sd} R_{ic}/(R_{ic}+R_s) + A_C v_{sd} R_{ic} \delta R/[2(R_{ic}+R_s)^2] \tag{19}$$

$$\begin{aligned} CMRR_{sys} &= \frac{A_D/A_C + \delta R/[2(R_{ic}+R_s)]}{[A_D/A_C]\delta R/[2(R_{ic}+R_s)]+1} \\ &\approx \frac{CMRR_A}{CMRR_A \delta R/[2(R_{ic}+R_s)]+1} \end{aligned} \tag{20}$$

$CMRR_A$ is specified by the manufacturer 2 - A.11

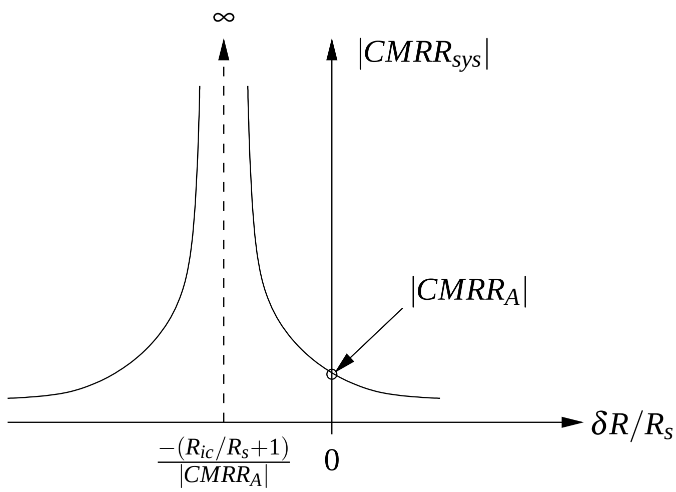

Figure 3: Differential amplifier CMRR magnitude vs fractional unbalance in source resistance.

CMRR - Special Cases

- If the thevenin source resistance are matched

$$CMRR_{sys} = CMRR_A \tag{21}$$

- When

$$\delta R/R_s = -2(R_{ic}/R_s + 1)/CMRR_A$$

  then

$$CMRR_{sys} \to \infty$$

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Source Resistance Asymmetry

See Figure 3 We can increase the systems CMRR by adding an external resistance. 2 - A.13

3 Operational Amplifiers

Typical Op-Amp

Open-loop Transfer Function

$$A_D = \frac{v_o}{v_i - v_i'} = \frac{k_{ov}}{(\tau_1 s + 1)(\tau_2 s + 1)} \tag{22}$$

- $f_1 = 1/(2\pi\tau_1)$ and $f_2 = 1/(2\pi\tau_2)$.
- To ensure stability $|A_D(jf_2)| \ll 1$.
- f_1 occurs at a relatively low value.
- Small-signal gain $\times$ bandwidth product

$$GBWP \approx k_{ov}/(2\pi\tau_1) \tag{23}$$

- The unity gain of 0dB frequency of the open loop, f_T, is approximately equal to the $GBWP$.
- Slew rate η.

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Notes

- Two pieces of information define are required to define the op-amp's open-loop characteristics.
  - DC open-loop gain k_{ov}, and
  - 0dB frequency, f_T.
- Closed-loop gain is limited by the open-loop gain.
- The higher the closed-loop gain is the smaller the bandwidth.
- To overcome this problem, it is better to cascade identical amplification stages rather than having one op-amp with a high gain.

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3.1 Broadband Amplifier

Non-inverting Amplifier

See Figure 4A.

$$v_o = (v_s - v_i')\frac{k_{vo}}{\tau s + 1} \tag{24}$$

$$v_i' = v_o \frac{R_1}{R_1 + R_F} = \beta v_o \tag{25}$$

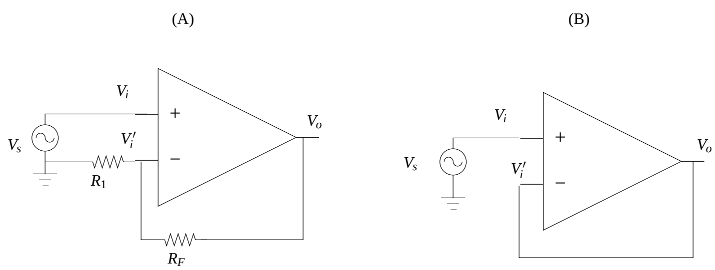

Figure 4: Non-inverting op-amp circuits

$$v_o/v_s = \frac{k_{ov}/(\tau s + 1)}{1 + \beta k_{ov}/(\tau s + 1)} \tag{26}$$

which, assuming that $\beta k_{ov} \gg 1$ reduces to

$$v_o/v_s = \frac{1/\beta}{s(\tau/(\beta k_{ov})) + 1} \tag{27}$$

$$GBWP = [k_{ov}/(1 + \beta k_{ov})][(\beta k_{ov})/(2\pi\tau)] = k_{ov}/(2\pi\tau) \tag{28}$$

If R_1 is infinite and R_F is shortcircuit, then we obtain a voltage follower that can be used as impedance isolation, see Figure 4B. 2 - A.16

Inverting Amplifier and Summer

See Figure 5. The gain for the kth inverting input is

$$v_o/v_{sk} = \frac{-(G_1/G_F)}{s(\tau \sum G/(k_{ov} G_F) + 1} \tag{29}$$

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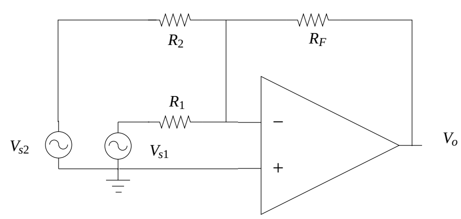

Figure 5: Summing op-amp