

Simulation of Instrumentation Amplifier Using LM741 with Wheatstone Bridge using eSim

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Abstract

This report presents the design and simulation of an instrumentation amplifier using LM741 operational amplifiers in the eSim environment. The implemented circuit consists of a Wheatstone bridge at the input stage followed by a three-op-amp instrumentation amplifier. The Wheatstone bridge is used to generate a small differential voltage corresponding to imbalance conditions, which is then amplified by the instrumentation amplifier. The first two LM741 op-amps form the input gain stage and the third LM741 acts as a differential amplifier. Transient and node-voltage results obtained from NGSpice are analyzed to study the behavior of the circuit. The report discusses the theory, circuit operation, gain expression, simulation procedure, observed output values, and applications of bridge-based instrumentation amplifiers in sensor and measurement systems.

1. Introduction

An instrumentation amplifier is a precision differential amplifier designed to amplify small voltage differences while rejecting common-mode signals and noise. It is widely used in measurement systems, biomedical instruments, and sensor interfaces. In many practical applications, the input to an instrumentation amplifier is not applied directly from a voltage source, but is obtained from a sensor bridge such as a Wheatstone bridge.

In this project, a Wheatstone bridge is placed at the beginning of the circuit to emulate a bridge-type sensor arrangement. A Wheatstone bridge is commonly used with strain gauges, load cells, pressure sensors, and RTDs, where a small change in resistance produces a small differential voltage. This differential voltage is often too small to be measured directly and therefore requires amplification. To perform this amplification, a three-op-amp instrumentation amplifier using LM741 op-amps is designed and simulated in eSim.

2. Objectives

- To study the operation of a Wheatstone bridge and its role in generating a small differential input signal.
- To design a three-op-amp instrumentation amplifier using LM741 op-amps in eSim.
- To interface the Wheatstone bridge with the instrumentation amplifier and observe the output response.
- To verify the node voltages and output waveform using NGSpice transient analysis.
- To understand the use of instrumentation amplifiers in bridge-based sensor signal conditioning.

3. Theory

3.1 Wheatstone Bridge

A Wheatstone bridge is a four-resistor network supplied by a DC source. The output of the bridge is the voltage difference between the two midpoints of the resistor branches. If the ratio of resistors in both branches is equal,

the bridge is balanced and the differential output is ideally zero. If one resistor changes slightly, the bridge becomes unbalanced and a small differential voltage appears between the midpoint nodes. This makes the bridge highly useful for converting resistance variation into voltage variation.

In the present circuit, the bridge is formed using resistors R1, R2, R3, and R4. Three resistors are 1 kΩ and one resistor is slightly different (1.01 kΩ), intentionally creating a small imbalance. This imbalance produces two midpoint voltages V1 and V2. From the simulation results, $V1 \approx 7.49993$ V and $V2 \approx 7.53724$ V, giving a differential bridge voltage of about 37.31 mV.

3.2 Instrumentation Amplifier

A standard instrumentation amplifier uses three op-amps. The first two op-amps act as input buffer/gain stages, providing very high input impedance so that the bridge is not loaded. The third op-amp acts as a differential amplifier, subtracting the outputs of the first stage and rejecting common-mode components.

For the standard three-op-amp instrumentation amplifier, the overall gain is given by:

$$V_{out} = (V2 - V1) \times [1 + (2R / R_g)] \times (R3 / R2)$$

where R is the feedback resistor in the first stage, R_g is the gain-setting resistor between the inverting terminals of the first two op-amps, and R2 and R3 are the resistor pairs of the final differential stage.

4. Circuit Description

The complete circuit contains two main parts: (1) Wheatstone bridge input network and (2) instrumentation amplifier. The bridge is powered from a 15 V source and creates the input nodes V1 and V2. These two voltages are fed into the first-stage LM741 op-amps X1 and X2. Resistors R5, R6, and R7 form the gain-setting network between the first-stage op-amps. The outputs of the first stage are labelled vo1 and vo2. These outputs are then applied to the third LM741 op-amp X3 through resistors R8 and R9. Resistors R10 and R11 complete the differential amplifier stage and produce the final output.

The bridge is included at the beginning because, in practical instrumentation systems, the source of the signal is often a bridge sensor rather than a direct voltage source. Using the bridge demonstrates how a small imbalance voltage can be amplified and converted into a measurable output. This is the same idea used in load cells, strain gauge measurement circuits, and other transducer-based systems.

5. Components Used

<u>Component</u>	<u>Value / Quantity</u>	<u>Purpose</u>
LM741 op-amp	3	Instrumentation amplifier stages
R1, R2, R3	1 kΩ	Wheatstone bridge arms
R4	1.01 kΩ	Bridge imbalance resistor
R5	2 kΩ	First-stage feedback
R6	0.5 kΩ	Gain-setting resistor
R7	2 kΩ	First-stage feedback
R8, R9	10 kΩ	Input resistors of differential stage
R10, R11	12 kΩ	Feedback / gain resistors of differential stage
DC sources	15 V	Supply for bridge and op-amps

6. Design Procedure in eSim

1. Create a new project in eSim and place four bridge resistors, three LM741 op-amps, power sources, and probes.
2. Form the Wheatstone bridge using R1, R2, R3, and R4 and connect it to the 15 V supply.
3. Take the two bridge midpoint voltages as V1 and V2.
4. Connect V1 and V2 to the non-inverting inputs of the first two LM741 op-amps.
5. Use R5, R6, and R7 to form the gain-setting network of the first stage.
6. Connect the outputs of the first stage to the third LM741 configured as a differential amplifier using R8, R9, R10, and R11.
7. Apply the required supply voltages to all LM741 op-amps and connect the ground node.
8. Run transient analysis / NGSpice simulation and observe the node voltages and output waveform.

7. Simulation Results and Discussion

The following node voltages were obtained from the NGSpice initial transient solution:

<u>Node</u>	<u>Voltage</u>
V1	7.49993 V
V2	7.53724 V
vo1	7.3517 V
vo2	7.68744 V
Vsupply	15 V
VCC	15 V
VEE	15 V (as shown in the schematic setup)
Output	0.404939 V

From the bridge section, the differential input is:
 $\Delta V_{in} = V2 - V1 = 7.53724 - 7.49993 \approx 0.03731 \text{ V} = 37.31 \text{ mV}$

The first-stage outputs are vo1 = 7.3517 V and vo2 = 7.68744 V. These values show that the first two LM741 stages respond to the small difference generated by the bridge and create a larger separation between the two signals before they are applied to the final differential stage. The final output obtained is 0.404939 V. Hence, the approximate overall amplification from bridge differential input to final output is:

$$V_{out} = (V2 - V1) [1 + 2R/R_g] (R3/R2) \Rightarrow (7.53724 - 7.49993) [1 + 2 \times 2k/0.5k] (12k/10k)$$

$$\Rightarrow (0.03731)(9)(1.2) = 0.40295 \text{ V} \approx 0.403 \text{ V}$$

$$\text{Overall gain} \approx V_{out} / (V2 - V1) \approx 0.404939 / 0.03731 \approx 10.85$$

The transient plots show that the node voltages remain nearly constant over the simulation interval, indicating that the circuit is operating for a DC bridge imbalance condition rather than a time-varying AC input. The small ripple/noise visible in the plotted bridge node is due to numerical simulation variation and does not change the steady-state conclusion.

8. Waveform Interpretation

The waveform of V2 is centered around 7.53724 V with negligible variation, confirming that the bridge output is essentially a DC level produced by resistor mismatch. The combined plot of V1, V2, vo1, vo2, and output shows that the bridge voltages lie close to 7.5 V, the first-stage outputs are separated further, and the final output settles around 0.405 V. This validates the operation of the instrumentation amplifier in amplifying a very small differential bridge signal into a larger measurable output.

9. Advantages of Using a Bridge with Instrumentation Amplifier

- Converts small resistance changes into measurable differential voltage.
- Suitable for strain gauges, pressure sensors, load cells, and RTDs.
- Instrumentation amplifier provides high input impedance and does not load the bridge.
- Improves sensitivity for low-level sensor outputs.
- Offers better common-mode rejection and noise immunity.

10. Applications

- Load cell and weighing systems
- Strain gauge and pressure sensor signal conditioning
- Biomedical measurement systems
- Industrial process monitoring
- Temperature measurement using bridge-based sensors

11. Precautions / Limitations

- LM741 is a general-purpose op-amp and not a precision instrumentation amplifier IC.
- Proper resistor matching is necessary in the differential stage for good CMRR.
- Large gain may lead to output saturation if the bridge imbalance becomes high.
- In practical hardware, a true dual supply (+VCC and -VEE) is normally used with LM741.
- Real circuits may show offset and bias-current effects that are not ideal.

12. Conclusion

The instrumentation amplifier using LM741 with a Wheatstone bridge input was successfully simulated in eSim. The bridge produced a small differential voltage of approximately 37.31 mV due to intentional resistor imbalance. The three-op-amp instrumentation amplifier amplified this small difference and generated a final output of about 0.405 V. The results confirm the usefulness of an instrumentation amplifier for bridge-based sensor applications where very small differential signals must be measured accurately. This project also

demonstrates the importance of the Wheatstone bridge as the front-end transducer interface in practical measurement systems.

14. References

"Wheatstone Bridge Sensor Signal Conditioning Using Instrumentation Amplifiers"

Schematic Diagram:

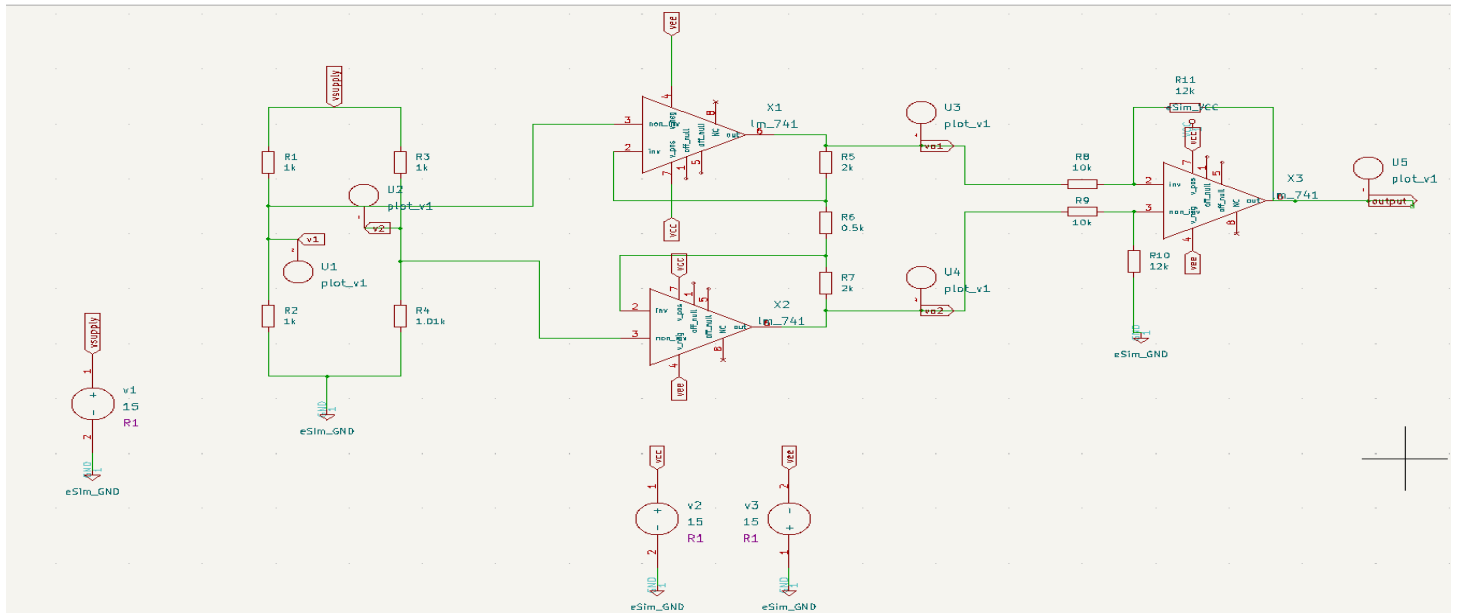


Fig. 1: eSim schematic of Wheatstone bridge with LM741 instrumentation amplifier

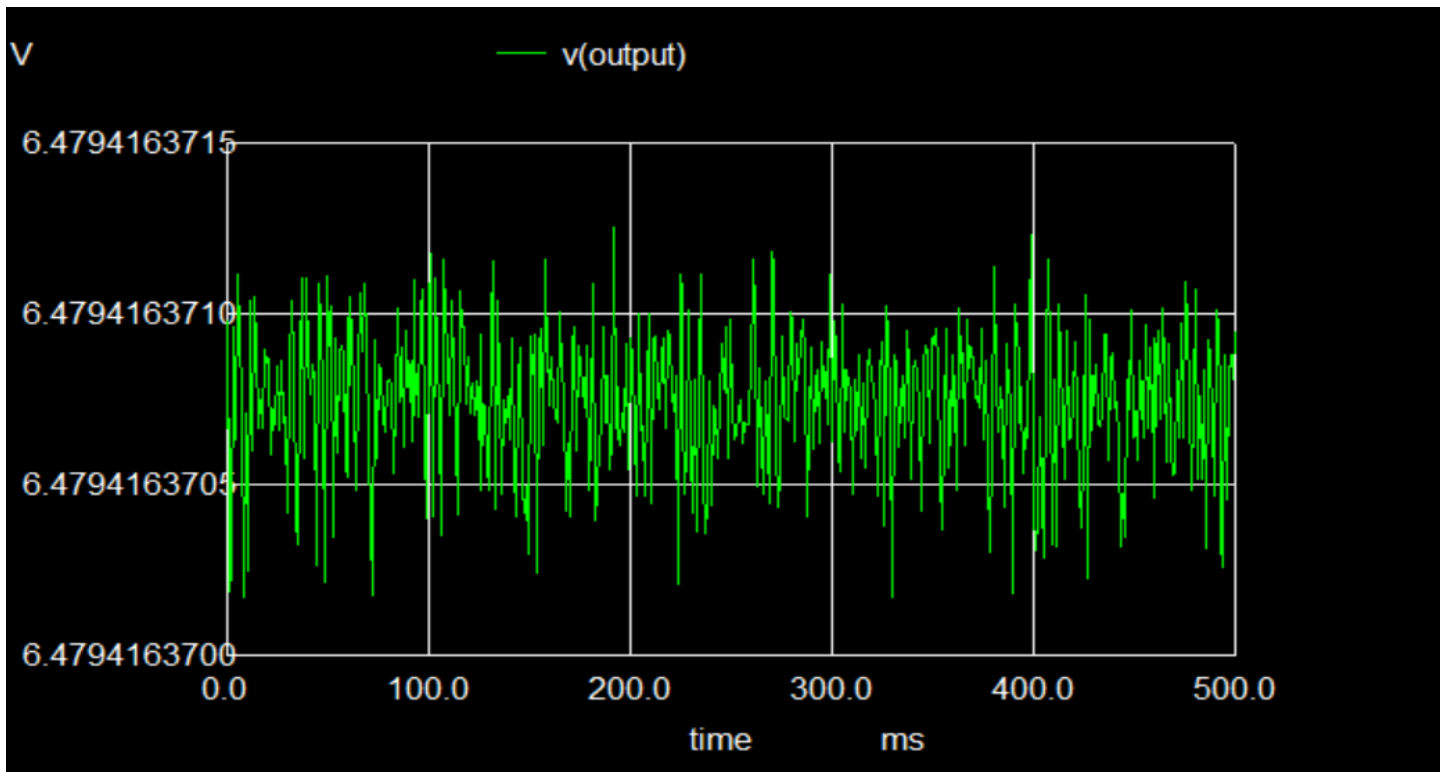


Fig. 2: Transient waveform

Initial Transient Solution

Node	Voltage
1. v1	7.49993
2. v2	7.53724
3. vo1	7.3517
4. vo2	7.68744
1. vsupply	15
2. vcc	15
3. vee	15
4. output	0.404939

Fig. 3: NGSpice initial transient node-voltage output

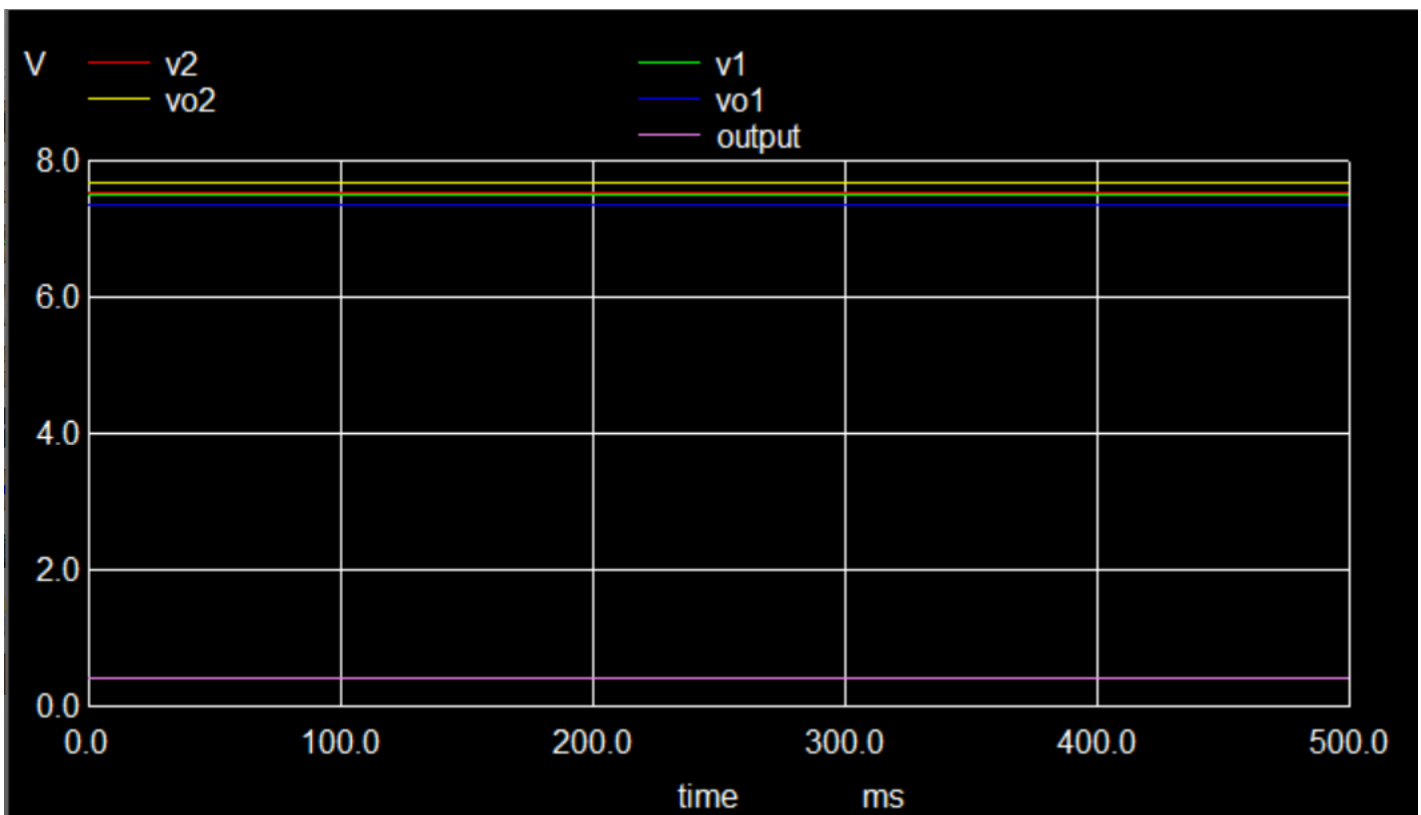


Fig. 4: Combined waveform plot of V1, V2, vo1, vo2 and output