# DESIGN AND SIMULATION OF A DISTRIBUTED PIPELINE HEALTH MONITORING AND LEAK LOCALIZATION SYSTEM USING ESIM

**FOSSEE ESIM SEMESTER LONG INTERNSHIP AUTUMN 2026**

**ABSTRACT & SIMULATION REPORT**

**TASK 3**


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# ABSTRACT:

Underground pipeline leaks are difficult to detect because the damaged section of a buried pipeline cannot be directly observed, and a conventional single-point alarm can indicate that an abnormal condition exists without indicating where along the pipeline it has occurred. This project proposes a circuit-level simulation of a Distributed Pipeline Health Monitoring and Leak Localization System using FOSSEE eSim, in which the focus is not a simple threshold alarm but the comparison of spatially separated sensor readings to localize an abnormal section.

Three sensor nodes are placed at known locations along the pipeline. Each node generates a sensor-equivalent electrical signal representing local pressure/flow behaviour, which is conditioned by an LM741-based non-inverting amplifier (gain = 2) and cleaned by an RC low-pass filter before being tapped as a node-conditioned signal (node1_cond, node2_cond, node3_cond).

Node 1 and Node 3 represent healthy pipeline sections and are held at a constant sensor voltage of 2.5 V. Node 2 represents the section experiencing a leak and uses a time-varying PULSE source that dips from 2.5 V to 1.3 V for a defined interval, emulating a temporary pressure/flow drop at the leak site.

The three conditioned outputs are compared: the node whose conditioned signal drops relative to its neighbouring nodes identifies the pipeline section in which the leak is located. The complete system is evaluated using transient SPICE simulation in eSim.

*Keywords: Distributed Pipeline Monitoring, Leak Localization, LM741, Non-Inverting Amplifier, Signal Conditioning, RC Filter, Sensor Node, SPICE, eSim, FOSSEE.*

# COMPLETE SCHEMATIC DIAGRAM:

The complete schematic diagram of the proposed Distributed Pipeline Health Monitoring and Leak Localization System is shown in the figure below. It integrates three identical sensor-node conditioning stages, each built around an LM741 op-amp, an RC output filter, and a sensor-equivalent source (DC or PULSE) representing the local pipeline condition.

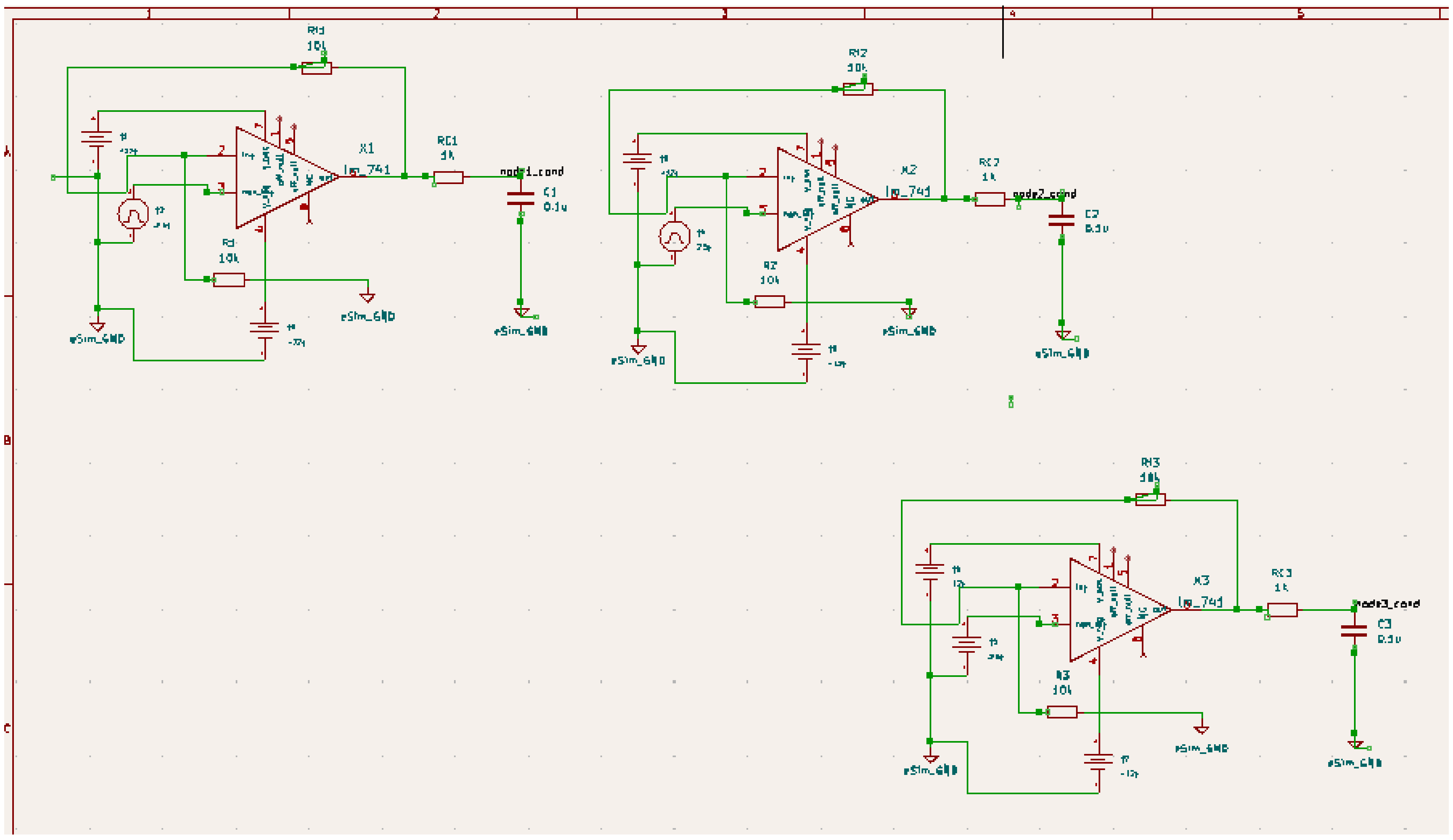

*Figure: Complete schematic diagram of the Distributed Pipeline Health Monitoring and Leak Localization System (Node 1, Node 2, and Node 3 conditioning stages).*

## Circuit Design Stages:

| Stage | Name | Purpose |
|---|---|---|
| Node 1 | Sensor Node 1 Conditioning Stage (Healthy) | Represents a healthy pipeline section using a constant 2.5 V sensor-equivalent source; conditions and filters the signal to produce node1_cond. |
| Node 2 | Sensor Node 2 Conditioning Stage (Leak Site) | Represents the leak-affected section using a PULSE source that dips from 2.5 V to 1.3 V; conditions and filters the signal to produce node2_cond. |
| Node 3 | Sensor Node 3 Conditioning Stage (Healthy) | Represents a second healthy section, identical to Node 1, bracketing Node 2 to enable comparison-based localization. |

# SENSOR NODE 1 — HEALTHY SECTION CONDITIONING STAGE:

## 1. Objective:

To model the sensor-equivalent output of a healthy pipeline section and condition it through an LM741 non-inverting amplifier and RC filter to produce the node1_cond reference signal.

## 2. Components List:

| Sl No | Component Name | Value / Model | Quantity |
|---|---|---|---|
| 1 | DC Voltage Source (Sensor 1) | 2.5 V (constant) | 1 |
| 2 | Op-Amp (X1) | LM741 (lm_741) | 1 |
| 3 | Dual Supply Rail | ±12 V | 1 set |
| 4 | Feedback Resistor (Rf1) | 10 kΩ | 1 |
| 5 | Gain Resistor (Rg1) | 10 kΩ | 1 |
| 6 | Output Filter Resistor (RC1) | 1 kΩ | 1 |
| 7 | Output Filter Capacitor (C1) | 0.1 µF | 1 |
| 8 | Ground | eSim_GND | as required |

## 3. Operation Principle:

The sensor-equivalent DC source (2.5 V, representing a healthy reading) is applied to the non-inverting input (pin 3) of X1. The inverting input (pin 2) is set by the junction of Rg1 (10 kΩ to ground) and Rf1 (10 kΩ feedback from the output), giving a non-inverting gain of Av = 1 + (Rf1/Rg1) = 1 + (10k/10k) = 2. The amplified signal is passed through an RC low-pass filter (RC1 = 1 kΩ, C1 = 0.1 µF, cutoff ≈ 1.59 kHz) before being tapped as node1_cond.

## 4. Expected Signal:

Since the input is a steady 2.5 V with no time variation, node1_cond settles at a constant 2.5 V × 2 = 5 V. This constant value is used as the healthy-section reference against which Node 2 is compared (see the combined waveform in the System-Level Result section).

## 5. Result:

- node1_cond settles at a constant ≈ 5 V, consistent with a healthy pipeline section.
- No transient variation is observed, since the sensor-equivalent input is a fixed DC level.
- Confirms correct non-inverting gain (Av = 2) and stable operation of the RC output filter.
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# SENSOR NODE 2 — LEAK-SITE CONDITIONING STAGE:

## 1. Objective:

To model the sensor-equivalent output of a pipeline section experiencing a temporary leak and condition it through an identical LM741 amplifier/RC filter stage to produce the node2_cond signal.

## 2. Components List:

| Sl No | Component Name | Value / Model | Quantity |
|---|---|---|---|
| 1 | PULSE Voltage Source (Sensor 2) | PULSE(2.5 1.3 0.3 0.01 0.01 0.4 1) | 1 |
| 2 | Op-Amp (X2) | LM741 (lm_741) | 1 |
| 3 | Dual Supply Rail | ±12 V | 1 set |
| 4 | Feedback Resistor (Rf2) | 10 kΩ | 1 |
| 5 | Gain Resistor (Rg2) | 10 kΩ | 1 |
| 6 | Output Filter Resistor (RC2) | 1 kΩ | 1 |
| 7 | Output Filter Capacitor (C2) | 0.1 µF | 1 |
| 8 | Ground | eSim_GND | as required |

## 3. Operation Principle:

The sensor-equivalent source at Node 2 is defined as PULSE(2.5 1.3 0.3 0.01 0.01 0.4 1): a baseline of 2.5 V (V1) that transitions to 1.3 V (V2) starting at t = 0.3 s (TD), with 10 ms rise/fall times (TR, TF), remaining at 1.3 V for a 0.4 s pulse width (PW) — i.e. until t = 0.71 s — before returning to 2.5 V, representing the pressure/flow drop during a leak event. As with Node 1, X2 is configured as a non-inverting amplifier (Rf2 = Rg2 = 10 kΩ, Av = 2), followed by an RC1-equivalent filter (RC2 = 1 kΩ, C2 = 0.1 µF).

## 4. Expected Signal:

node2_cond follows the doubled input: a steady ≈5 V baseline, dropping to ≈2.6 V between t ≈ 0.3 s and t ≈ 0.71 s, then returning to ≈5 V. Because the RC time constant (τ = RC2 = 100 µs) is far shorter than the 10 ms pulse edges, the filter does not materially slow the transition — the conditioned signal tracks the sensor pulse shape closely.

## 5. Result:

- node2_cond baseline ≈ 5 V, dropping to ≈ 2.6 V during the simulated leak window (t ≈ 0.3 s- 0.71 s).

- Transition edges remain sharp, confirming the RC filter (fc ≈ 1.59 kHz) does not distort the leak-event timing.
- The dip is clearly distinguishable from the constant 5 V baseline of the healthy neighbouring nodes.

# SENSOR NODE 3 — HEALTHY SECTION CONDITIONING STAGE:

## 1. Objective:

To model a second healthy pipeline section, identical in configuration to Node 1, bracketing Node 2 so that the leak can be localized by comparison rather than by a single-point threshold.

## 2. Components List:

| Sl No | Component Name | Value / Model | Quantity |
|---|---|---|---|
| 1 | DC Voltage Source (Sensor 3) | 2.5 V (constant) | 1 |
| 2 | Op-Amp (X3) | LM741 (lm_741) | 1 |
| 3 | Dual Supply Rail | ±12 V | 1 set |
| 4 | Feedback Resistor (Rf3) | 10 kΩ | 1 |
| 5 | Gain Resistor (Rg3) | 10 kΩ | 1 |
| 6 | Output Filter Resistor (RC3) | 1 kΩ | 1 |
| 7 | Output Filter Capacitor (C3) | 0.1 µF | 1 |
| 8 | Ground | eSim_GND | as required |

## 3. Operation Principle:

Configured identically to Node 1 (non-inverting amplifier, Av = 2, RC output filter), Node 3 is held at a constant 2.5 V sensor-equivalent input, representing a healthy section on the opposite side of the leak site from Node 1.

## 4. Expected Signal:

node3_cond settles at a constant ≈5 V, identical to node1_cond, providing a second healthy reference for comparison against node2_cond.

## 5. Result:

- node3_cond settles at a constant ≈ 5 V, matching node1_cond.
- Confirms symmetric, repeatable behaviour of the conditioning stage across independent sensor nodes.

# SYSTEM-LEVEL RESULT: COMPARATIVE ANALYSIS&LEAK LOCALIZATION:

## 1. Objective:

To compare the three conditioned node outputs (node1_cond, node2_cond, node3_cond) and demonstrate that a localized leak can be identified from the relative behaviour of neighbouring sensor nodes, rather than from a single-point alarm.

## 2. Combined Simulated Waveform:

*Figure: Combined conditioned-signal waveform. node1_cond and node3_cond remain a constant ≈5 V (green trace) throughout the simulation, while node2_cond (blue trace) dips to ≈2.6 V during the simulated leak window before returning to ≈5 V.*

## 3. Analysis:

The waveform confirms that the two healthy nodes (Node 1 and Node 3) hold a steady ≈5 V output for the full 1 s simulation, while Node 2 alone shows a sustained voltage dip during the interval defined by its PULSE source. Because Node 2 is the only node bracketed between two stable healthy readings, the system can localize the abnormal condition to the pipeline segment represented by Node 2, rather than merely flagging that an anomaly exists somewhere on the line. This matches the distributed spatial monitoring and localization objective described in the project proposal: comparing measurements from multiple known locations narrows the fault to a specific segment instead of relying on a single global threshold.

## 4. Result:

| Sl No | Stage | Results |
|---|---|---|
| 1 | Node 1 (Healthy) | node1_cond constant ≈ 5 V for the full simulation |
| 2 | Node 2 (Leak Site) | node2_cond ≈ 5 V baseline, dropping to ≈ 2.6 V from t ≈ 0.3 s–0.71 s |
| 3 | Node 3 (Healthy) | node3_cond constant ≈ 5 V, matching Node 1 |
| 4 | System-Level Comparison | Leak localized to the Node 2 segment; Node 1 and Node 3 confirm healthy neighbours |

# FINAL RESULT:

Under the selected simulation conditions, representative DC and PULSE sensor-equivalent sources were used to emulate two healthy pipeline sections and one section undergoing a temporary leak. The complete circuit demonstrated correct operation of all three sensor-node conditioning stages, and the simulated waveforms showed consistent, synchronized behaviour that allowed the leak-affected segment to be distinguished from its healthy neighbours purely by comparing conditioned node outputs.

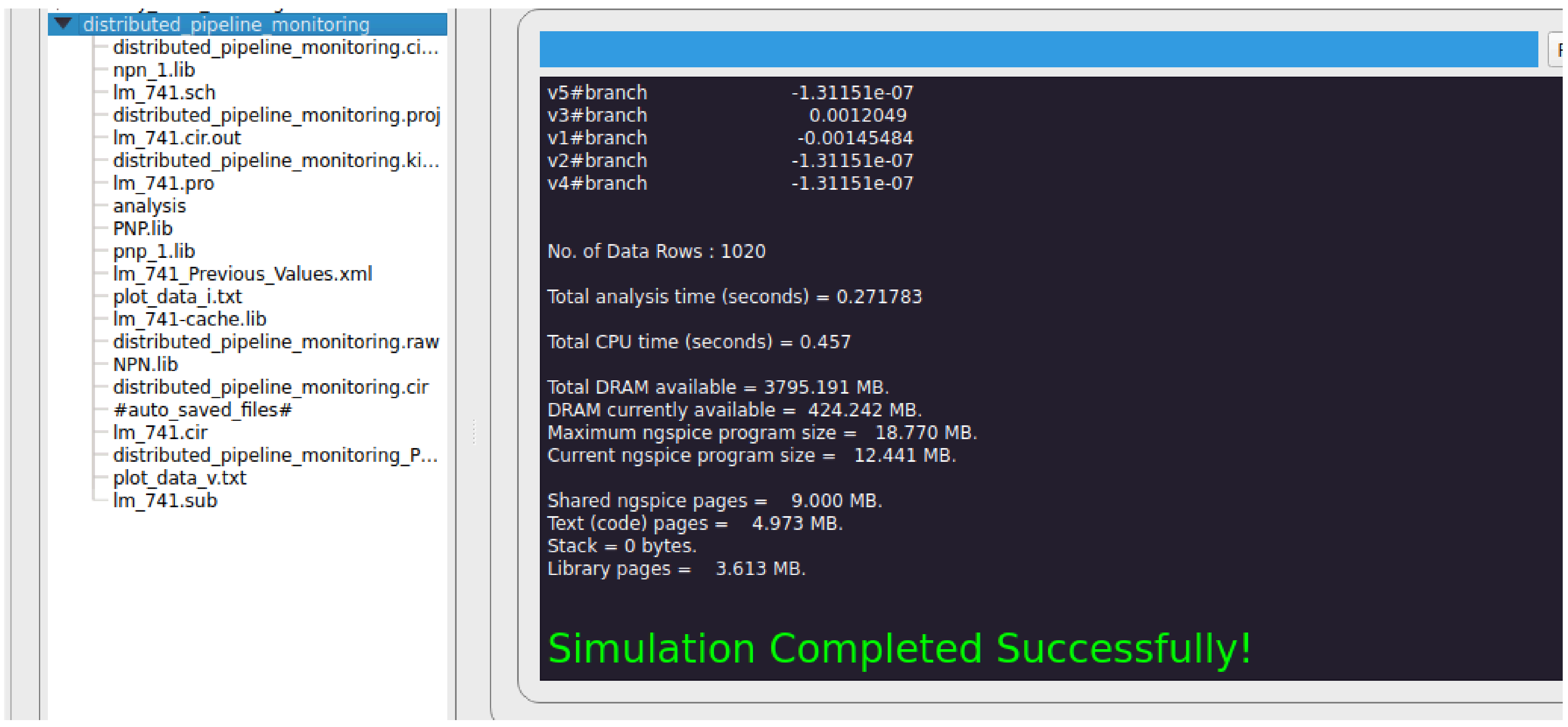


*Figure: eSim/ngspice transient simulation log confirming successful completion of the distributed pipeline monitoring circuit simulation.*

# CONCLUSION:

The proposed Distributed Pipeline Health Monitoring and Leak Localization System demonstrates a circuit-level approach to spatial, multi-node sensing rather than a simple single-point leak alarm, simulated entirely in FOSSEE eSim. The design combines sensor-equivalent DC/PULSE sources, LM741-based non-inverting signal conditioning, and RC output filtering across three sensor nodes to show how comparing spatially separated readings can localize an abnormal pipeline section.

The project demonstrates how fundamental analog signal-conditioning circuits — amplification and filtering — can be integrated across multiple sensor nodes to model a distributed, comparison-based sensing application in eSim. It also provides a practical understanding of non-inverting amplifier design, RC filtering, and how relative (rather than absolute) sensor readings enable fault localization in a multi-node system.

# REFERENCES:


[1] FOSSEE, IIT Bombay, eSim: Open Source EDA Tool, FOSSEE, IIT Bombay – eSim Official Website and Documentation.

[2] Texas Instruments, LM741 Operational Amplifier Datasheet.

[3] ngspice – Open Source Mixed-Level/Mixed-Signal Circuit Simulator, User Manual.

## BILL OF MATERIALS (COMPLETE COMPONENT SUMMARY):

| Component | Value / Model | Total Qty. |
|---|---|---|
| DC Voltage Source (Sensor) | 2.5 V | 2 |
| PULSE Voltage Source (Sensor) | PULSE(2.5 1.3 0.3 0.01 0.01 0.4 1) | 1 |
| Dual Supply Rail | ±12 V | 3 sets |
| Op-Amp | LM741 (lm_741) | 3 |
| Resistor | 10 kΩ | 6 |
| Resistor | 1 kΩ | 3 |
| Capacitor | 0.1 µF | 3 |
| Ground | eSim_GND | as required |