A Frequency-Sensing Readout using Piezoelectric Sensors for Sensing of Physiological Signals

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***Abstract*— Together with a charge or voltage amplifier, piezoelectric sensors are commonly used to pick up physiological vibrations from the body. As an alternative to chopper or auto-zero amplifiers, frequency sensing is known in literature to provide advantages of noise immunity, interfacing to digital readout systems as well as tunable range of sensing. A frequency-sensing readout circuit for sensing low voltage signals from piezoelectric sensors is successfully developed and tested in this work. The output voltage of a piezoelectric sensor is fed to a varactor, which is part of an Colpitts LC oscillator. The oscillation frequency is converted into a voltage using a phase locked loop. The circuit is compared to a reference design in terms of linearity, noise and transfer function. The readout has a input-referred noise voltage of 2.24$\mu V/\sqrt{Hz}$ and consumes 15 mA at 5V supply. Arterial pulse wave signals and the cardiac vibrations from the chest are measured from one subject to show the proof of concept of the proposed readout. The results of this work are intended to contribute towards alternative low noise analog front end designs for piezoelectric sensors.**

I. Introduction

The piezoelectric effect refers to the conversion of mechanical stress into electricity and vice versa. Piezoelectric sensors measure pressure, acceleration, strain or force by converting them to an electrical charge. A high sensitivity to strain or force makes them popular in physiological monitoring [1].

Typically a voltage or charge amplifier is used as a readout [1]. When using a voltage amplifier, the sensor must be biased using either an additional resistor or the input impedance of the non-inverting amplifier to allow the strain-induced charge to be dissipated [1]. The combination of the piezoelectric sensor and the bias resistor results in a high pass cut-off frequency, which can lead to difficulty in measurement at frequencies below the cut-off frequency [2] if the amplifier noise current is very large i.e. in the order of several hundred $fA/\sqrt{Hz}$. This difficulty is exacerbated with decreasing sensor size i.e. the sensor's electrode capacitance. A typical approach to decrease the cut-off frequency is to use a larger biasing resistor. The overall noise contribution, especially from thermal noise and input current noise of the amplifier, increases with a reduction in the cut-off frequency, even if the input signal bandwidth is purposely set in the stopband of the highpass filter. In order to minimize low frequency noise and DC errors such as drift, auto-zero and chopper amplifiers are used [3].

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M. R. Yuces work is supported by Australian Research Council Future Fellowships Grant FT130100430

Where amplification of the piezoelectric signal is concerned, the SNR is not only subject to thermal and 1/f noise but also to low frequency disturbances such as offset, drift over time and temperature variations [3]. These disturbances are reduced using trimming, chopping and auto-zero techniques. Trimming involves measuring and reducing the offset voltage during production as well as the design stages of a commercial opamp. In the auto-zero technique, the offset voltage is measured and subtracted in two different phases of a clock cycle. While 1/f noise and drift are eliminated dynamically, under-sampling of noise above the auto-zero clock frequency results in folding of high frequency noise into the base-band. The chopping technique involves sampling and holding the input signal at a clock frequency above the 1/f corner frequency of the opamp. The modulated signal is amplified and subsequently demodulated into the baseband followed by low-pass filtering. This technique is better than auto-zero in terms of noise at lower frequencies but can suffer from ripples due to chopping of the offset voltage or jitter in the chopper clock. Additionally there is an upper limit to the input signal bandwidth. The chopper stabilized technique overcomes the input signal bandwidth limitation by employing a wideband amplifier to amplify signals of higher frequency. The output of the chopper and the wideband amplifier is subsequently summed by a third amplifier. The current limitations of stabilized chopper method are that it can only be used in inverting mode. Furthermore increased circuit complexity is required to reduce the high residual output noise amplified by the wideband amplifier.

The concept of a low phase noise at higher oscillation frequencies [4] is been applied in this investigation to frequency sensing. The sensor's output voltage is converted into an oscillation frequency using a varactor in a Colpitts oscillator. The proposed readout is compared to a commercial auto-zero amplifier in terms of linearity, noise and transfer function. Additionally, we have investigated the ability of the proposed readout to measure medical signals on the radial and carotid arteries as well as the chest. The contribution of this paper is the proof of concept on frequency sensing in order to trigger new ideas on the interfacing with piezoelectric sensors at lower noise.

II. Circuit Design

The architecture is shown as a block diagram in Fig. 1a. The piezoelectric sensor is connected to a common-drain (CD) amplifier whose output is connected to the voltage to frequency (VF) converter (Fig. 2). The VF converter is a Colpitts LC oscillator containing a varactor C_v in its LC tank. The output of the CD amplifier directly modulates the varactor bias voltage. The frequency to voltage (FV) conversion can be done using a FV converter or a phase locked loop (PLL) containing a voltage controlled oscillator (VCO). In this investigation we chose a commercially available PLL in order to adjust its VCO's centre and minimum frequencies over a wide frequency range. This helps to adjust the overall gain of the readout. The demodulated output of the PLL is low-pass filtered using an R-C lowpass filter to remove spurious high frequency components created by the PLL's phase detector.

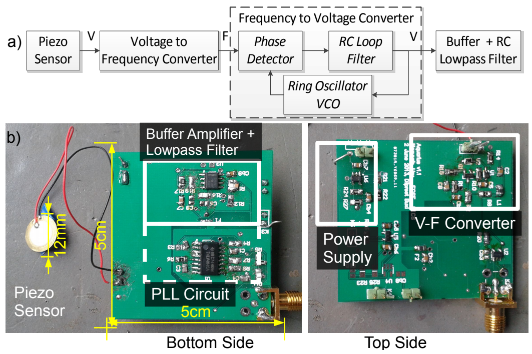

Fig. 1. a) Block diagram of readout circuit, b) annotated PCBs.

The piezoelectric generator voltage is directly proportional to the applied mechanical stimulus, where the proportionality coefficient is the piezoelectric constant of the material. If the sensor is connected to a resistive load [2], the equivalent circuit acts as a highpass filter. In this work, a sensor (AB1290B-LW100-R) of $C_p \approx$ 8nF and resonant frequency of approximately 9kHz is used. The sensor connected to the VF converter is shown in Fig. 2.

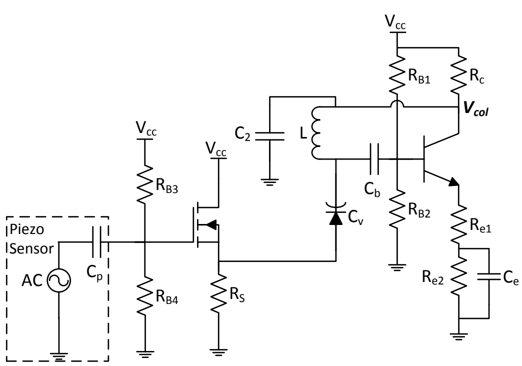

Fig. 2. Schematic of piezo sensor and VF converter.

The oscillator resonates at the oscillation frequency:

$$f_{osc} = \frac{1}{2\pi\sqrt{LC_{eff}}} \tag{1}$$

where $C_{eff} = \frac{1}{\frac{1}{C_2}+\frac{1}{C_3}+\frac{1}{C_v}}$ is the effective capacitance of the LC tank. The VF gain is the derivative of f_{osc} with respect to the piezoelectric output V_p:

$$\begin{aligned} K_{VF} &= \frac{df_{osc}}{dV_p} \\ &= -\frac{m\left(1+\frac{V_c-V_p}{\phi}\right)^{m-1}}{4\pi\phi\sqrt{C_{jo}L\left[\left(1+\frac{V_c-V_p}{\phi}\right)^{m}+C_{jo}(1/C_2+1/C_3)\right]}} \end{aligned} \tag{2}$$

The value of K_{VF} is most sensitive to the value of the varactor's junction capacitance C_{jo} and the inductor L. The dynamic range of the input voltage is determined by the terms in V_c. The relationship between the piezo sensor's output voltage V_p and f_{osc} is an inverting one. We have used a commercial off-the-shelf Phase Locked Loop (PLL) (SN74LV4046A, Texas Instruments) as the FV converter [5]. The collector voltage output V_{col} from the VF converter is capacitively coupled to the phase detector input of the PLL. A XOR network is used as a phase detector, whose output signal is a square of twice the frequency of the locked signal. The PLL's VCO is a ring oscillator whose frequency depends on the delay of the inverters, which in turn is controlled by the current through them.

The choice of loop filter also plays an important role in the noise suppression versus capture bandwidth of the PLL. As a starting point, we have used an RC filter, which although possessing a wider bandwidth and less thermal noise, will contain more spurious components from the PLL. The PLL contains an internal voltage buffer whose output is considered to be the FM demodulated output. The total gain of the readout is $K_{tot} = K_{VF}K_{FV}$.

The FM demodulated output signal is fed to a buffer amplifier followed by a 1st order lowpass filter of 200Hz cutoff frequency to filter spurious components from the FM demodulated output. The filtered signal is then converted into a digital one using a 16 bit ADC in a data acquisition card. The noise contribution of an amplifier at the sensor output is negligible, provided the overall gain K_{tot} of the VF and FV converter is substantially larger than unity (shown by Friis' formula, where F refers to the noise figure of each stage):

$$F = F_{VF} + \frac{F_{FV}}{K_{VF}} + \frac{F_{amp}}{K_{tot}} \tag{3}$$

III. Circuit Characterization

The goal of the circuit characterization was to compare the proposed readout to a commercial auto-zero amplifier (Texas Instruments OPA333) with input voltage and current noise values of 55 nV/$\sqrt{Hz}$ and 100fA/$\sqrt{Hz}$. From commercially available chopper, chopper-stabilized and auto-zero amplifiers This amplifier was chosen for its relatively low values of input voltage and current noise.

In the first experiment, the linearity of the proposed readout was examined for low voltage signals. A sine wave of 100Hz with Vpp ranging from 20mV to 200mV was fed from a signal generator (Tektronix AFG3022) to the negative terminal of the piezoelectric sensor. The peak to peak voltage and total harmonic distortion (THD) were estimated from the output signal. The total gain K_{tot} was estimated from the measured data using linear best fit in Matlab. Results are shown in Fig. 3.

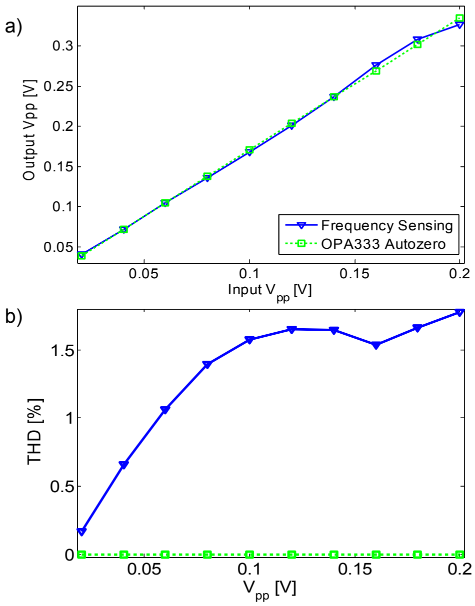

Fig. 3. a) V_{pp} of output vs input, b) total harmonic distortion vs input V_{pp}.

It can be seen in Fig. 3a that the actual V_{pp} deviates from the amplifier output with increasing input V_{pp}, indicating the effects of nonlinearity in the proposed readout. The total harmonic distortion (THD) was calculated from the Welch power spectrum estimate of the output signal, where one minute of data was divided into eight equal windows which were weighted with a Blackman Harris window. It is seen in Fig. 3b that the average THD for frequency sensing is estimated to be 1.5% in comparison to the amplifier, which has less than 0.01% THD.

In the next experiment, the input referred noise was measured, taking in to account the values of K_{tot} from the previous experiment. The noise signal was measured for 15 minutes. Detailed results are in Fig. 4 and Table I.

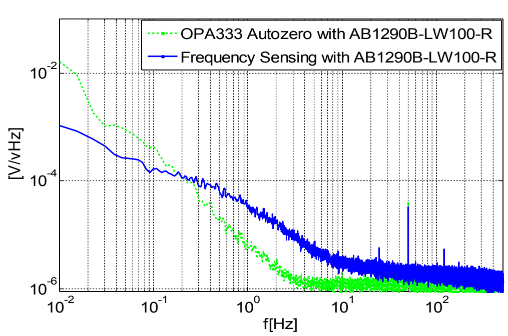

Fig. 4. Input Referred Noise.

The transfer function was computed using a sine wave of $V_{pp} = 100mV$ from 0.1Hz to 2000Hz (Fig. 5). The data shows a bandpass behaviour between approximately 0.2-400Hz with a 1dB increase from 1 Hz till 200 Hz. There is a -20dB/decade roll off in the frequencies about 400Hz.

TABLE I

MEASURED INPUT REFERRED NOISE.

	RMS mV_{rms}	Thermal Noise Floor $\mu V/\sqrt{Hz}$	1/f corner freq. [Hz]
Auto-zero OPA333	3.1	1.21	1.9
Freq. Sensing	3.8	2.24	10

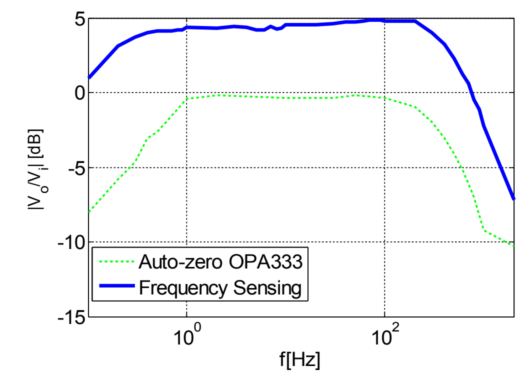

Fig. 5. Transfer function using a sine wave of 100mV_{pp}.

The readout's specifications are summarized in Table II.

IV. MEASUREMENTS ON THE BODY

The proposed readout described in section II was used to acquire the arterial signals from the left radial artery as well as the left common carotid artery at the neck from one subject in sitting position. The ECG was acquired simultaneously to ensure that the piezoelectric signals indeed correspond to the desired physiological signal.

Using masking tape, the piezoelectric sensor was attached to the palmar side of a human left wrist above the radial artery. The arm was held still during measurement but allowed to move during respiration. In Fig. 6, the radial arterial pulse is visible after the ECG R-peak. For comparison, the signal from the amplifier method is shown from the same position, but from another time point.

TABLE II

SUMMARY OF READOUT

Part	**Details**
Sensor Make	AB1290B-LW100-R (PUI Audio)
Dimensions	12mm diameter, 1mm thickness
Measured C_p	6nF
VF Converter Osc. frequency f_s	32.58MHz
VF Gain K_s	5470kHz/V
Current consumption	6mA at 5V
FV Converter Gain K_{PLL}	2.92 x $10^{-7} V/rads^{-1}$
Current consumption	9mA at 5V
Low Pass Filter f_c	200Hz
Current consumption	0.05mA at 5V
Overall RMS Noise	3.8mV_{rms}
Thermal Noise Floor	2.24 $\mu V/\sqrt{Hz}$
Current consumption	15.1 mA at 5V

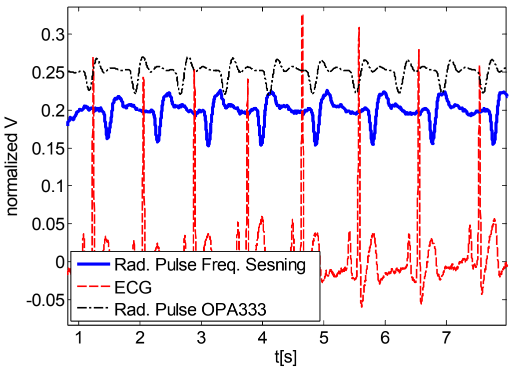

Fig. 6. Simultaneously measured ECG and arterial pulse from the left radial artery using frequency sensing. Pulse from amplifier method was recorded from the same position at a later time.

The piezoelectric sensor was pressed against the neck above the Adam's apple of a human neck to acquire palpitations at the carotid artery. Signals are shown in Fig. 7.

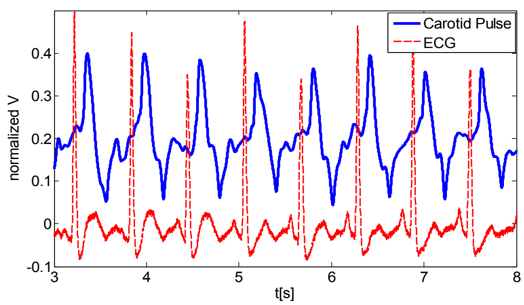

Fig. 7. ECG and carotid arterial pulse using frequency sensing.

In order to measure vibrations on the chest due to cardiac pumping, the sensor was held by hand against the chest wall on the 5th intercostal space approximately 5mm to left of the sternum. Fig. 8 shows the ECG and chest vibrations from the reference piezoelectric sensor CM-01B as well as the proposed readout. The signals from both piezoelectric signals are similar in amplitude, with a phase difference which is likely due to the sensors being at a different position and varying contact pressure to the chest.

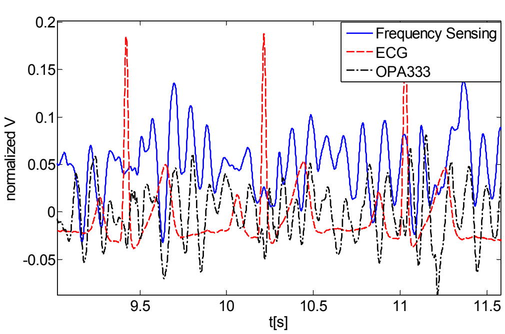

Fig. 8. Simultaneously measured ECG and cardiac chest vibrations.

V. Discussion

In this investigation, frequency sensing using piezoelectric sensor is investigated as an alternative to the amplifier technique in order to sense vibrations from several parts of the body. Using the same piezoelectric sensor, we have compared the linearity, input referred noise and transfer function of the proposed readout to that of a commercial auto-zero amplifier. We have subsequently acquired the arterial pulse wave signal from the radial and carotid arteries as well as cardiac vibrations at the chest (Figs. 6-8).

The proposed readout shows an average of 1.6% nonlinearity in Fig. 3b. Initial investigations show that the nonlinear transfer curve of the VCO is the biggest contributor due to the nonlinear relation between the oscillator frequency and the transconductance of the ring oscillator transistors [6]. Increasing the overall gain of the readout requires that the VCO output frequency range needs to be decreased. This is expected to further increase the nonlinearity in the FV conversion. An alternate VCO topology e.g. charge pump should be investigated to see if its linearity is better.

Overall, the auto-zero amplifier OPA333 has shown slightly better noise properties. The thermal noise floor of the proposed readout is approximately twice the value of OPA333 (Table I). From a total of 2.24 $\mu V/\sqrt{Hz}$ mean noise floor, about 0.64 $\mu V/\sqrt{Hz}$ is obtained using the two 50MΩ bias resistors R_{B3} and R_{B4}. This means that about 2.14$\mu V/\sqrt{Hz}$ appears to be contributed by the rest of the circuit. In addition, the 1/f, shot and thermal noise from CD amplifier output continues to modulate the VF converter. The 1/f corner frequency of our readout using off-the-shelf components and sensor combination is also five times higher than OPA333. The noise from the CD transistor can be reduced by appropriate dimensioning in an IC implementation. Our readout consumes 15mA current at 5V supply. The CD amplifier and VF converter consume approximately 1mA and 5mA, while the PLL consumes 9mA. An IC design is expected to yield much more significant power savings.

VI. Conclusion

A frequency sensing circuit has been successfully developed and tested to acquire cardiovascular vibrations from the body using a piezoelectric sensor. Similar signals are obtained from our proposed readout and the reference design.

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