Sensors and Actuators A 199 (2013) 49–55

Contents lists available at SciVerse ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

FM-based piezoelectric strain voltage sensor at ultra-low frequencies with wireless capability

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ARTICLE INFO

Article history:
Received 25 February 2013
Received in revised form 21 April 2013
Accepted 22 April 2013
Available online 9 May 2013

Keywords:
Piezoelectric
FM
Colpitts
Wireless
Nanopositioning
Ultra-low frequency sensing

ABSTRACT

An FM-based ultra low frequency piezoelectric strain voltage sensing system is proposed. The sensing frequencies possible in this system are orders of magnitude lower than those of traditional methods. This method involves the conversion of changes in piezoelectric device's strain voltage to changes in capacitance with a varactor diode. This diode forms part of a feedback network in a Colpitts oscillator, converting variations in capacitance to variations in frequency. The frequency variations are demodulated using an FM demodulator. Demodulated signals as low as 1 mHz were achieved and measured. The system was also implemented and measured with a wireless transmission and demodulation of the FM signal.

1. Introduction

Piezoelectric materials display a natural property whereby an interaction between electrical and mechanical states takes place. This essentially makes them naturally occurring transducers. A number of opportunities in sensing and actuating systems are available due to these unique properties.

Piezoelectric materials have a high modulus of elasticity that is similar to most metals, with zero deflection when compressed. They are also unaffected by electromagnetic fields and radiation. These properties make piezoelectric materials rugged and stable, therefore a logical choice in electromechanical sensing [1].

Piezoelectric tubes such as the one shown in Fig. 1 are used in scanning probe microscopy (SPM) for the purpose of accurate nanopositioning. 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 at a much lower frequency.

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, forcing slow and low-bandwidth operation.

The mechanical actuation of piezoelectric materials produce a number of changes in their electrical properties such as piezoelectric strain voltage, piezoresistivity, inductance or capacitance. Of these properties, piezoelectric strain voltage is orders of magnitude more sensitive [1]. Piezoelectric sensing has been used in a number of applications including biomedical instrumentation [2–4]. It has been a suitable choice in aerospace [5] due to the high performance and robustness of piezoelectric materials, in addition to their high temperature tolerance [6].

They were historically used in the automotive industry as accelerometers prior to the introduction of MEMS [7], used as torque sensors [8] and integrated in aluminium die casting techniques for the purpose of mechanical sensing in automotive parts [9]. Due to their desirable characteristics, piezoelectric sensors are also used widely for vibration sensing in smart structures [10–14].

The high accuracy of piezoelectric devices makes them a natural choice in micromanipulation, scanning probe microscopy in particular [15–18]. The tube shown in Fig. 1 is one such example, where a stage holding a sample is actuated to perform a rastering pattern. This involves one axis being actuated horizontally row by row, while another axis slowly creeps down for each scanning row. A digital image of the sample is achieved after matching the associated z-axis terrain values with the x–y coordinates of each pixel [19,20].

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http://dx.doi.org/10.1016/j.sna.2013.04.034

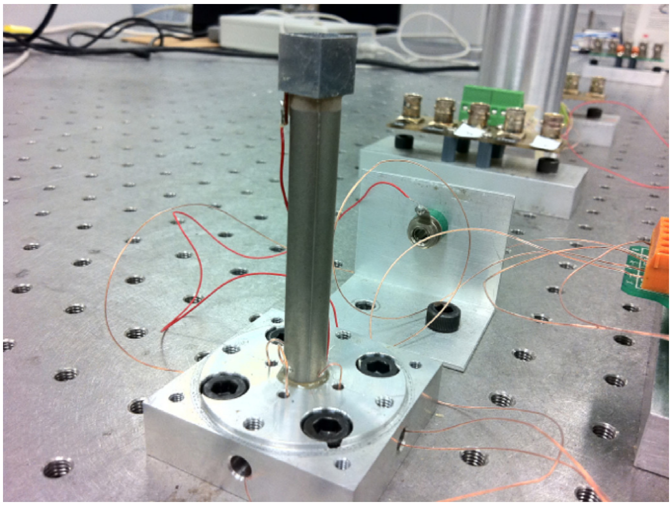


Fig. 1. A photo of the piezoelectric tube used in these experiments.

The introduction of closed-loop control to nanopositioning systems will increase the speed and accuracy of scanning, therefore simultaneous sensing and actuating is a natural point of interest [21].

Dedicated displacement sensors limit the speed and bandwidth of operation due to their poor noise properties [22,23], and an idea was recently proposed to bypass this problem. The idea involves using one of the two piezoelectric axis pairs to actuate, and the other as a piezoelectric sensor. The movements created by the actuating half of the pair produce a voltage signal on the other terminal, which may be used as a sensing signal [24].

Piezoelectric strain-voltage sensing suffers from roll-off at low frequencies according a $1/R_{load}C_{piezo}$ relationship, where R_{load} is the 1 MΩ impedance of the signal analyzer and C_{piezo} is 50 nF for the piezoelectric tube in Fig. 1. This roll-off can be seen in the open-loop frequency magnitude and responses of the piezoelectric tube shown in Fig. 2a and b, respectively, where the magnitude and phase begin to change dramatically at scanning/sensing rates below 30 Hz. High-impedance buffers are often employed on the output/sensing terminal of piezoelectric devices in order to push the roll-off to lower frequencies. A 100 MΩ Stanford Research Systems SR560 Preamplifier was connected to the sensing cable and a frequency response was conducted. The buffer pushed the roll-off to occur closer to 300 mHz, as shown by the Hi-Z buffer curves in Fig. 2a and b.

High impedance buffers are often used to increase the low frequency range in which sensing can occur, however their introduction causes the appearance of $1/f$ noise. There is also a limit as to how much this corner frequency can be reduced. The effect of phase shift may also occur one to two decades earlier, as can be observed in Fig. 2a and b, making high impedance buffers a non-ideal solution to the problem of measuring piezoelectric strain voltage at near-DC frequencies.

One method includes the complimentary use of capacitive and piezoelectric sensors to form a low noise sensing and control method across a wide frequency range [25]. Until recently piezoelectric strain-voltage signals have not been measured at near-DC frequencies with a single solution [26].

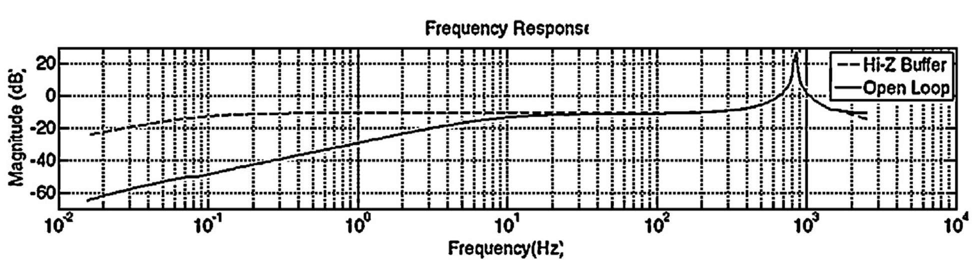
A sensing method capable of measuring piezoelectric strain voltage across a range of frequencies including extremely low frequencies would make a considerable contribution to the area. Such a technique will be proposed in Section 2 and verified with measured results in Section 3 including wireless capability, which was mentioned as to an earlier note [27].

2. Sensing technique

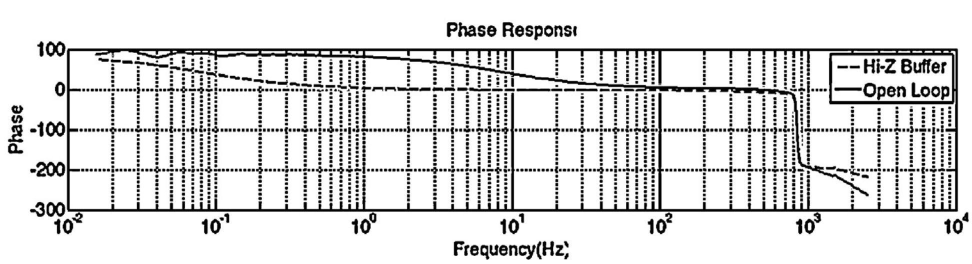
This section presents a new sensing technique which measures piezoelectric strain voltage over a range of frequencies, including extremely low frequencies. A conceptual block diagram of this system is shown in Fig. 3.

The technique involves using the piezoelectric strain voltage of the sensing element to modulate a high frequency oscillator by using a varactor diode. Varactor diodes – also known as varicaps – are high-impedance electronic devices that convert changes in voltage to changes in the capacitance seen across the varactor's terminals [28].

An actuation signal v_{act} is amplified using a NANOIS HVA4 voltage amplifier, and supplied to one of two axial-pair terminals on the piezoelectric tube. The second terminal of this axial pair is



(a) Magnitude Response



(b) Phase Response

Fig. 2. A frequency response of the piezoelectric tube of Fig. 1 with and without a high impedance buffer. (a) Magnitude response. (b) Phase response.