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Frequency sensing of medical signals using low-voltage piezoelectric sensors

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ABSTRACT

Piezoelectric sensors are used to pick up low level vibrations in automotive, biomedical and industrial fields and are subject to errors due to the input current and voltage noise of amplifiers, when connected with a large bias resistor. The noise levels, especially from the bias resistor, degrade the signal to noise ratio of the signal which leads to less reliable feature detection. We report the experimental investigation of a frequency sensing front-end in terms of its linearity, noise and gain in order to acquire medical signals at low frequencies and voltages, e.g. arterial pulse signal, Ballistocardiogram and heart sounds. An LC oscillator is used with a commercial phase locked loop for this purpose. We show that the noise levels in frequency sensing can be reduced by increasing the oscillation frequency, while maintaining 1% non-linearity. Overall, the readout runs at 5 V and has a mean noise floor of 1.43 $\mu V/\sqrt{Hz}$ and a non-linearity of 1% when subject to a sine wave between 20 mV and 200 mV peak to peak amplitude. The results of this work are expected to contribute towards low noise analog front end designs for piezoelectric sensors using frequency sensing as an alternate architecture.

1. 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. Their high sensitivity to strain or force makes them popular in transportation [1], robotics, industrial monitoring [2] and medicine [3–8].

Piezoelectric sensors are typically connected using a voltage or charge amplifier. When using a voltage amplifier, the sensor must be biased using either an additional resistor or the input impedance of the non-inverting amplifier (Fig. 1) to allow the strain-induced charge to be dissipated. 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 [9] if the amplifier noise current is very large [10], 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 stop band of the high pass filter. Subsequent integration after A/D conversion can restore the original signal [11] from its derivative. In order to minimize low frequency noise and DC errors such as drift, auto-zero and chopper amplifiers are used [12].

Slowly varying signals such as heart sounds (20–400 Hz) or the arterial pulse (0.5–30 Hz) are typically measured using piezoelectric sensors. The arterial pulse can also be measured using optical sensing [13] or bioimpedance [14], but these suffer from the drawbacks of high power consumption or bulky electrode configuration. If slowly varying signals of low amplitude are to be measured, the conversion of the sensor outputs into signals modulated in the frequency domain can possibly benefit from advantages seen in sensing applications using resistive sensors. These are namely noise immunity, interfacing to digital readout systems [15] as well as tunable range of sensing [16,17]. In [2], a frequency-sensing circuit using an LC oscillator for low frequency and high voltage signals applied to actuation and control in nano-positioning is shown with frequencies as low as 1 mHz with a wireless transmission between voltage-to-frequency (V–F) and frequency-to-voltage (F–V) converters being measured. However, frequency sensing especially for low voltage piezoelectric signals in terms of its linearity, noise and signal to noise ratio is still unexplored in the literature.

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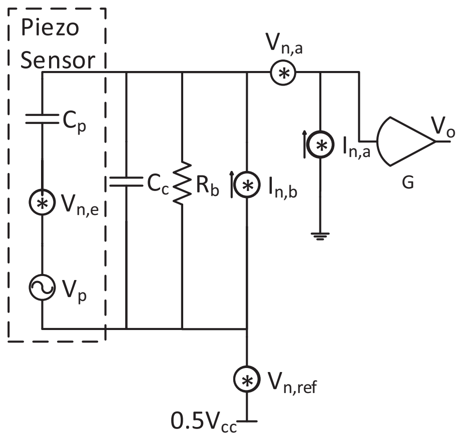

Fig. 1. Equivalent noise circuit of a piezoelectric sensor and connected amplifier readout with gain G [18].

This work investigates a frequency sensing method for measuring low voltage signals from a piezoelectric sensor. We have experimentally characterized a frequency sensing circuit in terms of its input referred noise, signal to noise ratio (SNR) of sine waves, distortion in output versus input function as well as the transfer function in the frequency domain. The arterial pulse from the left arm using the proposed method is obtained and measured. These insights are expected to contribute to future designs as an alternative to chopper-stabilized or auto-zero techniques.

This paper is organized as follows: in Section 2 the design of the proposed readout circuit is described. Section 3 contains its experimental characterization of the proposed readout. The results are discussed in Section 4 and the investigation is wrapped up in Section 5.

2. Design

2.1. Piezoelectric sensor and reference designs

In this investigation, the piezoelectric transducer is used as a vibration sensor where mechanical strain is converted into electrical charge or voltage. A noise equivalent for the piezoelectric sensor working below its resonant frequency along with a connected amplifier readout circuit is given in Fig. 1 [18,19]. The AC voltage source V_p represents the electrical signal generated in the sensor by a mechanical deformation. The equivalent electrode and cable capacitances of the sensor are represented by C_p and C_c. At lower frequencies, the electrical thermal noise of a piezoelectric sensor $V_{n,e}$ will dominate the noise sources. This noise source is due to frequency-dependent ohmic losses across C_p. The sensor also requires a load resistor R_b to bias its output to the amplifier.

At frequencies below the piezoelectric sensor's resonant frequency, the dominant impedance in Z_P is usually the load resistor R_b. The equivalent input noise at the amplifier input (Fig. 1) is therefore [18,19]:

$$V_{n,i}^2 = V_{n,a}^2 + (I_{n,a}^2 + I_{n,b}^2)R_b^2 + V_{n,ref}^2 + V_{n,e}^2 \frac{(2\pi f C_p R_b)^2}{(2\pi f C_p R_b)^2 + 1} \quad (1)$$

The noise terms $V_{n,a}$ and $I_{n,a}$ are the voltage and current input noise of the amplifier whereas $I_{n,b} = \sqrt{4kTB/R_b}$ is the thermal noise current of the bias resistor R_b. In a single supply system, there can be an additional noise contribution if a voltage reference IC or a buffered resistive divider is used to bias the sensor's output to $0.5V_{cc}$.

Assuming a sine wave of frequency f_o: $V_p(t) = V_{pp}\sin(2\pi f_o t)$ whose signal power is $V_{pp}/\sqrt{2}$. Given the high pass characteristic of the load resistor R_b with the sensor's terminal capacitance C_p, the output root mean square voltage of the piezoelectric sensor at the amplifier input will be:

$$V_{rms} = \frac{V_{pp}}{\sqrt{2}} \frac{2\pi f_o C_p R_b}{\sqrt{(2\pi f_o C_p R_b)^2 + 1}} = 0.707 V_{pp} |H_{hp}(f_o)| \quad (2)$$

The SNR of the reference method can thus be calculated as:

$$\begin{aligned} SNR &= 20\log_{10}\left(\frac{V_{rms}}{V_{n,i}}\right) \\ \frac{V_{rms}}{V_{n,i}} &= \frac{0.707 V_{pp}|H_{hp}(f_o)|}{\sqrt{V_{n,a}^2 + (I_{n,a}^2 + I_{n,b}^2)R_b^2 + V_{n,ref}^2 + V_{n,e}^2 |H_{hp}(f_o)|^2}} \end{aligned} \quad (3)$$

It becomes clear that a large input noise current $I_{n,a}$ as well as a larger bias resistor R_b will result in a lower SNR. A large bias current of the opamp will also contribute to the offset voltage. At low frequencies, R_b forms a high-pass filter together with the sensor's terminal capacitance C_p. The SNR can be increased by lowering the amplifier's input noise current or by using a lower value of R_b, such that the input signal bandwidth is below the cut-off frequency of H_{hp}, where the signal is integrated after A/D conversion [11]. The electromechanical properties of the piezoelectric sensor also affect the SNR [19], but these are not considered in this investigation.

2.2. Proposed design

The proposed design investigates sensing using frequency modulation at low input voltage where the sensed signal is translated to a higher frequency.

The architecture is divided into four parts, which are shown as a block diagram in Fig. 2. The piezoelectric sensor is connected to a common-drain amplifier whose output is connected to the VF converter which is a Colpitts LC oscillator containing a varactor in its LC tank. The 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 with a voltage controlled oscillator (VCO) in order to adjust the VCO's centre and minimum frequencies over a wide frequency range. The demodulated output of the PLL is low-pass filtered using an R-C low pass filter to remove spurious high frequency components created by the PLL's phase detector.

The piezoelectric generator voltage V_p 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 R_{bias} [9], the equivalent circuit acts as a high pass filter. In this work, a sensor (AB1290B-LW100-R) of $C_p \approx$ 8 nF and resonant frequency of approximately 9 kHz is used. The sensor connected to the VF converter is shown in Fig. 3.

The VF converter consists of two parts, which are a common drain (CD) amplifier in active mode and a common emitter (CE) Colpitts LC oscillator with a varactor C_v in its LC tank. The oscillator resonates at the oscillation frequency:

$$f_{osc} = \frac{1}{2\pi\sqrt{LC_{eff}}} \quad (4)$$

where the effective capacitance is $C_{eff} = \frac{1}{(1/C_2)+(1/C_3)+(1/C_v)}$.

The varactor's capacitance C_v in turn depends on its bias voltage V_v:

$$C_v = \frac{C_{jo}}{(1 + V_v/\Phi)^m} \quad (5)$$

$$V_v = \underbrace{(V_{cc} - I_c R_c)}_{V_{cathode}} - \underbrace{V_{cc}\frac{R_{B4}}{R_{B3} + R_{B4}} + V_{gs} - V_p|H_{hp}(f)|}_{V_{anode}} \quad (6)$$