ECG Amplifier and Heart Rate Measurement

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Table of Contents

Chapter No.	Name	Page No.
1	**Introduction**	**1**
1.1	Instrumentation Amplifier	1
1.2	ECG	1
2.1	LTspice Circuit Simulation and Results	2
2.2	Waveform of ECG	4
3	**Observations and Calculations**	**5**
4	**Arduino Code for Digital Filter**	**6**
5.1	**Derivations**	**8**
5.1.1	Fourier Transfrom of ECG Signal	8
5.1.2	Common Mode Gain	10

Chapter 1

1 Introduction

1.1 Instrumentation Amplifier

Instrumentation amplifiers are used in any measuremment system using electrical transducers to enhance the signal level which is often at low level range. They are also required in certain cases to provide impedence matching and isolation. The characterisitics of Instrumentation Amplifier is speficied in terms of:

1. Input impedance
2. Output impedance
3. Gain and frequency response.
4. Noise.

1.2 ECG

Electrocardiography (ECG) is the process of recording the electrical activity of the heart over a period of time using electrodes placed on the skin. These electrodes detect the tiny electrical changes on the skin that arise from the heart muscle's electrophysiologic pattern of depolarizing during each heartbeat.

Chapter 2

2.1 LTspice Circuit Simulation and Results

The Instrumentation Amplifier was built and then the noise of 50Hz was filtered using notch filter by eliminating 50Hz frequency. This is shown in Fig.1.

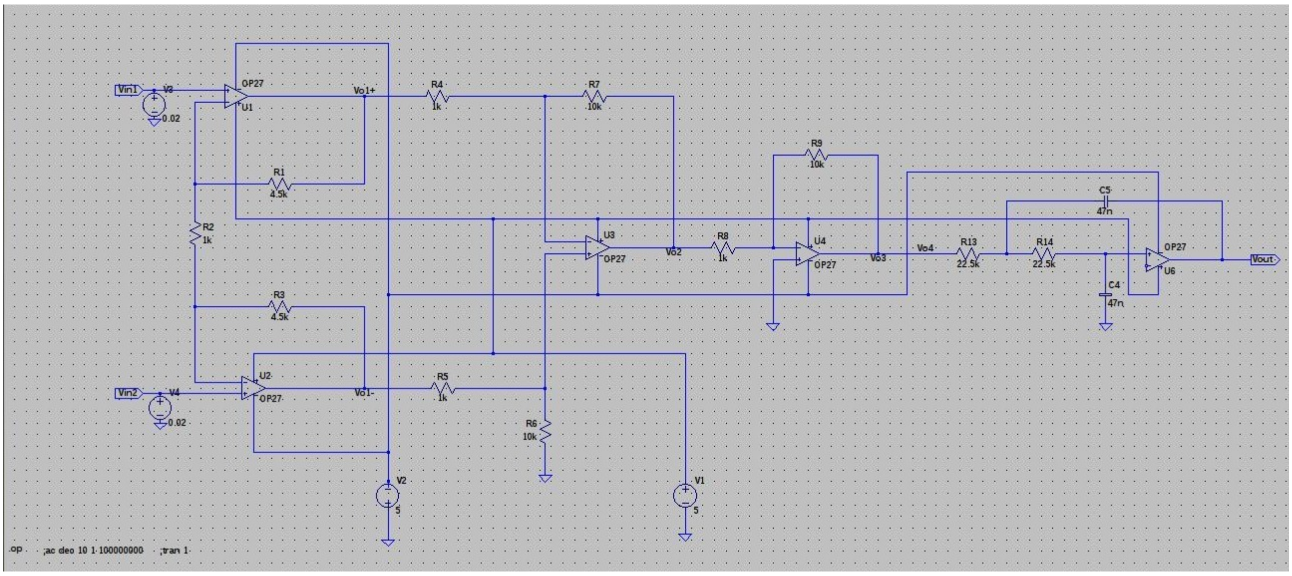


Fig.1: Schematic of ECG Amplifier and Filter

DC Analysis was done on the circuit shown in Fig.1. with Input Voltage as 1mV and output is shown in Fig.2.

--- Operating Point ---

V(n002):	-0.00454545	voltage
V(n007):	-0.00454545	voltage
V(n006):	5	voltage
V(vo2):	-0.0999999	voltage
V(n001):	-5	voltage
V(n004):	-4.54112e-008	voltage
V(vo4):	0.999999	voltage
V(vo1+):	0.005	voltage
V(n003):	0.0005	voltage
V(n009):	-0.0005	voltage
V(vo1-):	-0.005	voltage
V(vin1):	0.0005	voltage
V(n010):	-0.0005	voltage
V(n005):	0.999996	voltage
V(n008):	0.999993	voltage
V(vout):	3.99596	voltage
V(nc_01):	0.380994	voltage
I(C5):	1.4081e-019	device_current
I(C4):	4.69997e-020	device_current
I(R14):	-1.31523e-010	device_current
I(R13):	-1.31523e-010	device_current
I(R9):	-9.99999e-005	device_current
I(R8):	-9.99999e-005	device_current
I(R7):	9.54545e-006	device_current
I(R6):	4.54545e-007	device_current
I(R5):	4.54546e-007	device_current
I(R4):	-9.54545e-006	device_current
I(R3):	-1e-006	device_current
I(R2):	1e-006	device_current
I(R1):	1e-006	device_current
I(V3):	-4.76191e-014	device_current
I(V2):	-0.0133313	device_current
I(V1):	-0.0133116	device_current
Ix(u3:1):	-4.329e-013	subckt_current
Ix(u3:2):	-4.32899e-013	subckt_current
Ix(u3:3):	0.00261181	subckt_current
Ix(u3:4):	-0.00272135	subckt_current
Ix(u3:5):	0.000109545	subckt_current
Ix(u4:1):	2.66196e-018	subckt_current
Ix(u4:2):	-6.98683e-018	subckt_current
Ix(u4:3):	0.00271648	subckt_current
Ix(u4:4):	-0.00261648	subckt_current
Ix(u4:5):	-0.0001	subckt_current
Ix(u1:1):	4.76191e-014	subckt_current
Ix(u1:2):	4.7619e-014	subckt_current
Ix(u1:3):	0.00267128	subckt_current
Ix(u1:4):	-0.00266073	subckt_current

Fig.2: DC Analysis

AC Analysis was done of the circuit and Bode Plot of the circuit after filtering and before filtering is shown in Fig.3.

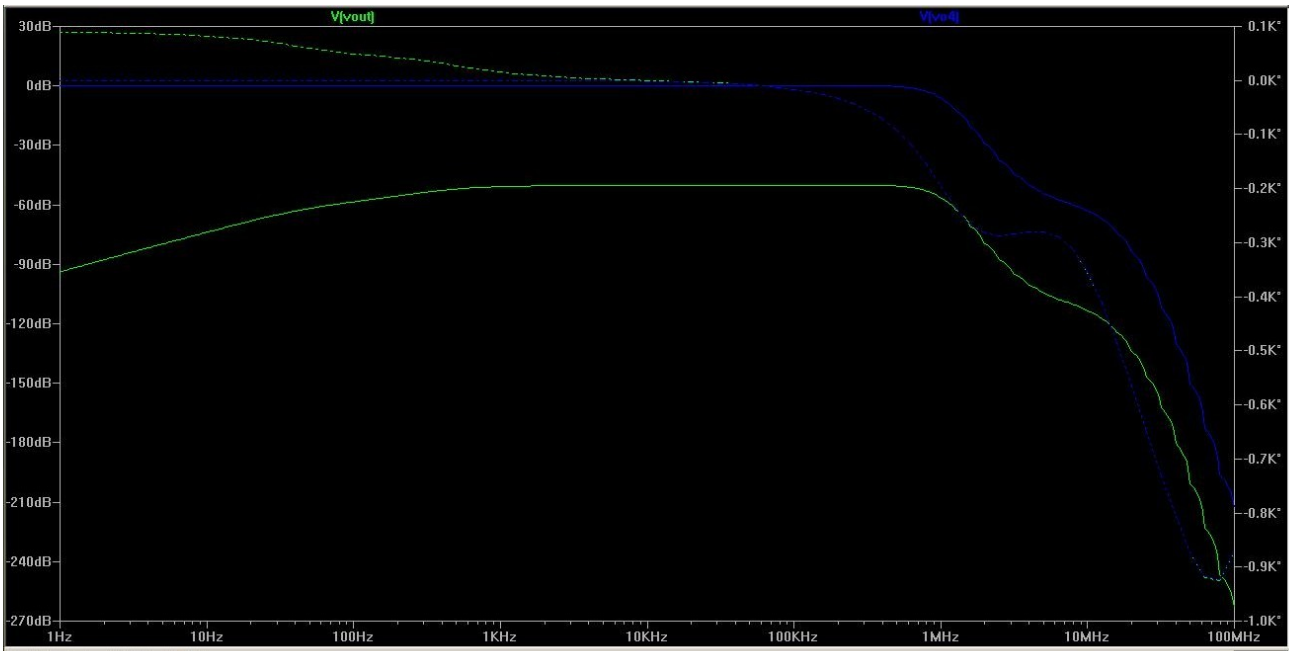


Fig.3: AC Analysis

Transient Analysis with Input Voltage as 1mV and Frequeency 100Hz was carried out and the result is showm in Fig.4.

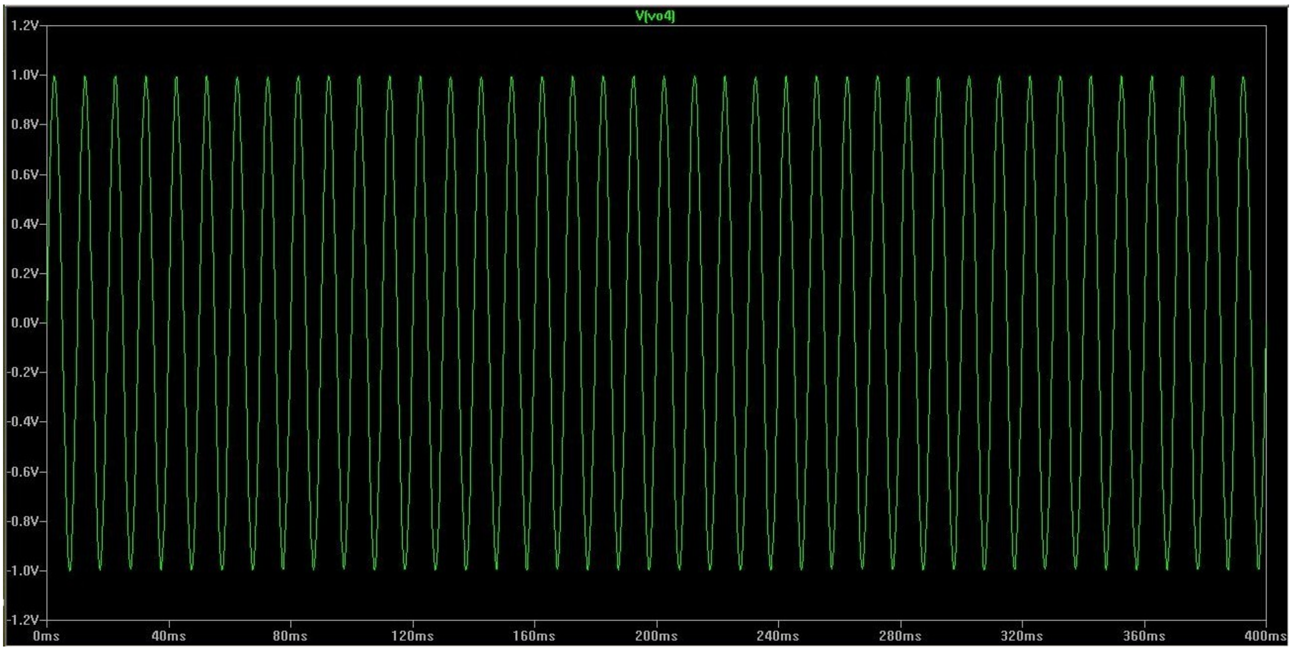


Fig.4: Transient Analysis

Input Impedance and Output Impedance is calculated using Transfer Function and the result is shown in Fig.5.

--- Transfer Function ---

Transfer_function:	3.37071e-011	transfer	
v3#Input_impedance:		2.1e+010	impedance
output_impedance_at_V(vout):		69.4447	impedance

Fig.5: Transfer Function

2.2 Waveform of ECG

ECG waveform is obtained on CRO without filtering by connecting spoons. Since, there was noise notch filter was built to eliminate noise of 50Hz. The output without filter is shown in Fig.6 and output after filtering is shown in Fig.7.

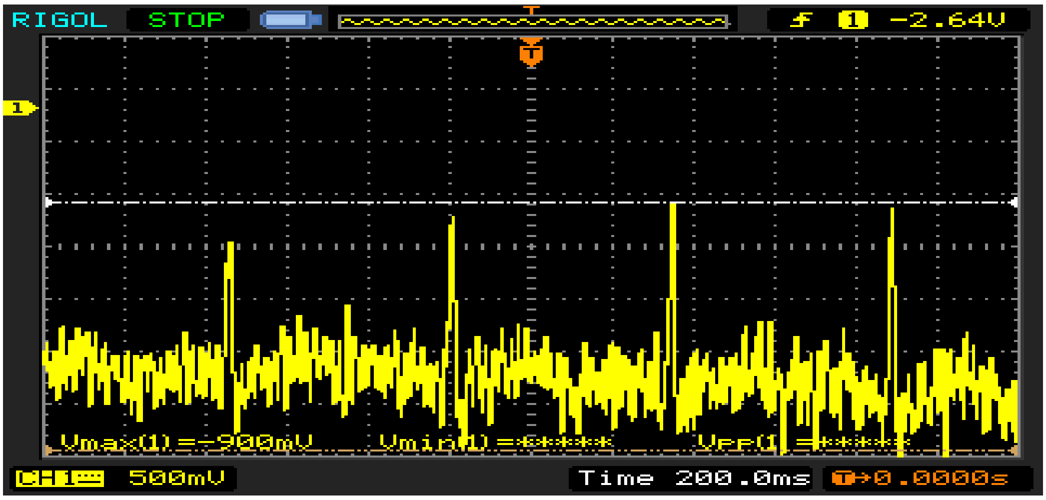


Fig.6: ECG Waveform without filter

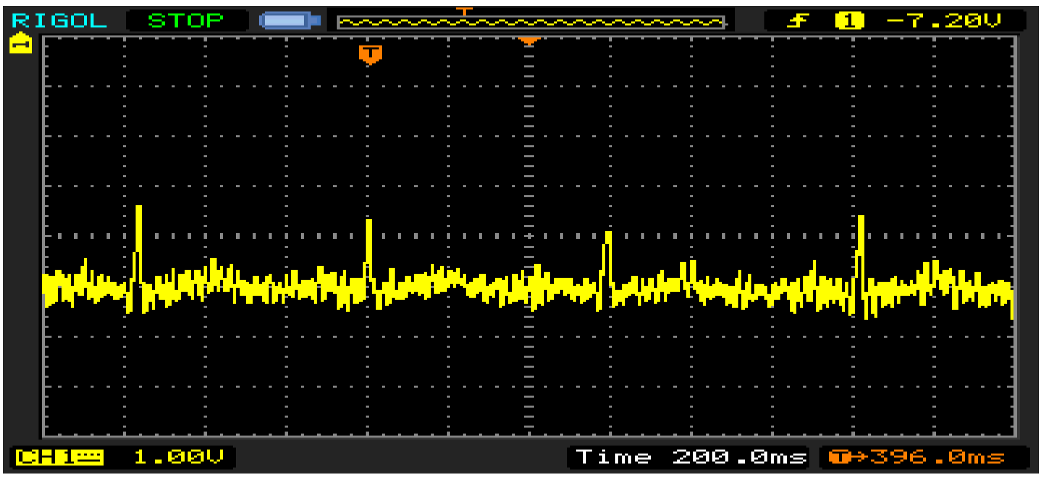


Fig.7: ECG Waveform after Filtering

Chapter 3

Observations and Calculations:

1. Offset Voltage:
1^{st} Stage:
Voltage at pin1 = -7.3mV
Voltage at pin7 = -1.2mV
Offset at 1^{st} stage = -6.1mV

2^{nd} Stage:
Offset at 2^{nd} Stage = 87mV

3^{rd} Stage:
Offset at 3^{rd} Stage = -850mV

2. Common Mode Gain:
Input Voltage = 0.716 Vrms
Output Voltage = 0.086 Vrms
Common Mode Gain = 0.086 / 0.716 = 0.12

3. Differential Gain:
Input Voltage = 20mV
1^{st} Stage = 170mV
2^{nd} Stage = 2.18V
3^{rd} Stage = 20.6Vp-p

Gain = 1030

Common Mode Rejection Ratio (CMRR) = 20 log(1030 / 0.12) = **78.67dB**

Chapter 4

Arduino Code for Digital Filter

```
/*

Simple FIR filter implementation

*/

#define FILTERTAPS 5            // The number of taps in your filter, or better the number of coefficients

// declare array for values
float values[FILTERTAPS] = {0, 0, 0, 0, 0}; // to have a nice start up, fill the array with 0's
// NOTE: this could be 1 shorter, as we already have the input in a variable. This would save stack
size/memory

// declare input and output variables
float input = 1; // without a real input, looking at the step respons (input at unity, 1) would be nice to see
float output = 0; // output as a 0, but that doesn't really matter

// our counter, real life applications won't need this
byte n = 0;

void setup() {
    Serial.begin(115200);     // open the serial port, I like them fast ;-)
}

float fir(float in){
    static byte k;                  // k stores a pointer to create a circular memory through the array. This
variable remains its value the next time we call the fir routine (hence 'static')
    byte i = 0;                     // i is a counter to step through the filter coefficients and stored values
    float out = 0;                      // out is the return variable. It is set to 0 every time we call the filter!

    values[k] = in;                     // store the input of the routine (contents of the 'in' variable) in the array
at the current pointer position


    // declare variables for coefficients
      // these should be calculated by hand, or using a tool
    // in case a phase linear filter is required, the coefficients are symmetric
    // for time optimization it seems best to enter symmetric values like below
    float coef[FILTERTAPS] = { 0.021, 0.096, 0.146, 0.096, 0.021};

    //declare gain coefficient to scale the output back to normal
    float gain = 0.38; // set to 1 and input unity to see what this needs to be


    for (i=0; i<FILTERTAPS; i++) {            // we step through the array
          out += coef[i] * values[(i + k) % FILTERTAPS];      // ... and add and multiply each value to
accumulate the output
                                  //  (i + k) % FILTERTAPS creates a cyclic way of getting through the array
      }
    out /= gain;                      // We need to scale the output (unless the coefficients provide unity gain in
the passband)

    k = (k+1) % FILTERTAPS;                 // k is increased and wraps around the FILTERTAPS, so next time we
will overwrite the oldest saved sample in the array

      return out;                      // we send the output value back to whoever called the routine

}
```

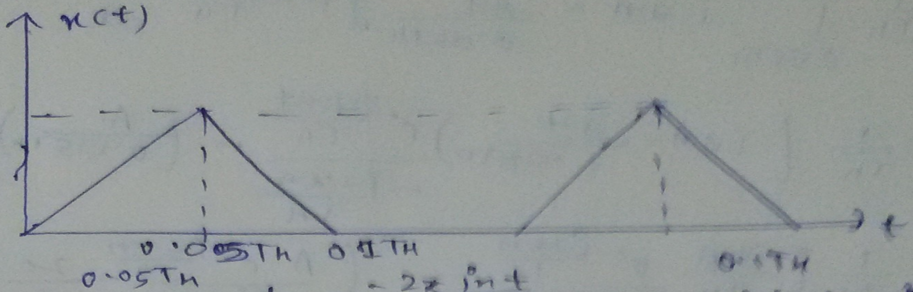
```
void loop() {

    // This is the loop that takes care of calling the FIR filter for some samples

    for (n = 0; n < FILTERTAPS + 2; n++) {          // If you like to see the step response, take at least as
many cycles as the length of your FIR filter (FILTERTAPS + 1 or 2)
        Serial.print("n= ");          // print the sample number
        Serial.println(n, DEC);
        Serial.println("Now calling fir...");
        output = fir(input);          // here we call the fir routine with the input. The value 'fir' spits out is
stored in the output variable.
        Serial.print("fir presented the following value= ");
        Serial.println(output);          // just for debugging or to understand what it does, print the output
value
    }
    while (true) {};          // endless loop
}
```

5.1 Derivations:

5.1.1 Fourier Transform of ECG Signal

$\Rightarrow \quad \int^{0.1T_H} \left(2A - \frac{At}{\ldots}\right.$

→ fourier series to find the Bandwidth of ECG:-



$$C_n = \underbrace{\frac{1}{T_H}\int_0^{0.05T_H} \frac{A}{0.05T_H}\, t\, e^{-\frac{2\pi j n t}{T_H}}\, dt}_{\mathrm{I}} + \underbrace{\frac{1}{T_H}\int_{0.05T_H} \left(2A - \frac{At}{0.05T_H}\right) e}_{\mathrm{II}}$$

$$\mathrm{I} \Rightarrow \frac{1}{T_H}\int_0^{0.05T_H} \frac{At}{0.05T_H}\, e^{-j\frac{n 2\pi t}{T_H}}\, dt$$

$$= \frac{20A}{T_H^2}\left[\int_0^{0.05T_H} t\, e^{-\frac{j2\pi n t}{T_H}}\, dt\right]$$

$$= \frac{20A}{T_H^2}\left[\frac{t\, e^{-\frac{j2\pi n t}{T_H}}}{-j\frac{2\pi n}{T_H}} - \frac{e^{-\frac{j2\pi n t}{T_H}}}{\left(j\frac{2\pi n}{T_H}\right)^2}\right]_0^{0.05T_H}$$

$$= \frac{20A}{T_H^2}\left[\frac{0.05T_H\, e^{-\frac{j2\pi n}{20}}}{-j\frac{2\pi n}{T_H}} + \frac{e^{-\frac{j2\pi n}{20}}}{\left(\frac{2\pi n}{T_H}\right)^2} - \frac{1}{\left(\frac{2\pi n}{T_H}\right)^2}\right]$$

$$= 20\left[\frac{j0.05\, e^{-\frac{j2\pi n}{20}}}{-j2\pi n} + \frac{e^{-\frac{j2\pi n}{20}}}{(2\pi n)^2} - \frac{1}{(2\pi n)^2}\right]$$

$$= e^{-\frac{j2\pi n}{20}}\left[\frac{jA}{20\pi n} + \frac{20A}{(2\pi n)^2}\right] - \left[\frac{20A}{(2\pi n)^2}\right] -$$

(II) $\Rightarrow$ $\left(2A - \frac{At}{}\right.$

(II) $\Rightarrow \frac{1}{T_H}\int_{0.05T_H}^{0.1T_H}\left(2A - \frac{At}{0.05T_H}\right)e^{-\frac{i2\pi nt}{T_H}}\,dt$

$$= \frac{1}{T_H}\left[\left(2A - \frac{At}{0.05T_H}\right)\frac{e^{-\frac{i2\pi nt}{T_H}}}{-i\frac{2\pi n}{T_H}} - \left(\frac{A}{0.05T_H}\right)\frac{e^{-\frac{i2\pi nt}{T_H}}}{\left(\frac{2\pi n}{T_H}\right)}\right]$$

$$= \frac{1}{T_H}\left[\frac{-20A}{T_H}\frac{e^{-\frac{i2\pi n}{10}}}{\left(\frac{2\pi n}{T_H}\right)^2} - \left(\frac{A\,e^{-\frac{i2\pi n}{20}}}{-i\frac{2\pi n}{T_H}} - \frac{20A}{T_H}\frac{e^{-\frac{i2\pi n}{10}}}{\left(\frac{2\pi n}{T_H}\right)^2}\right.\right.$$

$$= \frac{-20A}{(2\pi n)^2}e^{-\frac{i\pi n}{5}} - \frac{Ai}{20n}e^{-\frac{i\pi n}{10}} + \frac{20A}{(2\pi n)^2}e^{-\frac{i\pi n}{10}}$$

$$= e^{-\frac{i\pi n}{5}}\frac{20A}{(2\pi n)^2} + e^{-\frac{i\pi n}{10}}\left(\frac{20A}{(2\pi n)^2} - \frac{Ai}{2\pi n}\right) - ($$

$C_n =$ (I) + (II)

$$= \left[-\frac{20A}{(2\pi n)^2} + e^{-\frac{i\pi n}{10}}\left[\frac{iA}{2\pi n} + \frac{20A}{(2\pi n)^2} - \frac{Ai}{2\pi n} + \frac{20A}{(2\pi n}\right.\right.$$

$$\left. - e^{-\frac{i\pi n}{5}}\frac{20A}{(2\pi n)^2}\right]$$

$$C_n = \frac{-20A}{(2\pi n)^2} + e^{-\frac{i\pi n}{10}}\frac{40A}{(2\pi n)^2} - e^{-\frac{i\pi n}{5}}\frac{20A}{(2\pi n)^2}$$

Case $n=0$

$$C_n = \frac{20A}{T_H^2}\int_0^{0.05T_H} t\,dt + \frac{1}{T_H}\int_{0.05T_H}^{0.1T_H}\left(2A - \frac{At}{0.05T_H}\right)dt$$

$$= A[0.025] + 0.1A - 0.075A$$

$$\boxed{C_0 = 0.05A} \quad \text{———} \; *$$

5.1.2 Common Mode Gain

COMMON MODE GAIN

$R_{Gain} = R_{11} + \Delta R \,, \quad R_{21} = R_{22} \,, \quad R_{32} = R$

1st stage :-

$$\frac{V_{01}}{V_{in}} = 1 + \frac{2R_{11}}{R_{12}}$$

$$\frac{V_{02}}{V_{in}} = 1 + \frac{2(R_{11} + \Delta R)}{R_2}$$

$$\Rightarrow \frac{V_{01} - V_{02}}{V_{in}} = -\frac{2\Delta R}{R_{12}} = \frac{\Delta V}{V_{in}}$$

IInd stage :-

$$\frac{V_{03}}{\Delta V} = -\frac{R_{32}}{R_{21}}$$

IIIrd stage :-

$$\frac{V_{04}}{V_{03}} = -\frac{R_5}{R_4}$$

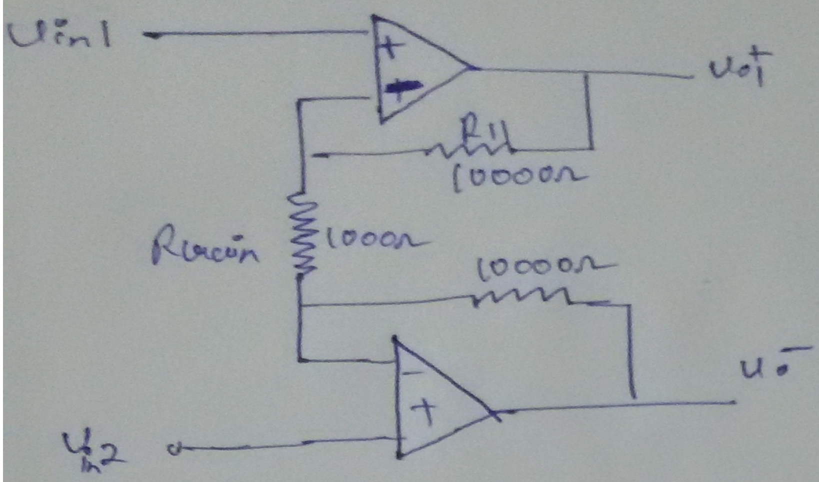
total common mode gain $= \frac{V_{04}}{V_{in}} = -\left(\frac{2\Delta R}{R_{in}}\right)\left(\frac{R_{32}}{R_{21}}\right)\left(\right.$

$$CMRR = \frac{A_{DM}}{A_{CM}}$$

$$CMRR = -\frac{\left(1 + \frac{2R_{11}}{R_{12}}\right)}{\left(2 \frac{\Delta R}{R_{12}}\right)} = -\left(\frac{R_{12} + 2R}{2\Delta R}\right.$$

Vo1- Vo2   R4

INTRUMENTATION AMPLIFIER



⇒ 1st stage

$$\frac{V_{o1}}{V^+} = 1 + \frac{2R_{11}}{R_{12}}$$

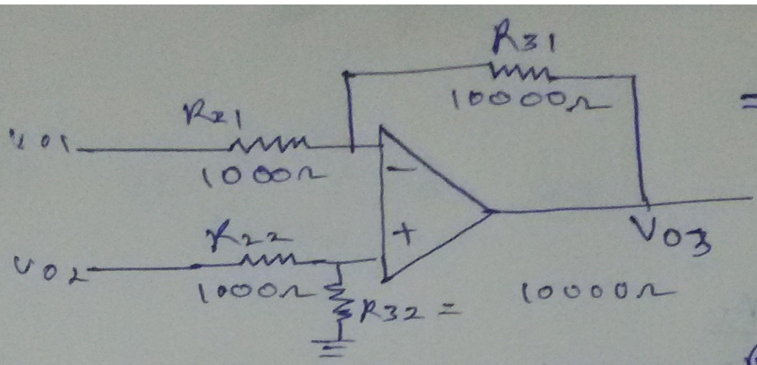
$$\frac{V_{o2}}{V^-} = 1 + \frac{2\,R_{gain}}{R_{12}}$$

$$\frac{V_{o1}}{V^+} = 1 + \frac{2R_{11}}{R_{12}} \Rightarrow V_{o1} = \left(1 + \frac{2R_{11}}{R_{12}}\right) V^+$$

$$\frac{V_{o2}}{V^-} = 1 + \frac{2R_{11}}{R_{12}} \Rightarrow V_{o2} = \left(1 + \frac{2R_{11}}{R_{12}}\right) V^-$$

$$\Rightarrow \frac{V_{o1}}{V_{in}} = \frac{V_{o1} - V_{o2}}{V^+ - V^-} = 1 + \frac{2R_{11}}{R_{12}} = 1 + \frac{2(1000}{1000}$$

Gain of 1st stage = 21



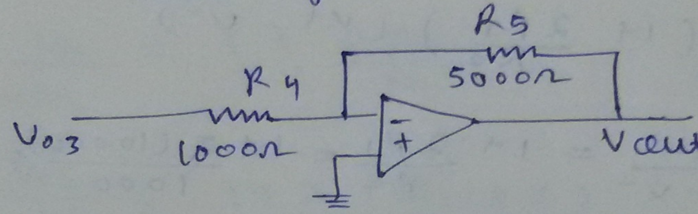
⇒ II^{nd} Stage

⇒ $R_{21} = 1000\Omega$, $R_{22} = 1000\Omega$, $R_{31} = 10000\Omega$

$$V_{o3} = \left(-\frac{R_{32}}{R_{21}}\right) V_{o1} + V_{o2}\left(\frac{R_{32}}{R_{21}}\right)$$

$$\Rightarrow \frac{V_{o3}}{V_{o1} - V_2} = \frac{-R_{32}}{R_{21}} = \frac{-10000}{1000} = -10$$

Gain of II^{nd} stage $= -10$



⇒ III^{rd} stage

$$\frac{V_{out1}}{V_{o3}} = -\frac{R_5}{R_4} = \frac{-5000}{1000} = -5$$

Gain of III^{rd} stage $= -5$