Note: Piezoelectric strain voltage sensing at ultra-low frequencies

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Piezoelectric sensors have emerged as a versatile tool for measurement of various quantities such as pressure, acceleration, strain, or force across many industrial applications. When mechanically strained, electric charges are produced inside a piezoelectric transducer. These charges result in an electric field that may be measured as a voltage difference between two electrodes, from which the strain can be inferred. To measure this voltage the sensor must be interfaced with an external device that would typically have a finite input impedance. This, together with the capacitive nature of the piezoelectric sensor, results in an inability to measure strain at low frequencies. We propose a method, based on using a varactor diode in an oscillator circuit, which can result in accurate measurements of the piezoelectric voltage at ultra-low frequencies. We demonstrate successful measurements at 1 mHz. © *2011 American Institute of Physics*. [doi:10.1063/1.3628664]

Amongst numerous applications for piezoelectric sensors, their capacity to measure displacement, with subnanometer precision, has proven to be of vital importance in nanotechnology. In particular, piezoelectric tube scanners such as the one shown in Fig. 1 have been used in scanning probe microscopy, for the purpose of accurate nanopositioning, since their invention in 1980s.[1] Their function is the execution of rastering patterns under a stage on which the sample sits. One axis moves horizontally across several rows of the sample, while the other axis steps down line by line. This generates a digital image of the sample that is being scanned.[2,3]

The ability to sense and actuate piezoelectric tubes simultaneously allows for the development of closed loop control systems that can accurately control the position of the stage. The performance of such feedback schemes is heavily affected by the noise properties of the displacement sensors (capacitive, inductive, etc.), forcing slow, low-bandwidth operation.[4,5]

An idea has been proposed recently to address this problem, in quartered electrode tube scanners, which is based on using one of the two electrodes associated with each axis for actuation and the opposite electrode for sensing.[6] Compared to other non-contact sensing methods, such as capacitive or inductive sensing, piezoelectric sensors offer much lower sensor noise (about three orders of magnitude lower).[7] However, their measurements are highly inaccurate at low frequencies due to the loading effect associated with the electronic circuit that interfaces the piezoelectric device to the measurement system.

The method proposed in Ref. 8 attempts to address this issue by complementary use of a capacitive sensor (at low frequencies) and a piezoelectric sensor (at high frequencies), which together form a low noise sensing and control method across a high frequency range. This approach, however, still requires having access to another, external, sensor for low frequency measurements. Thus, there is significant interest to extend the measurement range of piezoelectric sensors all the way to DC. One approach to extending the lower frequency limit at which sensing can take place is to interface the sensor to external devices through a high impedance buffer.[9] However, there is often a limit below which accurate sensing is infeasible, and this method is known to introduce significant $1/f$ noise into the low frequency measurements.[7]

The existence of a sensing method that uses one sensing device to measure across a range of frequencies, including extremely low frequencies, would provide a simple solution to the problem mentioned above. Such a solution may exist with the use of varactor diodes in oscillator circuits. Varactor diodes (or varicaps) are high-impedance electronic devices in which a variation in the voltage applied across their terminals causes a variation in capacitance. The sensing output of one of the terminals of the piezoelectric tube may be directly connected to a varactor diode, translating any voltage change to a change in capacitance. When used as part of an oscillator circuit, this will translate the change in capacitance to a modulation in the frequency of the output signal. The varactor diode works at extremely low frequencies.

One type of oscillator which may be used as a sensing circuit is the Colpitts oscillator. It comprises an inductor-capacitor (LC) network connected to a transistor in a feedback arrangement. It is a popular circuit in radio frequency (RF) electronic circuits, and the frequency of oscillation is determined by the expression (1), where C_1 is the varactor diode.

$$f_{\mathrm{Osc}} = \frac{1}{2\pi\sqrt{L\left(\frac{1}{C_1}+\frac{1}{\mathrm{DCB}_1}+\frac{1}{C_2}\right)^{-1}}}. \tag{1}$$

A Colpitts oscillator has been constructed to present the idea of frequency modulation for piezoelectric sensing, the circuit diagram of which is shown in Fig. 2. The circuit is a common-base Colpitts oscillator oscillating at around the ISM band 27 MHz. The resonating elements are L, C_1, DCB_1, and

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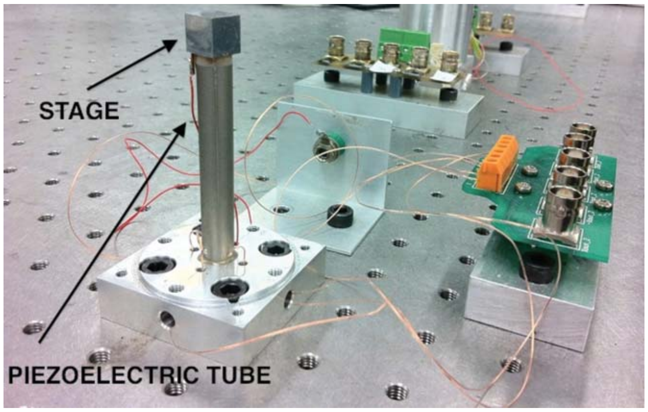

FIG. 1. (Color online) A photo of the piezoelectric tube used in these experiments.

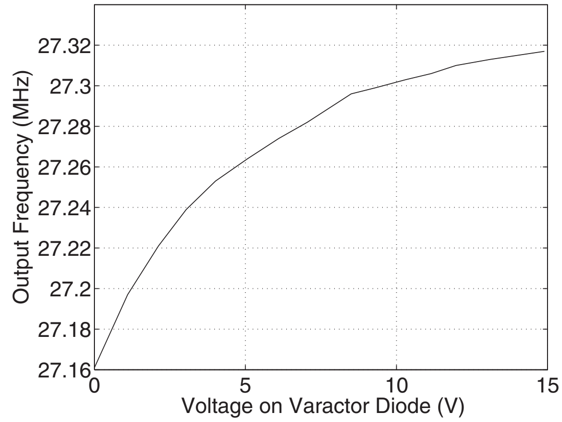

FIG. 3. A plot showing the output frequency of the sensing circuit as the voltage across the varactor diode C_1 is varied.

C_2. L_2 is a choke inductor, and R_1 and R_2 are biasing resistors. The capacitors with the DCB label serve the purpose of blocking DC voltage. In the feedback network, C_1 is not a fixed capacitor, rather a varactor diode [NXP-BB131]. Given that this varactor is connected in the resonant feedback network, this implies that varying the voltage across the terminals of C_1 will result in a frequency variation at the output of the circuit v_{out}, as indicated in measured results of Fig. 3.

It is important to note that the equivalent circuit of a varactor diode only consists of a capacitor at low frequencies.[10] The presence of parasitic resistor and capacitor is only noticeable when a diode is operated at frequencies beyond 1 MHz.[11] In our experiment, the desired actuation voltage is extremely low, lower than 100 Hz. At these range of frequencies and using the maximum capacitive value of 13 pF, it is straightforward to show that the varactor's impedance is $1.2 \times 10^{13}\ \Omega$ at 1 mHz and $1.2 \times 10^{8}\ \Omega$ at 100 Hz. These are extremely large values. Thus, at low frequencies, the varactor can be viewed as a loss-less voltage-to-capacitor converter since there is no current leakage from the piezoelecric sensor to the varactor.

A series of experiments have been conducted in order to observe the sensing circuit's performance at low frequencies. A piezoelectric actuation voltage is applied to one axis of the piezoelectric tube shown in Fig. 1 using an amplifier that produces $400V_{pp}$ sinusoidal waves at various frequencies, ranging from 1 mHz to 100 Hz. The other terminal of the same axis is connected across the varactor diode C_1 to the sensing circuit. All other electrodes, including the continuous electrode inside the tube, are grounded.

The amplitude of a sinusoidal wave varies with time. For the sensing circuit of Fig. 2, a change in the sensed voltage is reflected as a change in oscillation frequency. This implies that the application of a lower frequency sinusoidal actuation signal to the piezoelectric device will result in a variation in the frequency of the sensing circuit's output signal. This frequency drift occurs at the same rate as the actuating signal

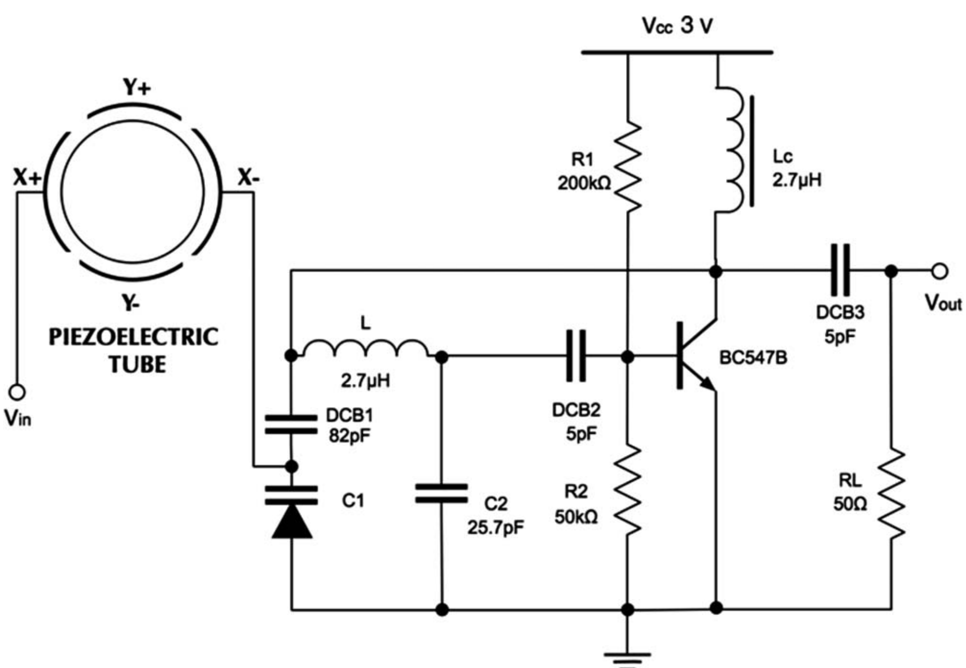

FIG. 2. The common-base Colpitts oscillator sensing circuit including a varactor diode C_1 in the feedback network.

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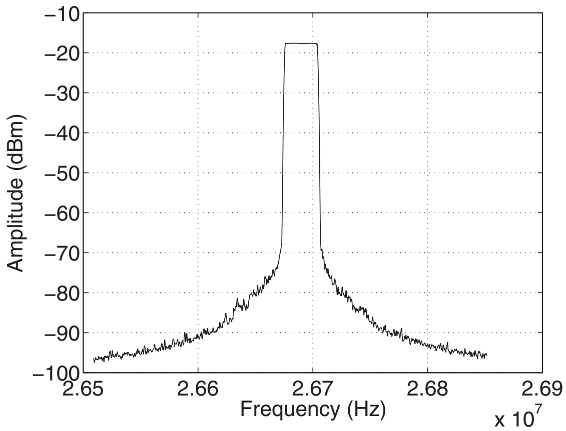

FIG. 4. A frequency spectrum showing the range of spectral movement at the output of the sensing circuit when the piezoelectric tube was actuated at 1 mHz.

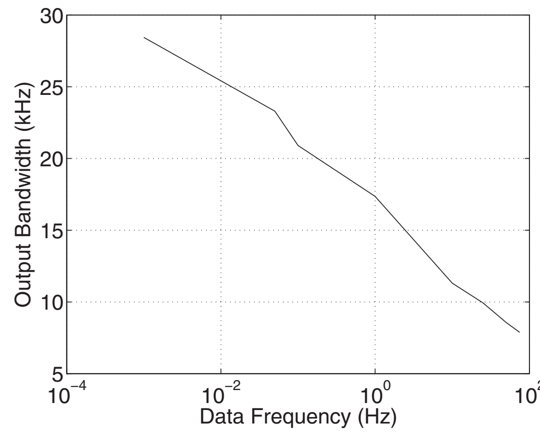

FIG. 5. A plot comparing the bandwidth (range) of the output frequency of the sensing circuit, compared with the rate of oscillation of the piezoelectric oscillation signal.

varies in amplitude, and the output moves back and forth on the frequency spectrum as the amplitude of the actuating signal varies. The outer bounds of this frequency range define the bandwidth of the frequency variation, illustrated in Fig. 4.

Different frequencies of actuation with the same peak to peak amplitudes have been applied to the piezoelectric tube and the frequency variation bandwidths were recorded at the output of the sensing circuit. The relationship between these parameters is shown in Fig. 5. Interestingly, the lower the frequency of the piezoelectric manipulation, the higher the bandwidth resolution is obtained. The lowest frequency of actuation was 1 mHz, which translates to a period of 16.7 min. This produced a frequency variation bandwidth of 28.4 kHz.

These preliminary findings show that it is possible to measure piezoelectric voltage at extremely low frequencies with the use of a varactor diode device implemented in the feedback loop of an RF oscillator. While the sensing circuit is suitable for piezoelectric strain voltage sensing, it may be used in other situations where a high impedance sensor interface is required at ultra-low frequencies. This concept will be further analyzed and investigated in subsequent publications.

The proposed sensing circuit consists of very few electronic elements which can lead to a small form factor device. Efforts are currently under way to add wireless capability to the sensing circuit by coupling its output stage to an antenna. The sensed signal can then be transmitted wirelessly as a frequency modulated signal to a nearby computer for further processing and controlling. This will eliminate wires associated with the testing and measurement of current piezoelectric tubes.

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