Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 168 (2016) 1585 – 1588

Procedia Engineering

www.elsevier.com/locate/procedia

30th Eurosensors Conference, EUROSENSORS 2016

Automatic bridge-based interface for differential capacitive full sensing

G. Ferri*, F. R. Parente, V. Stornelli, G. Barile, L. Pantoli

Department of Industrial and Information Engineering and Economics, University of L'Aquila, 67100, L'Aquila, Italy

Abstract

The authors here propose, for the first time, an automatic analog interface for differential capacitance estimation, able to reveal and quantify both low and high (full-range) capacitive variations. The working principle is based on a modified De-Sauty AC bridge configuration where two differential capacitances and two resistances are employed, one of which is implemented by a Voltage Controlled Resistor (VCR). Through a suitable feedback loop, a very accurate estimation over the complete range of the differential capacitance variation is possible, while the bridge allows a continuous differential capacitance evaluation without the need of knowing the accurate value of the sensor baseline and/or its variation range. A general but very simple formula, considering both the "autobalancing" and the "out-of-equilibrium" ranges, is also given. Theoretical, experimental and simulated results are in a very good agreement. Sensitivity and resolution values, typical of sensors and their interfaces, have been determined in a practical case, showing satisfactory values.

Peer-review under responsibility of the organizing committee of the 30th Eurosensors Conference

Keywords: Differential capacitance sensors; bridge-based circuits; analog circuits; Wheatstone bridge; electronic interface.

1. Introduction

In the last years, some research studies on commercial capacitive transducers have been proposed, especially in capacitive displacement applications. A differential capacitive sensor is a particular kind of capacitive sensors having the sensing element formed by two plates and a common mobile one, in the middle (see Fig. 1).

* G. Ferri. Tel.: +39 0862 434446; fax: +39 0862 434403.
E-mail address: giuseppe.ferri@univaq.it.

Peer-review under responsibility of the organizing committee of the 30th Eurosensors Conference
doi:10.1016/j.proeng.2016.11.466

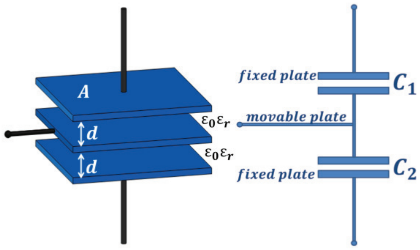

Fig. 1. Differential capacitive sensor structure.

Defining x as a dimensionless variable, related to the sensor measurand variations x the two relative capacitors change their values in a complementary way under an external stimulus [1] and the x can be expressed as:

$$x = \frac{C_1 - C_2}{C_1 + C_2} \quad (1)$$

Differential capacitive sensors find applications in accelerometers, position or rotation detection, force, etc. [2-4]. In the literature, a differential capacitive sensing is performed in different ways: capacitance-to-frequency conversion, capacitance-to-phase conversion, switched-capacitor A/D technique, etc. [5-7]. Bridge-based front-ends are typically employed in those applications where the sensing element shows reduced variations with respect to its baseline. Some recent works on resistive sensors [8-10] have demonstrated that high sensitivity and other features of the classical Wheatstone bridge can be improved by using an "autobalancing" architecture.

2. The proposed interface

The novelty of our work consists in the employing a capacitance-to-voltage conversion in continuous time, using a particular impedance bridge (Fig. 1), whose left branch is formed by the differential capacitive sensor (C_1, C_2) and the right one by a fixed resistance (R) and a Voltage Controlled Resistor (VCR), as shown in Fig. 2 (a).

The feedback loop through a tuning of the VCR allows to handle the bridge output voltage: in fact, in the autobalancing range, the VCR changes its value according to the capacitive variation. The VCR is implemented by means of AD633 component, connected in a Zhong configuration [11] as in Fig. 2 (b):

$$R_{vcr} = \frac{10R}{10 - V_{ctrl}} \quad (2)$$

being "10" expressed in Volt.

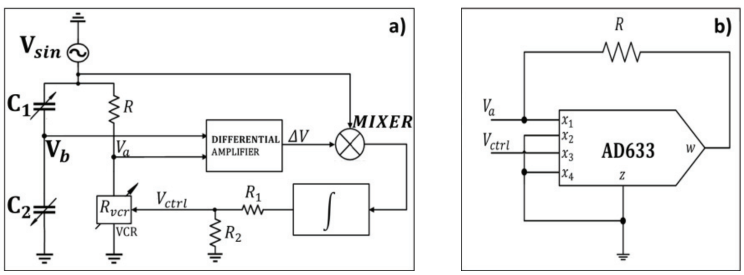

Fig. 2. (a) the proposed interface; (b)Voltage Controlled Resistance implementation by means of the commercial components AD633.

This architecture allows the accurate estimation of the measurand variable x, according to the following general formula, valid for the full range of x variation (±100 %):

$$x = \frac{V_{ctrl}}{20 - V_{ctrl}} - 2\frac{\Delta V_{pp}}{V_{\sin,pp}} \tag{3}$$

where: 20 is expressed in Volt, $V_{sin,pp}$ is the peak-to-peak value of the supply sinusoidal voltage, ΔV_{pp} the differential amplifier output and V_{ctrl} the voltage to be applied to VCR.

3. Results

Simulated results in the whole capacitance range (starting position $C_1 = C_2 = 200$ pF, with ±100% of variation), in the concrete case of a displacement/position sensor are shown in Fig. 3(a): according to (3) inside the autobalancing range, the bridge is in equilibrium and ΔV_{pp} is zero (in this case, V_{ctrl} changes its value) while in "out-of-range" V_{ctrl} is saturated (at ± 9.65 V) and ΔV_{pp} is not zero.

Fig. 3(b) shows the absolute error (defined as in [12]) between theory and simulation vs. x: it is lower than 0.07 V in the worst case.

Experimental tests have been conducted on a discrete element board, demonstrating the circuit capability to follow the capacitive sensor variations in a full estimation range, as shown in Fig. 4(a). In fact, the percentage relative error, defined as in [12], is lower than 0.45 %, see Fig. 4(b).

We have considered a possible plates distance variation Δd starting from an initial distance of d_0 = 1 mm. The sensitivity trend as a function of Δd is shown in Fig. 5(a): sensitivity values tens of V/µm. Having evaluated about 170 µV of output voltage noise, resolution in terms of distance variation is in the range 4.2-14.2 nm, i.e., at capacitive level in the range 0.28-0.84 fF (that is about one hundred of dB).

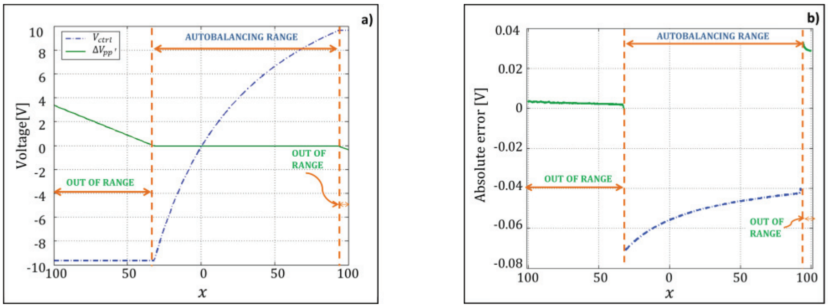

Fig. 3. (a) voltage vs x%: simulated results; (b) absolute error (theoretical vs. simulated) in "autobalancing" interval and "out-of-range" vs. x%.

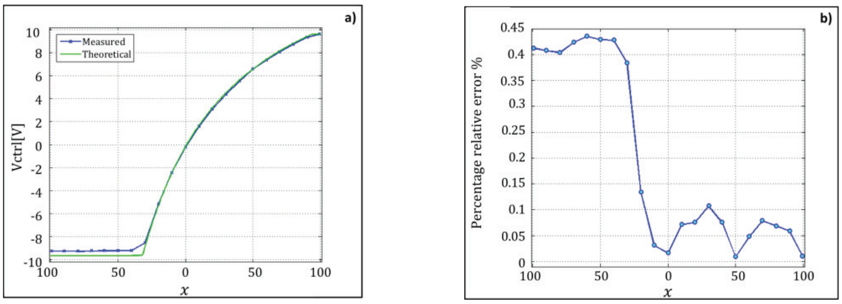

Fig. 4. (a) Vctrl behaviour vs x: theoretical and experimental results; (b) percentage relative error vs. x: theoretical vs. experimental results.

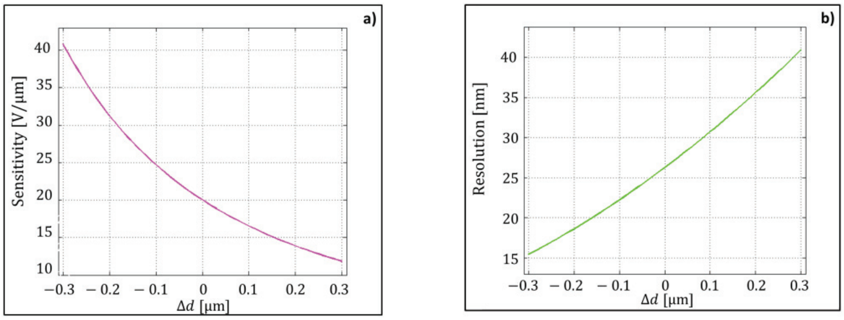

Fig. 5. (a) sensitivity vs. *Δd*; (b) resolution vs. *Δd*.

4. Conclusions

We have developed a novel automatic bridge-based circuit performing a fully-range differential capacitive sensor evaluation through a suitable modification of the classical De-Sauty bridge. Simulated and experimental results have confirmed theoretical expectations which allow the capacitance estimation in its the full variations range with good accuracy, making the proposed interface solution suitable for several capacitive sensor application..

References

[1] K. Mochizuki, K. Watanabe, T. Masuda, A High-Accuracy High-Speed Signal Processing Circuit of Differential-Capacitance Transducers, IEEE Trans. Instrum. Meas. 47 (1998), 1244-1247.

[2] L. K. Baxter, Capacitive sensor basics, in: Capacitive Sensors: Design and Applications, : The Institute of Electrical and Electronics Engineers, New York, 1997, pp. 1–46.

[3] C. Falconi, E. Martinelli, C. Di Natale, A. D'Amico, P. Malcovati, A. Baschirotto, V. Stornelli G. Ferri, "Electronic interfaces", Sensors & Actuators B, 121 (2007) 295–329.

[4] T. Zeng, Y. Lu, Y. Liu, H. Yang, Y. Bai, P. Hu, Capacitive Sensor for the Measurement of Departure From the Vertical Movement, IEEE Trans. Instrum. Meas., 65.2 (2016) 458-466.

[5] B. George and V. J. Kumar, Switched capacitor signal conditioning for differential capacitive sensors, IEEE Trans. Instrum. Meas., 56 (2007) 913-917.

[6] G. Scotti, S. Pennisi, P. Monsurrò, A. Trifiletti, 88-A 1-MHz Stray-Insensitive CMOS Current-Mode Interface IC for Differential Capacitive Sensors, IEEE Transactions on Circuits and Systems I: Regular Papers, 61.7 (2014) 1905-1916.

[7] G. Ferri, F. R. Parente, V. Stornelli, Analog current-mode interfaces for differential capacitance sensing, Proc. of IEEE Sensors Applications Symposium (SAS), Catania, IT, April 2016.

[8] V. Ferrari, A. Ghisla, Z. K. Vajna, D. Marioli, A. Taroni, ASIC front-end interface with frequency and duty cycle output for resistive-bridge sensors, Sensors and Actuators A: Physical, 138.1 (2007) 112-119.

[9] A. De Marcellis, G. Ferri, P. Mantenuto, A novel 6-decades fully-analog uncalibrated Wheatstone bridge-based resistive sensor interface, Sensors and Actuators B: Chemical, 189 (2013) 130-140.

[10] F. M. Van der Goes, G. C. Meijer, A simple accurate bridge-transducer interface with continuous autocalibration, IEEE transactions on instrumentation and measurement, 46.3 (1997) 704-710.

[11] Analog Devices, Norwood, MA, USA. Datasheet, AD633, Low Cost Analog Multiplier. [Online]. Available: http://www.analog.com/media/en/technical-documentation/data-sheets/AD633.pdf, April 2016.

[12] A. D'Amico, C. Di Natale, A contribution on some basic definitions of sensors properties, IEEE Sensors Journal, (2001) 183–190.