

# Self-Powered Sensing for Mechanical System Condition Monitoring

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## ABSTRACT

A self-powered wireless sensing module for the condition monitoring of mechanical systems and high energy manufacturing processes is described, with injection molding as a special application. The design and analysis of three constituent components in such a sensing module: an energy converter consisting of a piezoceramic stack, an energy regulator based on a pair of bipolar transistors, and a piezoelectric transmitter that transmits ultrasound signals proportional to the pressure within the injection mold, are presented in this paper. The energy extraction mechanism is investigated based on the interactions between the mechanical strain and the electric field developed within the piezoceramic stack. Analytical models for the energy modulator and signal transmitter are also established. Quantitative results are obtained that describe the energy flow among the three components and guide the parametric design of the three constituent components. Simulations and experimental studies have validated the functionality of each component. The models established can be used to subsequently optimize the design of the entire sensor module in terms of minimizing the energy requirement for the sensor and identifying the minimum level of signal intensity required to ensure successful detection of the signal by the signal receiver on the outside of the injection mold. The proposed self-powered sensing technique enables a new generation of sensors that can be employed for the condition monitoring and health diagnosis of a wide range of mechanical and civil systems that are characterized by high energy contents.

**Keywords:** Self-energized sensing, energy extraction, equipment and process monitoring

## 1. INTRODUCTION

With the prolific use of sensors for mechanical system and civil structure condition monitoring and the growing demand for system integration, the issue of sensor powering has assumed an increasingly central role. Powering through cable connections, while commonly seen on the factory floor, face constraints in field applications. Battery-based operation, although compact and eliminating the cable attachment, has the ultimate drawback of requiring periodic replacement due to wear-and-tear. Thus, extracting energy from the system or structure being monitored itself becomes a logical and ideal solution. The deployment of a self-powered sensor is particularly attractive for monitoring injection molding, given the high temperature, high pressure nature of the process, and the various practical constraints in process measurement from within an enclosed, metallic environment.

Direct measurement of cavity pressure and temperature has shown to be more reflective of the final part quality produced by the injection molding process than any indirect methods [1, 2]. Wired pressure sensors, while still commonly used on the factory floor, face various constraints. Because of the structural complexity of most injection molds, the cost to install a wired sensor is generally on the same order of cost as that of the sensor itself. The majority of the installation cost is associated with cabling or providing a *pathway* for the information to travel from the sensor to the process controller. While these problems are not new to the industry at large and have been fueling the development of wireless sensor technology for the past several years, injection molding has presented special problems for wireless sensor systems [3]. The presence of a steel cavity completely surrounding the sensor makes it nearly impossible to effectively transmit a process signal using electromagnetic waves as the medium for signal transmission. Furthermore, the size of the power source for a long life sensor can be un-proportionally large in comparison to the sensing system itself, thus leading to unpractical sensor designs. To enable self-powered pressure sensing, a novel approach has been developed

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that utilizes the pressure differential associated with the filling and packing of an injection mold to generate power, based on the mechanical-electrical transduction principle of the piezoelectric elements [4]. Specifically, a self-powered sensor was designed to be installed within the cavity of the injection mold, extract energy from the injection pressure, and send the pressure information in the form of a train of ultrasonic pulses through the mold steel to a receiver located outside the mold. Such a wireless, self-powered pressure-sensing scheme allows single or multiple sensors installed per mold cavity for in-process measurement in an economically viable way (Fig. 1).

This paper is focused on the analysis of energy extraction and transmission mechanisms. Three analytical models have been developed to analyze the energy transfer process from a piezoelectric energy converter that interacts with the polymer melt within the injection mold via a threshold modulator to a ultrasonic transmitter, through which information on the melt pressure is carried out of the mold cavity. The analysis establishes the theoretical foundation for the parametric design of the self-powered sensor. The validity of the models is then evaluated experimentally from a functional prototype. Good agreement has been shown between the modeling and experimental results. The remaining of this paper is organized as follows: after presenting the underlying sensing principle in section 2, the analytical models of three major constituent components are presented in section 3. Experimental validation of the components is described in section 4. The paper ends with section 5, where conclusions on the applicability of the sensor are drawn.

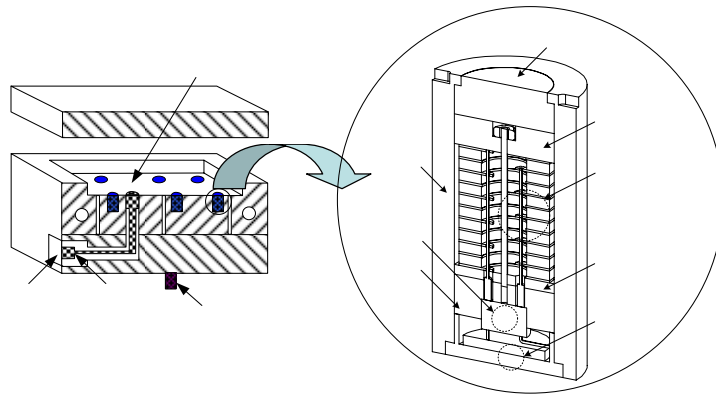


Fig. 1. Self-energized, mechanical wireless sensor installed within an injection mold cavity

## 2. SENSING PRINCIPLE

As illustrated in Fig. 2, the self-powered wireless pressure sensor consists of three constituent components: energy converter, threshold modulator, and signal transmitter. The energy converter is made of a multi-layer piezoceramic element. When the polymer melt reaches the sensor, the element is compressed, developing an electrical charge that is proportional to the melt pressure. The developed charge is then stored in a capacitor, which is part of the energy converter, in the form of a voltage output. This voltage is proportional to the melt pressure, and thus can be used as a measure for the pressure. For wireless transmission of an electrical voltage signal, sampling, quantization, and encoding are the three common steps [5]. Those processes are energy consuming and thus not suited for the intended in-mold pressure sensing. A different digitizing and transmission principle is thus devised based on a threshold modulator. Each time the voltage across the capacitor exceeds a preset threshold level, the threshold modulator will be actuated and the accumulated charge then released to a subsequent signal transmitter, in the form of an electrical pulse. Upon such an impulsive excitation, the signal transmitter would generate ultrasonic pulses that propagate through the mold steel and reach a signal receiver installed outside the mold. After each measurement cycle, the collected charge is released and the modulator deactivated, making the system ready for the next cycle. As a result of this process, the cavity pressure is discretized by means of a series of ultrasonic pulses. The actual cavity pressure profile is then reconstructed by multiplying the total number of the pulses with the preset pressure threshold. This sensing principle is illustrated in Fig. 3, where curve ❶ illustrates the actual pressure, and curve ❷ is the reconstructed pressure from the ultrasonic pulses. An ultrasonic pulse is generated each time the cavity pressure increases by 1 MPa, as indicated by curve ❸.

To measure melt pressure at multiple locations along the cavity, a Multiple-Sensor-Single-Receiver (MSSR) configuration would be required. In a mechanical wireless data transmission setting, different sensors can be identified by the respective center frequencies of the associated ultrasonic pulses. Therefore, each signal transmitter needs to be designed for a specific natural frequency. For pressure discretization, the threshold level represents the smallest measurement unit. Determination of the threshold is based on the consideration that, while a smaller threshold provides higher measurement resolution, it must contain sufficient energy in order to generate a detectable ultrasonic pulse. Thus, a design trade-off needs to be made, as part of the overall sensor design process.

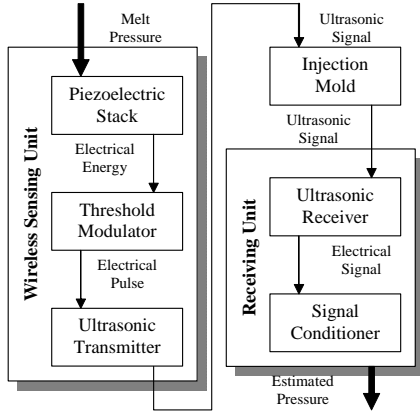


Fig. 2. Signal path functional decomposition of the wireless sensor system

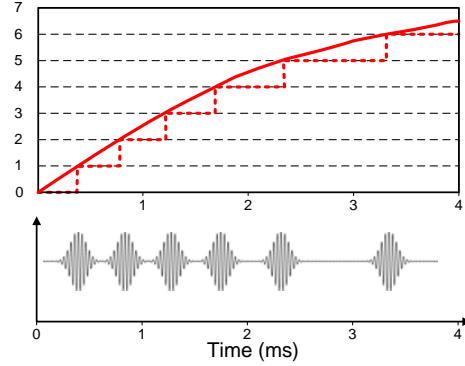


Fig. 3. Digitization of the mold cavity pressure through ultrasonic pulses

### 3. MODEL DEVELOPMENT

The electrical charge generated by the piezoelectric element upon the application of a mechanical stress is associated with the deformation of the highly polarized molecules within the element [6]. The energy stored within the element takes two forms: 1) electrically in the form of an electric field and 2) mechanically as strain. The interaction between the strain and the electric field is therefore the basis for the energy extraction mechanism and is studied in the analytical model presented. Since the electromechanical behavior of a piezoelectric element is also heavily dependant on the geometry of the element, it is necessary to model geometrically complex piezoelectric elements to obtain quantitative insight into the extraction mechanism. The threshold modulator model is presented in the second part of this section. Finally, the ultrasound transmitter and receiver model is discussed. Based on these models and the requirement on the receiver, the geometrical and electrical characteristics of the piezoelectric element can be determined.

#### 3.1 Energy converter model

The energy stored within the piezoelectric element expresses itself electrically as an electric field and mechanically as a strain. The interaction between the strain and the electric field forms the basis for the energy extraction [7]. If the piezoelectric element is loaded parallel to the axis of symmetry, it is in a state of approximately constant stress through its thickness. If this element is also polarized in the axial direction, the constitutive model of the piezoelectric element can be applied. In the presented study, the piezoelectric element takes the form of a piezoceramic ring. When installed as a mold cavity pressure sensor, the piezoelectric ring needs to be protected against thermal stress from the high-temperature molten plastic. A cap design was employed in the presented study, which decouples the ring from the mechanical force acting on the ring.

Using a piezoceramic ring as the basic element for the energy converter, the electric charge generated under the melt pressure  $P$  is given as  $Q_d = d_{33} \cdot A_{cr} \cdot P$ , with  $d_{33}$  and  $A_{cr} = (d_o^2 - d_i^2)\pi/4$  being the piezoelectric charge constant in axial direction and the cross-sectional area of the piezoelectric ring, respectively. Symbols  $d_o$  and  $d_i$  denote the outer and inner diameter of the piezoceramic ring, respectively. To increase the amount of electrical charge generated by a given pressure, multiple piezoceramic rings were stacked on top of each other and electrically connected in parallel. The developed charge then becomes:

$$Q_s = \frac{n \cdot d_{33} \cdot \pi \cdot d_o^2 \cdot P}{4} \quad (1)$$

where  $n$  is the number of piezoelectric rings in the stack. The voltage associated with the charge on the stack is calculated by approximating the stack of rings electrically as a parallel plate capacitor:

$$V = g_{33} \frac{d_o^2}{d_o^2 - d_i^2} P \cdot h \quad (2)$$

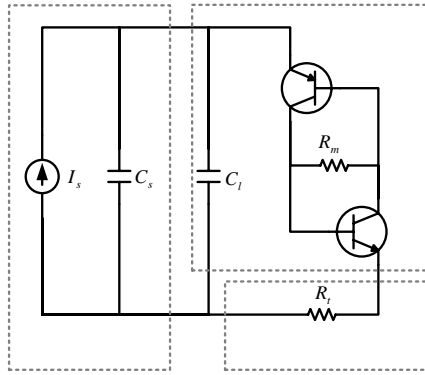
where  $g_{33}$  is the piezoelectric voltage constant and  $h$  is the thickness of the piezoceramic ring. The equivalent capacitance of the stack is given by:

$$C_s = n \cdot e_{33} \cdot e_r \frac{\pi \cdot (d_o^2 - d_i^2)}{4h} \quad (3)$$

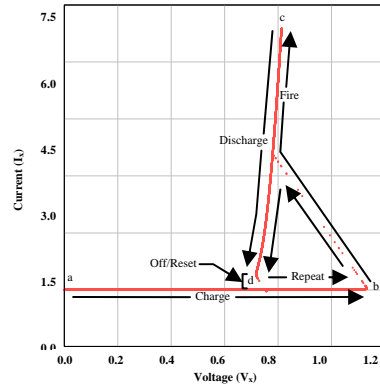
where  $e_{33}$  is the permittivity constant, and  $e_r = 8.85 \times 10^{-12}$  F/m is the permittivity of free space.

Compared to a single ring, the stacked design enables higher capacitance. It can be seen from Equation (3) that reducing the disk thickness  $h$  increases the capacitance  $C_s$ . Thus, a 1mm thick disk has ten times the capacitance compared to a 10mm disk with the same diameter. With ten 1mm thick disks are electrically connected in parallel, the capacitance will increase by 100 times, thus allowing for more energy to be stored within the same geometrical volume. Furthermore, when ten thin disks are stacked above each other, they are all subjected to the same melt pressure. The generated charge will be ten times greater than that from one 10mm disk. A parallel capacitance  $C_l$  is used to adjust the voltage generated, as shown in Fig. 4 (a). This capacitance is usually chosen to be equal to the capacitance  $C_s$ , in order to achieve high energy efficiency. Therefore, the energy stored in a piezoceramic ring stack under a mechanical pressure  $P$  is given as:

$$E = \frac{Q_s^2}{2(C_s + C_l)} = n \cdot h \frac{\pi \cdot d_{33}^2 \cdot d_o^4}{16(d_o^2 - d_i^2) \cdot e_{33} \cdot e_r} P^2 \quad (4)$$



(a) Schematic diagram



(b) I-V curve of the threshold modulator

Fig. 4. Schematic diagram of the threshold modulator with piezoelectric stack and the ultrasonic transmitter.

Using the piezoceramic stack as the energy converter, the mechanical energy from the melt pressure is *extracted* and converted into electrical energy in the form of a voltage that is proportional to the mold cavity pressure. As Eq. (4) indicates, when the diameters and thickness of the piezoelectric ring are given, the energy *extracted* is proportional to the number of rings used in the stack. In order to discretize the pressure signal and generate ultrasonic pulses, a threshold modulator needs to be designed.

### 3.2 Threshold modulator model

The charge generated by the energy converter is proportional to the melt pressure in the mold cavity. The charge is measured and controlled through the use of a dual-transistor modulator. As shown in Fig. 4 (b), the piezoelectric stack is modeled as a current source  $I_s$ , and  $R_m$  represents the clamp resistor. To simplify the modeling, the ultrasound transmitter is modeled as a load resistor  $R_t$ . The transmitter consists of a PNP ( $Q1$ ) and an NPN ( $Q2$ ) transistor that are connected such that the Base of transistor  $Q1$  is connected to the Collector of the transistor  $Q2$ , and vice versa. Because the transistors have a finite “off state” resistance, with current passing through  $Q1$  as the input voltage rises,  $Q2$  will be activated, which in turn causes  $Q1$  to cascade activate. At this point, the switch represented in the figure by  $Q1$ ,  $Q2$  and  $R_t$  changes from the relative “off state” to the “on state”. The capacitor  $C_l$  is then discharged in the form of an electrical pulse, until there is no longer enough current to maintain the “on states” of the two transistors. The switch then changes to the “off state”. The cycle repeats itself, as long as current is supplied as the input. The current  $I_s$  of the current source can be expressed as:

$$I_s = \frac{dQ}{dt} = K_{sc} \frac{dP}{dt} \quad (5)$$

where  $dP/dt$  is the time derivative of the melt pressure applied on to the energy converter, and  $K_{sc} = n \cdot d_{33} \cdot \pi \cdot d_o^2 / 4$  is the stack constant, which is determined by the material and geometric properties of the piezoelectric stack. Equation (5) indicates that a change in pressure is converted to a charge by the piezoelectric stack. Once the voltage across the piezoelectric stack reaches a given threshold, the modulator converts this charge to a current pulse transmitted through the ultrasonic transmitter. The resulting dynamics of the circuit can be broken down into four distinct phases as illustrated in Fig. 5, in which the voltages resulted from the current pulse are shown for the modulator and the load resistor, respectively. Phase one includes the time that the modulator is in its “off state” and the capacitive elements are charging. Phase two begins at  $t_1$  and includes a very short time where the threshold modulator changes from its relative “off state” to its “on state”. Phase three begins at time  $t_2$  and includes the time that the modulator is in its “on state” while the capacitive elements discharge through the modulator and load transmitter until time  $t_3$ . After time  $t_3$  the transistors turn “off” and reset while the capacitive elements begin to charge again.

In Phase one ( $t_0 < t < t_1$ ), the modulator is turned “off” as illustrated in Fig. 5(a). At  $t = t_1$ , the voltage associated with the equivalent combined capacitor  $C_e = C_s + C_l$  can be expressed as:

$$V_c(t_1) = \frac{1}{C_e} \int_{t_0}^{t_1} I_s \cdot dt \quad (6)$$

During each charging cycle, the change of  $dP/dt$  is very small and thus can be approximated as a constant. Thus, at  $t_1$  the voltage can be expressed as:

$$V_c(t_1) = \frac{1}{C_e} I_s (t_1 - t_0) \quad (7)$$

Since Phase two ( $t_1 < t < t_2$ ) lasts only for a very short period of time, the voltage change across  $C_e$  can be neglected ( $V_c(t_2) = V_c(t_1)$ ) as shown in Fig. 5(b). In Phase three ( $t_2 < t < t_3$ ), the modulator is turned “on”. For an ideal modulator, its resistance should be much smaller compared with the resistance of ultrasonic transmitter at the “on” state. The voltage across  $C_e$  can be expressed as:

$$I_s = \frac{V_c(t)}{R_t} + C_e \frac{dV_c(t)}{dt}, \quad t_2 < t < t_3 \quad (8)$$

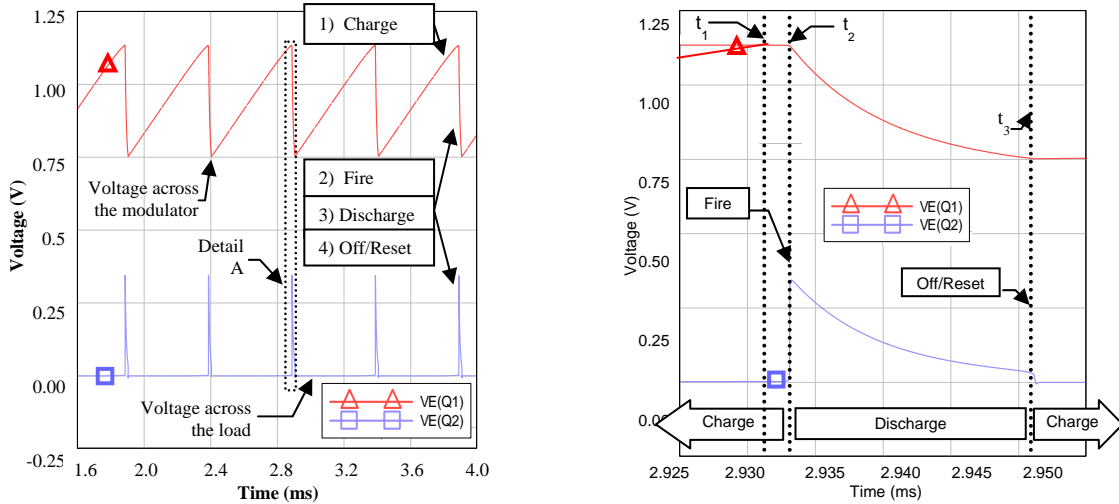
Since  $V_{R_t} = V_c$ , the voltage across the ultrasound transmitter can be determined as:

$$V_{R_t}(t) = \frac{I_s}{C_e^2 R_t} + \left[ V_c(t_2) - \frac{I_s}{C_e^2 R_t} \right] e^{-\frac{1}{C_e R_t}(t-t_2)}, \quad t_2 < t < t_3 \quad (9)$$

The energy transferred from the energy converter to the transmitter can be calculated as:

$$E_t = \int_{t_2}^{t_3} \frac{V_{R_t}(t)^2}{R_t} dt \quad (10)$$

The geometrical and electrical characteristics of the stack elements can be designed based on the energy needed by the ultrasound transmitter, which is discussed in the next section.



(a) Four distinct phases of the threshold modulator cycle

(b) Detail A: the output pulse of the threshold modulator

Fig. 5. Illustration of the performance of the threshold modulator.

### 3.3 Transmitter and receiver model

Discretized by the threshold modulator, the cavity pressure is converted to a series of electrical pulses. To wirelessly transmit such information to the outside of the mold steel, an information carrier is needed. Given that electromagnetic waves are shielded by the mold steel, and optical means are unrealistic due to the block of line of sight, a mechanical wireless transmission scheme was investigated in this study. Based on the electrical-to-mechanical transduction principle of piezoceramic materials [8], the use of ultrasound as the information carrier was explored, for which a piezoceramic signal transmitter was incorporated into the sensor package.

With input from the electrical pulse generated by the threshold modulator, the transmitter resonates at its natural frequency and transmits ultrasonic pulse into the adjacent mold steel. An ultrasonic receiver located outside the mold is needed to receive the ultrasonic pulses and convert them back into electrical voltage, which can be evaluated as a direct measure for the melt pressure. To investigate the ultrasonic energy transmission from the transmitter to the receiver through the mold, an equivalent circuit modeling approach [9] is used in this study. The circuit model of the transmitter is given in Fig. 6, where the input voltage to the signal transmitter resulted in an ultrasonic force in the adjacent mold steel.

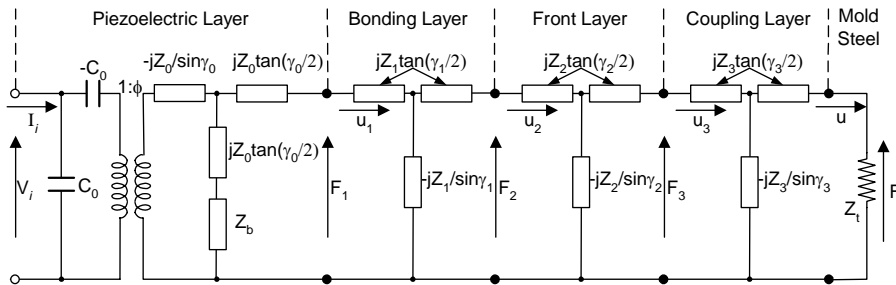


Fig. 6. Equivalent circuit model of the ultrasonic signal transmitter coupled to a mold steel

A detailed description of this model is given in [9]. Using this model, the voltage transfer function  $V_r/V_{R_t}$  between the transmitter and receiver, which describes the dynamic behavior of the transmitter, mold steel and ultrasound receiver, is established as:

$$\frac{V_r}{V_{R_t}} = \frac{2R_t Z_{0t}}{[A_t Z_t + B_t + Z_s (C_t Z_{0t} + D_t)][A_r Z_t + B_r + Z_t (C_r Z_{0t} + D_r)]} \quad (11)$$

where  $V_{R_t}$  is the electric pulse voltage generated by the threshold modulator,  $V_r$  is the output voltage of the receiver,  $A_t$ ,  $B_t$ ,  $C_t$ , and  $D_t$  are the transfer matrix terms associated with the transmitter,  $A_r$ ,  $B_r$ ,  $C_r$ , and  $D_r$  are the matrix terms for the receiver,  $Z_t$  represents the impedance of the measurement equipment,  $Z_s$  is the impedance of the threshold modulator,  $R_t$  is the resistance of the measurement equipment, and  $Z_{0t}$  is the mechanical impedance of the mold. Knowing the voltage transfer function, the received ultrasonic pulse upon the electric excitation generated by the threshold modulator can then be modeled. Examples of the voltage transfer function for three transmitters with different bonding layer thickness are given in Fig. 7.

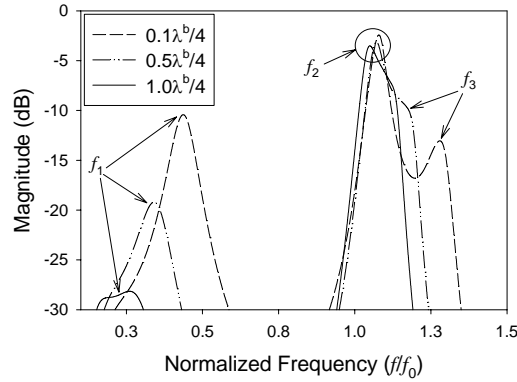


Fig. 7. Examples of the voltage transfer function for three transmitters.

In Fig. 7,  $f_1$ ,  $f_2$ , and  $f_3$  represent the three natural frequencies of the transmitters. It is seen that the transmitter with a bonding layer thickness of a quarter wavelength ( $1.0\lambda^b/4$ ) has the highest magnitude at frequency  $f_2$ , therefore it can most efficiently transmit the energy at this frequency. Based on Equation (11), the energy transfer between the transmitter and receiver can be expressed as [10]:

$$E_r = e^{-\alpha d_m} \int_{-\infty}^{+\infty} \left| \frac{V_r(f)}{V_{R_t}(f)} \right|^2 df \cdot E_{R_t} \quad (12)$$

where  $E_r$  is the energy of the received ultrasonic pulse and  $E_{R_t}$  is the energy contained in the electric pulse generated by the threshold modulator. Since the attenuation of ultrasonic energy in the mold steel is not included in the equivalent circuit model, an additional attenuation constant  $\alpha$  associated with the steel is included. The ultrasonic energy drops exponentially with the increasing transmission distance (mold thickness)  $d_m$ .

## 4 EXPERIMENTAL EVALUATION

Three constituent components were designed corresponding to their modeling results. To verify the functionality and performance of each individual component, they were tested individually, as described below.

### 4.1 Energy converter

The energy converter prototype will allow quantification of the model inaccuracies as well as validation of the developed models themselves. The energy converter prototype consists of a stack of ten piezoelectric rings. The prototype design includes electrodes to electrically couple the rings, thermal insulators to thermally decouple the stack from the polymer

melt. The performance of the prototype was evaluated using a commercially available pressure sensor, with the result shown in Fig. 8. It is apparent that the prototype not only truthfully traced the pressure profile of the mold cavity pressure, but the output has contained less noise. The high frequency noise associated with the predicted voltage resulted from the fact that the predicted voltage is based on the mechanical stress within the energy converter, as experimentally measured by the load cell. The load cell signal is comparatively noisy, thus resulting in a noisy predicted voltage. The Pearson product moment correlation [11] for the modeled and the actual voltage is approximately 0.905, indicating very good fitness for the modeled data.

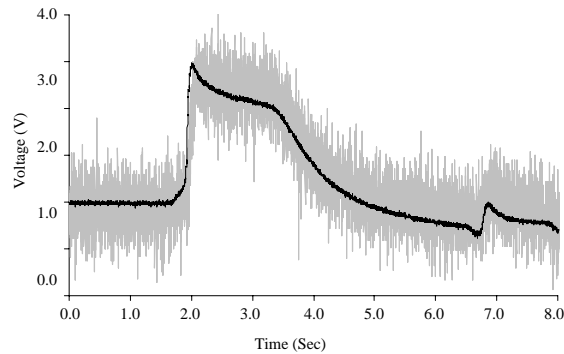
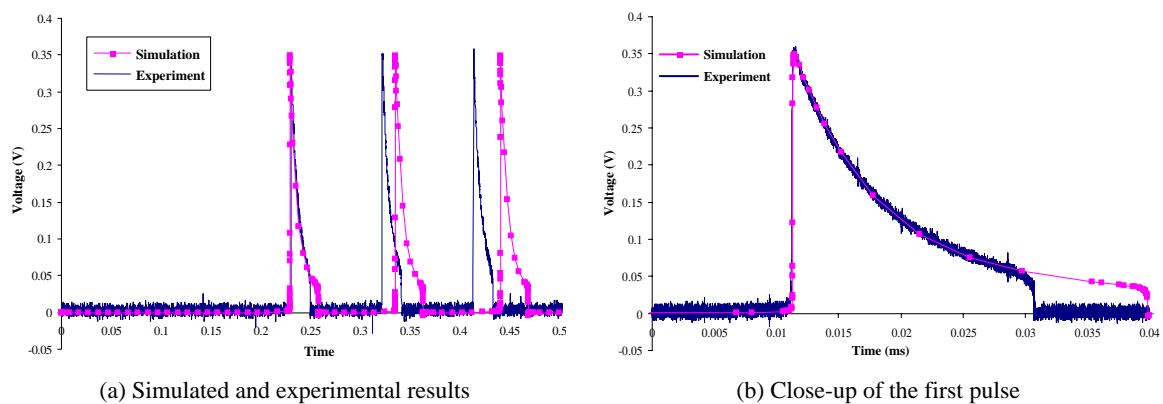


Fig. 8. A comparison of the predicted voltage (dark) and the actual voltage of the prototype sensor (gray).

#### 4.2 Threshold modulator

For testing the threshold modulator, the energy converter is approximated as a current source. The signal transmitter, which is connected to the output of the threshold modulator, is modeled as a resistive load. The resulting electrical model is an approximation of the pressure sensor as shown in Fig. 4. The capacitor  $C_s$  represents the actual capacitance of the piezoelectric stack. The transistor models  $Q1$  and  $Q2$  are general-purpose transistors for switching and amplifier applications manufactured by Semicoa™ and Fairchild Semiconductor™ respectively. The remainder of the circuit elements  $C_l$ ,  $R_m$  and  $R_t$  are nominal values that produce a pulsed output at transmitter.

A prototype of the above circuit was built using a Keithley 2400 source meter in place of the ideal current source. The voltages in the circuit was measured using a Tektronix 3012 100 M& digital oscilloscope. The input and output voltages were measured between the emitter of  $Q1$  to ground and the emitter of  $Q2$  to ground respectively. The output current was calculated using Ohm’s law.



(a) Simulated and experimental results

(b) Close-up of the first pulse

Fig. 9. Transient (startup) experimental and simulation results for the threshold modulator

The experimental and simulation results of a transient analysis of the threshold modulator are presented in Fig. 9, which shows the converted voltage and current output for the model with a pressure ramp rate of 100 MPa/sec. Each current pulse represents a pressure change of 10.8 kPa, corresponding to 0.001% of a possible 100 MPa pressure range. The current source was switched on at time = 0 and the circuit began stable oscillation after reaching the switch breakdown

voltage. The magnitude of the experimental results matched very closely that of the simulation. The total pulse width varies by about 25%. The variance appears to be from a difference in holding current between the transistors used in the simulation and those used in the experiment. Otherwise, however, the experimental results closely matched those predicted. The output pulse width shown is approximately  $30 \mu s$ . This pulse width corresponds to a 33 kHz (tip to tail) maximum repetition frequency. The corresponding rise time of the pulse leading edge is approximately 40 ns; this rise time represents a maximum excitation frequency of 12.5 MHz. This is well above the minimum repetition frequency required for the cavity pressure discretization.

### 4.3 Ultrasound transmitter

Signal transmitters were prototyped using piezoelectric disks with thickness of 0.92 mm and free resonant frequency of 2,100 kHz. The piezoelectric disk was bonded to a stainless steel front layer using conductive epoxy. To reduce the effect of bonding layer thickness, a front layer of  $1.8 \lambda / 4$  ( $1140 \mu m$ ) was chosen in the design. The bonding layer thickness was measured to be approximately  $40 \mu m$ .

The transmitters were coupled to a steel block using a thin grease coupling layer. A PAC C-101-HV pulser system was used to generate electrical pulses simulating the threshold modulator. The signal transmitter excited by the electrical pulse generated ultrasonic pulses, which were transmitted through the mold steel and received by the receiver. Simulation of the ultrasonic pulse was obtained by taking the inverse Fourier transform of the voltage transfer function. Comparison of measured and simulated ultrasonic pulse generated by the transmitter under the electric pulse excitation is shown in Fig. 10. It was found the measured and simulated ultrasonic pulses are in very good agreement, both in time and frequency domains.

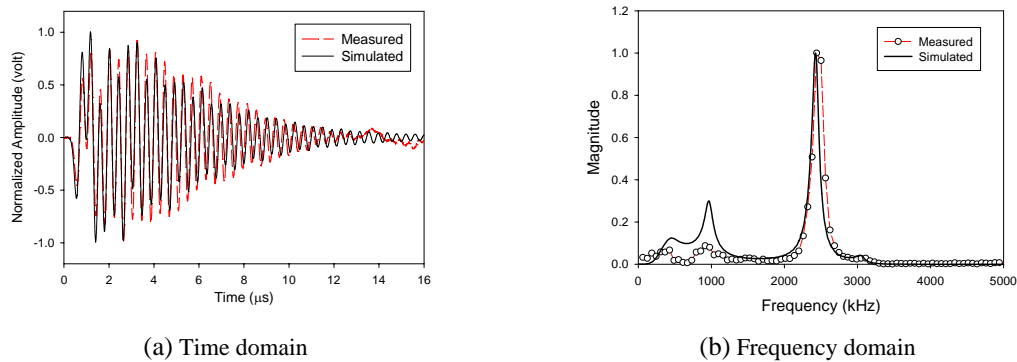


Fig. 10. Measured and simulated ultrasonic pulses.

## 5 CONCLUSIONS

Several fundamental aspects related to the design of a new type of self-powered sensor for wireless injection mold cavity pressure measurement were discussed. The fundamental idea of this new sensor is to extract energy from the injection molding process itself and using this energy to discretize the pressure information into a series of ultrasonic pulse signals. The sensor consists of an energy converter, a threshold modulator, and a signal transmitter.

The energy converter was designed using a stack of piezoceramic rings to convert mechanical energy from the melt pressure into proportional electrical energy. The converted electrical voltage was discretized into electrical pulses by a threshold modulator. The threshold of the modulator can be adjusted by changing the parallel capacitor to allow the generation of detectable ultrasonic pulses. Electrical pulses were converted into ultrasonic pulses for wireless pressure data transmission. To investigate the energy extraction and transmission, analytical models for the three components have been developed. The theoretical foundation for the design of the self-powered sensor was established through the analysis of the models. These energy models can be further employed to achieve a more efficient energy utilization of the proposed sensing technique.

The three components were built and tested individually. Good agreement between the experimental and modeling results was found for each individual component. It can be concluded that the proposed new sensing system is applicable and the prototype sensor is functional. The presented sensor design enables a new generation of self-powered sensors that can be employed for the condition monitoring of not only injection molding process, but also a wide range of mechanical and civil systems that are characterized by high energy contents.

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## REFERENCES

- [1] I. A. Rawabdeh and P. F. Petersen, "In-Line Monitoring of Injection Molding Operations: A Literature Review," *Injection Molding Technology*, vol. 3, pp. 47-53, 1999.
- [2] B. H. Watkins, "Five myths about sensing mold pressure," *Sensors Magazine*, vol. 14, pp. 73-78, 1997.
- [3] M. Rafizadeh, W. I. Patterson, and M. R. Kamal, "Physically-Based Model of Thermoplastics Injection Molding for Control Applications," *International Polymer Processing*, vol. 11, pp. 352, 1996.
- [4] C. Theurer, L. Zhang, D. Kazmer, and R. Gao, "In-Situ Evaluation of a Piezoelectric Energy Extraction Device for Wireless Cavity Pressure Sensing in Injection Molding," presented at Proceedings of the 2003 ASME International Mechanical Engineering Congress & Exposition, Dynamic Systems & Control Division, Washington, D. C., 2003.
- [5] S. Haykin, *An Introduction to Analog and Digital Communications*. New York: John Wiley & Sons, Inc., 1989.
- [6] J. V. Randerat and R. E. Seterington, *Piezoelectric Ceramics*. London: Mullard, 1974.
- [7] J. W. Waanders, *Piezoelectric Ceramics Properties and Applications*: The Netherlands: Philips, 1991.
- [8] O. E. Mattiat, *Ultrasonic Transducer Materials*. New York - London: Plenum Press, 1971.
- [9] L. Zhang, C. B. Theurer, R. X. Gao, and D. O. Kazmer, "A Self-energized Sensor for Wireless Injection Mold Cavity Pressure Measurement: Design and Evaluation," *ASME Journal of Dynamic Systems, Measurement, and Control*, June, 2004 (to appear).
- [10] D. B. Percival and A. T. Walden, *Spectral Analysis for Physical Applications: Multitaper and Conventional Univariate Techniques*. Cambridge, UK: Cambridge University Press, 1993.
- [11] J. Neter, *Applied Linear Statistical Models*: McGraw-Hill, 1996.