CAPACITIVE SENSOR INTERFACE USING OP-AMP BASED CHARGE AMPLIFIER IN ESIM

ABSTRACT

Capacitive sensors are widely used in modern electronic systems for proximity sensing, touch detection, and material characterization due to their high sensitivity and low power operation. However, the output of a capacitive sensor is extremely small and requires an appropriate signal-conditioning interface for reliable measurement.

This project presents the **design, simulation, and validation of a capacitive sensor interface using an op-amp based charge amplifier architecture**. The proposed interface converts minute capacitance variations into a measurable voltage signal with high stability and linearity. The complete system is designed and verified using **KiCad schematic capture and NGSpice simulation within the eSim environment**.

A **741 operational amplifier** configured as a charge amplifier is employed, where the sensor capacitance is connected to the inverting input and a feedback network consisting of a resistor and capacitor ensures stable operation and controlled bandwidth. A pulse excitation source is applied to emulate sensor stimulus, and the resulting output voltage clearly demonstrates the capacitance-to-voltage conversion principle.

The simulation results validate the theoretical operation of the charge amplifier and confirm the suitability of the proposed interface for capacitive sensing applications. This project demonstrates practical analog front-end design skills, correct op-amp biasing, feedback stabilization techniques, and professional circuit verification using industry-standard tools.

1. Introduction

Capacitive sensors operate by detecting changes in capacitance caused by environmental factors such as proximity, pressure, or material properties. Since these capacitance changes are typically very small (in the pico-farad range), a robust analog interface is required to convert them into a usable voltage signal.

The **charge amplifier** is one of the most effective architectures for capacitive sensor interfaces because it offers:

- High sensitivity
- Immunity to parasitic capacitances
- Stable frequency response

This project focuses on implementing a charge-amplifier-based capacitive sensor interface and validating its operation through simulation.

2. System Architecture

The proposed system consists of the following blocks:

1. **Capacitive Sensor (Cs)**
   Represents the sensing element whose capacitance varies with physical stimulus.
2. **Operational Amplifier (LM741)**
   Configured as a charge amplifier.
3. **Feedback Network (Rf ∥ Cf)**
   - Feedback capacitor (Cf) converts input charge into voltage
   - Feedback resistor (Rf) provides DC stability and prevents saturation
4. **Biasing Network (Rbias)**
   Ensures proper DC biasing of the inverting input node.
5. **Excitation Source (Vpulse)**
   Used to simulate sensor excitation and observe dynamic response.

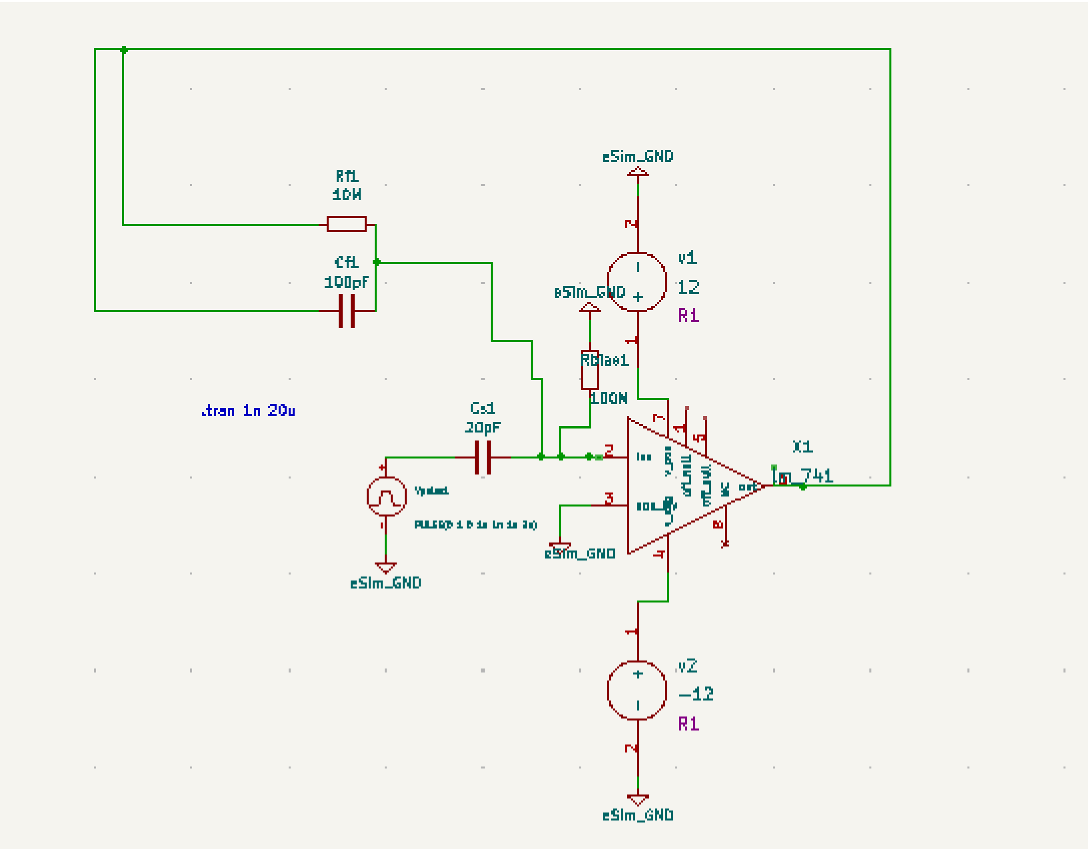


FIGURE1: *KiCad schematic showing complete capacitive sensor interface circuit*

3. Circuit Operation

When a voltage pulse is applied to the capacitive sensor, a charge proportional to the sensor capacitance is transferred to the inverting input of the op-amp. Due to the high open-loop gain of the op-amp, this charge is forced through the feedback capacitor, generating an output voltage given by:

$V_{out} = -Q / C_f$

Where:

- Q is the charge from the sensor capacitor
- C_f is the feedback capacitor

This results in a **linear voltage output proportional to the sensor capacitance**, enabling accurate measurement of small capacitance changes.

4. Simulation Setup

- **Simulation Tool:** eSim (KiCad + NGSpice)
- **Analysis Type:** Transient Analysis
- **Input Excitation:** Pulse voltage source
- **Op-Amp Model:** LM741 subcircuit
- **Simulation Duration:** 20 µs
- **Time Step:** 1 ns

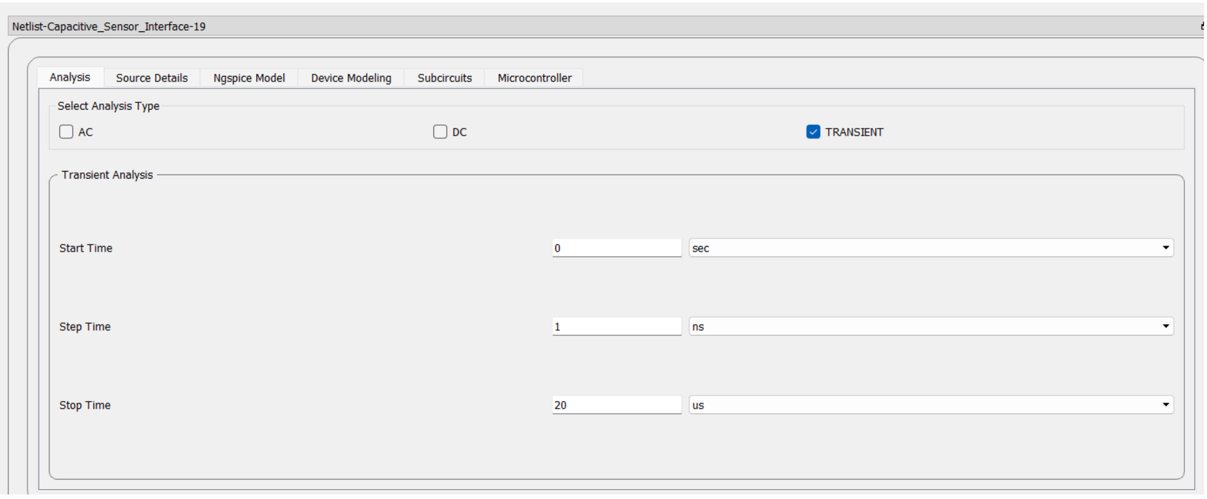


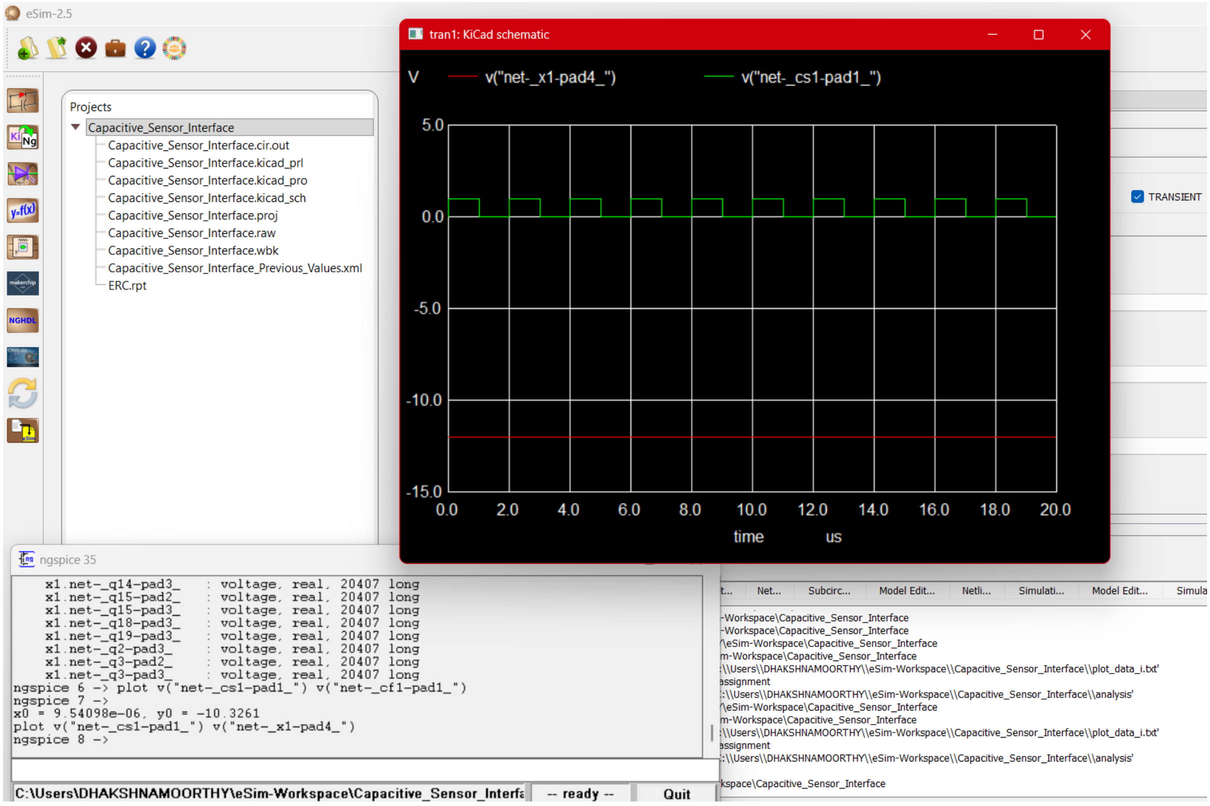
FIGURE2: transient analysis parameters

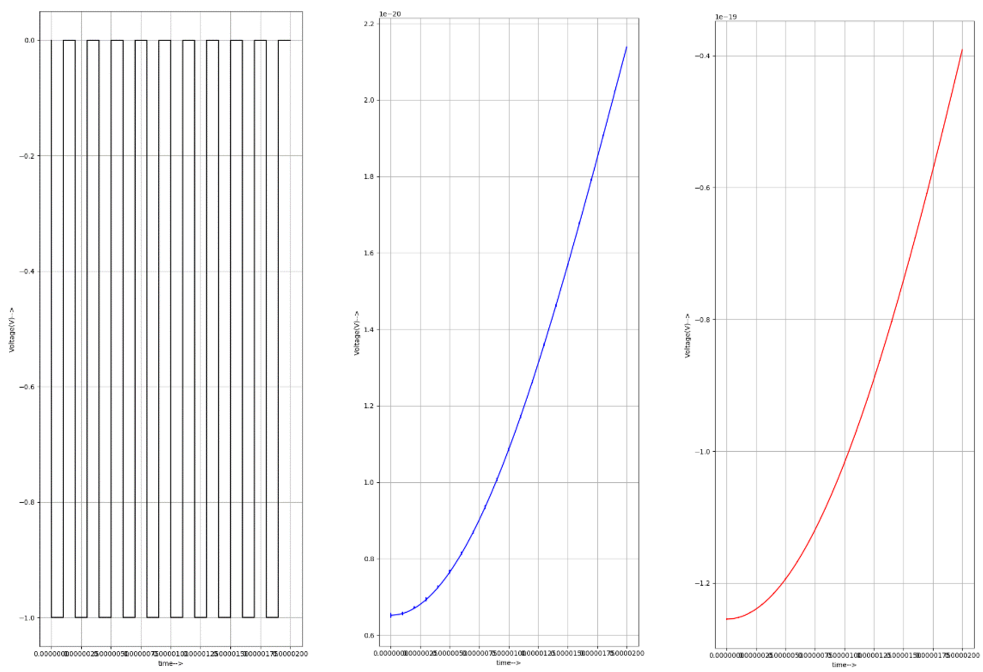
5. Results and Discussion

The simulation results show:

- Proper pulse excitation at the sensor input
- Stable and predictable output voltage response
- Linear charge-to-voltage conversion behavior
- Correct feedback-controlled waveform shaping

The output waveform confirms that the circuit successfully converts capacitance variations into a measurable voltage signal, validating the effectiveness of the charge amplifier topology for capacitive sensing applications.





The observed waveforms collectively validate the correct operation of the capacitive sensor interface, demonstrating stable excitation, effective capacitance-to-voltage conversion, and reliable signal conditioning.

Simulation Observation Instructions: plot the following to see results in esim,

Input Signal	***V(Net-_Vpulse1-Pad-_)***
Output of Charge Amplifier	***V(Net-_X1-Pad4_)***
Feedback capacitor node	***V(Net-_Cf1-Pad1_)***

6. Applications

The proposed capacitive sensor interface can be used in:

- Touch sensing systems
- Proximity sensors
- Liquid level sensing
- Biomedical instrumentation
- Industrial sensing applications

7. Conclusion

This project successfully demonstrates the design and simulation of a **capacitive sensor interface using an op-amp based charge amplifier**. The circuit effectively converts small capacitance changes into a stable voltage output and is validated through NGSpice simulation in the eSim environment.

The work highlights strong understanding of:

- Analog circuit design
- Op-amp feedback systems
- Capacitive sensing principles
- Professional simulation workflow

This interface serves as a solid foundation for further hardware implementation and advanced sensor system development.