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Differential capacitive sensing circuit for a multi-electrode capacitive force sensor

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ABSTRACT

A multi-electrode differential capacitive sensing circuit is designed and realized for the read-out of a multi-axis capacitive force–torque sensor. The sensing circuit is based on a differential relaxation oscillator, to which multiple capacitances can be connected. For selecting the capacitances, reprogrammable asynchronous logic can be used, such that any desired combination of differential or single-ended capacitance can be determined. The noise performance of the oscillator in the system is analysed and measured, revealing the influence of individual component values on the noise performance of the system. Capacitance measurements show that a deviation of 0.9 fF is obtained at an acquisition rate of 225 Hz including auto-calibration, which is mainly limited by the quantization noise due to the frequency counter. The lowest obtained deviation is 0.12 fF at an acquisition rate of 3.5 Hz. The system is successfully interfaced to the multi-axis capacitive force–torque for the read-out of six capacitor configurations at an acquisition rate of 38 Hz.

1. Introduction

Capacitive sensing technology is widely used for sensor systems which require high sensitivity and low power consumption. In a differential configuration, capacitive sensing principles offer effective reduction of common-mode noise and parasitic effects [1,2]. Differential capacitive sensing can therefore be found in many sensor systems such as accelerometers [3–5], gyroscopes [6–8], pressure sensors [9], flow sensors [10,11] and force sensors [12–14]. For the read-out of a differential capacitor pair various sensing techniques can be used in which the difference in capacitance is converted to a voltage, duty cycle or frequency. If the sensor consists of multiple electrode pairs, e.g. for the detection of multiple-degrees of freedom acceleration, angular acceleration, flow or force, each individual pair of electrodes needs to be interfaced. For a limited number of electrodes, each differential pair can be provided with an individual sensing circuit, referred to as space division multiplexing (SDM). When the number of electrodes increases, for example an array of differential capacitor pairs, techniques such as frequency division multiplexing (FDM) or time division multiplexing (TDM) can be used [15].

Capacitive read-out interfaces in which square-wave signals are used to determine the capacitance are an attractive candidate to combine with TDM since standard logic components can be used. Meijer et al. [16–19] presented an elegant low-cost and high resolution single-ended capacitive read-out system based on a relaxation oscillator and a TDM approach by multiplexing square wave signals. Several improvements to this circuit were presented later with, e.g. a high tolerance for a parasitic parallel conductance [20] and lower power consumption [21]. The resulting output of the sensing circuit is a square-wave signal with a frequency proportional to the measured capacitance that can easily be interfaced to a microcontroller to determine the frequency. Previously, successful read-out of a capacitive 1-D force sensor comprising of 16 single-ended capacitors using this system is demonstrated by Wiegerink et al. [22].

For a sensor application which we presented in [14,23], a capacitive read-out system is required which can measure both single-ended and differential capacitance to a common node with an accuracy better than 0.1% of the full scale, i.e. better than 1 fF accuracy, at an acquisition rate of 200 Hz per capacitor configuration. For this sensor a direct differential measurement is required; subtracting two single ended measurements can result in large errors if the measurements are not performed exactly at the same moment while the capacitances are changing in time due to a dynamic load. Commercially available capacitance to digital

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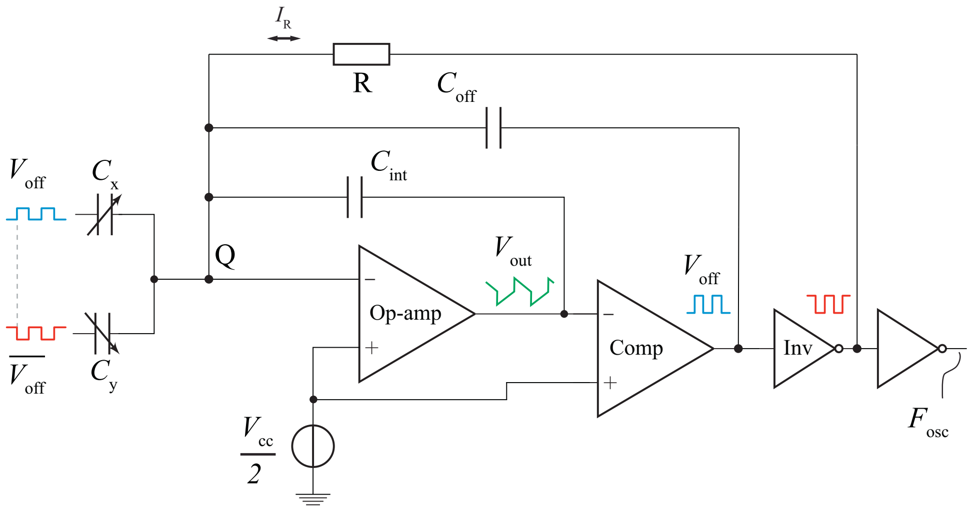

Fig. 1. Relaxation oscillator schematic with differential capacitor pair C_x and C_y.

converters (CDCs), such as [24–26] have excellent resolution, but are not suitable for multiple differential capacitance pairs to a common node. Furthermore, for optimal sensitivity of the force sensor, the same electrode must be combined in multiple differential configurations. CDCs that are capable of measuring multiple differential capacitance pairs to a common node, e.g. [27,28], are not intended for high accuracy capacitance measurements at relatively high acquisition rates.

The requirements described above make commercially available CDCs not suitable, which initiated the research described in this paper. We modified the measurement system presented by Meijer et al. [16–19] such that the oscillation period is proportional to differential capacitance with the capability to determine any combination of differential or single-ended capacitance [29]. In this work, the basic measurement principle is shown and the noise performance of the proposed system is analysed. To prove and assess its functionality and performance we interface the circuit to the force sensor in [14] and perform force and moment measurements.

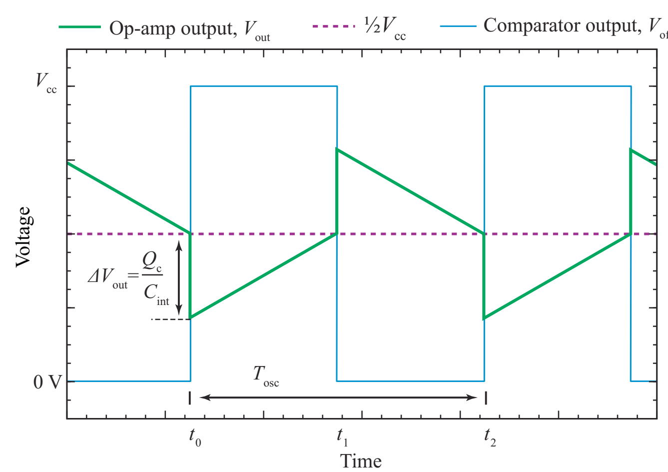

Fig. 2. Oscillator signals of the op-amp output and the comparator output.

2. Theory and modelling

2.1. Differential relaxation oscillator

The proposed differential capacitive read-out system is based on a relaxation oscillator presented by Martin [30] and modified by Meijer et al. [16–19]. We adapted the oscillator such that the oscillation period is proportional to differential capacitance. The circuit of the relaxation oscillator is illustrated in Fig. 1 and the oscillator signals are shown in Fig. 2. The basic circuit consists of an op-amp, comparator, inverter, two capacitors and a resistor. The op-amp in the circuit regulates the voltage at point Q such that it is kept at a constant level of $V_{cc}/2$ by regulating its output voltage V_{out}. When the circuit oscillates, charge is transferred from C_{off} to C_{int} and vice versa. The charge transfer occurs when voltage V_{off} at the right-hand side of capacitor C_{off} switches between 0 V and V_{cc}, which is controlled by the output of the comparator. When V_{off} switches from 0 V to V_{cc} (t_0 in Fig. 2), an amount of charge equal to $Q_c = V_{cc}C_{off}$ will flow into node Q. Because the op-amp regulates the voltage at this point such that it kept constant, this charge will go into C_{int}. The change in voltage at the output of the op-amp is equal to $\Delta V_{out} = Q_c/C_{int}$. The current I_R through resistance R will discharge capacitance C_{int}. This discharge current is constant, since the voltage drop over R is constant. The discharging current results in a decrease in voltage over C_{int} and hence an increase in voltage at the output of the op-amp ($t_0 - t_1$ in Fig. 2). When V_{out} crosses the threshold level of the comparator ($V_{cc}/2$), the output of the comparator switches from V_{cc} to 0 V (t_1 in Fig. 2). This voltage swing will transfer charge from C_{int} to C_{off}, resulting in a voltage jump ΔV_{out} at the output of the op-amp in opposite direction (t_1 in Fig. 2). Because the comparator switches to low-state, the output of the inverter will switch to high-state, which changes the direction of the current through R such that it will discharge C_{int} again. Since the discharge current is constant, the time duration before C_{int} is discharged and V_{out} crosses the threshold level again is $Q_c/I_R = 2RC_{off}$. Since this discharging occurs twice per period, the total oscillation period is given by

$$T_{off} = 2\frac{Q_c}{I_R} = 4RC_{off}. \quad (1)$$

As can be seen from (1), the oscillation time is proportional to the amount of charge Q_c transferred to and from C_{int}. If additional capacitors are connected in parallel to C_{off}, this will increase the amount of transferred charge and hence the oscillation time. This is the basic principle for measuring an unknown capacitance as demonstrated by Toth et al. [19]. We propose to extend the principle for the measurement of differential capacitance by switching capacitors in-phase and out-of-phase with respect to the comparator output. Doing so, the oscillation period becomes proportional to the net resulting charge from the capacitors which are switched