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Washing Appliance Sensor Selection

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INTRODUCTION

North American washing machines currently in production use mechanical sensors for water level measurement function. These sensors are either purely mechanical pressure switch with discrete trip points or electromechanical pressure sensor with an on-board electronics for a frequency output.

High efficiency machines require high performance sensors (accuracy, linearity, repeatability) even at lower pressure ranges. Benchmarks indicate that these performance goals is difficult to achieve using current mechanical pressure sensors.

In Europe, where energy conservation is mandated, washing machine manufacturers have started to look at electronic solutions where accuracy, reliability, repeatability and additional functionality is to be implemented. North American and Asia Pacific manufacturers are also looking for better solutions.

From surveys of customer requirements, a typical vertical-axis machine calls for a sensor with 600 mm H_2O (24 “ H_2O ~ 6 kPa) sensor with a 5% FS accuracy spec. Certain appliances call for a lower pressure range especially in Europe where horizontal axis machines are common.

SENSOR SOLUTIONS

For the typical 600 mm H_2O, 5% FS spec, an off the shelf solution available today is the MPX10/MPX12, MXP2010 and the MPXV4006G sensor. The MPX10 (or the MPX12) is 10 kPa (40 “ H_2O) full-scale pressure range device. It is uncompensated for temperature and untrimmed offset and full-scale span. This means that the end user must temperature compensate as well as calibrate the full-scale offset and span of the device. The output of the device must be amplified using a differential amplifier (see Figure 1) so it can be interfaced to an A/D and to obtain the desired range.

Since the MPX10/MPX12 sensors must be calibrated, the implications of this device being used in high-volume production is expensive. Because the offset and full-scale output can vary from part to part, a two-point calibration is required as a minimum. A two point calibration is a time consuming procedure as well as possible modification to the production line to accommodate the calibration process. The circuitry must also accommodate for trimming, i.e., via trimpots and/or EEPROM to store the calibration data. This adds extra cost to the system.

The MPX2010 is a 10 kPa (40" H_2O), temperature compensated, offset and full-scale output calibrated device. A differential amplifier like the one shown in Figure 1 should be used to amplify its output. Unlike the MPX10 or MPX12, this device does not need a two-point calibration but auto-zeroing can improve its performance. This procedure is easily implemented using the system MCU.

The MPXV4006G is a fully integrated pressure sensor specifically designed for appliance water level sensing application. This device has an on board amplification, temperature compensation and trimmed span. An auto-zero procedure should be implemented with this device (refer to Application Note AN1636). Because expensive and time consuming calibration, temperature compensation and amplification is already implemented, this device is more suitable for high volume production. The MPXV4006G integrated sensor is guaranteed to be have an accuracy of ± 3% FS over its pressure and temperature range.

For washing machine applications where low cost and high volume productions are involved, both the MPX2010 and MPXV4006G are recommended. Both solutions can be used in current vertical axis machines where the water level in the 600 mm H_2O or 24 “ H_2O range. In the following, a comparison is made between MPX2010 and MPXV4006G in terms of system and performance considerations to help the customer make a decision.

EXPECTED ACCURACY OF THE MPX2010 SYSTEM SOLUTION

The MPX2010 compensated sensor has an off the shelf overall RMS accuracy of ± 7.2% FS over 0 to 85°C temperature range.

Auto-zeroing can improve the sensor accuracy to ± 4.42% FS. However, since this sensor does not have an integrated amplification, its amplifier section must be designed carefully in order to meet the target accuracy requirement. The MPX2010 compensated sensor has the following specifications shown on Table 1.

Table 1. MPX2010 Specifications

Characteristic	Min	Typ	Max	Unit
Pressure Range	0		10	kPa
Supply Voltage		10	16	Vdc
Supply Current		6		mA
Full Scale Span	24	25	26	mV
Offset	*1		1	mV
Sensitivity		25		mV/kPa
Linearity	*1		1	$\%V_{FSS}$
Pressure Hysterisis		0.1		$\%V_{FSS}$
Temperature Hysterisis (*40 to 125°C)		0.5		$\%V_{FSS}$
Temperature Effect on Span	*1		1	$\%V_{FSS}$
Temperature Effect Offset (0 to 85°C)	*1		1	mV
Input Impedance	1300		2550	W
Output Impedance	1400		3000	W
Response Time (10% to 90%)		1		ms
Warm-Up		20		ms

The sensor system errors is made up of the sensor errors, amplifier errors and A/D errors. In other words,

$$\varepsilon\text{System} = \sqrt{\varepsilon\text{Sensor}^2 + \varepsilon\text{Amplifier}^2 + \varepsilon\text{ADResolution}^2} \quad (1)$$

Table 2 shows the MPX2010 with the errors converted to $\%V_{FSS}$. The expected maximum root mean squared error of the sensor is

$$\varepsilon\text{Sensor} = \sqrt{\text{SpanCal}^2 + \text{Lin}^2 + \text{Phys}^2 + \text{Thys}^2 + \text{TCS}^2 + \text{OffCal}^2 + \text{Tco}^2 + \text{OffStab}^2} \quad (2)$$

$$= \pm 7.19\%\ \text{FS.}$$

With auto-zeroing, the offset calibration, temperature effect on offset and offset stability is reduced or eliminated,

$$\varepsilon\text{Sensor} = \sqrt{\text{SpanCal}^2 + \text{Lin}^2 + \text{Phys}^2 + \text{Thys}^2 + \text{TCS}^2} \quad (3)$$

$$= +/- 4.42\%\ \text{FS.}$$

The sensor error is calculated using the full-scale pressure range of the device, 0 to 85°C temperature and 10 V excitation.

In comparison with the MPXV4006G solution, the expected accuracy of the system (MPXV4006G + 8 bit A/D) with auto-zero is 3.1% FS.

Table 2. MPX2010 Span, Offset and Calculated Maximum RMS Error*

Span Errors (converted to $\%V_{FSS}$)	Symbol	Error Value	Note	Unit
Span Calibration	SpanCal	4		$\%V_{FSS}$
Linearity	Lin	1		$\%V_{FSS}$
Pressure Hysterisis	Phys	0.1		$\%V_{FSS}$
Temperature Hysterisis	Thys	0.5		$\%V_{FSS}$
Temperature Effect on Span	Tcs	1.5		$\%V_{FSS}$

Offset Errors (converted to $\%V_{FSS}$)				
Offset Calibration	OffCal	4		$\%V_{FSS}$
Temperature Effect on Offset	Tco	4		$\%V_{FSS}$
Offset Stability	OffStab	0.5		$\%V_{FSS}$

Calculated Maximum RMS Errors		RMS Error		
No Compensation*		7.19		$\%_{FS}$
With auto-zero		4.42		$\%_{FS}$

* This assumes the power supply is constant.

AMPLIFIER SELECTION AND AMPLIFIER INDUCED ERRORS

A differential amplifier is needed to convert the differential output of the MPX2010 sensor to a high level ground-referenced (single-ended). The classic three-op amp instrumentation amplifier can be used. However, it requires additional components (3 op-amps and possibly a split power supply). An instrumentation topology shown in Figure 1 requires only a single supply and only 2 op-amps and 1% resistors.

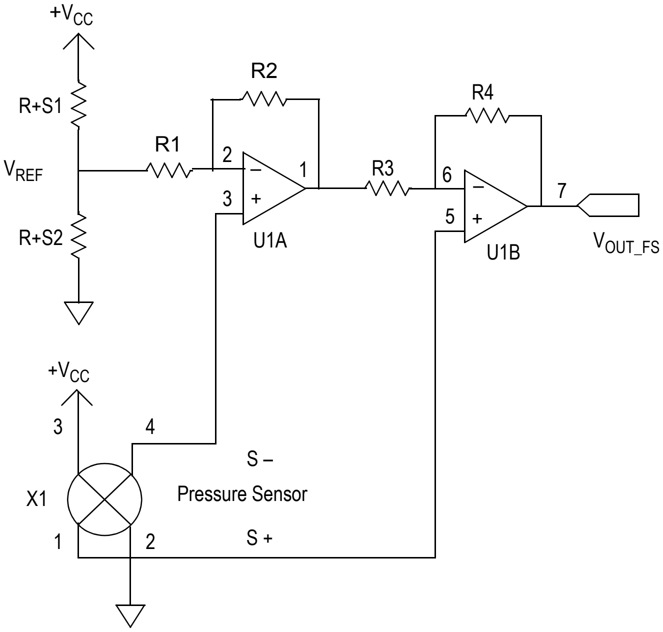

Figure 1. MPX2010 Amplifier Circuit

The circuit uses a voltage divider R+S1 and R+S2 to provide the reference (level shift), U1A and U1B are non-inverting amplifiers arranged in a differential configuration with gain resistors R1, R2, R3, and R4. Note that U1B is the main gain stage and it has the most gain. It is recommended to place a 0.015 μF capacitor in it's feedback loop (in parallel with R4) to reduce noise. The amplifier output can be characterized with the equation below:

$$\text{Gain} = \frac{R4}{R3} + 1 \tag{4}$$

$$\text{Voffset} = \text{VREF}\left(\frac{R2 \cdot R1}{R1 \cdot R3}\right) - \text{VSCM}\left[\left(\frac{R2 \cdot R4}{R1 \cdot R3}\right)\right] - 1 \tag{5}$$

$$\text{Vout} = (S+ - S-)\ \text{Gain} + \text{Voffset} \tag{6}$$

where (S+ - S-) = Sensor differential output + Sensor offset (7)

Equation 4 is the differential gain of the amplifier and equation 5 is the resulting offset voltage of the amplifier.

The above equations assume that the amplifier is close to ideal (high A_{OL}, low input offset voltage and low input offset bias currents). Since an ideal op-amp is hard to come by, the customer should select an op-amp based on cost and performance. Below are some points to keep in mind when selecting an op-amp and designing the amplifier circuit.

Note that the ratio R2*R4/R1*R3 controls the system offset as well as the common mode error of the amplifier. Mismatches in these resistors will result in an offset and common mode error which appear as offset. It is therefore recommended to use 1% metal film resistors to reduce these errors. Also, V_{REF} source impedance should be minimized in comparison with R1 in order to reduce common mode error.

Amplifier input offset and input bias currents can induce errors. For example, an input offset (Vio) of the amplifier can become significant when the closed-loop gain of the amplifier is increased. Furthermore, there is also a temperature coefficient of the input voltage offset which contribute an additional error across temperature. If the input bias current of the amplifier is not taken into account in the design, it can also become a source of error. A technique to reduce this error is to match the impedance the source impedance of what the op-amp input pins sees.

It is important to note that high performance op-amps are more expensive. An MC33272 op-amp has a low input offset and low input bias current which is suitable for the two-op amp amplifier design. We can see that there is a tradeoff between accuracy and cost when designing a solution with the MPX2010.

When designing a system based on the MPX2010, it is important to take into account errors due to parametric variation of the sensor (i.e., offset calibration, span calibration, TcS, TcO), power supply and the inherent errors of the amplification circuit. The offset and span errors greatly determines the resolution of the system (which adds to the system error). Even though the system offset error can be nulled out by auto-zeroing, these errors must be accounted for when setting the system gain (refer to AN1556 for more details). This forces the total span of the system to be smaller, because we must reserve an extra headroom from the total span to account for amplifier and A/D variations (i.e., amp. sat. voltage, power supply variation, A/D quantization error, and gain errors). If these errors are not accounted for, it could, for example, result in non-linearity errors if the sensor span or offset error causes the amplified output of the sensor to reach the saturation voltage of the amplifier.

As an example, a MPX2010 sensor system is designed which has a range of 600 mm H_2O FS range with a ±5% FS RMS error. The system uses a +5.0 V ±5% linear regulated power supply, a MC33272 dual op-amp and a 1% resistors.

Table 3 shows the resulting specification and component values for the system based on MPX2010 sensor.

Table 3. MPX2010 Sensor System Values

MPX2010 Sensor Design			
Parameter	Description	Value	Units
V_{CC}	Reg Power Supply	5	V
Differential Gain	Gain	433	V/V
Vout_FS	Full Scale Span	3.02	V
V_{REF}	Offset Reference	0.66	V
Parts List			
U1A,U1B	MC33272 Op-amp		
R1	Gain Resistor	39.2K	Ω
R2	Gain Resistor	90.9	Ω
R3	Gain Resistor	909	Ω
R4	Gain Resistor	392K	Ω
R + S1	Level Shift Resistor	1K	Ω
R + S2	Level Shift Resistor	150	Ω
X1	MPX2010		

Table 4. Performance Comparison between MPX2010 and MPXV4006G Solution

Error Contribution	**MPX2010 Solution Error (FS = 600 mm H_2O)**		**MPXV4006G Solution Error (FS = 612 mm H_2O)**	
	± % FS	± mm H_2O	± % FS	± mm H_2O
Max Sensor Error	7.19	43	3.00	18
System Resolution (A/D + Amplification)	1.30	8	0.80	5
System Error (Sensor + A/D + Amplification)	7.3	44	3.10	19
System Error with Auto-Zero	4.6	28	t3	t19

Note that the error due to system resolution is higher for the MPX2010 solution (± 2 bit A/D accuracy). This is because the MPX2010 span is limited as discussed above. Also, this accuracy assumes that the amplifier does not induce significant errors. As noted MPXV4006G sensor has better overall accuracy. The system resolution is very good because of its large span (4.6 V versus 3.0 V typical).

SUMMARY

Several washing machine solutions were examined. The MPX10/12 solution can be expensive in terms of additional support circuitry and the added time and labor involved during the calibration procedure. The MPX2010 is good alternative for high volume manufacturing because is already calibrated. With this solution, however, the system amplifier design must be chosen and designed carefully in order to minimize the system error. This is a consideration when deciding to implement a high accuracy solution with the MPX2010 because the cost of the system will go up.

The MPXV4006G solution is geared towards high volume manufacturing because trimming, compensation and amplification is already on board. Besides the system simplicity and using less component, the resolution and overall accuracy of this solution is better than the MPX2010 solution. In some cases, less components can actually improve the reliability and manufacturability the system.

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NOTES

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