WIRELESS PRESSURE SENSOR FOR INJECTION MOLDING

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Abstract

Development of a wireless pressure sensor is motivated to reduce instrumentation and mold modification cost, improve lifecycle robustness, and thereby facilitate the widespread use of in-process sensing for process monitoring and control. In the presented design, the dynamic pressure in the mold cavity compresses a stack of piezoelectric rings, which generate a proportional electrical charge. Using an oscillator-based threshold switching device, the collected charge is relayed to an ultrasonic transmitter, which sends an acoustic signal at specific center frequencies to a receiver outside of the mold. Such a mechanical-electrical transduction process enables the on-line measurement of mold cavity pressure in a wireless fashion, without any external power supply.

Introduction

Observability of the process dynamics within an injection mold remains a fundamental issue in the molding industry. Current molding quality control strategies require the use of cavity pressure sensors mounted in the mold that are connected to external data processing devices by cables. The location of the sensors must be predetermined so that holes and channels can be machined in the mold to accommodate the cables for sensor installation. As such, the number of pressure sensors that can be installed in a mold is restricted by economic and geometrical constraints. Furthermore, the desirability of the location of the pressure sensors is not well understood prior to molding, and identifying the need for process information at specific locations in the mold cavity.

The objective of this research is to revolutionize the use of sensors in the molding industry through the development of a lower cost, small, wireless sensor that can be installed in the field…from the parting plane with the mold in the machine! As shown in Figure 1, the sensor can be fit into a blind hole at varying locations during the pre-production stage while the mold is being commissioned and the molded part quality verified. As such, the wireless sensor is intended to provide a direct replacement for traditional cabled sensors, but enable a greater number of sensors to be easily utilized at strategic locations.

With respect to sensor development, metal molds prevent communication of process data using radio frequency-based signal transmission. As such, the developed wireless sensor utilizes ultrasonic acoustic transmission to propagate through the metal without limitation to a cabled receiver. In the sensor, the piezoelectric (PE) effect and inverse PE effect are being utilized in an integrated fashion. Upon transient load application from the injected polymer melt acting on the sensor, a primary piezoceramic element will generate electrical charges proportional to the melt pressure. The charge will in turn be applied to a secondary piezoceramic element that subsequently vibrates and emits ultrasound signals.

During the injection molding process, the change in melt pressure inside the cavity is typically 100-200 MPa. This pressure differential was experimentally determined to be sufficient to energize the secondary piezoceramic element to produce a series of acoustic pulses that correlates to predetermined threshold values of the melt pressure differential. The pulses effectively “discretize” the pressure differential, enabling a energy-efficient way of signal transmission, as compared to using a continuous signal. A typical cavity pressure curve is illustrated in Fig. 2. The thresholding and discretization of the pressure curve is achieved by an electronic switching circuit which controls the generation of ultrasonic pulses. The total number of pulses is a direct measure of the in-process melt pressure.

As implied by this introduction, the self-energized sensor consists of two primary subsystems: 1) a power module for generating and modulating power to 2) a signal transmission module that sends an acoustic signal to a receiver outside the mold. This paper focuses on the validation of these two subsystems, and establishes the technical feasibility of the developed sensor technology.

Sensor Development & Validation

Power Module

As shown in Figure 3, a stack of piezoelectric rings is used to generate charge from the dynamic stress state imposed by the melt pressure in the injection mold. The charge generated by a piezoelectric element upon mechanical stress is associated with the deformation of the polarized molecules in the crystal structure. If electrodes are placed on opposite sides of the element, the charge can be collected and used. The energy stored in the element is stored in two forms: 1) electrically in the form of an electric field and, 2) mechanically in the form of strain. The interaction between the strain and the electric field is the subject of models presented in [1-3].

Models have been developed [4] to predict the voltage and current output as a function of the critical design variables, which include the diameter, height, and thickness of the piezoelectric rings, and the connectivity. To validate this model, a loading apparatus was built with a load cell placed under a sensor stack in order to simultaneously measure the force acting on the stack and its electrical output. Two scenarios were then evaluated, in both cases force was applied to the stack; 1) the stack was connected to the measuring scope (10 MΩ), simulating as close as possible an electrically open circuit, and 2) then a resistor (99.4 kΩ) was connected between the electrodes of the stack (simulating an electrically closed circuit to ground). The loading and unloading of the piezoelectric stack spanned approximately 0.12 seconds. The stress in piezoelectric elements was assumed to be constant in the axial direction and was approximated using the load-cell output. As shown in Figure 4, the resulting stress and voltage from the energy extraction module closely correlate to the observed output from the load cell.

The characterized piezoelectric stack can be modeled as an electric circuit consisting of a current source in parallel with a capacitor. The supply current at any point in time is directly proportional to the pressure ramp rate while the capacitance can be calculated from the stack parameters. The charge will continue to accumulate on the stack electrodes producing a voltage potential. Once this voltage reaches a predetermined threshold the energy associated with the charge at this voltage level is used to power an acoustic transmitter that will transmit the pressure information out of the mold.

The resolution of any threshold sensor can be controlled by the amount of energy required to change the state of the switching element. However, a certain amount of energy will be required to send an acoustic signal through the mold to the receiver The energy requirements of the sensor place a constraint on the number of pulses the sensor can emit during a single molding cycle and consequently there is a constraint on sensor resolution. However, a discrete signal (pulse) emitted from the sensor would transmit less information and therefore need less power when compared with a continuous acoustic signal. As shown in Figure 2, this approach generates a close approximation of the pressure dynamics with relatively few acoustic pulses. For this example, the continuous signal required a minimum of 6000 units of energy (12 bits * 500 signals at 100 Hz), compared to the discrete signal requiring only 40 units of energy (2 bits * 20 signals).

The threshold switch can be modeled and designed as a relaxation oscillator. This device consists of PNP (Q1) and NPN (Q2) transistors connected such that the gate of the first is connected to the emitter of the second and the gate of the second is connected to the emitter of the first. Because the transistors have a finite off resistance, some current passes through Q1 as the input signal voltage rises, which causes Q2 to be triggered which in turn causes Q1 to trigger. At this point, the switch represented in the figure by Q1, Q2 and R2 changes from the relative off state to the on state (B to C). The capacitor C2 is then discharged through the output signal, in the form of a 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 (D) and the cycle repeated.

The complete circuit model for the piezoelectric stack, relaxation oscillator, and load including nominal values for each of the circuit elements is presented in Figure 5. The capacitor C1 represents the actual capacitance of the piezoelectric stack calculated using analytical models. The transistor models Q1 and Q2 are general-purpose transistors for switching and amplifications, manufactured by *Semicoa* and *Fairchild Semiconductor*, respectively. The remainder of the circuit elements C2, R2 and R3 were nominal values that produce a pulsed output at R3.

This 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 MΩ digital oscilloscope. The input and output voltages were measured at the emitters of Q1 and Q2, respectively. The experimental and simulated behavior of the power module is provided in Figure 6. Each current pulse represents a pressure change of 10.8 kPa for every output pulse, corresponding to 0.001% of a possible 100 MPa pressure range (12 bit accuracy). 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 output pulse width shown is approximately 30μs. This pulse width corresponds to a 33 kHz (tip to tail) maximum repetition frequency, though higher frequency signals may be used for transmission.

Transmission Module

To realize widespread wireless sensing in injection molding, a Multiple-Sensor-Single-Receiver (MSSR) configuration is needed to measure pressure variations at different locations along the cavity. In order for the receiver to differentiate the individual sensors, the ultrasonic signals generated by each sensor must be distinctly identifiable.. Since an ultrasonic wave can be readily characterized by its center frequency, it is then natural to assign non-overlapping frequency bands to the transmitters. On the receiver side, appropriate signal processing techniques, such as short-time Fourier transform or wavelet transform, can then be used to separate and identify the individual pulses.

Piezoelectric ceramics have long been used for making ultrasonic transmitters for non-destructive testing of materials and medical imaging. Figure 7 shows the cross-section of such a transmitter. The ultrasonic wave is generated by the thickness mode vibration of the piezoelectric disk upon application of an alternating electrical voltage. A piezoelectric disk driven at its mechanical resonant frequency will exhibit a large mechanical displacement and thus convert electrical energy into ultrasonic energy most efficiently. If the excitation is in the form of an electrical pulse, the piezoelectric disk will "ring" at this resonant frequency and generate short ultrasonic pulse. Due to the multiple vibrational modes associated with a piezoelectric disk, more than one resonant frequencies exist in reality. Therefore, to design an ultrasonic transmitter with a specific center frequency,

frequency response of the piezoelectric disk need to be understood to properly choose a specific vibration mode. Furthermore, the design will need to consider the effect of wear-plate, which is glued to the piezoelectric disk for protecting against environmental effects (e.g. mechanical wear and chemical erosion). In order to characterize the frequency behavior of piezoelectric disks and dependence of their resonant frequencies on their geometry, the finite element method was applied to investigate piezoelectric disks with thickness T= 1 mm and aspect ratio D/T varying from 0.4 to 20. Specifically, piezoelectric material PZT-5A with material constants as shown in Table 1 was used for this application [5].

Since the purpose of the ultrasonic transmitter is to propagate an ultrasonic wave into the medium, the piezoelectric disk should vibrate like a piston with a uniformly displaced surface. Such a behavior is best induced using a thickness extensional (TE) mode. For validation purposes, harmonic analysis with frequency ranging from 0 to 2,200 kHz was conducted. The absolute values of the normal displacement for four aspect ratios (radius/thickness) were selected and plotted in Figure 8. For a piezoelectric disk with an aspect ratio of 3, no "TE" mode exists. Therefore it is not a suitable transmitter design for the wireless sensor. As the aspect ratio increases to 6, a peak displacement appears at the "TE" mode resonant frequency constant around 2,000 kHz•mm. However, several other "R" modes are also significant at this aspect ratio, which indicates that the disk has strong electromechanical coupling at those resonant frequencies. An ultrasonic transmitter made out of a piezoelectric disk like this will generate ultrasonic pulse having more than one center frequencies and is thus not suitable for the wireless measurement purpose. As the aspect ratio continues to increase the peak displacement at "TE" mode increases and becomes dominant for aspect ratio over 10, as shown in Figure 8 for aspect ratios 13 and 20, respectively. This indicates that a piezoelectric disk with an aspect ratio larger than 10 is preferred for the design of ultrasonic transmitters used in the wireless pressure sensing.

To protect the piezoelectric disk from mechanical wear and chemical erosion, a wear-plate is needed, which in the present design was glued to the front surface of the piezoelectric disk. The inclusion of an additional plate acts as a mass load to the piezoelectric disk and therefore changes the "TE" resonant frequency of the transmitter. It is important for the transmitter design to investigate the influence of the wear-plate to the overall frequency response. Piezoceramic disks with thickness T=1mm and aspect ratio D/T=10 in conjunction with a common wear-plate material, nylon, was used in the analysis. The material properties of Nylon are listed in Table 2.

To study the dependency of resonant frequency shift on the wear-plate thickness, nylon plates with thickness varies from 0 to 1.6 times of the quarter-wavelength thickness at the "TE" resonant frequency were investigated. Harmonic analysis with frequency ranging from 800 kHz to 2,800 kHz was performed and the average displacements across the wear-plate surface are shown in Figure 9 as a contour plot. Two bright traces can be clearly seen from the plot, which represent two groups of resonant frequencies that have distinct high displacements. The trace labeled f_1 is the resonant frequency of the transmitter associated with the "TE" mode of the piezoelectric disk. The trace labeled f_2 is the resonant frequency introduced by the wear-plate. Two additional lines were drawn overlaid on the plot. The horizontal short dashed line labeled as f_r^{TE} is the "TE" mode resonant frequency of the piezoelectric disk without wear-plate. The long dashed line is the quarter-wavelength frequency of the wear-plate, which is labeled as $f_{\lambda/4}$. At this frequency, the thickness of the wear-plate is equal to a quarter of the wavelength of the ultrasound transmitted in that wear-plate. The resonant frequency f_1 for the transmitter with zero thickness wear-plate is the same as the "TE" mode resonant frequency f_r^{TE}. When the normalized wear-plate thickness is less than 0.2, the f_1 resonant frequency remains unchanged. For plate thickness greater than 0.2, the f_1 resonant frequency drops with the increase of the wear-plate thickness. As the normalized exceeds the value of 1, the f_1 resonant frequency shifts further away from f_r^{TE} and converges to the quarter-wavelength frequency $f_{\lambda/4}$. For the normalized wear-plate thicknesses 0.2 and 0.5, only one distinct displacement exists in the frequency range under study. This single peak indicates that there is only one frequency at which the transmitter can be strongly excited and the ultrasonic pulse generated by this transmitter could have only one single center frequency, and therefore is suitable for a MSSR sensing configuration.

Conclusions

The realization of a functional, self-energizing, wireless sensor requires the research & development of functioning power and transmission modules. With respect to power generation, validation of the described analytical models with the designed piezoelectric stack showed agreement within about 10% of the predicted energy. With respect to power modulation, which is necessary to excite the transmission module, the threshold switch was found to be only stable between two frequency limits. Below a lower frequency limit, the current supply leaks and the sensor could not reach the switch's required on-voltage. Above an upper frequency limit, the current did not drop below the switch's holding current. These limits are the reason for including the parallel resistor R2. By adjusting the resistance of this element it was possible to change the characteristics associated with the switch. The stable ramp rates associated with the nominal value of 2 kΩ for R2 are between 9.87E4 MPa/sec and 1.24E6 MPa/sec. Ramp rates outside of this limit will not produce output pulses. While the upper limit on ramp rate far exceeds the capability of actual manufacturing processes, further design refinement is required to operate at lower ramp values.

For the purpose of designing ultrasonic transmitters used in the wireless pressure measurement, a complete study on the frequency response of the transmitter was performed. Resonant frequencies of a thin piezoelectric disk were predicted using finite element method. The observed resonant frequencies were classified. Their dependence on the disk aspect ratio and strength of coupling were also studied. It was found that piezoelectric disks with an aspect ratio larger than 10 have strong “TE” mode excitation and therefore can generate ultrasonic pulse of a distinct center frequency. Therefore, it can be utilized for the design of transmitters used in the MSSR configuration. The frequency response of the piezoelectric disk glued with a nylon wear-plate was also investigated. It was found that the “TE” mode resonant frequency of the transmitter decreases as the wear-plate thickness increases. To avoid transmission disturbance, wear-plates with a normalized thickness less than 0.8 are recommended.

This research has proven the technical feasibility of a wireless, self-energizing pressure sensor. Further development is on-going to shrink the package, improve low frequency response, and customize an ultrasonic receiver to validate commercial feasibility.

References

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Tables & Figures

Table 1: Material Constants of PZT-5A

e_{31} (C/m^2)	-5.4
e_{33}	15.8
e_{51}	12.3
c_{11}^E ($\times 10^{10}$ N/m^2)	12.1
c_{12}^E	7.52
c_{13}^E	7.51
c_{33}^E	11.1
c_{44}^E	2.11
c_{66}^E	2.29
$\varepsilon_{11}^S / \varepsilon_0$	916
$\varepsilon_{33}^S / \varepsilon_0$	830
ρ (kg/m^3)	7750

Table 2: Table 2. Material Properties of Nylon Wear-Plate

Density (kg/m^3)	1120
Elastic Modulus (Gpa)	3.8
Poisson’s Ratio	0.4
Sound Velocity (m/s)	2620
Acoustic Impedance (Mrayl)	2.93

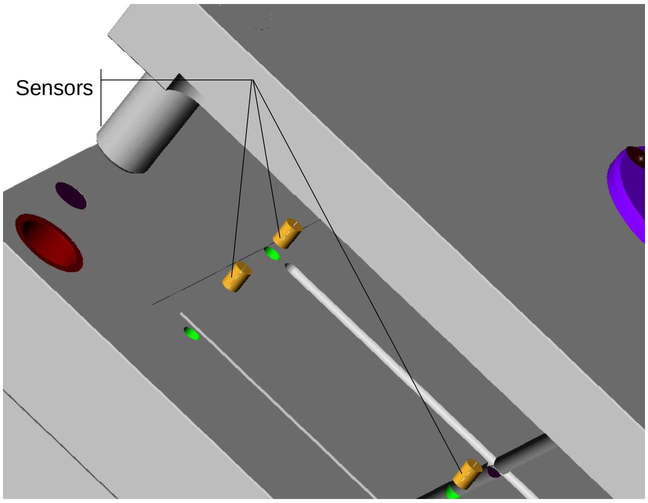

Figure 1: Remote Sensor Installation

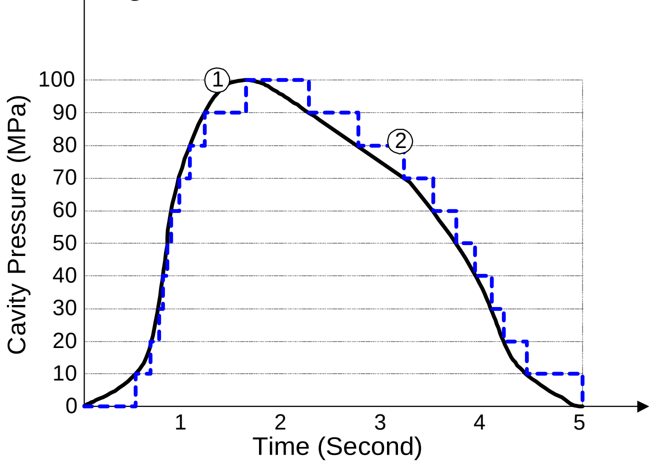

Figure 2: Traces for ① Observed and ② Digitized Pressure

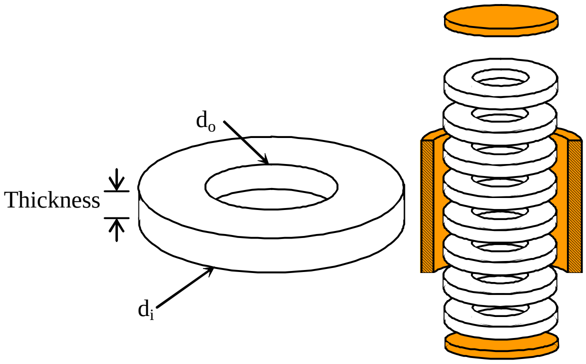

Figure 3: Piezoelectric Stack

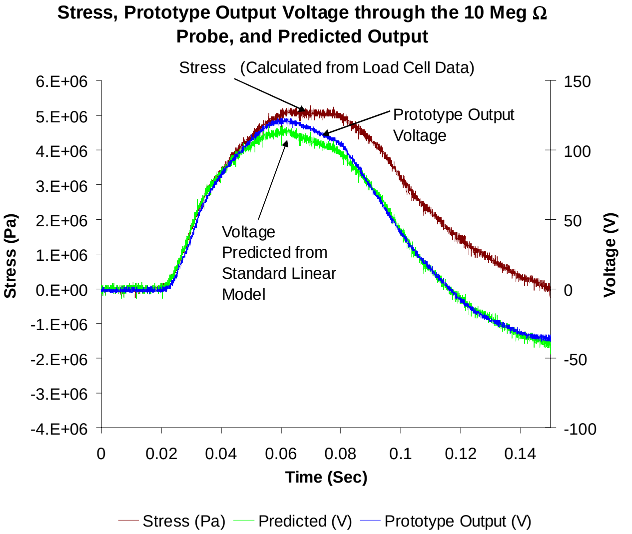

Figure 4: Stress and Voltage for the Piezoelectric Stack

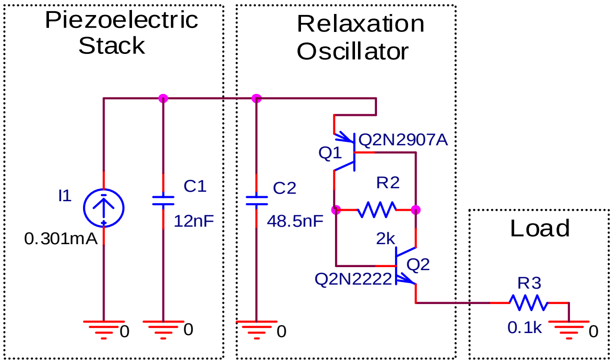

Figure 5: Piezoelectric Power Module

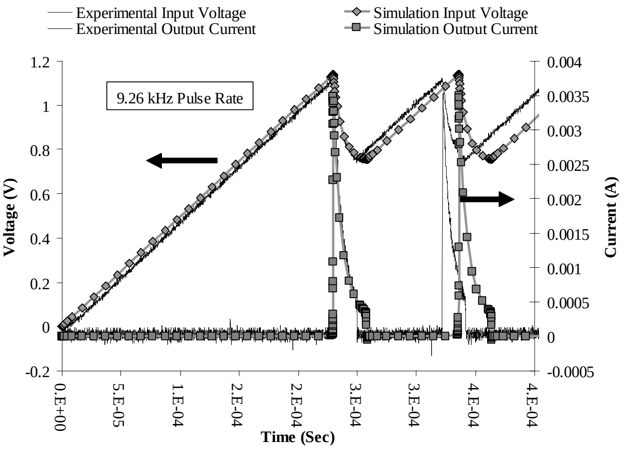

Figure 6: Experimental and Simulation Results at Startup

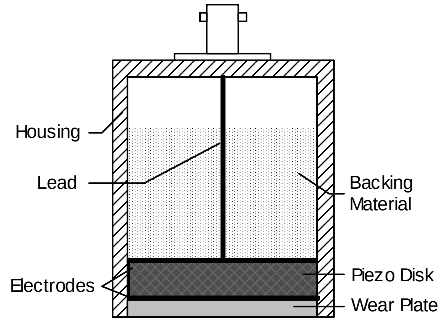

Figure 7: Piezoelectric Ultrasonic Transmitter

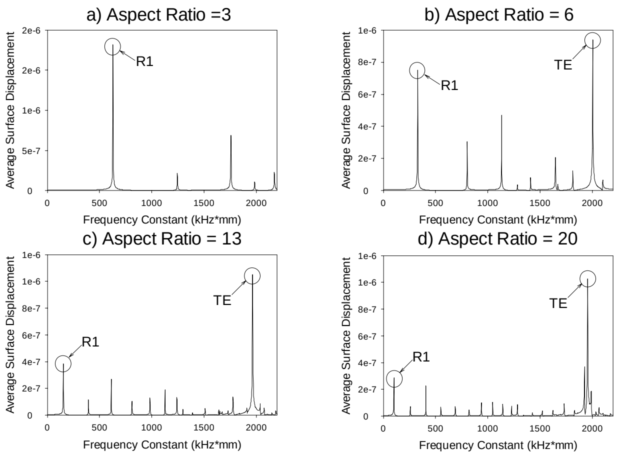

Figure 8: Average Surface Displacements 3, 6, 13, 20 L:T

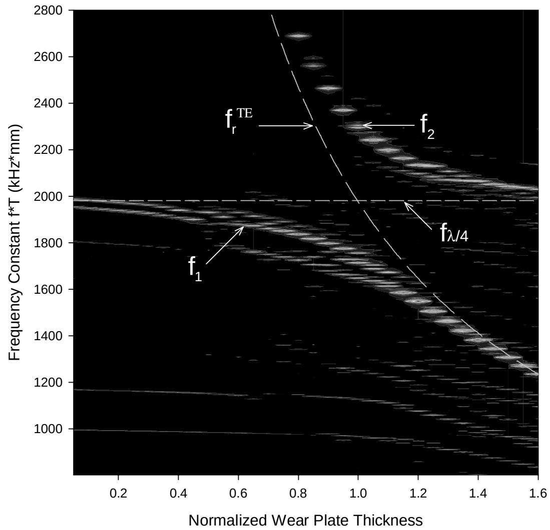

Figure 9: Displacement Peak Frequency vs. Wear-Plate Thickness