EE230: Experiment 4
Instrumentation Amplifier on load cell sensor

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1 Overview of the experiment

1.1 Aim of the experiment

- In this experiment, we wish to implement instrumentation amplifier to amplify output from a load cell sensor. This is done in two parts:
  - In part 1, we build the instrumentation amplifier using TL084 IC.
  - In part 2, we implement the instrumentation amplifier using INA128 IC.
- To observe/compare the output from the above two methods.

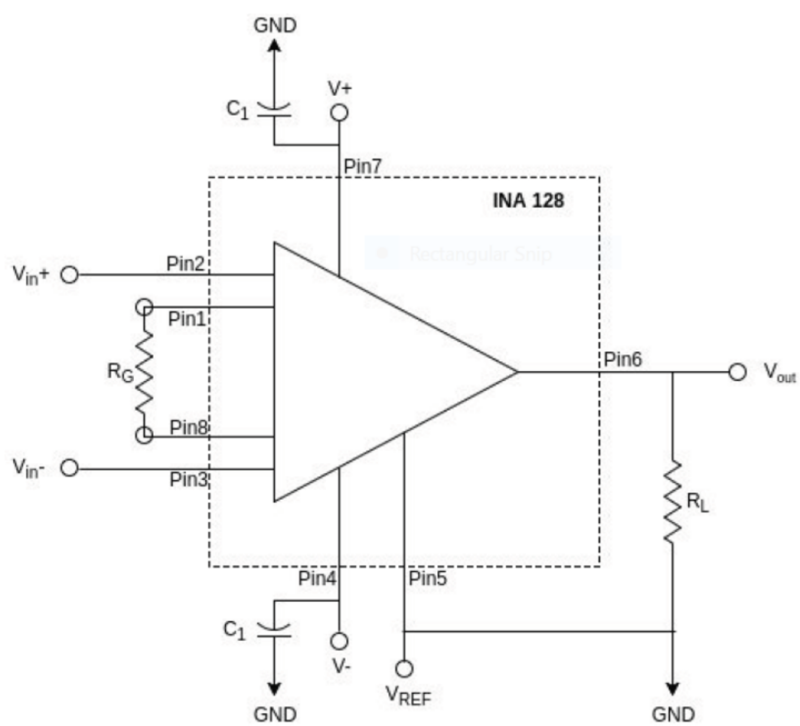


Figure 1: Pin diagram of INA128

1.2 Theory

1.2.1 Load Cell

A load cell is based on an electrical circuit called Wheatstone bridge. It consists of 4 strain gauges connected on a cantilever beam that undergo change in resistance when deformed (i.e. when the object to which they are connected to experiences strain).

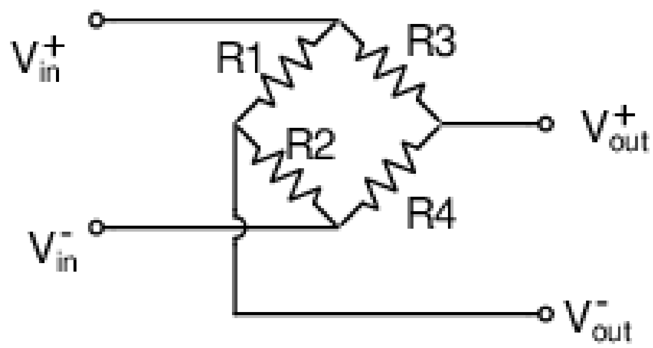


Figure 2: Circuit Diagram of the Load Cell

This arrangement allows to measure very small changes in the resistance R, which occurs in the strain gauges placed in the arms of the bridge: R_1, R_2, R_3 and R_4. When the load cell has no load, the four gauges are at rest and have the same ohmic value, the nominal value of the strain gauge Rg:

$$R_1 = R_2 = R_3 = R_4 = R_g \tag{1}$$

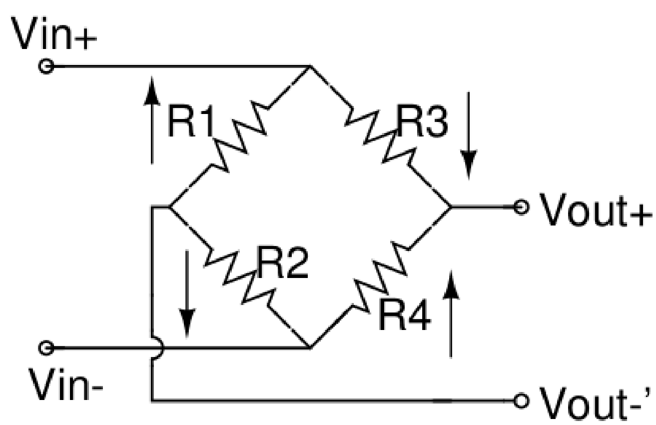


Figure 3: Strained resistors of Load Cell

When the load cell experiences deformation due to externally applied force, the resistance of each strain gauge changes by a very small amount ΔR. Hence, the differential voltage ΔV as a result of ΔR is as follows:

$$R1 = R_g + \Delta R \qquad R2 = R_g - \Delta R \qquad R3 = R_g - \Delta R \qquad R4 = R_g + \Delta R \tag{2}$$

$$\Delta V_{in} = V_{in}^{+} - V_{in}^{-} \tag{3}$$

$$\text{As the resistors act as voltage dividers, we see} \tag{4}$$

$$V_{out}^{+} = \frac{R_4}{R_4 + R_3} \Delta V_{in} \tag{5}$$

$$V_{out}^{-} = \frac{R_2}{R_2 + R_1} \Delta V_{in} \tag{6}$$

$$\Delta V_{out} = V_{out}^{+} - V_{out}^{-} \tag{7}$$

$$\implies \Delta V_{out} = \left(\frac{R_g + \Delta R}{2R_g} - \frac{R_g - \Delta R}{2R_g} \right) \Delta V_{in} \tag{8}$$

$$\implies \Delta V_{out} = \frac{\Delta R}{R_g} \Delta V_{in} \tag{9}$$

Hence we see that V_{out} depends *linearly* on ΔR.

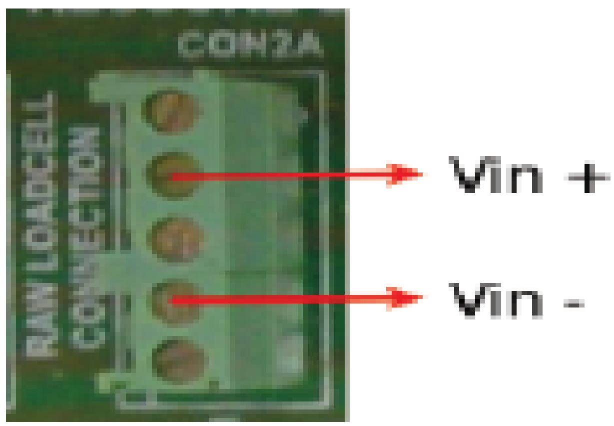


Figure 4: Raw load cell output to the input of instrumentation amplifier

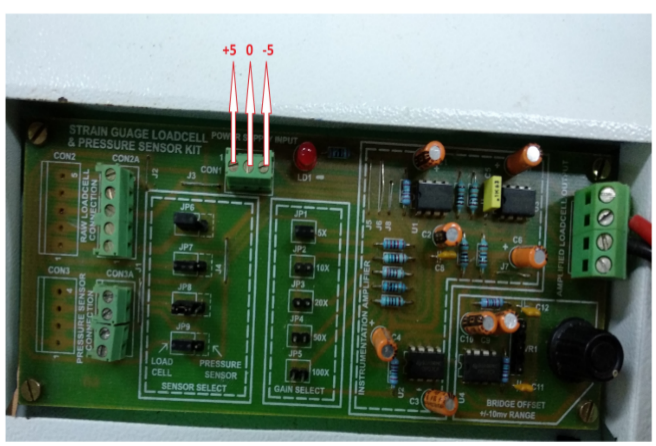


Figure 5: Power supply connections to the weighing machine

1.2.2 Instrumentation Amplifier

An instrumentation amplifier is a type of differential amplifier that has been outfitted with input buffer amplifiers. These input buffers eliminate the need for input impedance matching and thus make the amplifier particularly suitable for use in measurement and test equipment. Additional characteristics include very low DC offset, low drift, low noise, very high open-loop gain, very high common-mode rejection ratio, and very high input impedance. Instrumentation amplifiers are used to achieve high accuracy and stability.

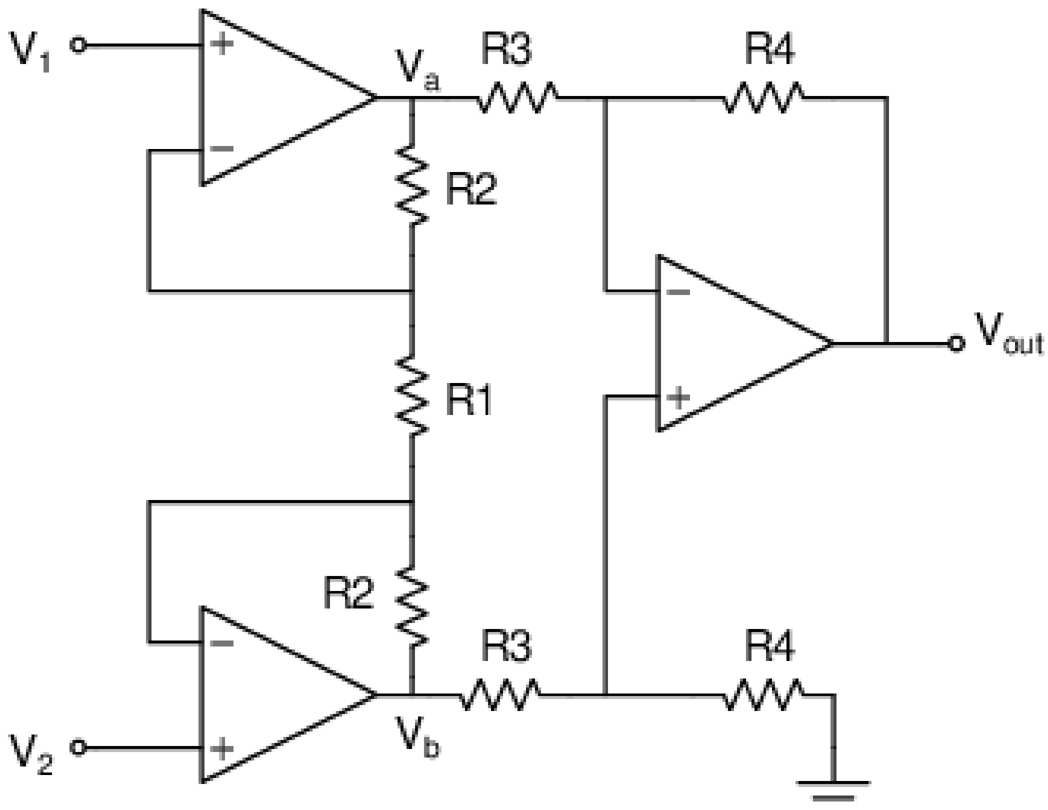


Figure 6: Circuit for Instrumentation Amplifier

Here, we define the input voltage signals small signal AC differential input V_1 and V_2, as the input of first stage OPAMPs of the instrumentation amplifier. We assume input resistance of OPAMPs to be infinite. Now applying KCL at inverting input of first stage OPAMPs. We get,

$$V_a = V_1(1 + R_2/R_1) + V_2(R_2/R_1) \tag{10}$$

$$V_b = -V_1(R_2/R_1) + V_2(1 + R_2/R_1) \tag{11}$$

Using superposition principle of voltages at second stage OPAMP,

$$V_{out} = R_4/R_3(1 + 2R_2/R_1)(V_2 - V_1) \tag{12}$$

The gain is

$$A_v = \frac{V_{out}}{V_1 - V_2} = \frac{R_4}{R_3}(1 + \frac{2R_2}{R_1}) \tag{13}$$

2 Experimental results

2.1 Part 1 : Using Operational amplifier TL084

Procedure

- You will use Operational amplifier TL084. Refer to the data sheet of TL084.
- Refer to figure 6. Use Load Resistance of $10k\Omega$. $V_+ = 12V$, $V_- = -12V$ to power op-amp. Calculate the values of R_1, R_2, R_3 and R_4 properly to get a gain of about 300. Apply a single ended signal of $20mV_{p-p}$ 1kHz sine wave as input to tune the circuit to achieve the required amplification. Use decoupling capacitance if necessary.
- Connect power supply ($\pm 5V$ and ground for bridge) to the weighing machine as shown in figure 5. Connect raw load cell output to the input of your 3 op-amp instrumentation amplifier. Refer to figure 4.
- Measure DMM voltage by varying weights. Calculate sensitivity of your instrumentation amplifier output to applied load in (mV/gm).
- Adjust R_1 value to double the sensitivity. Plot voltage vs weight to verify.
- Preserve the circuit of Part 1 till end of the experiment.

Observations and Inferences

To get a gain of 300, we choose resistances R_1, R_2, R_3 and R_4 as $1k\Omega$, $1k\Omega$, $1k\Omega$ and $100k\Omega$.

$$\begin{aligned} A_V &= \frac{R_4}{R_3}(1 + \frac{2R_2}{R_1}) \\ &= 100(1+2) \\ &= 300 \end{aligned}$$

The actual resistance values used in the figure 6 are $R_1 = 1k$, $R_2 = 1k$, $R_2 = 0.97k$, $R_3 = 0.98k$, $R_3 = 0.98k$, $R_4 = 98.9k$, $R_4 = 99.2k$

$*$ Since the resistors value are not as desired there is some offset in the gains at the output of the first pair of op-amps which gets amplified from the last op-amp.

$*$ The offset after the first pair of op-amps is -3.32mV and at the final output is 770mV.

The waveforms of V_{in} and V_{out} can be seen in the figure below

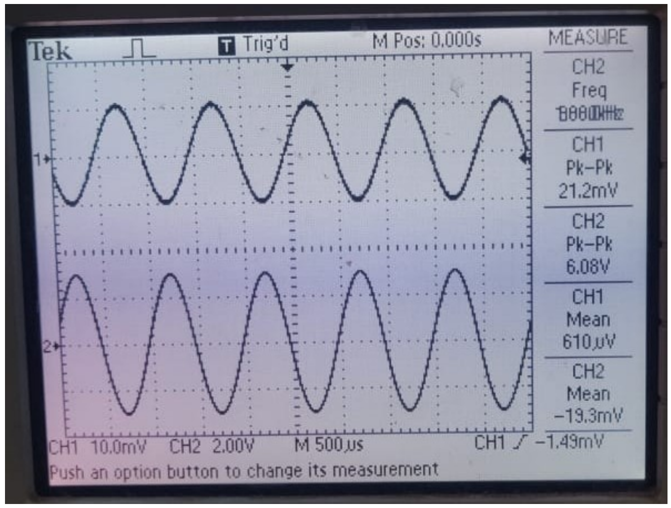
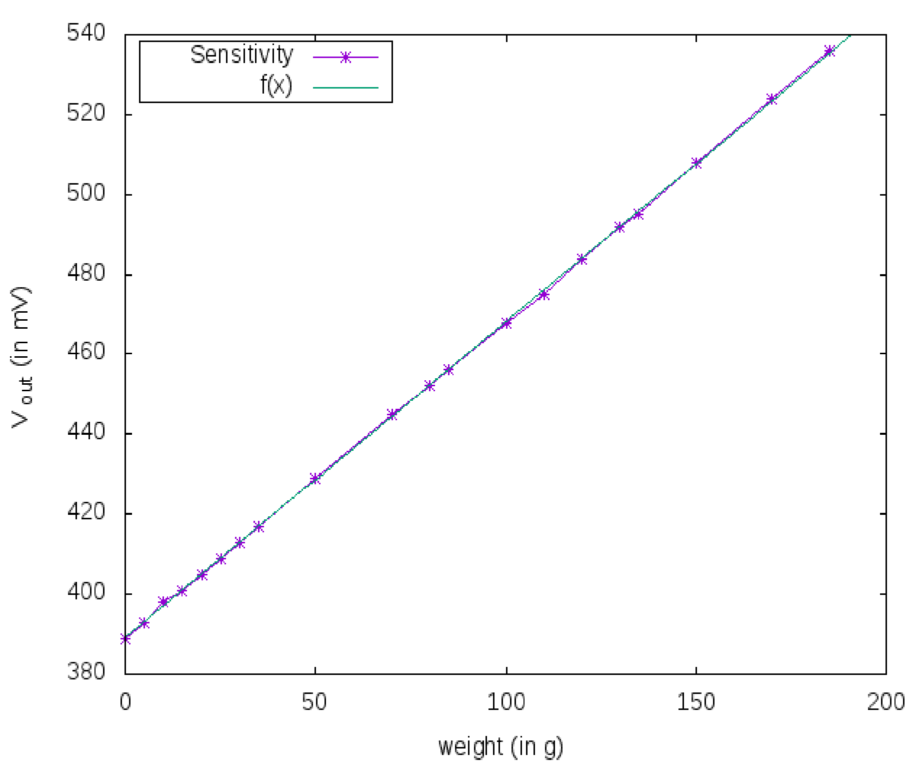


Figure 7: Waveform of V_{in} and V_{out} for $A_V \approx 300$

Now using input from load cell sensor:
We get the following results on the sensitivity of the instrumentation amplifier:



(a) Plot of output voltage vs weight for $A_V \approx 300$

$\mathbf{V_{out}}$**(in mV)**	**Weight(in gm)**
0	389
5	393
10	398
15	401
20	405
25	409
30	413
35	417
50	429
70	445
80	452
85	456
100	468
110	475
120	484
130	492
135	495
150	508
170	524
185	536

The values of slope and intercept of the above plot are 0.789 and 389.22 respectively.

$$\boxed{\text{Sensitivity} = 0.79 \text{ mV/gm}} \tag{14}$$

Now we adjust R_1 value such that the gain gets double to approx 600.
We can see this gain on the DSO in the figure below:

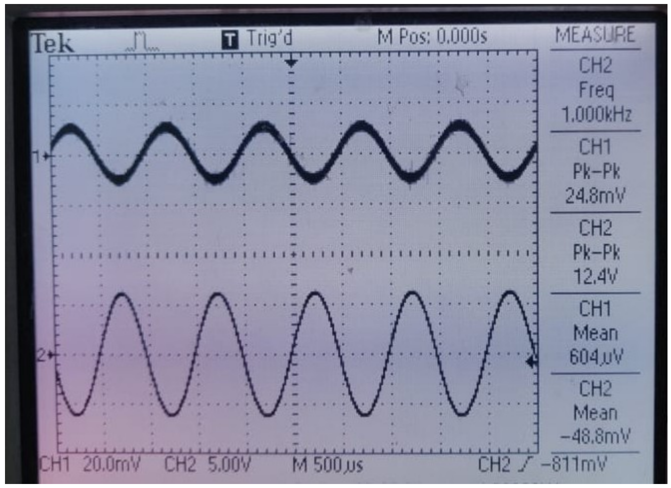
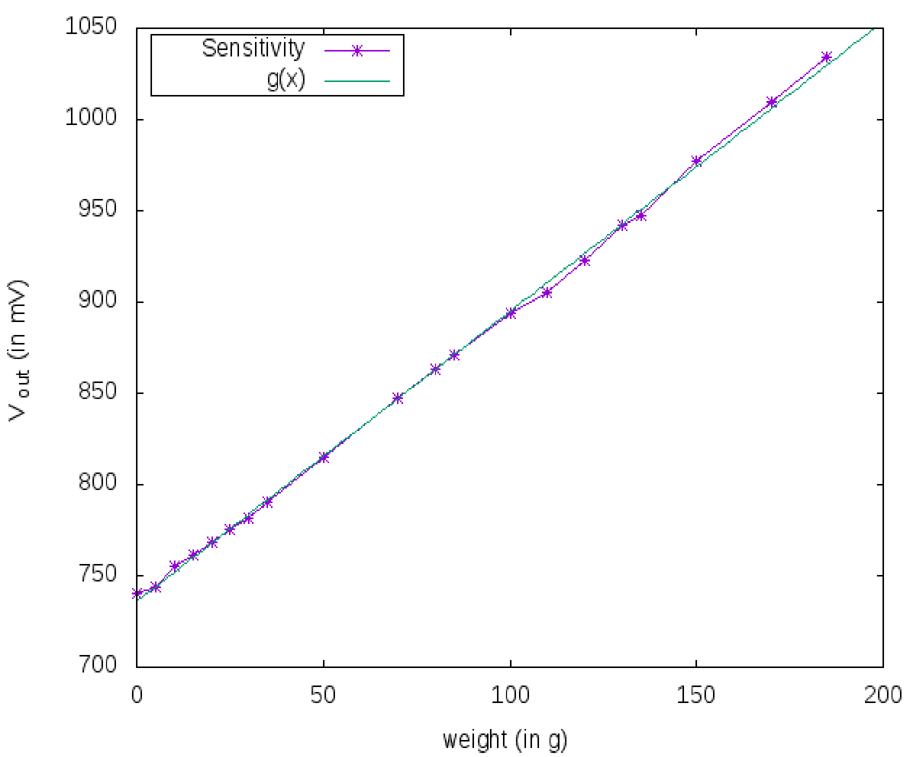


Figure 9: Waveform of V_{in} and V_{out} for $A_V \approx 600$

We get the following results on the sensitivity of the instrumentation amplifier for gain ≈ 600 :



(a) Plot of output voltage vs weight for $A_V \approx 600$

$\mathbf{V_{out}}$**(in mV)**	**Weight(in gm)**
0	740
5	744
10	755
15	761
20	768
25	775
30	782
35	790
50	815
70	847
80	863
85	871
100	894
110	905
120	923
130	942
135	947
150	977
170	1010
185	1034

The values of slope and intercept of the above plot are 1.58 and 736.016 respectively.

$$\boxed{\text{Sensitivity} = 1.58 \text{ mV/gm}} \tag{15}$$

$*$ Therefore, as predicted the sensitivity got doubled.

2.2 Part 2 : Using Instrumentation Amplifier INA128

Procedure

- Now you will use instrumentation amplifier INA128 for load cell signal amplification. Refer to the data sheet of INA128.
- Using $R_G = 220\Omega$, $R_L = 10k\Omega$, $C_1 = 0.1\mu F$, $V_+ = 12V$, and $V_- = -12V$, wire up the instrumentation amplifier circuit. Refer to figure 1. Explain the purpose of capacitor C_1 connected in parallel with the power supply. Note polarity of C_1 and connect accordingly.
- Connect raw output (un-amplified differential output) of load cell to the designed instrumentation amplifier. Refer to figure 4.
- Note down the DMM voltage by varying weights. Plot voltage vs weight. Calculate sensitivity in (mV/gm).
- Adjust R_G value such that you get twice the previous gain. Plot voltage vs weight.

Observations and Inferences

∗ The capacitor C_1 used in the above circuit is called the *Decoupling Capacitor* which provides a low-resistance path for the noise/fluctuations that may occur in the power supply, which is a DC supply.

Now using input from load cell sensor:

Here, the gain depends on the external resistor R_G as:

$$G = 1 + \frac{50k\Omega}{R_G} \tag{16}$$

Therefore, for $R_G = 220\Omega$, $\mathbf{G = 228.27}$

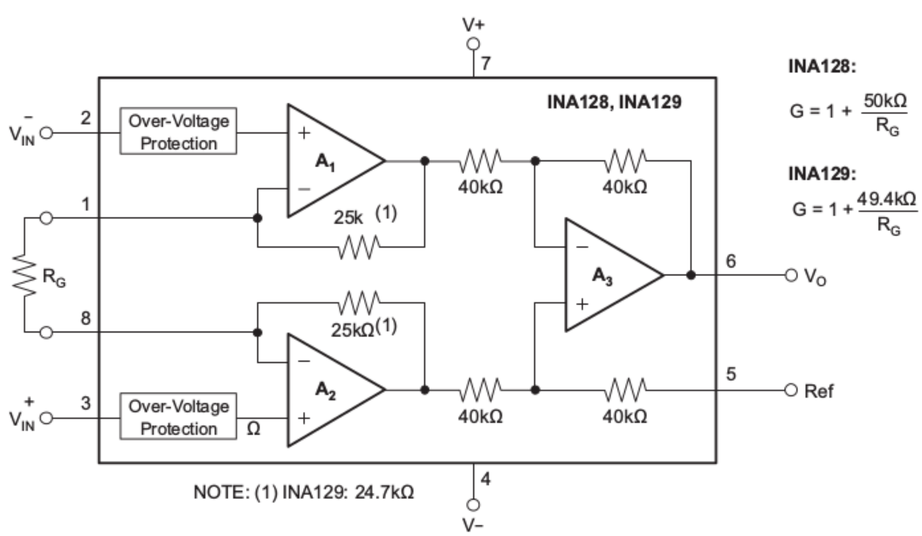
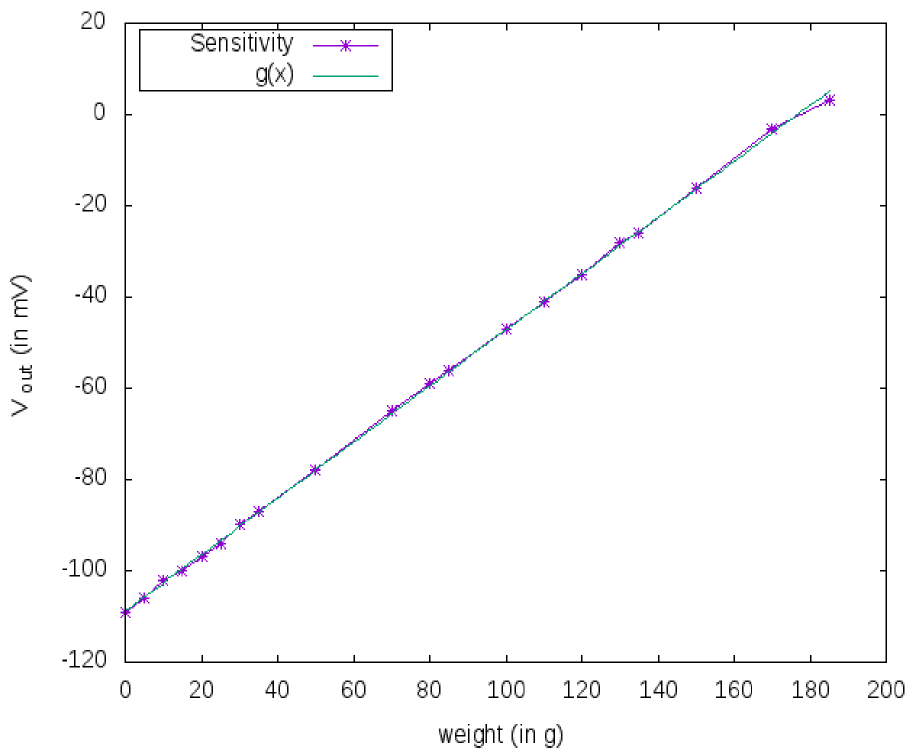


Figure 11: Schematic diagram of INA128

We get the following results on the sensitivity of the instrumentation amplifier:



(a) Plot of output voltage vs weight for G = 228.27

$\mathbf{V_{out}}$ **(in mV)**	**Weight(in gm)**
0	-109
5	-106
10	-102
15	-100
20	-97
25	-94
30	-90
35	-87
50	-78
70	-65
80	-59
85	-56
100	-47
110	-41
120	-35
130	-28
135	-26
150	-16
170	-3
185	3

The values of slope and intercept of the above plot are 0.61 and -108.73 respectively.

We could approximate gain as

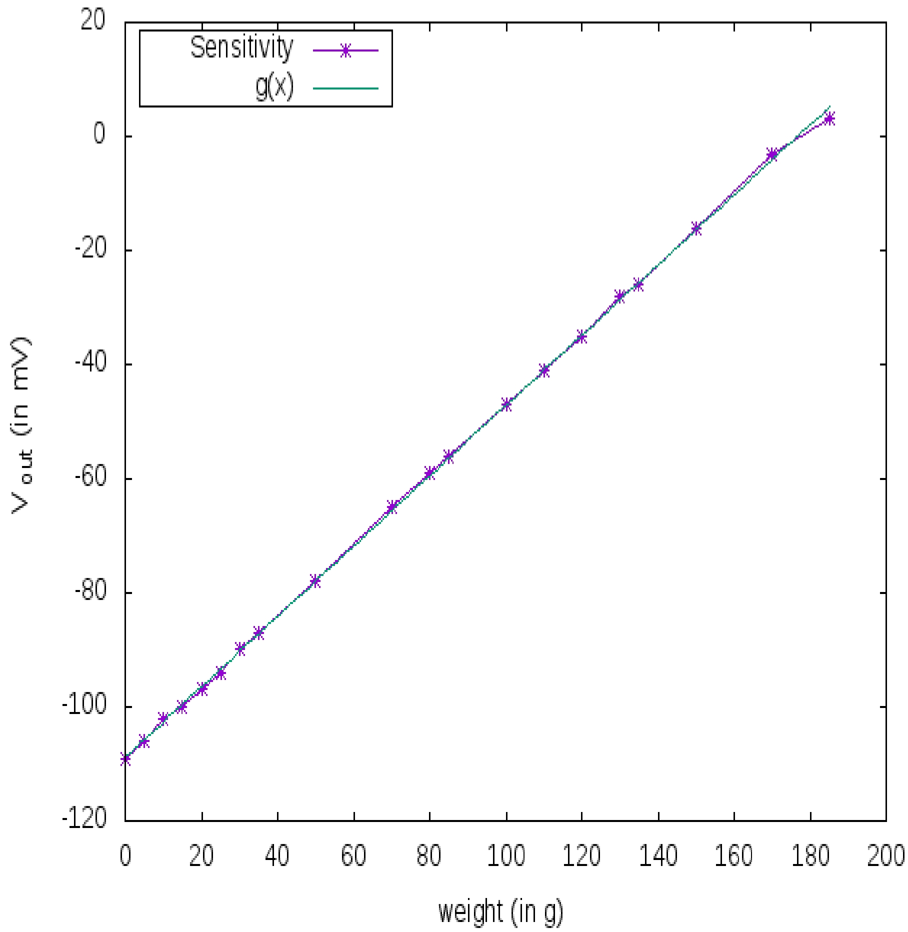
$$G = 1 + \frac{50k\Omega}{R_G} \approx \frac{50k\Omega}{R_G} \tag{17}$$

since the resistor values that we are using are small. Therefore to double the gain, we connect another resistor of value 220Ω in parallel with R_G.

$$R'_G = R_G \,||\, 220\Omega$$
$$R'_G = 110\Omega$$

Therefore the gain for this new value of R'_G is $\mathbf{G = 455.54}$

We get the following results on the sensitivity of the instrumentation amplifier:



(a) Plot of output voltage vs weight for G = 455.54

V_{out}(in mV)	Weight(in gm)
0	-218
5	-212
10	-205
15	-199
20	-193
25	-187
30	-181
35	-175
50	-155
70	-131
80	-119
85	-113
100	-95
110	-82
120	-70
130	-58
135	-52
150	-33
170	-8
185	7

The values of slope and intercept of the above plot are 1.22 and -217.43 respectively.

∗ Here as well the slope got doubled for twice the gain.

∗ Another thing to note is that, the intercept which denotes the offset in the voltage at the output terminals of the op-amp also gets doubled indicating better impedance matching in the in-built instrumentation amplifier which was not the case in the instrumentation amplifier built by three op-amps in the first part.

3 Additional Questions

(1) Mention the reasons of the difference in performance of instrumentation amplifiers.
Ans: The performance of the the instrumentation amplifier using INA128 should be better than that of using op-amp TL084, since there would be better matching of the resistors in the in-built IC thus reducing the noise and offset.

(2) You measured the readings in parts 1, 2 and 3 with a DMM - observe the same on an oscilloscope. What do you observe? Is there a discrepancy? What is the reason for the discrepancy, if any?
Ans: On oscilloscope, we see that the waveform is somewhat periodic and quite noisy.

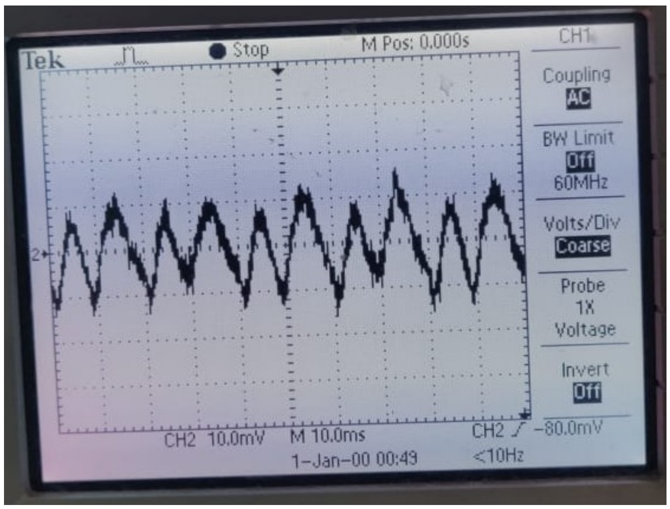


Figure 14: Waveform of part 2 as seen in DSO

The oscilloscope picks up noise from the surroundings as is seen in the below figure.

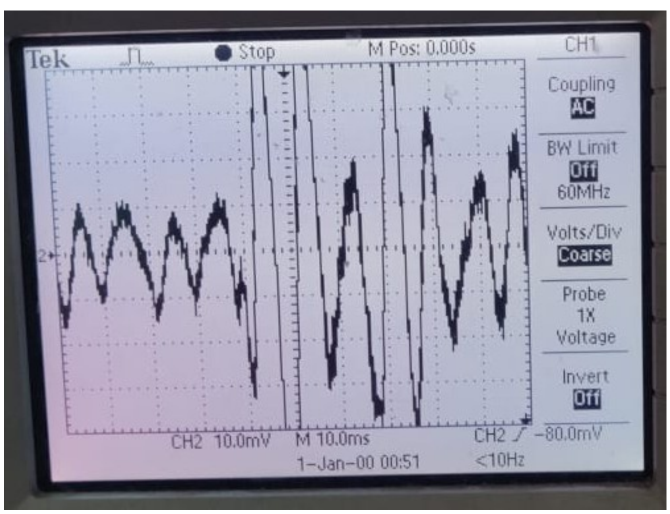


Figure 15: Above waveform with noise indicating high sensitivity to surroundings

4 Pre-Lab

Here is the code used in simulating the instrumentation amplifier we implemented using TL084 :

```
Instrumentation Amplifier Using the IC TL084
.include TL084_model_file.txt
x1 11 1 12 13 3 TL084
x2 10 9 12 13 8 TL084
x3 4 7 12 13 6 TL084
r1 9 1 1k
r2 3 1 1k
r3 8 9 1k
r4 3 4 1k
r5 8 7 1k
r6 7 6 10k
r7 4 0 100k
r8 6 0 100k
vcc 12 0 dc 15v
vee 13 0 dc -15v
vin1 11 0 sin (0 20mV 1k 0 0)
vin2 10 0 sin (0 0mV 1k 0 0)
.tran .1ms 10ms
.control
run
plot V(6) (V(11)-V(10))
.endc
.end
```

Its simulation output can be seen in the figure below.

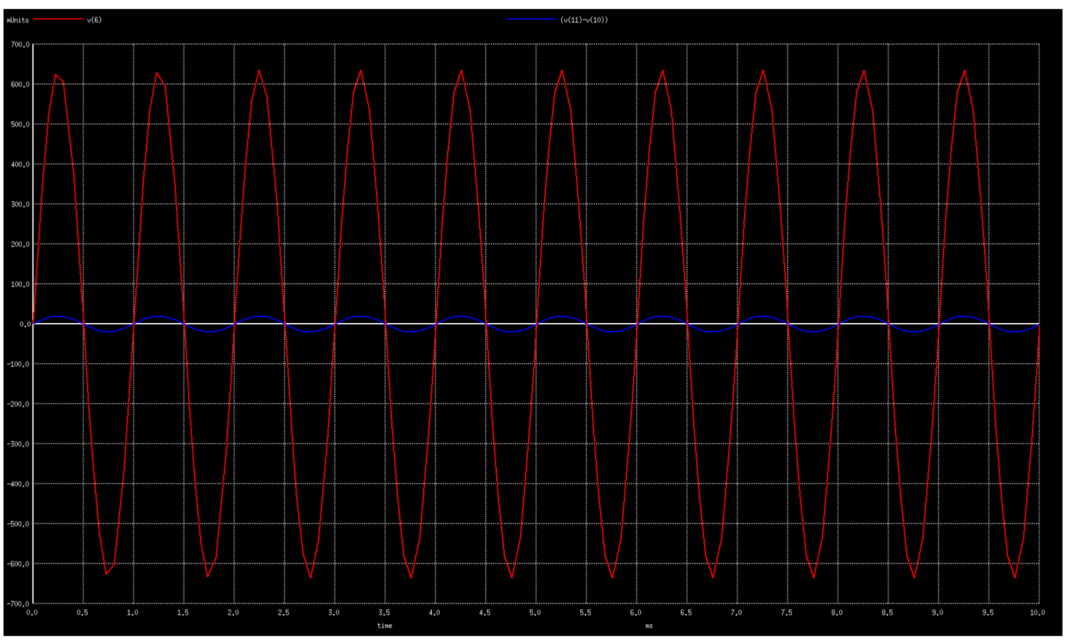


Figure 16: Plot of ΔV_{out} vs ΔV_{in}, $A_v = 300$

The TL084_model_file.txt file has the following code:

```
* TL084 OPERATIONAL AMPLIFIER "MACROMODEL" SUBCIRCUIT
* CREATED USING PARTS RELEASE 4.01 ON 06/16/89 AT 13:08
* (REV N/A)       SUPPLY VOLTAGE: +/-15V
* CONNECTIONS:    NON-INVERTING INPUT
*                 | INVERTING INPUT
*                 | | POSITIVE POWER SUPPLY
*                 | | | NEGATIVE POWER SUPPLY
*                 | | | | OUTPUT
*                 | | | | |
.SUBCKT TL084     1 2 3 4 5
*
  C1   11 12 3.498E-12
  C2    6  7 15.00E-12
  DC    5 53 DX
  DE   54  5 DX
  DLP  90 91 DX
  DLN  92 90 DX
  DP    4  3 DX
  EGND 99  0 POLY(2) (3,0) (4,0) 0 .5 .5
  FB    7 99 POLY(5) VB VC VE VLP VLN 0 4.715E6 -5E6 5E6 5E6 -5E6
  GA    6  0 11 12 282.8E-6
  GCM   0  6 10 99 8.942E-9
  ISS   3 10 DC 195.0E-6
  HLIM 90  0 VLIM 1K
  J1   11  2 10 JX
  J2   12  1 10 JX
  R2    6  9 100.0E3
  RD1   4 11 3.536E3
  RD2   4 12 3.536E3
  RO1   8  5 150
  RO2   7 99 150
  RP    3  4 2.143E3
  RSS  10 99 1.026E6
  VB    9  0 DC 0
  VC    3 53 DC 2.200
  VE   54  4 DC 2.200
  VLIM  7  8 DC 0
  VLP  91  0 DC 25
  VLN   0 92 DC 25
.MODEL DX D(IS=800.0E-18)
.MODEL JX PJF(IS=15.00E-12 BETA=270.1E-6 VTO=-1)
.ENDS
```

5 In Lab Circuit

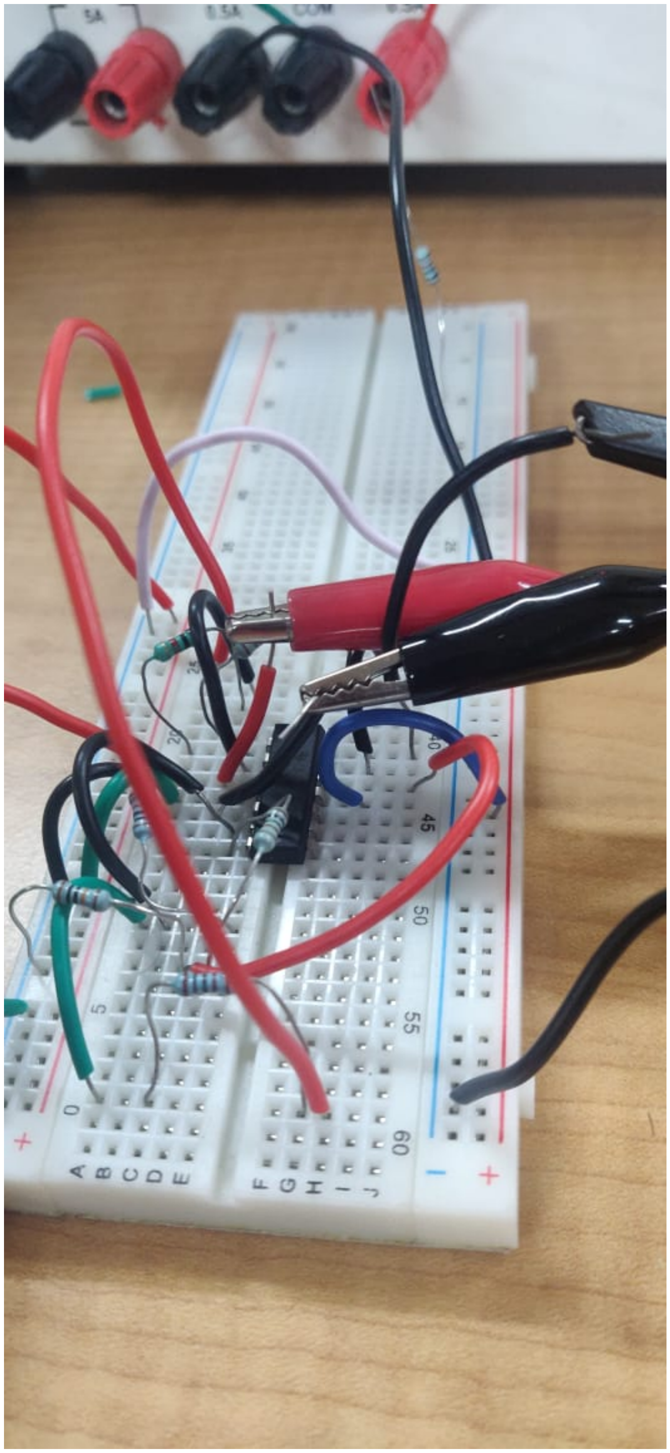


Figure 17: Circuit of instrumentation amplifier on breadboard

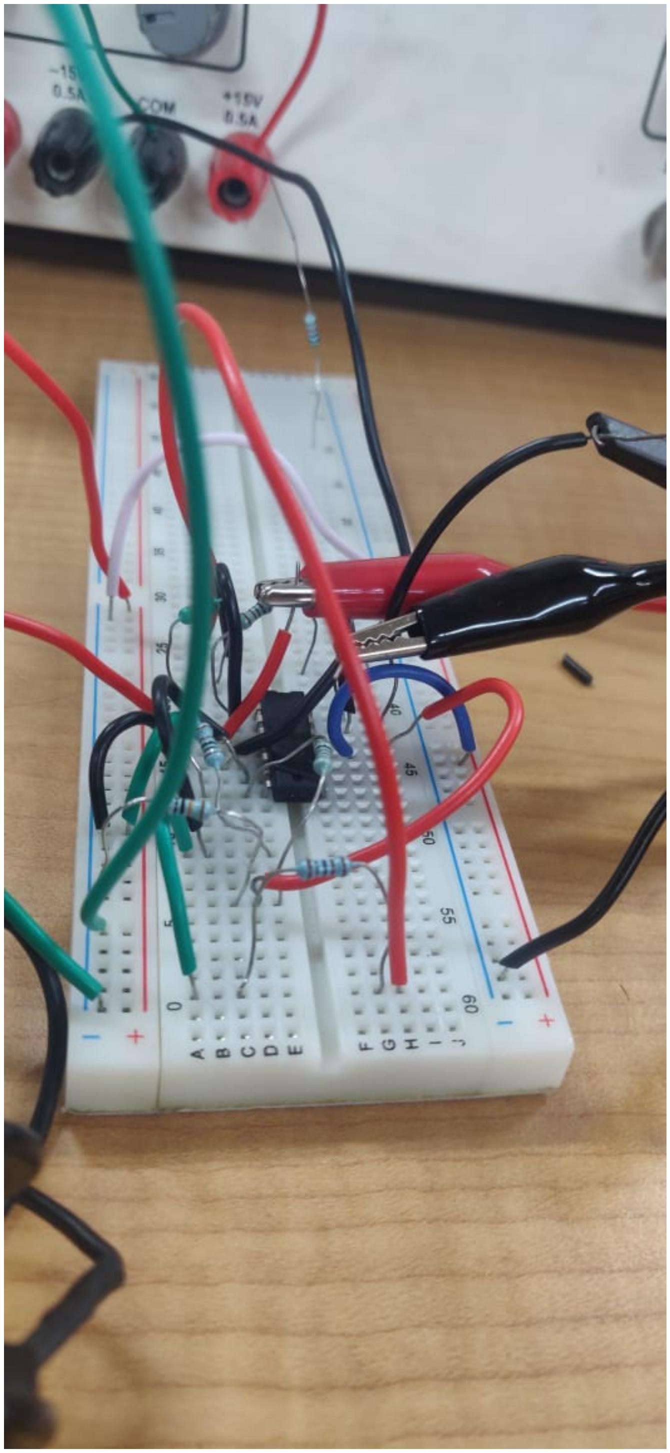


Figure 18: Circuit of instrumentation amplifier on breadboard

References

[1] Experiment Handout
http://wel.ee.iitb.ac.in/teaching_labs/WEL%20Site/ee230/Labsheets-2020/Handouts/Instrumentation%20_amp_LoadCell.pdf

[2] Supporting material for Instrumentation amplifier with datasheet of TL084 and INA128
http://wel.ee.iitb.ac.in/teaching_labs/WEL%20Site/ee230/Labsheets-2020/supporting_documents/Instrumentation_loadcell.zip