Stability Analysis of Transimpedance Amplifier for Capacitive Sensor Applications

B. P. Joshi, T. P. Mahajan, D. C. Gharpure

Department of Electronic and Instrumentation Science, Savitribai Phule Pune University, Pune, Maharashtra, India

Corresponding author: B. P. Joshi, Email: bpj_disc@unipune.ac.in

The aim of this study is to analyze transimpedance amplifier with a feedback network (TIA-Fn) for measuring unknown capacitance value. Mathematical analysis along with electronic circuit simulation results are presented. The selection criterion of feedback components (Cf and Rf) is discussed. The circuit is capable of measuring unknown capacitance in the range of 1pF to 10pF which is useful in many applications such as thickness measurement, Electrical Capacitance Tomography, Moisture measurement to name a few. Frequency domain analysis has been carried out for gain and stability parameters of the proposed circuit with AD LT spice simulation software. While simulating, non-ideal components are taken in to consideration. Mathematical and simulation results are mutually related. The designed amplifiers suitable for connecting the unknown capacitance terminal with AC excitation.

Keywords: Capacitance Measurement, Transimpedance Amplifier, Stability Analysis.

2021. In Rahul Srivastava & Aditya Kumar Singh Pundir (eds.), *New Frontiers in Communication and Intelligent Systems*, 77–83. Computing & Intelligent Systems, SCRS, India. https://doi.org/10.52458/978-81-95502-00-4-10

1 Introduction

The application of capacitor sensors in non-contactand non-intrusive measurement is one of the non-destructive techniques used in various applications viz. Non-destructive evaluation of multiphase fluid/liquid using a capacitive tomographic technique [1], non-contact wafer thickness measurement [2], Electrical Capacitance Tomography[3], pressure sensors[4]. Asa specific example, a capacitive sensor with coplanar electrode arrangement used for moisture measurement results into small capacitance values in the range of 1and 28 pF. [5]. Some capacitive sensors measure displacement, where the resulting output capacitance isusually small, in the 0.75pF to 1pF range [6]. Inter electrode capacitance measurements in ECT systems are in the range of few fF to pF [7,8].

Several methods for such low value capacitancemeasurements are available. These techniques comprise of Capacitance-to-Voltage (C-V) conversion as well as and Capacitance-to-Time(C-T) conversion [9–11]. The first method commonly employs voltage/trans-impedance amplifiers whereas, relaxation oscillators with PWM measurement is used for C-T technique. Another method predominantly used is Capacitance-to-Frequency (C- F) conversion, where output signal frequency is proportional to the sensor differential capacitance [12].

In this study, transimpedance amplifier with feed- back network (TIA-Fn) is analysed for capacitance measurement in the range of 1pF to 10 pF. The work is divided into three sections. First section gives the explanation regarding circuit design and component selection. In second section, frequency domain analysis for gain and stability parameters are discussed. The knowledge of stability is necessary in order to design the feedback network optimally, since the feedback network consists of resistor and capacitor. Whereas, with the help of gain analysis, the unknown value of capacitance can be determined. The mathematical analysis provides an insight into the behavior of the physical system and its parameters. Followed by, conclusion, section three, suggests the limitations and the futuristic scope of the proposed design.

2 Amplifier Design and Component Selection

The design of TIA-Fn used to measure an unknown capacitance is shown in Figure 1. TIA is an active current to voltage converter since it uses an active component like Op-amp to convert input current to proportional output voltage. Here, in the circuit, V_{in} is the sinusoidal input signal of the frequency anywhere between 100KHz to 500KHz. C_x is the unknown input capacitance. Feedback network comprises of parallel combination of R_f and C_f, whereC_f is the feedback capacitor while R_f is the feedback resistor. Effect of C_f and its values are discussed later in section two. C_s represents the differential mode input capacitanceof the op-amp. For this study, Analog devices' AD8086 high performance, fast FET input op-amp is used[12]. For the mathematical as well as for simulator purpose non ideal characteristics of the op-amp is taken into consideration. All other parameters except C_x in the circuit are known and hence the unknown capacitance value C_x can be determined by using gain analysis.

Here, the unknown capacitance range is choosen as 1pF to 10pF, which makes this circuit suiatable for many application as mentioned earlier. The different values of Cf (0 pf, 3.3Pf, 6.8pF, 9.1pF) are used as per the compensation required to stabilize the amplifier's output. The detailed circuit diagram of the proposed sytem is depicted in fig. 1.

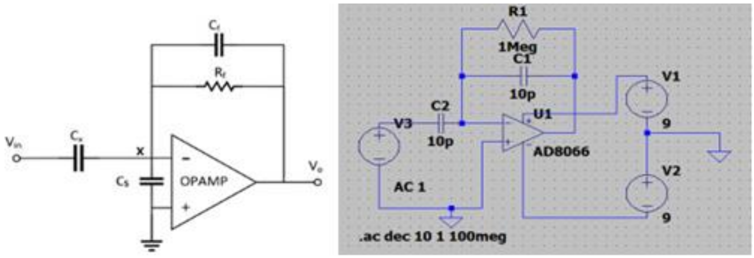

Fig. 1. Design of TIA-Fn and componet selection

3 Frequency Domain Analysis

3.1 Gain Analysis

As shown in Fig.1, C_x is the unknown capacitance to be measured. Here, the entire analysis has be carried out in 'S' domain using Laplace transform. The input current can be represented by following equation:

$$I_{in}(S) = \frac{V_{in}(S) - V_x(S)}{1/SC_x} = \frac{V_x(S)}{1/SC_s} + \frac{V_x(S) - V_o(S)}{R_f} + \frac{V_x(S) - V_o(S)}{1/SC_f} \tag{1}$$

$$\therefore SC_x V_{in}(S) = V_x(S)\left[SC_s + \frac{1}{R_f} + SC_f + SC_x\right] - V_o(S)\left[\frac{1}{R_f} + SC_F\right] \tag{2}$$

$$Here, \quad A_{OL} = -\frac{V_o}{V_x}$$

$$\therefore \; V_x(S) = -\frac{V_o(S)}{A_{OL}} \tag{3}$$

Substituting eq^n (3) into (2) and solving further,

$$\frac{V_o(S)}{V_{in}(S)} \cong -\left[\frac{SC_xR_f}{SC_fR_f + 1}\right] \tag{4}$$

Substituting S=jω in eq^n(4),

$$\frac{V_o(S)}{V_{in}(S)} \cong -\left[\frac{j\omega C_xR_f}{j\omega C_fR_f + 1}\right]$$

This equation can further be approximated to –

$$\frac{V_o(S)}{V_{in}(S)} \cong -\left[\frac{j\omega C_xR_f}{j\omega C_fR_f}\right]$$

$$\therefore \frac{V_o(S)}{V_{in}(S)} \cong -\left[\frac{C_x}{C_f}\right]$$

$$\text{i.e.,} \boldsymbol{V_o(S)} \cong -\left[\frac{C_x}{C_f}\boldsymbol{V_{in}}\right] \tag{5}$$

From above equation, it is clear that, the unknown value of capacitor can be determined with the help of input and output signal's magnitude if the circuit is designed for optimum value of feedback capacitor C_f.

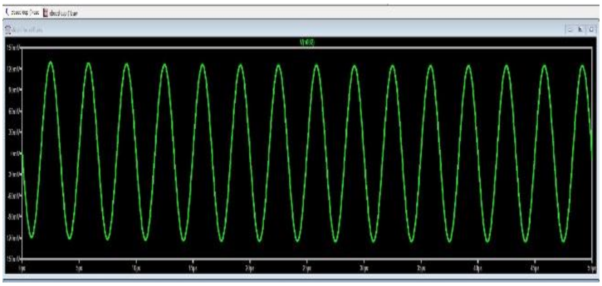

Fig 2: Output Signal for measured Cx

The above graph shows the output signal when 1pF is considered as unknown capacitor and AC excitation of amplitude of 1.25V @ 300KHz. The simulator shows the output magnitude of 0.2496816V. as per equation (5), the unknown capacitor C_x is found to be 0.9984pF.

3.2 Stability Analysis

For stability analysis, the fig.3 below can be assumed as combination of two networks – amplifier and feedback network. Stability can be achieved with optimize values of feedback components. Below are the two cases can be simplified for analysis purpose.

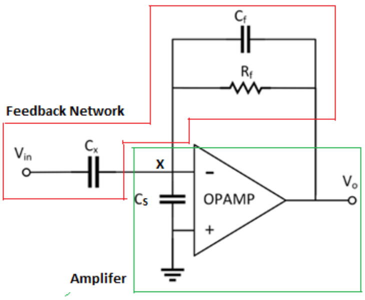

Fig. 3. TIA-Fn circuit for stability analysis

a) Effect of Feedback Capacitor C_f:

For open loop amplifier, the dominant pole occurs at ω_o where the gain starts to roll off at the rate of 20dB/decade. The transfer function of amplifier is given by:

$$A = \frac{A_{OL}}{1+p} \tag{6}$$

where, A_{OL} is the DC open loop gain of amplifier and p is the dominant pole. It is initially assumed that the feedback network consists of only R_f and C_x.Therefore, the feedback factor of such network is given by:

$$\beta = \frac{1}{1+SR_f(C_x+C_s)} \tag{7}$$

With increase in frequency above the corner frequency,due to the dominant pole of the op amp,90° phase shift is occured and due to the pole introduced by the feedback network additional 90° of phase shift is occured. Thus a total phase shift of about 360° at $A\beta$ = 1 is observed, due to which oscillations are obtained. This makes the system unstable as shown in fig 4.

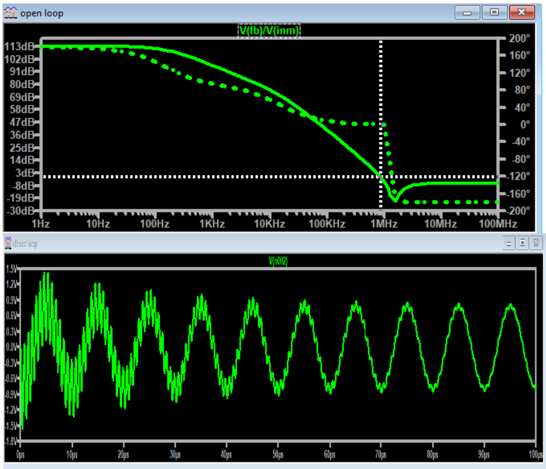

Fig. 4. Oscillating Output without Feedback C_f

To compensate these oscillations, a capacitor C_f is added in the feedback path in parallel with the feedback resistor R_f, as shown in above fig. 3.

When feedback capacitor is used, the feedback factor of the feedback network is given by –

$$\beta = \frac{1 + SR_f C_f}{1 + SR_f\left(C_f + C_x + C_s\right)} \tag{8}$$

This shows that, a zero is added in the transfer function because of the feedback capacitor C_f and the phase margin of 90° is obtained, which makes the system stable as shown in fig. 5.

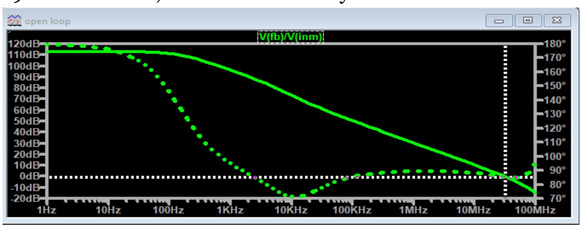

Fig. 5. Oscillating Output with Feedback Cf

b) Selection of Feedback Capacitor:

To avoid the oscillating conditions as discussed above, it is required to have 45°of phase margin at the frequency of intercept (where the open loop gain curve and reciprocal of feedback factor curve intersects)[13].This can be achieved by selecting appropriate value of $C_f$which introduces a zero in the feedback factor as mentioned above at the frequency where Aβ = 1.The intercept frequency is given by

$$F_i = \frac{1}{2\pi R_f C_f} \tag{9}$$

Also, depending on the gain bandwidth product of the op-amp, the intercept frequency can be given as

$$F_i = \sqrt{\frac{F_{GBW}}{2\pi R_f (C_f + C_x + C_s)}} \tag{10}$$

Solving equation (9) and (10) for C_f,

$$\therefore C_f \cong \sqrt{\frac{(C_x + C_s)}{2\pi R_f F_{GBW}}} \tag{11}$$

Hence, if the range of unknown capacitor is known based on the application, the feedback capacitor can be selected on the basis of gain bandwidth product of selected op-amp.

To achieve stability of the circuit, larger value of feedback capacitor is required but it simultaneously affects the settling time of the system. In order to observe the settling time a step input is applied and the output is observed with different values of feedback capacitor C_f. It is been observedthat when feedback capacitor is not connected, underdamped oscillations are obtained, making the system unstable. But with selecting a large value of C_f, settling time is increased as shown in fig. 6. Table 1 provids the comparision of settiling time with feedback capacitor value.

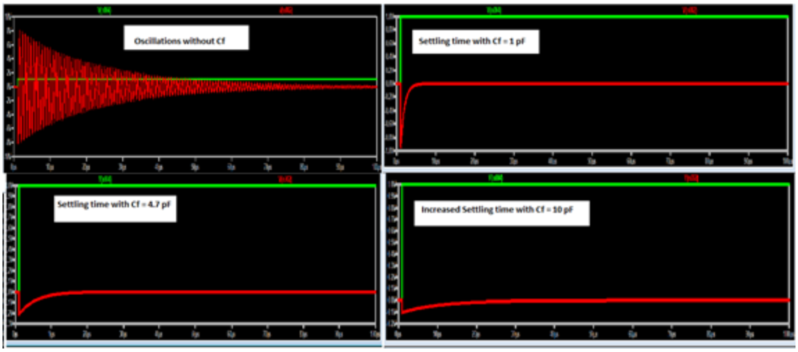

Fig. 6. Effect of C_f on Settling Time

Tabel 1. Effect of Feedback Capacitance on the Output of TIA

C_f (pF)	Settling time (µs)	Nature of Output
0	Infinite	Decaying Oscillations
1	5.36	Stable output with increased settling time
4.7	26.6630	Stable output with increased settling time
6.8	37.0177	Stable output with increased settling time
10	59.866962	Stable output with increased settling time

4 Conclusion

In this study, a transimpedance amplifier with feedback network has been designed. The performance analysis of this circuit using LTspice electronic simulator is done. With supporting mathematical analysis, it is observed that designing feedback network is a critical constraint as it has various effects on amplifier's performance.

While analyzing the circuit, the stray components at op-amp as well as unknown capacitor have been considered. But it is necessary to consider various effects of noise also, especially when lower values of unknown capacitor are to be detected. With the proposed circuit, for higher values of unknown capacitor(>10 pF), the gain of the amplifier is significantly dropped and hence the output signal is more susceptible to noise which in turn degrades the performance of the amplifier. For measurement of such unknown capacitance values, relaxation oscillator can be a better method.

References

[1] A. Hosani et al., "Imaging metallic samples using electrical capacitance tomography: forward modelling and reconstruction algorithms", *Measur. Sci. Tech-nology*, vol. *27, no.* 11, 2016.

[2] Y. J. Yan, D. Zhao and Y. Chen, *MATEC Web of Conferences* 44, 02057(2016)

[3] C. G. Xie, "Applications of tomography in oil-gas industry-Part1", *Industrial Tomography*, pp.591, 2015.

[4] H. K. Wen and Q. Wang, "Touch mode capacitive pressure sensors and Actuators A", *Physical*, vol. 75, no. 3, pp. 242-251, 1999.

[5] K. K. Suratsavadee and S. Sakphrom, "Low-cost capacitive sensor for detecting palm-wood moisture content in real-time", *J. Heliyon.,* vol. 6, no. 8, e04555, 2020.

[6] X. Liu et al., "A new capacitive displacement sensor with nanometer accuracy and long range", *IEEE Sens. J.,* vol. 16, pp. 2306–2316, 2016.

[7] S. Setal, "A high-speed digital electrical capacitance tomography system combining digital recursivede modulation and parallel capacitance measurement", *IEEE Sens. J.,* vol. 17, no. 20, pp. 6690–6698, 2017.

[8] L. Xu et al., "A digital switching demodulator for electrical capacitance tomography", *IEEE Trans Instru Meas.*, vol. 62, no. 5, pp. 1025–1033, 2013.

[9] G. Scotti et al., "88-μA1-MHz stray-insensitive CMOS current-mode interface IC for differential capacitive sensors", *IEEE Trans. Circuits Syst.*, vol. 61, pp. 1905–1916, 2014.

[10] S. Wang et al., "A power-efficient capacitive read-out circuit with parasitic cancellation for MEMS cochlea sensors", *IEEE Trans. Bio-med.Circuits Syst.*, vol. 10, pp. 25–37, 2016.

[11] A. DeMarcellis, G. Ferri and P. Mantenuto, "ACCII-basednon-inverting Schmitt triggerandits application asastable multi vibrator for capacitive sensor interfacing", *Int. J. Circuit. Theory Appl.,* vol. 45, pp. 1060–1076, 2016.

[12] A. U. Khan, T. Islam and J. Akhtar, "A differential interface for trace moisture sensor", in *IEEE Int. Conf. on Signal Proce. Inform. Commun. Energy Systems*, 2015.

[13] High Performance, 145MHz Fast FETOp Amps, (2019) *AnalogDevices,* https://www.analog.com/me-dia/en/technical-documentation/data-sheets/AD8065_8066.pdf

[14] A. Bhat, "Stabilize Your Transimpedance Amplifier", 2012, https://www.maximinte-grated.com/en/appnotes/index.mvp/id/5129#