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Characterization of MEMS Automotive Sensor for Tire Pressure Monitoring System

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Abstract: Assessment to the investigated emerging sensor technologies indicates that the capacitive Microelectro-mechanical System (MEMS) pressure sensor has the highest potential used for the development of tire Pressure Monitoring System (TPMS). The potential owes to its robustness, small size and low power consumption, besides fitted well in total electronic system integration. This study describes the basic configuration, operating principle and experimental results of MEMS sensor for the development of TPMS. In addition, the application performance and experimental set up of the sensor are also discussed in this paper. Input and output pins configurations of the MEMS sensors at both standby and measured modes are studied, in order to relate to their unique construction. The threshold check is used by the tire pressure monitoring system through sensed signal extracted the data acquisition environment of the MEMS sensor. This study provides preliminary insight of using MEMS pressure sensor in a TPMS.

Key words: Microelectromechanical system, capacitive MEMS sensor, smart sensor

INTRODUCTION

Currently, electronic control system in a vehicle uses a wide variety of sensors input in order to enhance the safety and reliability in operation. Besides road safety, a Tire Pressure Monitoring System (TPMS) can increase tire life cycle and reduce fuel consumption. Under and over inflated tires cause abnormal tire wear, increase fuel consumption, reduce riding comfort and tire life, respectively (Ronald, 1989). Adoptions of such tires with TPMS capability is very much needed as a driver can identify run-flat condition; being used for a long period and driven at a higher rated speed. TPMS also provides early warning to the driver of pressure loss, tire running at low pressure, tire failure, prevention of errors on nominal pressure value and inflating tires, automatic identification and location of wheels (http://www.can-cia.de 2004).

To date, a TPMS uses various different kinds of sensors. BMW-Michelin developed a TPMS that placed sensors inside the tires to detect tire pressure and temperature for the BMW 850 model. The sensors are connected with a loop antenna on the rim of the wheels. Another antenna is fixed to the suspension which is near each wheel to the control unit with a high-frequency current. This current introduces a voltage to provide a wireless power source for the sensors and their associated circuits. Currently, most TPMS consists of active battery powered sensors unit inside each wheel (Wunderlich *et al*., 1999). However, problem for this type of sensors (microcontroller based system) is that it requires lithium battery. This limits the life cycle of the sensor units and also leads to problem regarding waste management (Schimetta *et al*., 2001).

To overcome such problem, Schimetta *et al.* (2001) introduced a wireless pressure and temperature monitoring system based on Surface Acoustic Wave (SAW) transponder. This enables the sensor units to obtain its energy from the electromagnetic RF transceiver unit. However, any mal-functioning in the system will trigger an alert. Yamamoto *et al*., 2002 introduced touch mode passive TPMS based on Radio Frequency Identification (RFID) to measure pressure, temperature and to read ID number of the tires (Yamamoto *et al*., 2002). Grossmann developed crystal based quartz resonator remote sensor for tire pressure monitoring to over come active sensor battery related problems (Rainer, 1999), however, as the pulse response is broadcasted over the same antenna, the sensor produces some kind of echo. This echo produces a huge noise in the RF transmission where the removal of noise requires an extra band pass filter.

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Sensors control important system parameters, whereas, the microprocessor evaluates signals and decide whether to give warning signal or carry out another action. For further improvement and enhancement in the robustness of the electronics, the TPMS has used many sensors such as acoustic sensor, optical sensor, vibrating string sensor, ultra wide band technology and capacitive sensor (Appollo, 2003). However, the appropriate sensor for different possibilities of TPMS are still investigated and discussed. Acoustic sensors and optical sensors have the potential to detect data on road condition that can be used to derive friction parameters, but they cannot be used for force measurement (Scholl *et al*., 2003; Schimetta *et al*., 2000; BMW, 2000). However, the main disadvantageous of optical sensors are low robustness in a harsh environment during vehicle operation.

The limiting capability factor of the mechanical sensor such as the vibrating string is during measurement tasks. Extensive investigation in the sensor technologies have shown that the capacitive Microelectro-mechanical System (MEMS) sensor has the highest potential to be used for the development of automotive intelligent safety system (Gogoi and Mladenvic, 2002; Quero and Bray, 2002). The main advantages are robustness, small size, low power consumption and can be fitted well in total electronics system integration. Thus, the capacitive MEMS sensor technology has opens up a new perspective for an automotive intelligent safety system. This in turn fulfils the requirements on high robustness and low power consumption and offers cost benefits.

This study reports an experimental data analysis through automatic and discrete monitoring of an automobile tire pressure using a surface micromachined capacitive MEMS sensor, which is based on Motorola MPXY8000 (Testing of MEMS, 2004). The study also describes the principle, measurement setup, experimental results and application. Sensing signal to the TPMS using threshold check is acquired from the data acquisition environment of the MEMS sensor.

MATERIALS AND METHODS

The eight pins MEMS sensor, MPXY8000 comprises of six I/O pins and two power supply pins (VDD and VSS). There are four input pins S0, S1, DATA and CLK whilst the other two are output pins, which are OUT and RST (Burgess, 2002). The pin assignment and function descriptions are shown in Fig. 1 and Table 1, respectively.

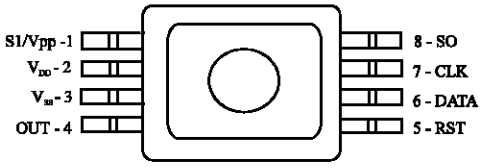

Fig. 1: Pin assignment of sensor

Table 1: Pin description and function of sensor

Pin No.	Pin name	Pin function	Direction
1	S1	Mode Select	Input
2	V_{DD}	Positive Power	Power
3	V_{SS}	Ground	Power
4	OUT	Comparator or Wake-up Output	Output
5	RST	MCU Reset	Output
6	DATA	Data	Input
7	CLK	Data Clock	Input
8	S0	Mode Select	Input

Pins Function: Power supply pins (V_{DD} and V_{SS}) are decoupled from the noise caused by digital switching currents and parasitic inductances. Inaccuracies in readings may be arisen from coupled noise in the sampling circuitry. It is preferable to mount a surface mount of 0.1 μF mica or ceramic capacitor close to the V_{DD} and V_{SS} pins. There are four available operating modes for the MEMS sensor, which are standby/reset, measure pressure, measure temperature and output read. The mode can be selected by setting the control pins of S1 and S0. The following section describes those modes. The MEMS sensor and the controller communicate through the CLK and DATA pins. The CLK pin is designed to operate at a maximum of 1 MHz. In order to avoid conversion errors when performing the successive approximations, minimum clock period is multiplied by 64 and should not be longer than the specified sample capacitor discharge time.

The rising edge of the CLK pin clocks DATA into the serial register, but at the eighth falling edge of the CLK pin, the 8 bit data in the serial register is transferred into the Data Accumulator Register-*DAR*. Shifting in undesired data might occur as the data is transferred on the rising edges of the CLK signal. The undesired shifting can be avoided by keeping the CLK signal from the MCU idle in the low state. Depending on the mode of control, the OUT pin serves three functions such as OUT pin during output read mode, OUT pin during standby/reset mode and OUT pin during IRQ pin connection. In output read mode, the OUT pin is connected to the analog comparator for sensor acquisition. During this mode, the OUT pin is either high or low depending on the DAC output of whether it is lower or higher than the sampled value in the sampling capacitor, respectively. During Standby/Reset mode, the output multiplexer connects the OUT pin to an active low wake-up pulse signal. This pulse can be used to wake up an MCU in stop mode. This low pulse is generated from the internal Low Frequency Oscillator-LFO and the divider chain. With the nominal frequency of the internal LFO at 5.4 kHz, the wake up pulse occurs approximately every 3 seconds. This pulse has twice the period of LFO or 370 μs as mentioned earlier. In IRQ connected mode, the OUT pin can be connected to an IRQ pin that supports wake up from idle or stop mode caused by a falling edge on its

input. Before initiating the standby mode on the MCU, the IRQ pin needs to be configured as an interrupt pin to wake up the MCU on a falling edge.

The RST pin is an output pin that serves as a periodic low-pulse reset, which triggers a signal approximately every 52 min to the microcontroller reset pin. Normally, a TPMS includes a watchdog timer to safeguard the system from crashing by applying a reset signal. Due to harsh environment and economical constraint, the MEMS sensor provides a fail-safe mechanism in the form of a reset signal regardless of the sensor operating modes. The reset pulse might occur in any of the four operating modes. If the reset signal occurs in the system, then data such as running averages of pressure should be calculated and stored at the receiver end since the periodic reset would destroy any data stored in RAM.

Serial interface description: During standby/reset and output read modes, the SPI loads data into the DAR of the MEMS sensor. During the loading, the MCU becomes the master whereas the MEMS sensor becomes the slave where the data transmission is unidirectional from the controller to the sensor. The data to be clocked in by MCU or controller must be synchronized with the SPI of the MEMS sensor, prior to data being clocked into the DAR.

For MCUs without a SPI, one needs to use software routines to emulate the SPI protocol. One must also ensure that the MEMS sensor's internal SPI bit counter is synchronized with the data that is shifted. During power up, this bit counter defaults to an unknown state. The bit counter resets to zero when entering into either the measured pressure or measured temperature modes. This counter reset provides a convenient method for providing one hundred percent assurance that the data shifted in is always synchronized with the DAR bit counter.

PRINCIPLE OPERATION

Daytona is a CMOS based circuit with a state-of-the-art surface micromachined capacitive MEMS pressure sensor cell with an integrated temperature sensor and interface circuit integrated in a single die. The device is able to measure absolute pressures and temperature with MCU control and converts these values to 8 bit digital value using successive approximation (Burgess, 2003). The device also includes MCU wake-up and periodic reset features controlled by an internal LFO. The main part of Daytona consists of two circuits on the same die. The first circuit includes the pressure and temperature sensors. This circuit is fully analog and it has two status pins S1/VPP and S0 determine which one is active. The sensed value is converted into a voltage, which is subsequently stored in the sampling capacitor.

Table 2: Mode of control of pin S1 and S0

S1	S0	Mode
0	0	Standby/reset (Idle)
0	1	Measure pressure
1	0	Measure temperature
1	1	Output read

The other part of the Daytona is mixed-signal, with a digital input and an analog output. The input is taken through the CLK and DATA pins using a simple serial communication protocol. The data is stored in the D/A register and converted to a DC voltage. This voltage is then compared to the voltage stored in the sampling capacitor that determines the state of the OUT pin by comparing it with by the 8-bit digital values using a successive approximation algorithm. A wake-up facility is also available where a signal is sent to the MCU from the OUT pin every three seconds. After 10 successive wake ups (30 sec), the module transmits its status to the receiver as well as a reset signal on the RST pin approximately every hour.

MODE OF CONTROL

Pins S1 and S0 determines the mode of control, which are summarized in Table 2.

In standby/reset mode, the MPXY8000 MEMS sensor consumes the lowest power. In this mode, the analog sections of the sensor are switched off, but LFO, SPI, DAR, wake-up pulse and reset pulse dividers are switched on. The controller may be able to shift threshold data into the DAR register during this mode. During Standby mode, the MPXY8000 MEMS sensor sends a 370 μs wake-up pulse through OUT pin approximately in 3 sec intervals. The negative pulse functions as a wake-up signal to a microcontroller that is in a stop mode.

In pressure measurement mode, the sensor multiplexer connects the output of the pressure sensor to the sampling capacitor. In order to allow the pressure sensor switched capacitor circuit to turn on and settle, the duration of this mode should be at least 500 μs. In a program sequence, a delay of at least 500 μs should be inserted after placing the MPXY8000 MEMS sensor in this mode to avoid sampling the pressure sensor output while the circuitry is still unstable. An erroneous reading might occur due to failure to include a sufficient delay. The bit counter is reset during pressure measurement mode, thus allowing the synchronization with the external clock at the CLK pin.

In temperature measurement mode, the sensor multiplexer connects the output of the temperature sensor

to the sampling capacitor. The circuit needs at least 200 µs to settle since initiation. The bit counter is reset during pressure measurement mode, thus allowing the synchronization with the external clock at the CLK pin.

In output read mode, the output multiplexer connects the comparator output to the OUT pin. After sampling the pressure or temperature sensor, this initiates the mode and immediately samples the OUT pin or performs successive approximation routine before the sensor voltage in the sampling capacitor discharges. In this mode, the sampled sensor voltage may be converted to an 8 bit value or a threshold check may be initiated.

SENSOR DATA ACQUISITION

There are two ways to acquire data from the MPXY8000 MEMS sensor by using a successive approximation and a threshold check. A successive approximation provides an accurate conversion of the sampled temperature or a pressure reading into an 8 bit value. In a threshold check, the DAR is preloaded with a threshold value during Standby/Reset mode to detect whether the pressure or temperature has crossed a particular level. The following section describes these two methods in detail.

Successive approximation: During analog to digital conversion, the MCU is used as a Successive Approximation Routine - *SAR* controller. The 8 bit DAC data is loaded serially by the MCU for each of the eight guesses. Therefore, a complete successive approximation conversion is completed in eight guesses with eight CLK cycles per guess, or 64 CLK cycles. In order to carry out a conversion, a half-scale (0xFF/2~0x80) guess byte is serially loaded into the DAR and the OUT pin is monitored by the MCU thereafter.

The process of monitoring the OUT pin and setting or clearing bit by bit in the SAR is performed until all eight guesses (8 bits) are determined. Soon after the guess is loaded and the state of the OUT pin is low, the guess in the DAR is too high or the guess matches the value in the sample capacitor. If the OUT pin remains high after a guess is loaded into the DAR, then the guess is too low.

Threshold check: While in output read mode, the MCU can initiate a threshold check on the MPXY8000 MEMS sensor. This process is to estimate whether the pressure or temperature is above or below a particular level without having to perform a full successive approximation routine. Separate pressure and temperature threshold can be set. However, several thresholds may also be set to check for a range of pressure or temperatures. When performing a threshold check, the DAR can be preloaded with a threshold value during standby/reset mode. The sensor output is then appropriately being sampled. The sensor output can also be compared to the threshold value during output read mode once the state of the OUT pin is read.

EXPERIMENTAL RESULTS

Agilent 54622D Mixed-Signal Oscilloscope was used to acquire data from the I/O pins of MEMS sensor. The data help the evaluation process of the testing and measurement performance of the MEMS sensor. The sensor is mounted on the rim in this experiment where the data is available by changing threshold value of the sensor in MCU. Indeed, the pressure sensor that comprises in the TPM module is secured in a housing of hard epoxy materials and secured by a nylon strap. The prototype then is used for the experimental measurements. The bottom surface of the housing is curved to fit snugly in the drop centre of a 15-inch rim. The module transmits the tire pressure signals to the receiver via a loop antenna. The prototype of the TPM module fitted on the rim is shown in Fig. 2.

Figure 3 shows the output of MEMS sensor from OUT pin, with and without analog comparator connection to the sensor data acquisition. In standby mode, the analog sections of the sensor are switched off and only LFO, SPI and DAR are switched on to generate wake up pulse. The wake up signal at standby mode is approximately 3 sec interval as shown in Fig. 3a. Figure 3b and 3c shows the output signals when OUT pin is connected to the analog comparator for the sensor acquisition during output read mode. When the DAC output from DAR is higher than the sampled value in the sampling capacitor i.e., DAC > sampled sensor voltage, the output of OUT pin is low indicated by a logic 0 as shown in Fig. 3b. On the other hand, if the DAC output is lower than the sampled value in the sampling capacitor, the OUT pin is high indicated by logic 1 as shown in Fig. 3c.

Fig. 2: Prototype of TPM module fitted on the rim

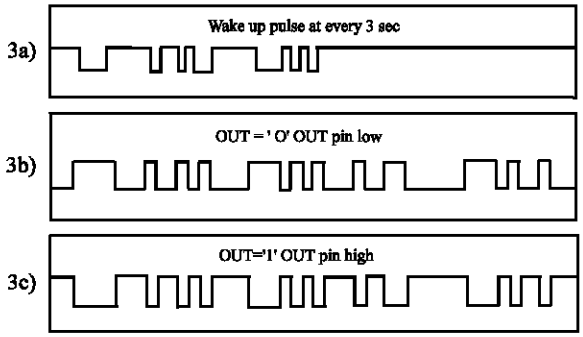

Fig. 3: MEMS sensor output signal a) standby Mode b) transmitted at DAC ≥ sampled sensor voltage c) transmitted at DAC < sampled sensor voltage

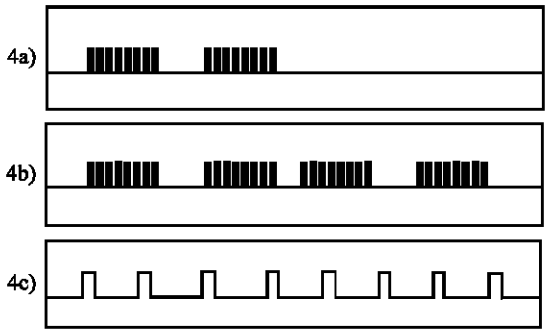

Fig. 4: Serial DATA of TPM MEMS sensor mode (a) standby (b) measured (c) extended form of DATA guesses

Fig. 5: Serial CLK of TPM MEMS sensor (a) standby mode (b) measured mode (c) extended form of CLK

Thus, the sensor monitors and transmits the tire pressure to the receiver either low or high in comparison to the threshold pressure.

Figure 4 and 5 shows the serial communication between sensor and the controller are achieved through the CLK and DATA pins. Data is clocked into the serial register on the edge of the CLK pin and at the eighth edge of CLK pin, the 8 bit data in the serial register is transferred in the DAR. Figure 4a, 4b and 4c are the serial data of DATA pin of MEMS sensor at standby mode, measured mode and extended form of data guesses, respectively. The CLK pin is also serial interface to the sensor DAR. The data clock from CLK pin is shown in Fig. 5 at standby mode, measured mode and extended form of CLK data.

CONCLUSIONS

In this study the implementation of MEMS sensor incorporating with tire pressure module mounted on the tire rim is tested and measured for tire pressure monitoring system through changing threshold value program in MCU. The measurement and data acquisition has been done using Agilent 54622D Mixed-Signal Oscilloscope. The results in the experimental system shows that the output signals from OUT pin transmit the signals based on the sampled value in the sampling capacitor i.e., real pressure inside tire. It also focused data communication and clocked time at standby mode and measured mode of the sensor. Therefore, it has been demonstrated that the MEMS pressure sensor is well suitable for a tire pressure monitoring robust application, requiring high accuracy pressure, temperature and low power consumption.

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