

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

Anthony N. Laskovski^{a,*}, Mehmet R. Yuce^b, S.O. Reza Moheimani^a

^a Department of Electrical Engineering and Computer Science, The University of Newcastle, Australia, Callaghan, NSW 2308, Australia

^b Monash University, Clayton, VIC, Australia

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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.

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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].

* Corresponding author. Tel.: +61 425201579.

E-mail addresses: alasko@ieee.org (A.N. Laskovski), Reza.Moheimani@newcastle.edu.au (S.O.R. Moheimani).

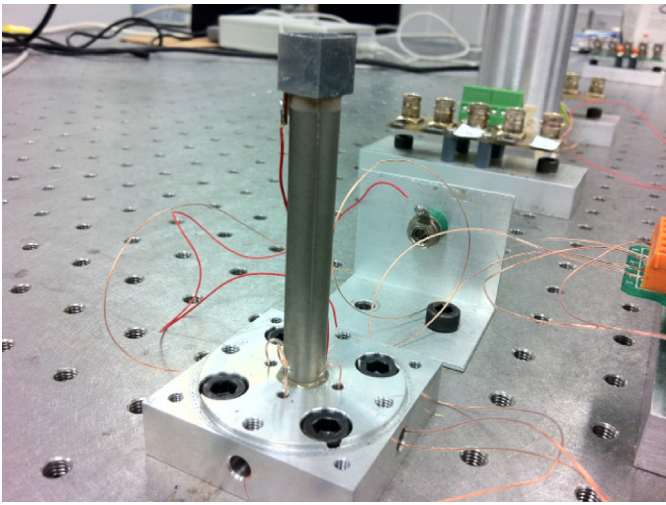


Fig. 1. A photo of the piezoelectric tube used in these experiments.

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 to a $1/R_{load}C_{piezo}$ relationship, where R_{load} is the $1\text{M}\Omega$ impedance of the signal analyzer and C_{piezo} is 50nF 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 30Hz . 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 $100\text{M}\Omega$ 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 300mHz , 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

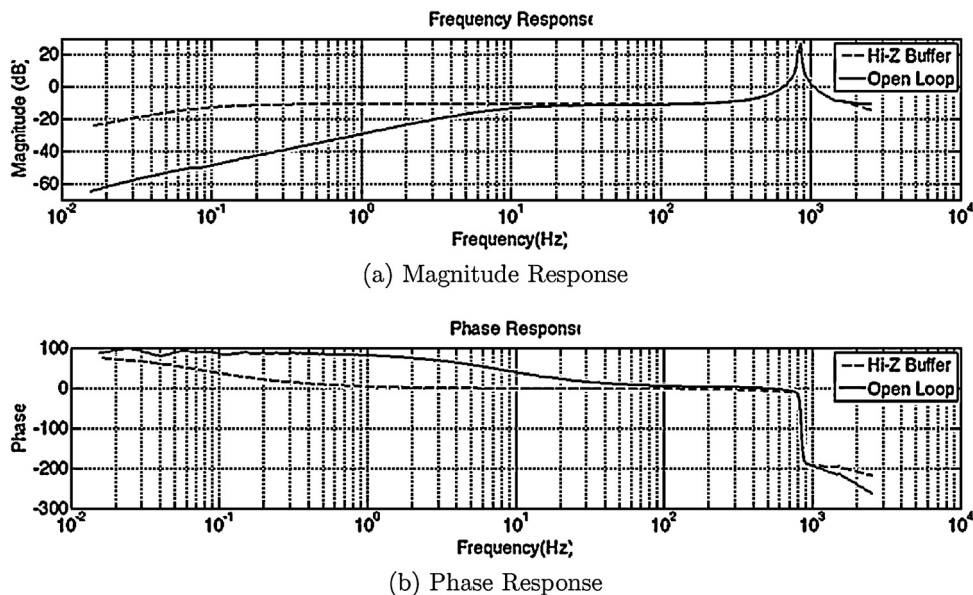


Fig. 2. A frequency response of the piezoelectric tube of Fig. 1 with and without a high impedance buffer. (a) Magnitude response. (b) Phase response.

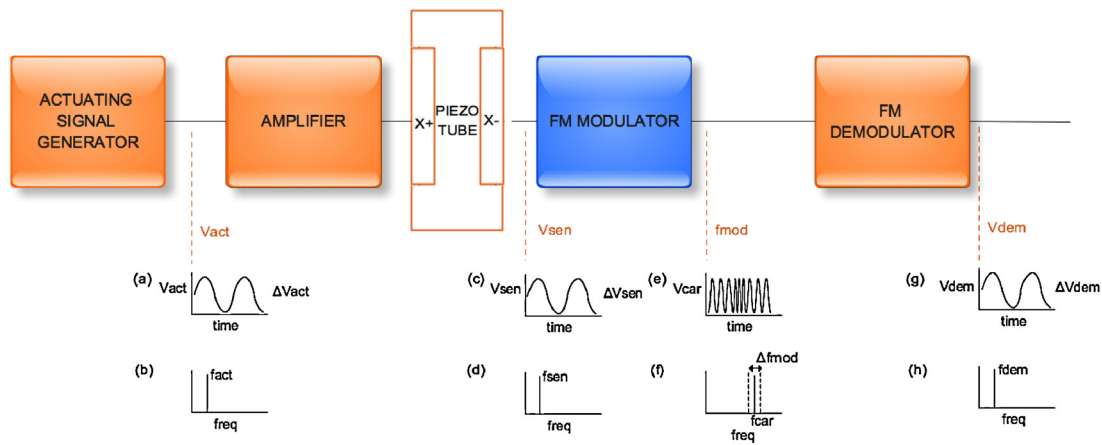


Fig. 3. A conceptual block diagram of the system.

connected to a varactor diode, which is a key element in the FM-modulator.

The FM-modulator is an LC-oscillator which naturally resonates at what is called the carrier frequency f_{car} , Fig. 3f. Changes in the sensed voltage Δv_{sen} cause changes of Δf_{mod} in the carrier frequency such that the frequency of oscillation is $f_{mod} = f_{car} + \Delta f_{mod}$. This means that as the actuation voltage in Fig. 3a rises and falls, the frequency of the modulated signal moves back and forth on the frequency spectrum in Fig. 3f.

The frequency-modulated signal is demodulated by the FM-demodulator, which converts changes in the frequency Δf_{mod} to voltage changes in the demodulated signal v_{dem} . This results in a signal v_{dem} which is representative of the sensed voltage v_{sen} , where $f_{dem} = f_{sen} = fact$.

The heart of this technique lies in the FM-modulator, for which a Colpitts LC oscillator is employed. 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. The LC oscillator topology need not be a Colpitts oscillator in order for the technique to work. The Colpitts oscillator was arbitrarily chosen to demonstrate this technique.

$$f = \frac{1}{2\pi\sqrt{L((1/C_1) + (1/DCB_1) + (1/C_2))^{-1}}} \quad (1)$$

A circuit diagram of the Colpitts oscillator is shown in Fig. 4. It is a common-base oscillator, oscillating at 2.9 MHz. The resonating elements are L , C_1 , DCB_1 and 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 but rather a varactor diode NTE-618, the characteristic curve of which is shown in Fig. 5. 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 $v_{carrier}$, as indicated in measured results of Fig. 6.

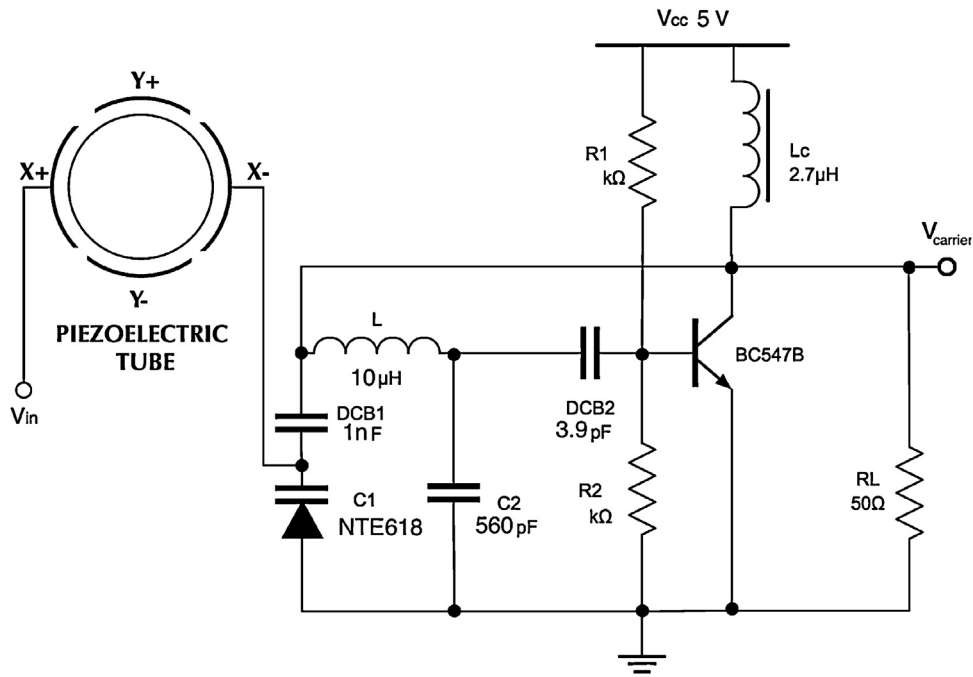


Fig. 4. The common-base Colpitts oscillator sensing circuit including a varactor diode C_1 in the feedback network.

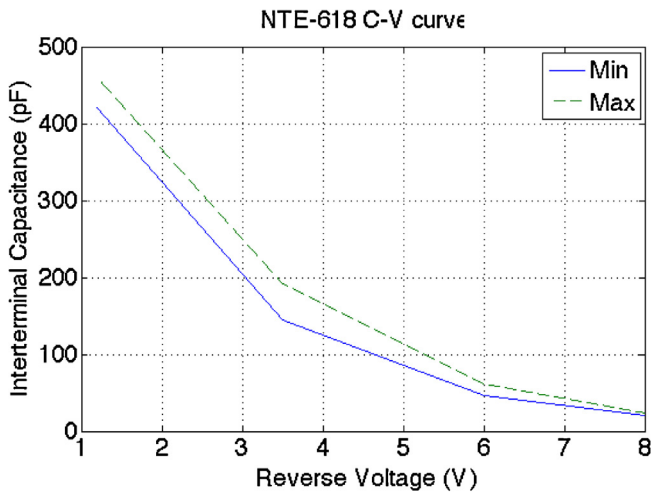


Fig. 5. The capacitance–voltage curve for the NTE-618 varactor diode.

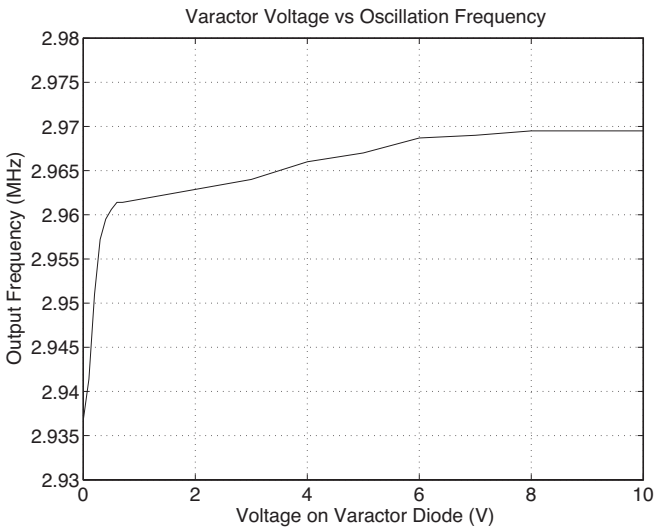


Fig. 6. A plot showing the output frequency of the sensing circuit as the voltage across the varactor diode C_1 is varied.

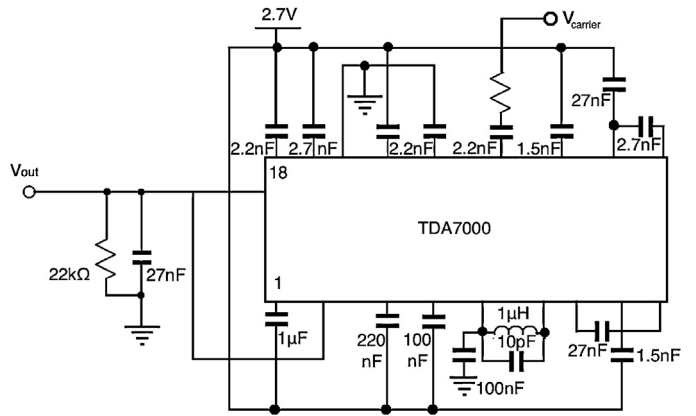


Fig. 7. FM demodulator using the TDA7000 chip.

3. Measured results

3.1. Frequency modulation

In order to show the modulation of frequency, various DC voltages were applied directly to the varactor diode C_1 and the circuit's oscillation frequency was recorded. Fig. 6 shows the relationship to be quite non-linear, which is expected given the relationship between capacitance and frequency in (1), as well as the high capacitance range of the NTE-618 varactor diode.

The sensing system was tested under a range of actuation frequencies and it showed to produce modulations of the oscillator's frequency $f_{mod} + \Delta f_{mod}$ at a range of actuation frequencies f_{act} as low as 1 mHz. In fact, rather than becoming less sensitive at lower frequencies, the technique showed a slight increase in sensitivity as the frequency of actuation decreased. This is due to the fact that as frequency decreases the impedance of a capacitor increases, which makes it more difficult for charge to dissipate from the piezoelectric device.

3.2. FM demodulation

The 2.9 MHz frequency-modulated signal was demodulated using a phase locked loop (PLL) and voltage controlled oscillator

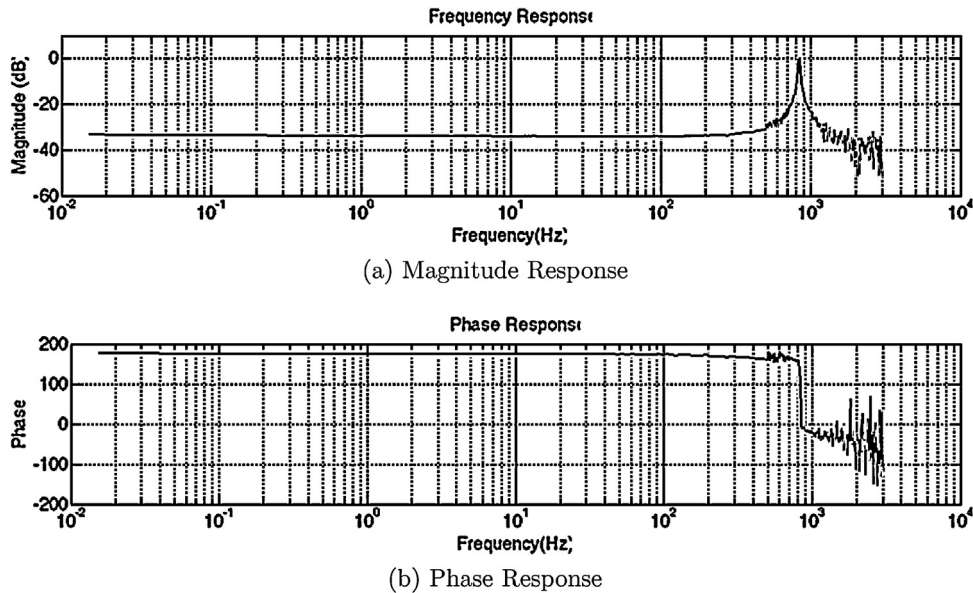


Fig. 8. Frequency response of the system, with actuation input signal and demodulated output signal. (a) Magnitude response. (b) Phase response.

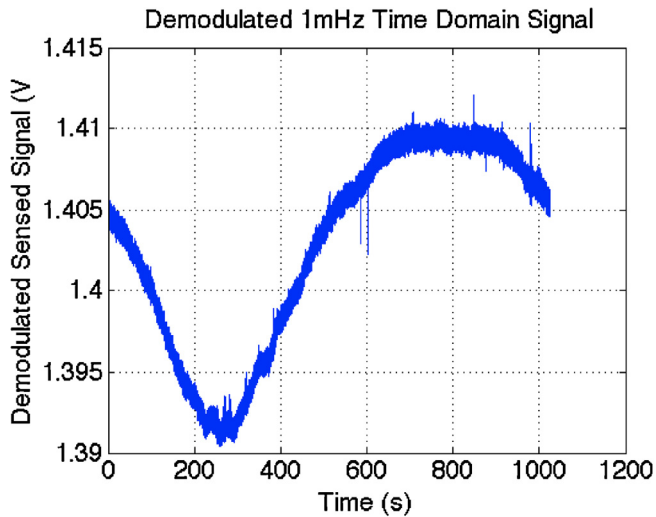


Fig. 9. A plot showing the demodulated output of a 1 mHz sensed signal.

(VCO) in the commonly available TDA7000 chip, the circuit arrangement of which is shown in Fig. 7. The PLL is a feedback control system that aims to maintain the frequency of an internal VCO by comparing the phase of the input and feedback signal. A voltage signal is used to control the frequency of the VCO.

When the incoming signal is frequency-modulated, meaning that its frequency is varying by Δf_{mod} , the control voltage of the VCO varies by Δv_{dem} . This feedback control signal may be interpreted as the demodulated sensing signal, or v_{dem} in Fig. 3g.

The demodulated output was analyzed by a HP 35670A Dynamic Signal Analyzer. The magnitude and phase of the frequency response of the system v_{dem}/v_{act} is shown in Fig. 8a and b, respectively.

It is evident that at frequencies as low as 15 mHz, the FM sensing system is capable of providing piezoelectric strain voltage data at 15 mHz, which is orders of magnitude lower than current low-frequency limits [26]. It was not possible to present

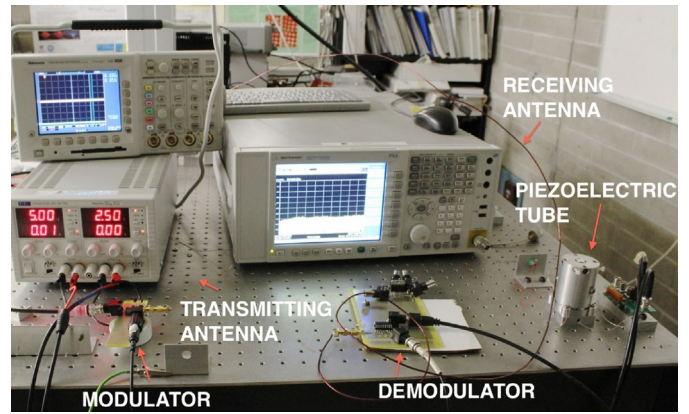


Fig. 10. A photo of the prototype setup with wireless capability.

frequency-response measurements below 15 mHz due to the limitations of the signal analyzer.

While the signal analyzer is not capable of providing and reading signals below 15 mHz, the Polytec MSA400 is capable of showing time-domain plots at lower frequencies. The piezoelectric tube was actuated at 1 mHz, and the signal was successfully demodulated at 1 mHz, and is shown in Fig. 9.

3.3. Wireless capability

The block diagram in Fig. 3 shows the FM modulation and demodulated blocks to be electrically connected. By the very nature of the high frequency FM modulated signal, this connection can naturally be replaced with a wireless link, which can be useful for remote control or the reduction of wires in the measurement environment. In order to show that this is possible two copper wires were attached at the output and input of the modulator and demodulators respectively, as shown in Fig. 10. The wires were not optimised for the carrier frequency, however, enough power was being sent to receive the wireless signal.

The frequency responses in magnitude and phase are shown in Fig. 11a and b, respectively. While much lower in gain the

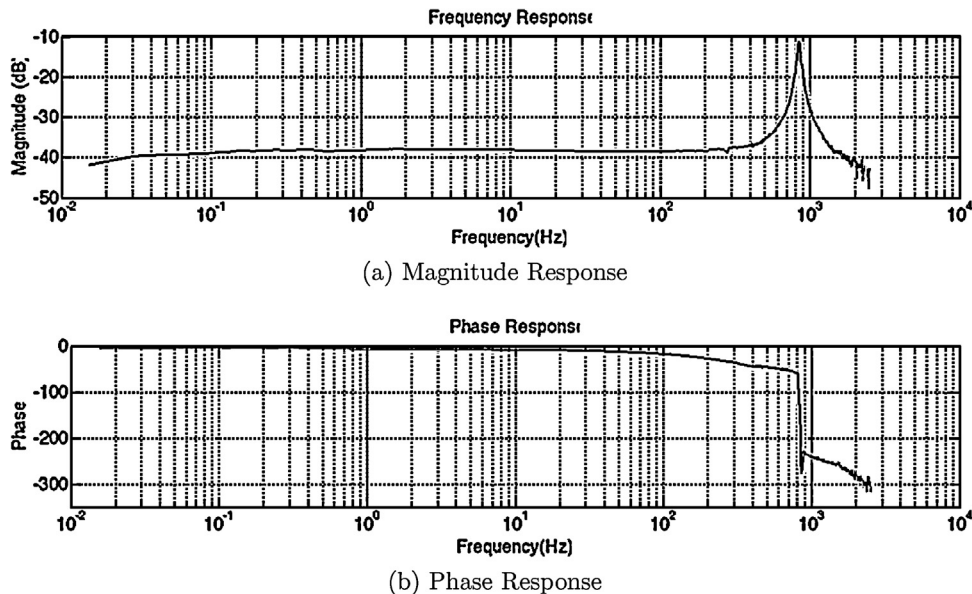


Fig. 11. Wireless magnitude and phase frequency responses of the system, with the actuation input signal and demodulated output signal. (a) Magnitude response. (b) Phase response.

responses are comparable with the wired system, meaning that this sensing technique could be implemented in a wireless arrangement.

This feature of the proposed sensing technique offers a range of opportunities in designing more customised sensing and actuating scenarios in laboratory or industrial environments. It also offers flexibility in the location of piezoelectric nanopositioners or sensors in relation to the receiving signal antennas and computer-based control systems.

It may also be used to create more distributed wireless sensor networks that use piezoelectric sensors tuned to different frequencies, and communicate with a central control unit. Some applications may involve distributed sensor networks in factories or civil structures for condition monitoring.

4. Conclusion

Piezoelectric materials are used in sensing systems due to their accuracy, stability and robustness, however static and low-frequency measurements are troublesome. This paper proposed a new FM-based technique to sense piezoelectric strain voltage at these low actuation frequencies.

A piezoelectric tube was used to demonstrate the technique. One terminal was actuated while the second piezoelectric terminal was used as a sensor, which was connected to a varactor diode. This element served as a voltage controlled capacitor in the feedback network of Colpitts oscillator, which modulated the changes in sensed voltage to changes in frequency. FM demodulation was achieved and a full system frequency response presented down to 15 mHz. Measurements were additionally made in the time domain at frequencies as low as 1 mHz. Lower frequencies were not attempted, however, given that the impedance of the varactor increases as frequency decreases it is feasible to operate at even lower frequencies.

In addition to dramatically lowering the frequency at which piezoelectric strain voltage can be sensed, the modulated FM signals can be transmitted wirelessly. This capability was demonstrated, with a measured frequency response presented. This additional wireless capability coupled with the low frequency capability of the sensing technique will open opportunities in distributed wireless piezoelectric sensing networks for low frequency sensing applications. Some obvious applications to this technology include structural monitoring in civil and industrial engineering environments.

References

- [1] G. Gautschi, *Piezoelectric Sensorics: Force, Strain, Pressure, Acceleration and Acoustic Emission Sensors, Materials and Amplifiers*, Springer, 2002.
- [2] K. Masuyama, Y. Kurihara, K. Watanabe, Measurement of vital signs of a person on concrete flooring, in: *SICE Annual Conference*, 2008, pp. 1823–1826.
- [3] A. Torres, J. Fiz, J. Morera, A. Grassino, R. Jane, Assessment of diaphragmatic contraction using a non-invasive piezoelectric contact sensor, in: *Engineering in Medicine and Biology Society. Proceedings of the 22nd Annual International Conference of the IEEE*, vol. 4, 2000, pp. 3126–3128.
- [4] Y.W. Kim, S. Sardari, A. Iliadis, R. Ghodssi, A bacterial biofilm surface acoustic wave sensor for real time biofilm growth monitoring, in: *Sensors*, 2010 IEEE, 2010, pp. 1568–1571.
- [5] J. Sirohi, I. Chopra, Fundamental understanding of piezoelectric strain sensors, *Journal of Intelligent Material Systems and Structures* 11 (2000) 246–257.
- [6] S. Zhang, X. Jiang, M. Lapsley, P. Moses, T.R. Shrout, Piezoelectric accelerometers for ultrahigh temperature application, *Applied Physics Letters* 96 (2010) 013506.
- [7] A. Beliveau, G. Spencer, K. Thomas, S. Roberson, Evaluation of mems capacitive accelerometers, *Design Test of Computers*, IEEE 16 (1999) 48–56.
- [8] J. Hammond, R. Lec, A non-contact piezoelectric torque sensor, in: *Frequency Control Symposium. Proceedings of the 1998 IEEE International*, 1998, pp. 715–723.
- [9] M. Flossel, U. Scheithauer, S. Gebhardt, A. Schonecker, A. Michaelis, Robust ltc/pzt sensor-actuator-module for aluminium die casting, in: *Microelectronics and Packaging Conference*, 2009. EMPC 2009. European, 2009, pp. 1–5.

- [10] J. Fanson, T. Caughey, Positive position feedback control for large space structures, *AAIA Journal* 28 (1990) 717–724.
- [11] J. Dosch, D. Inman, E. Garcia, A self-sensing piezoelectric actuator for collocated control, *J. Intell. Mater. Syst. Struct.* 3 (1992) 166–185.
- [12] A.J. Fleming, S.O.R. Moheimani, Control oriented synthesis of high performance piezoelectric shunt impedances for structural vibration control, *IEEE Transactions on Control Systems Technology* 13 (2005) 98–112.
- [13] S. Kuiper, G. Schitter, Active damping of a piezoelectric tube scanner using self-sensing piezo actuation, *Mechatronics* 20 (2010) 656–665.
- [14] S.O.R. Moheimani, Invited review article: accurate and fast nanopositioning with piezoelectric tube scanners: emerging trends and future challenges, *Review of Scientific Instruments* 79 (2008) (article number: 071101).
- [15] G. Binnig, D.P.E. Smith, Singletube threedimensional scanner for scanning tunneling microscopy, *Review of Scientific Instruments* 57 (1986) 1688–1689.
- [16] J.A. Vicary, M.J. Miles, Real-time nanofabrication with high-speed atomic force microscopy, *Nanotechnology* 20 (2009) 095302.
- [17] J. Rodriguez-Fortun, J. Orus, J. Alfonso, F. Gimeno, J. Castellanos, Flatness-based active vibration control for piezoelectric actuators, in: *IEEE/ASME Transactions on Mechatronics*, vol. 18, 2013, pp. 221–229.
- [18] H.C. Liaw, B. Shirinzadeh, Neural network motion tracking control of piezo-actuated flexure-based mechanisms for micro-/nanomanipulation, in: *IEEE/ASME Transactions on Mechatronics*, vol. 14, 2009, pp. 517–527.
- [19] G. Binnig, C.F. Quate, C. Gerber, Atomic force microscope, *Physical Review Letters* 56 (1986) 930–933.
- [20] P.K. Hansma, J. Tersoff, Scanning tunneling microscopy, *Journal of Applied Physics* 61 (1987) R1–R24.
- [21] A.J. Fleming, A. Wills, S.O.R. Moheimani, Sensor fusion for improved control of piezoelectric tube scanners, *IEEE Transactions on Control Systems Technology* 16 (2008) 1265–1276.
- [22] A. Daniele, S. Salapaka, M. Salapaka, M. Dahleh, Piezoelectric scanners for atomic force microscopes: design of lateral sensors, identification and control, in: *American Control Conference*, 1999. Proceedings of the 1999, vol. 1, 1999, pp. 253–257.
- [23] S. Salapaka, A. Sebastian, J.P. Cleveland, M.V. Salapaka, High bandwidth nanopositioner: a robust control approach, *Review of Scientific Instruments* 73 (2002) 3232–3241.
- [24] B. Bhikkaji, M. Ratnam, A. Fleming, S. Moheimani, High-performance control of piezoelectric tube scanners, in: *IEEE Transactions on Control Systems Technology*, vol. 15, 2007, pp. 853–866.
- [25] A.J. Fleming, K.K. Leang, Integrated strain and force feedback for high-performance control of piezoelectric actuators, *Sensors and Actuators A: Physical* 161 (2010) 256–265.
- [26] I. Mahmood, S. Moheimani, K. Liu, Tracking control of a nanopositioner using complementary sensors, in: *IEEE Transactions on Nanotechnology*, vol. 8, 2009, pp. 55–65.
- [27] A.N. Laskovski, S.O.R. Moheimani, M.R. Yuce, Note: Piezoelectric strain voltage sensing at ultra-low frequencies, *The Review of scientific instruments* 82 (2011) 086113.
- [28] S.W. Fardo, D. Patrick, *Electricity and Electronics Fundamentals*, 2nd ed., The Fairmont Press, 2008.

Biographies

Anthony Laskovski completed his Bachelor of Engineering (Electrical) degree with the University of Newcastle, Australia in 2006. He was awarded a Ph.D. in 2011 in microelectronics for biological signals also from the University of Newcastle. Dr. Laskovski was with the Laboratory for Dynamics and Control of Nanosystems between 2011 and 2012 working on interfacing sensor circuitry and MEMS design. His interests include biomedical engineering, MEMS design, RF-electronics and distributed intelligent sensing systems integrated with artificial intelligence. Since 2013 Dr. Laskovski has been with VIMOC Technologies as a co-founder and Vice President.

Mehmet Rasit Yuce received the M.S. degree in Electrical and Computer Engineering from the University of Florida, Gainesville, Florida in 2001, and the Ph.D. degree in Electrical and Computer Engineering from North Carolina State University (NCSU), Raleigh, NC in December 2004. He has served as a research assistant between August 2001 and October 2004 with the Department of Electrical and Computer Engineering at NCSU, Raleigh, NC. He was a post-doctoral researcher in the Electrical Engineering Department at the University of California at Santa Cruz in 2005. He was a Senior Lecturer in the School of Electrical Engineering and Computer Science, University of Newcastle, New South Wales, Australia until July 2011. In July 2011, he joined the Department of Electrical and Computer Systems Engineering, Monash University, Melbourne, Australia. His research interests include wireless implantable telemetry, wireless body area network (WBAN), bio-sensors, integrated circuit technology dealing with digital, analog and radio frequency circuit designs for wireless, biomedical, and RF applications. Dr. Yuce has published about 100 technical articles in the above areas and received a NASA group achievement award in 2007 for developing an SOI transceiver. He received a research excellence award in the Faculty of Engineering and Built Environment, University of Newcastle in 2010. He is an author of the book *Wireless Body Area Networks* published in 2011. He is a senior member of IEEE. He is an associate editor for *IEEE Sensors Journal*.

S. O. Reza Moheimani received a Ph.D. in electrical engineering from University of New South Wales at the Australian Defence Force Academy, Canberra, Australia in

1996. Since 1997 he has been with University of Newcastle, Australia, where he is currently a Professor and Australian Research Council Future Fellow in the School of Electrical Engineering and Computer Science. He has served on the editorial boards of a number of journals, including IEEE Transactions on Control Systems Technology, IEEE/ASME Transactions on Mechatronics and Control Engineering Practice. He is a

recipient of the 2007 IEEE Transactions on Control Systems Technology Outstanding Paper Award and the 2009 IEEE Control Systems Technology Award. He is a Fellow of the Institute of Physics and a Fellow of IEEE. His current research interests include applications of control and estimation in nanoscale positioning systems for scanning probe microscopy, control of microactuators in MEMS and data storage systems.