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CCII Based Current Signal Interface for Piezoresistive Pressure Sensor

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Abstract— **In this paper, we present a current mode interface design for full bridge MEMS piezoresistive pressure sensor utilizing a differential current signal with high sensitivity and linearity. MEMS-piezo resistive pressure sensors are popular as they are small, robust and low cost. Typical sensitivity of these sensors is of the order of few millivolts per Bar. The presented approach utilizes the current signal from the bridge output port and detects ultra-low variations in the sensor thus enhancing the sensitivity. The current mode approach uses two positive second-generation current conveyors (CCII+) in a closed loop fashion thus eliminating the use of negative current conveyor (CCII-). This approach conveys high common mode cancellation, ease of offset balancing, increased sensitivity and eliminates the use of the current source as excitation. The circuit performs trans-impedance conversion through a single ended gain resistance and eliminates the use of any further amplification stages. The performance of the interface design is evaluated in simulation using AD844 of analog devices which represents a functional current conveyor. Moreover, the results are evaluated with a MEMS pressure sensor and are characterized from 0 to 1000mBar using the interface circuit with an achieved sensitivity of 11.7V/Bar.**

Keywords— ***Current conveyor (CCII), MEMS Pressure Sensor, Resistive Bridge, Current Mode***

I. INTRODUCTION

MEMS-based pressure sensors are widely popular for measurement of pressure and have captured the consumer domain owing to its ease of fabrication, low cost, small size and direct DC output[1]. New applications in the area of the control system, aviation and medical are demanding for high-resolution pressure sensors [2][3]. Many of these applications fall in the category of hand-held or portable sensing units and so interface electronics plays a key role in achieving the target.

Piezo-resistive sensors work on the principle of change in resistance of the piezo-resistive element proportional to the applied input[4]. These elements can be in the form of a single resistive element or in a bridge configuration. Due to the advantages such as immunity to common mode noise and environmental disturbances, bridge configuration is preferred in many cases. The sensitivity of these sensors is of the order of few millivolts per Bar and the region of operation for many such sensors is in the range of mBar [5]. Thus, an appropriate interface circuit is needed for proper instrumentation, that can enhance the output by increasing the sensitivity of the sensor at the circuit level. As stated, these sensors utilize differential measurement through Wheatstone bridge architecture, achieving high common mode rejection and compensating for factors such as temperature and humidity. In order to have the largest output and utilize the full span output of the sensor, the piezo resistors are to be precisely matched. Although this is often not achieved and so the interface circuits cancel out the offset for full span sensor output[6].

Reported literature presents several solutions involving complex active blocks performing differential voltage sensing and amplification, current subtraction with half bridge elements causing sensitivity reduction and current instrumentation with current source excitation[7]–[14]. Majority of the approach including DC and frequency output involves multiple active and passive elements with mixed voltage/current topologies. The current mode solution involves the use of multiple current conveyors in order to realize positive and negative CCII for achieving differential current signal measurement [15].

In this paper, a novel approach for MEMS piezoresistive sensor for detection of very low variation in pressure is presented. The sensor interface design presents a unique method of using a closed loop to achieve differential current signal and hence eliminates the use of the negative current conveyor. The circuit topology consists of a positive second-generation current conveyor (CCII+) as the basic active block which acts as a buffer for the current signal from the bridge output port. This interface circuit has numerous applications and can serve as a suitable current mode solution in sensor interfacing applications.

The proposed solution maintains high common mode rejection, linearity, accuracy and allows optimization of sensitivity and resolution with the ease of offset cancellation without changing the sensor elements. The circuit directly operates in trans-impedance mode and gain adjustment is achieved through a single end grounded resistance without disturbing any of the sensing or active block components. Performance of the interface design is evaluated in PSPICE using AD844 by Analog Devices, indicating the validity of the reported work. The circuit is then tested with in-house fabricated MEMS piezoresistive pressure sensor and calibrated using a standard pressure pump in the range of 0 to 1000mBar. The sensor along with the evaluation of the interface circuit is presented in the experimental result section.

II. CCII BASIC THEORY

Current Conveyors (CC), first introduced by Sedra and Smith in 1968[16] are the basic block of current-mode design widely used in integrated application substituting the traditional operational amplifiers. The versatility of CC was recognized after the introduction of CCII and led to the novel realization of CCII in a variety of application circuits [17]–[20]. Recent high-level analog circuit design platform such as Field Programmable Analog Array (FPAA) utilizes CCII because of its high level of integration and other recognized advantages [21]. CCII also serves as the basic block for current-mode analog signal processing and related applications [17].

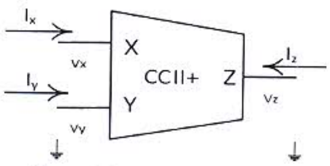

Figure 1. Ideal CCII+ schematic

An ideal CCII device shown in Fig 1. consists of a voltage follower (scale factor $\alpha \approx 1$) between terminal X and Y whereas a current follower (scale factor $\beta \approx 1$) between terminal X and Z. So, the X terminal has zero impedance and Z & Y terminals have infinite impedance. Current entering the terminal X will result in equal current entering terminal Z (CCII+) or an equal current leaving terminal Z (CCII-). The summarized characteristic is represented in a matrix form as:

$$\begin{bmatrix} i_y \\ v_x \\ i_z \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 \\ \alpha & 0 & 0 \\ 0 & \pm\beta_i & 0 \end{bmatrix} . \begin{bmatrix} v_y \\ i_x \\ v_z \end{bmatrix} \qquad (1)$$

AD844 of Analog Devices represents a practical current conveyor for implementing the salient feature of a CCII based circuit. This commercially available IC is modeled as ideal CCII+ with unity gain and current buffer ($v_x = v_y$ and $i_x = i_z$).

III. CCII Based Proposed Interface Circuit

With advancement in FPAA technology, more and more current based sensor interface designs are being introduced. There are still not many readout circuits based on CCII as sensor interfaces and this paper wants to further add on to this area of research.

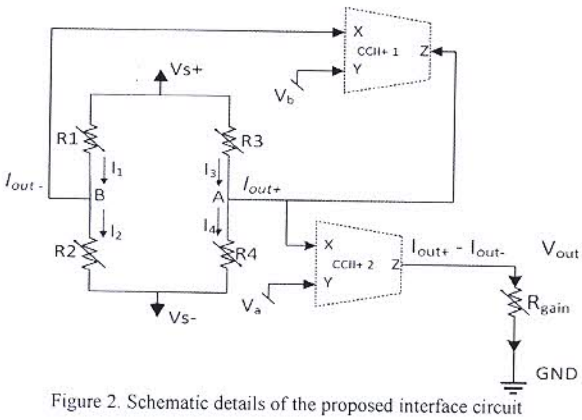

Figure 2. Schematic details of the proposed interface circuit

The proposed readout circuit for a MEMS piezoresistive sensor based on the current signal is depicted in Fig. 2. The CCII+1 act as the closed loop current conveyor and a differential current signal is generated at the 'X' terminal of the CCII+2. Unlike previously reported work, [15] which utilizes two output resistance to generate voltages that can be subtracted to get the total bridge output, this design exploits the fact that current can be easily added or subtracted at a node and thus a closed loop current signal from the CCII+1 generates a differential bridge current at 'X' terminal of CCII+2. This eliminated the use of negative CCII or an extra output resistance for doing the same. The resistive bridge shown are piezo resistors placed at the diaphragm edge of the sensor [22]. The bridge is excited with a DC bias voltage V_{s+} and V_{s-} with equal and opposite polarity. The piezo resistors are so designed that the resistor pair R_3 and R_2 vary equal and opposite with respect to pair R_1 and R_4 as shown by the arrows in Fig. 2. If R_o is taken as the baseline or the nominal resistance and ΔR_o as the change in piezo resistance with respect to nominal value R_o due to pressure input, then $R_1 = R_4 = R_o(1 + \Delta R_0/R_0)$ and $R_2 = R_3 = R_o(1 - \Delta R_0/R_0)$. The DC excitation results in current $I_{out-} = I_2 - I_1$ and $I_{out+} = I_3 - I_4$ from terminal B and A respectively. The two-current conveyors CCII+ 1 and CCII+ 2 act as current buffers that 'sense' the current signal and conveys it to their respective Z terminal. The X terminal of CCII+ 2 receives a feedback current I_{out-} thus the net current at this terminal is $I_{out+} - I_{out-}$. Any offset in the sensor's piezo resistors is compensated by setting the external control voltages V_b and V_a at Y terminal of CCII+1 and CCII+2 respectively, canceling the unbalanced output current from the bridge. Since the paper is aimed towards presenting a novel current mode approach towards resistive bridge sensor with minimal active components, the offset cancellation technique is not presented in here. Considering Ideal CCII presented in Fig. 1, the output voltage V_{out} can be written as:

$$V_{out} = (I_{out+} - I_{out-}).R_{gain} \qquad (2)$$

Before experimental evaluation, a thorough simulation study is performed using the following sensor parameters that taken from the pressure sensor to be used and AD844 of Analog Devices as practical current conveyor:
$V_{s+} = 3.3$v; $V_{s-} = -3.3$v; $R_1 = 9.868$kΩ; $R_2 = 10.35$kΩ; $R_3 = 10.486$kΩ; $R_4 = 10.06$kΩ; $V_b = 78.7$mV; $V_a = -68.4$mV. The resistances mentioned above are from the in-house fabricated MEMS pressure sensor and are measured from a calibrated multimeter. The simulation considers a maximum change of 3.5% in the nominal bridge resistance which corresponds to approximately 10μA of output current change.

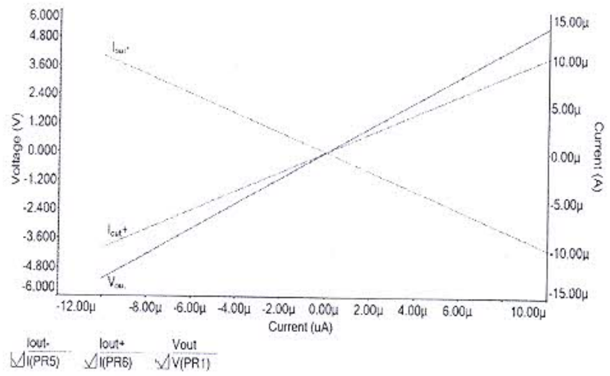

Figure 3. Simulation of proposed CCII based interface circuit with 3.5% relative change of bridge resistance (equal to 10uA current change).

With resistance sweep, the two currents I_{out-} and I_{out+} varies linearly and the corresponding output voltage V_{out} changes according to equation (2). The response of the circuit is shown in Fig. 3. As it can be noted that the output current from the bridge is equal and opposite which is justified and the output voltage which is controlled by the current input and the gain resistance, varies linearly with the input signal. In order to complete the circuit characterization, a noise simulation was also performed considering each resistance and semiconductor device as a source of noise generation. The contribution of each element is propagated by the appropriate transfer function of the circuit and the output thus achieved is represented root mean square sum (RMS) of the individual noise source. Fig. 4 presents the output noise calculated at the output resistance 'R_{gain}' with a bypass capacitor of 1uF. As noticed in the graph presented, the total simulated output noise is 2.9nV/√Hz which is acceptable as the nature of the pressure sensor is static. The subsequent experimental results also suggest that the circuit exhibits acceptable noise performance even in very low excitation ranging the mBar of pressure.

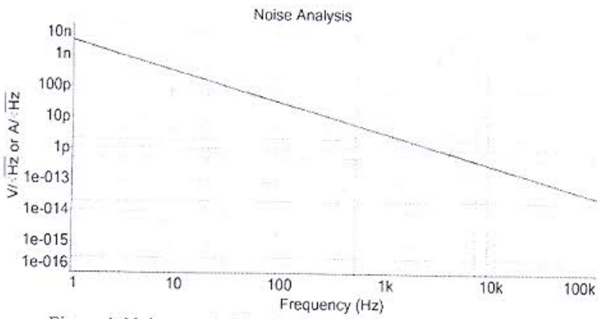

Figure 4. Noise spectral density curve at out gain resistor 'R_{gain}'.

IV. Prototyping and Experimental Result with Sensor

In order to test the real-time working of the interface circuit shown in Fig.2, a prototype circuit was built and tested with a MEMS pressure sensor. The full bridge resistive sensor is made by Implanted polysilicon piezo resistors as the sensing elements and the diaphragm of the pressure sensor is fabricated using wet bulk micromachining[22]. The packaged sensor is sealed in a brass housing with single-ended pressure inlet and four electrical connections at the other end.

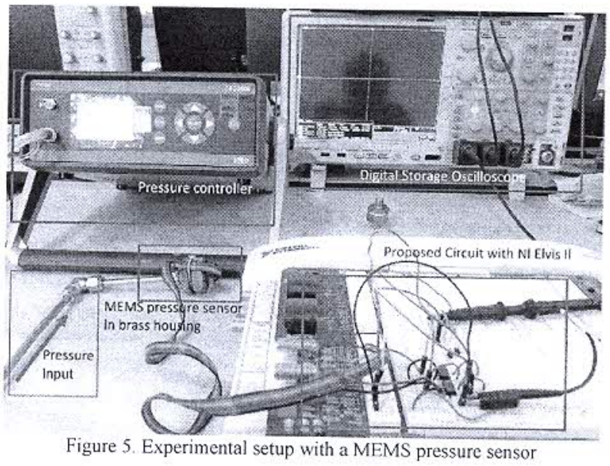

Figure 5. Experimental setup with a MEMS pressure sensor

Out of the 4 wires, two diagonally opposite wires are used for supply voltage and the other two wires are the output points from the sensor. The sensor is excited from a calibrated low-pressure controller from Mensor (CPC2000) capable of delivering positive pressure from 0 – 1100mBar with an accuracy of 0.1% Fs. NI Elvis II is used for supply and offset adjust and measurement from the output of proposed circuit was simultaneously acquired in LabView and on an oscilloscope. The entire setup is shown in Fig. 5. The primary test was carried out with supply voltage V_{s+} = 3.3V; V_{s-} = -3.3V; and R_{gain} = 6MΩ. The input pressure sweep was carried out from 0 to 1000 mBar in a step input fashion and the resulting output of the proposed electronic interface is shown in Fig. 6. Each pressure input step corresponds to 10% of the full span input. So, a total of 10 steps or 100mBar per step is applied to the sensor giving a sensitivity of 11.7V/Bar.

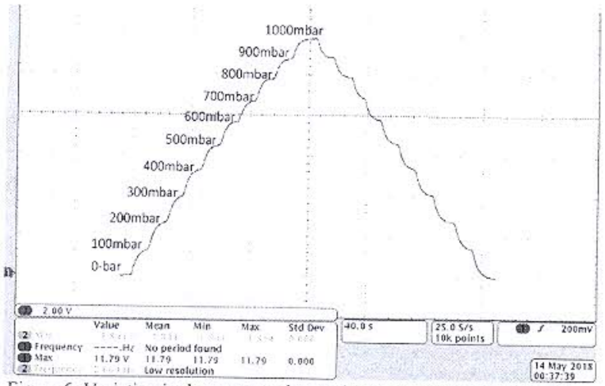

Figure 6. Variation in the output voltage of the current mode circuit with a pressure change of 100mBar per step.

In order to test the electronic circuit capability to enhance the ultra-low pressure input signals, another test was carried out with input pressure ranging from 0 – 100mBar with an input of 20mBar per step. The gain resistance is kept unchanged and the only the pressure range is reduced. The circuit is able to able to resolve ultra-low pressure inputs and the results shown in Fig. 7 clearly validates that the sensor can be used in mBar range with the reliable output from the proposed circuit even with pressure in mBar range. Although, the highest sensitivity achievable is limited by the supply voltage of current conveyor and the working range of the sensor being used. A practical application usually targets an ADC interface thus scaling the output to standard 3.3V or 5V.

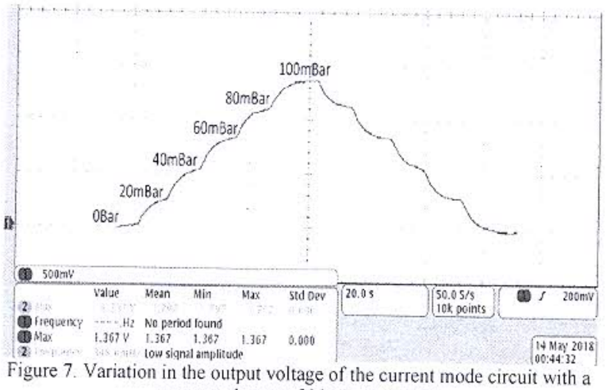

Figure 7. Variation in the output voltage of the current mode circuit with a pressure change of 20mBar per step.

The above-presented result just highlights the extent of sensitivity enhancement that can be achieved by the proposed interface. However, a practical interface is designed for 0-5v or 0-3.3v output in order to give a TTL/CMOS compatible voltage output. As suggested in Eq. 2, the gain of the circuit can easily be adjusted just by changing the output resistance. Keeping this in mind we have adjusted the output just by changing the gain resistor at the output. So, the actual interface design consists to R_{gain} = 492kΩ; V_b = -0.23V and an input pressure range from 0 to 1000 mBar with excitation voltage V_s = ±3.3V. The input pressure was applied in steps of 100mBar. The output voltage variation versus the pressure is noted and the resulting response curve is shown in Fig. 8.

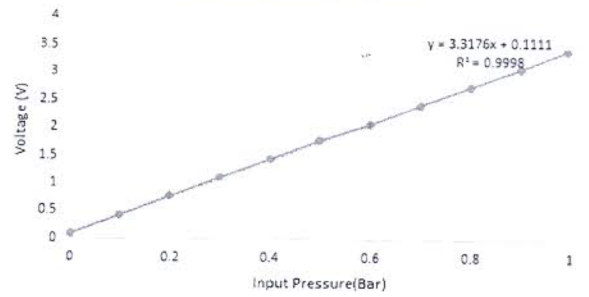

Figure 8. Pressure sensor response curve using the proposed circuit

The response of the sensor with the proposed interface circuit follows a perfect linear curve with a linear regression coefficient, R^2 = 0.998 with linear coefficients [3.31, 0.11]. Fig. 9 shows the ramp results for a pressure ramp input with multiple cycles starting from 0 to 1000 mBar indicating that the response of the sensor with the interface circuit is repeatable and the sensor works well in a repeated cycle.

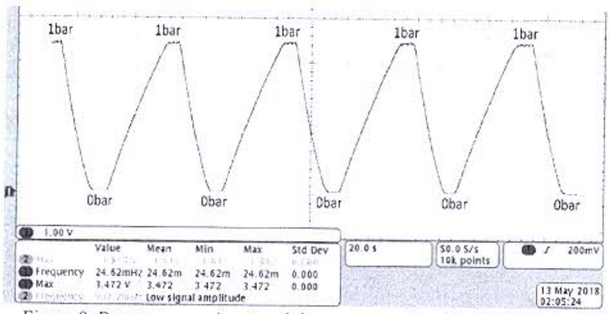

Figure 9. Pressure ramp input and the corresponding change in voltage from the circuit showing repeatability of the system

V. CONCLUSIONS

A current based interface circuit based on the current conveyor for MEMS piezoresistive pressure sensor is presented in this paper. The proposed circuit offer advantages such as high sensitivity, high common mode cancellation, linearity, ease of gain and offset adjustment and needs no current source for sensor excitation. The PSPICE simulation and the practical calibration agree well with the theory and real-time testing of the sensor proves this fact. The proposed circuit shows a good response with the sensor and compared to other current based approach offers enhanced sensitivity with fewer active components by using two CCII+ in a closed-loop fashion. This eliminates the use of extra current conveyor or negative current conveyor to achieve differential current measurement thus removing the effect of mismatch error due to positive and negative current conveyor design. We believe that the proposed interface circuit has numerous applications and can serve as a suitable current mode solution in sensor interfacing applications.

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