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A new 0.35 μm CMOS electronic interface for wide range floating capacitive and grounded/floating resistive sensor applications

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ABSTRACT

In this paper we propose a novel interface circuit suitable for the read-out of both wide range floating capacitive and grounded/floating resistive sensors. This solution, employing only two Operational Amplifiers (OAs) as active blocks and some passive components, is based on a square-wave oscillating circuit topology which, instead of a voltage integration typically performed by other solutions in the literature, operates a voltage differentiation. Therefore, the proposed circuit, performing an impedance-to-period (*Z–T*) conversion, results to be suitable as first analog front-end for both wide variation capacitive (e.g., relative humidity) and resistive (e.g., gas) sensors. Its sensitivity and dynamic range can be easily set through external passive components. Preliminary experimental measurements, which have characterized and validated this solution, have been conducted through a suitable prototype *PCB* fabricated with discrete commercial components. Then, the proposed interface has been also designed at transistor level, in a standard CMOS technology (AMS 0.35 um), developing a single-chip integrated circuit with low-voltage (1.8 V, single supply) low-power (about 350 μW) characteristics in a very small silicon area (lower than 0.6 mm^2) which results to be suitable for sensor array configurations and portable applications. Further experimental results, achieved utilizing commercial sample resistors and capacitors to emulate sensor behavior, have shown a linear trend and a satisfactory accuracy in the evaluation of floating capacitive (in the range 10 pF–1 μF), grounded resistive (in the range 150 kΩ–1.5 MΩ) and floating resistive (in the range 10 MΩ–1 GΩ) variations, also when compared to other solutions presented in the literature. The satisfactory interface behavior has been also confirmed by the measurement of both relative humidity through the commercial sensor Honeywell HCH-1000 (capacitive) and carbon monoxide CO through the commercial air quality sensor FIGARO TGS-2600 (resistive).

1. Introduction

Read-out analog circuits suitable for the interfacing of wide range resistive/capacitive sensors are typically based on either sinusoidal or square wave generators, also named as oscillators, so performing an impedance-to-period (*Z–T*) conversion. In this sense, in fact, when the sensing element shows larger variations and/or the sensor baseline is unknown/unpredictable, it is preferable to generate an AC signal since, considering the state of the art of the manufacturing, the sensing element may vary also across several decades, due to the combination of three variable components: the nominal baseline, the deviation from this nominal value (due to ageing, working temperature, operating condition, etc.) and the sensing element variation related to the physical/chemical phenomenon to be revealed. Since each contribution can be in the order of one-two decades, often wide range sensors have to be considered and interfaced. Therefore, since this type of wide range sensor signal conditioners (i.e., oscillators) covers several magnitude decades, it does not require any calibration procedures and/or manual settings (i.e., the so-called "uncalibrated" system), which typically depend on the employed sensor, and its frequency output (i.e., "digitalized" output signal), if compared to voltage output circuits, provides improved noise immunity (e.g., offsets, frequency disturbs, etc.), easiness in multiplexing, insulation and signal processing, and so on.

These electronic circuits, which are largely utilized in a lot of research and application fields (e.g., telecommunications, measurement systems, etc.), generate a periodic waveform with an output period proportional to the sensor component (linked to the measurand value) which is excited through the produced AC signal [1–20]. Internally, they are typically implemented with a Voltage-Mode (*VM*) approach by using Operational Amplifiers (*OAs*) and

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are based on an $R-C$ integrating cell, followed by a voltage hysteresis comparator, so they can be employed as first analog front-ends for both resistive and capacitive sensors capable to reveal physical/chemical phenomena [1,2,21–32].

Furthermore, these solutions allow overcoming typical problems related to interface circuits performing an impedance-to-voltage (*Z–V*) conversion. In particular, the volt-amperometric approaches, such as the simple voltage divider or the resistive DC-excited Wheatstone bridge topologies, typically perform a resistance-to-voltage (*R–V*) or resistance-to-current (*R–I*) conversion, but can be adopted only for reduced resistive variations, otherwise scaling factors, which typically require complex and expensive calibration procedures, must be utilized. In fact, in this sense, when the measurand shows a reduced variation, the output signal becomes comparable to noise level, while if it varies in a wide-range, the circuit saturation level can be easily reached, especially in low-voltage low-power solutions. In addition, considering the development of low-cost portable systems, the sensor electronic interface should be designed to be as universal as possible, without the need of calibration or tuning operations for a specific sensor. In this way, the same front-end should be also replicated for the use with multiple sensors and, thus, the implementation in integrated circuits for the realization of single-chip solutions could be furthermore simplified [1,2,33–47].

In this work we present a new low-cost fully-analog oscillating circuit, based on *OAs*, suitable for both wide range floating capacitive and grounded/floating resistive sensors interfacing, employing a reduced number of active and passive components [48,49]. The performed *Z–T* conversion is based on a voltage differentiation, instead of a voltage integration, so to achieve a better rejection of low-frequency disturbs (e.g., DC offsets and $1/f$ noise). In this interface, through a proper choice of some external passive components, it is possible both to easily select the working range and to fix the sensitivity to sensor parameters [50]. Preliminary experimental measurements have been performed implementing the proposed solution through the fabrication of a prototype Printed Circuit Board (*PCB*) that utilizes the commercial component low-cost low-offset OPA602 as *OA* and employs both passive high-accuracy sample resistors and capacitors so to emulate sensor behaviors. Experiments have confirmed the theoretical expectations and the validity of the proposed solution. Moreover, a transistor-level solution has been designed so developing a single-chip integrated version of the proposed circuit. In this sense, further experimental results have been achieved through the fabricated chip, integrated in a standard CMOS technology (AMS 0.35 μm). The interface shows a low single supply voltage (1.8 V) and a low power consumption (lower than 350 μW), thus being suitable for portable sensor applications. The integrated solution has been utilized also for the detection of the percentage relative humidity (*RH%*) through the use of a commercial capacitive sensor (i.e., HCH-1000 Series by Honeywell) as well as for the measurement of the CO concentration by means of a commercial air quality resistive sensor (i.e., TGS-2600 Series by FIGARO). Since the integrated circuit requires a very small silicon area (lower than 0.6 mm^2), it can be easily replicated on silicon substrate, giving the possibility to be employed also in sensor arrays. The achieved on-*PCB* and on-chip experimental results have shown good linearity (especially with respect to capacitive evaluations) and accuracy, as well as a reduced estimation error, due to the circuit simplicity.

2. The proposed novel sensor interface: circuit analysis and theory

The circuit implementation of the proposed interface is reported in Fig. 1. The front-end is very simple, consisting of eight resistors, a capacitor and only two main active blocks: the first, OA_1, is utilized in a non-inverting voltage differentiator configuration, while the second, OA_2, is employed as a non-inverting hysteresis voltage comparator which provides the output square waveform. Through a suitable closed loop, which avoids any system manual calibration, resistive or capacitive sensors can be excited by the generated AC signal. In addition, it is possible to easily set the interface working range through external passive components which also allow fixing the desired sensitivity of the read-out circuit.

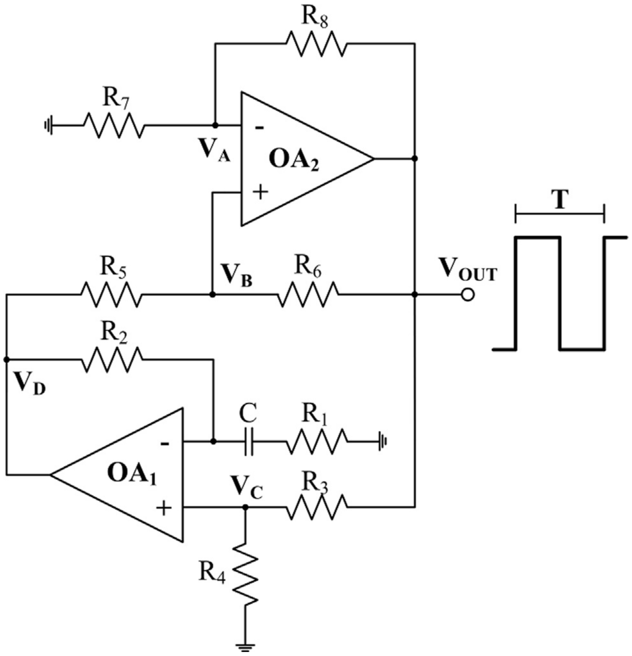

Fig. 1. Block scheme of the capacitive-resistive sensor interface: capacitor *C* (floating) and resistor R_1 (grounded) or R_2 (floating) can be replaced by suitable sensors.

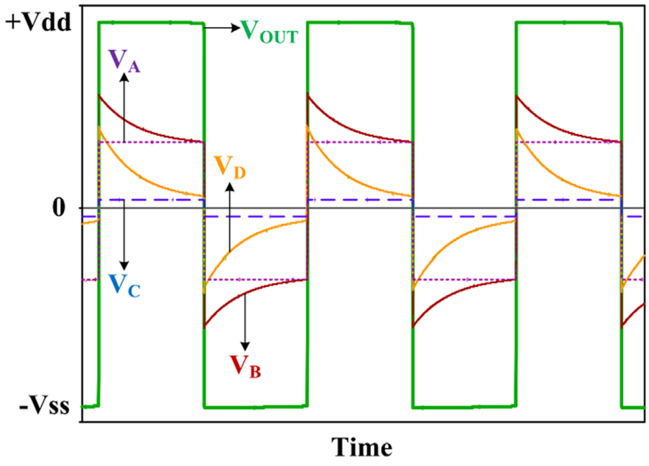

Fig. 2. Typical time responses evaluated at main interface nodes.

Fig. 2 shows the main voltage signal behaviors at circuit nodes from which the differentiating effect on V_D can be seen. The oscillating condition is guaranteed by a proper choice of R_3, R_4, R_7, and R_8 resistor values which create the suitable threshold levels used by OA_1 and OA_2 to switch between the two voltage saturation limits. In particular, it is important to consider also that the employed passive components have to be properly chosen so to